TRIGA 14 MW RESEARCH REACTOR STATUS AND UTILIZATION

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Abstract.
Institute for Nuclear Research is the owner of the largest family TRIGA research reactor, TRIGA14 MW research reactor. TRIGA14 MW reactor was designed to be operated with HEU nuclear fuel but now the reactor core was fully converted to LEU nuclear fuel. The full conversion of the core was a necessary step to ensure the continuous operation of the reactor. The core conversion took place gradually, using fuel manufactured in different batches by two qualified suppliers based on the same well qualified technology for TRIGA fuel, including some variability which might lead to a peculiar behaviour under specific conditions of reactor utilization. After the completion of the conversion a modernization program for the reactor systems was initiated in order to achieve two main objectives: safe operation of the reactor and reactor utilization in a competitive environment to satisfy the current and future demands and requirements. The 14 MW TRIGA research reactor operated by the Institute for Nuclear Research in Pitesti, Romania, is a relatively new reactor, commissioned 37 years ago. It is expected to operate for another 15-20 years, sustaining new fuel and testing of materials for future generations of power reactors, supporting radioisotopes production through the development of more efficient new technologies, sustaining research or enhanced safety, extended burn up and verification of new developments concerning nuclear power plants life extension, to sustain neutron application in physics research, thus becoming a centre for instruction and training in the near future. A main objective of the TRIGA14MW research reactor is the testing of nuclear fuel and nuclear material. The TRIGA 14 MW reactor is used for medical and industrial radioisotopes production (^{131}I, ^{125}I, ^{192}Ir etc.) and a method for ^{99}Mo-^{99}Tc production from fission is under development. For nuclear materials properties investigation, neutron radiography methods have been developed in the INR. The neutron beams are used for investigation of materials properties and components produced or under development for applications in the energy sector, mainly for fission and fusion. At the TRIGA 14 MW reactor a neutron diffractometer and a SANS device are available for material residual stress and texture measurement.

1. INTRODUCTION

Research reactors have an important role in the world for creating and maintaining the advanced infrastructure necessary for the progress of energy programs and also to offer support for the development of various research domains of each country. Nuclear power infrastructure means all tangible and no tangible assets of a country which provide researches for all spectrum of activities contributing to justification and construction of nuclear power strategy/programme. The nuclear power infrastructure should be developed and maintained for a long period of time longer than nuclear power plant life time. Special Governmental Resources should be continuous provided for maintenance and operation of nuclear power infrastructure. The Research Reactor will have a synergic role in a complex matrix activities contributing to nuclear power and development of a nuclear culture in the country. The Research Reactor should be seen justified built and operated in the assembly of the energy policy and economy of the national program not only in direct relation with nuclear power plant operation. The most important contribution of research program in the assembly of the nuclear power development concerns the human resources development for all activities of strategy which should be accomplished with knowledgeable peoples. This type of human resources having theoretical and practical knowledge at least at a mean power research reactor with inherently share the nuclear safety culture, radioprotection culture, security culture and quality culture long time before the power plant design, construction and operation.

At the INR there are two high intensity neutron sources. These sources are in fact the two nuclear TRIGA reactors: TRIGA SSR 14 MW and TRIGA ACPR. The TRIGA steady state reactor is provided with several in-core irradiation channels. Several more out-of-core irradiation channels are located in the vertical channels in the beryllium reflector blocks. The maximum value of the thermal neutron flux ($E < 0.55$ eV) in the central core channel XC-1 (water-filled) is 2.46×10^{14} $n \cdot cm^{-2} \cdot s^{-1}$ and of the fast neutron flux ($E > 1$ MeV), 6.89×10^{13} $n \cdot cm^{-2} \cdot s^{-1}$.

2. BRIEF HISTORY

First research reactor built in Romania was the VVR-S-2MW imported from Soviet Union and installed at the Institute for Atomic Physics in Bucharest in 1957, Romania being among the first European country operating research reactor for the scope of research and technology development.

Several schools were growing around the reactor utilization concerning:

- nuclear reactor core physics modelling and computation;
- reactor technology;
- nuclear safety;
- material testing;
- nuclear instrumentation developing and construction;
- neutron physics;
- radioisotope production and utilization;
- radioactive waste conditioning and storage.

Now the research reactor VVR-S-2MW is in the process of decommissioning and still producing practical knowledge and technologies for future nuclear installation decommissioning. The Institute for Atomic Physics was in year '50-60 the prime resource for knowledgeable human resource for nuclear power in Romania.

The second research reactor built in Romania was the 14 MW TRIGA at the Institute for Nuclear Technology set-up in 1970. The institute main objectives were to develop the nuclear technology for nuclear power in Romania based on national resources. At the beginning of the institute set-up most of the staff was employed from Institute for Atomic Physics Bucharest, staff motivated by new perspectives of nuclear power and technology development in Romania. The Institute for Nuclear Technology (ITN) was designed with an advanced research infrastructure for that time, 40 years ago.

Since the beginning of the design and construction of institute research infrastructure the 14 MW TRIGA Research Reactor was subject of project and supply agreement INFCIRC-206-1974 established between IAEA and Romanian Government and Mod 1 and Mod 2 dated 20 August and 30 August 1991, respectively. The agreement covers the reactor and the associated facilities. According to the agreement, the reactor is subject to application of the IAEA safety standards and measures as defined by the INFCIRC 18/Rev.1.

The reactor was commissioned in 1980 and went through a series of modifications and refurbishments during the mid to late 2000's. These included core fuel conversion from high enriched uranium (HEU) to low enriched uranium (LEU), changes to the design of the control rods, replacement of the Instrumentation and Control (I&C) system and refurbishment of the ventilation system.

3. CURRENT TECHNICAL STATUS

3.1. Technical data of research reactors

Reactor pool type 14 MW TRIGA Research Reactor contained in IAEA RRDB as TRIGA II PITESTI-SS Core, IAEA code RO0002. The reactor was commissioned and starts the continuous operation from 1980, the reactor was fully converted from HEU to LEU in 2006 and refurbished in 2009 and planned operational life is estimated till 2030.

The design of core incorporate features which ensure maintainability, testability and inspect ability for the lifetime of reactor. Fuel rods are manufactured from a hydrated alloy of uranium, zirconium and erbium, cladded in Incoloy 800 tubes with 13 mm O.D.

Fuel assemblies contains 25 fuel rods assembled in a 5 x 5 square lattice in a square Al 6061 tube with Inconel 600 spacers. The fuel assembly is provided with top and down cast aluminum alloys fittings. The top fitting allow the handling of assembly and control the water flow. The fuel assembly and core elements are placed into lower reactor gird with a lattice pitch of 90 mm. This design allows a large flexibility for core configuration and in core install of irradiation devices.

The fuel area is surrounded by vertical blocks of beryllium reflectors sustained also by reactor grid. The core contains also 8 square guide tubes for reactor control rods sustained by reactor grid. All irradiations in core devices are arranged inside of aluminum alloy guide tubes and sustained from the top to prevent the inadvertent reactor grid loading. All other free spaces in core are covered with square plugs.

The reactor grid call for a cross beams design manufactured from cast aluminum and precisely machined. The spatial structure of reactor grid is bolted on top part of core shroud which sustain entire core. In order to allow the installation of in core experiments or irradiation devices, the reactor grid contains several removable segments bolted in the grid frame, see Figs 1-2 [1].

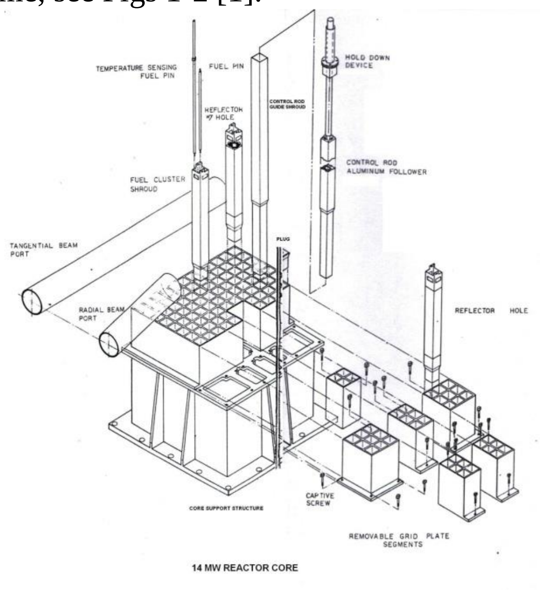

FIG. 1. Schematic reactor core structure.

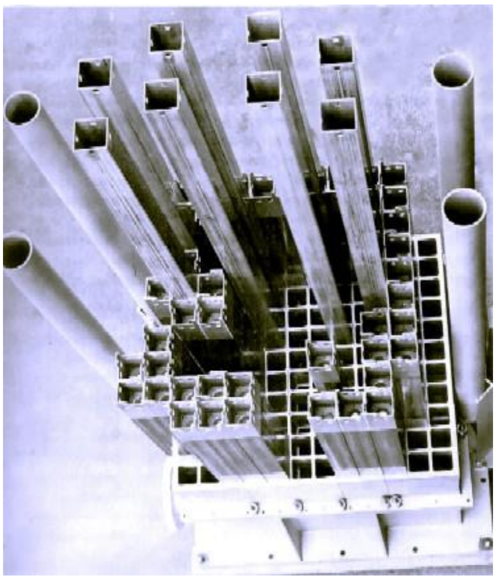

FIG. 2. Reactor core structure.

In Fig. 3 is presented a schematic layout of TRIGA14MW research reactor. Thermal and fast neutron flux spectrum was recently determined in the irradiation vertical channel XC1 at nominal power of reactor i.e.14 MW. The absolute neutron flux-spectrum in XC-1 irradiation channel (water filled) (Fig 5) is presented in Table 1[2].

TABLE 1. FLUX SPECTRUM VALUES

Neutron energy range (MeV)	**Neutron flux ($n/cm^2 \times s$)**	**Average energy (MeV)**
10^{-10} - 18	4.22×10^{14}	0.41
10^{-10} - 5.5×10^{-7}	2.63×10^{14}	
5.5×10^{-7}- 1.0	1.34×10^{14}	
1.0 - 18	6.89×10^{13}	2.46

The fast neutron contribution represent 16.33% from the integral flux density (E > 1MeV). The Cd ratio for the Au reaction is 2.45.

Those data where measured with all irradiation position (vertical channels) filled with water i.e. non perturbed flux.

Following each core configuration and experimental loading (in core irradiation devices) the neutron fluxes for each irradiation device is computed and verified by in core measurements.

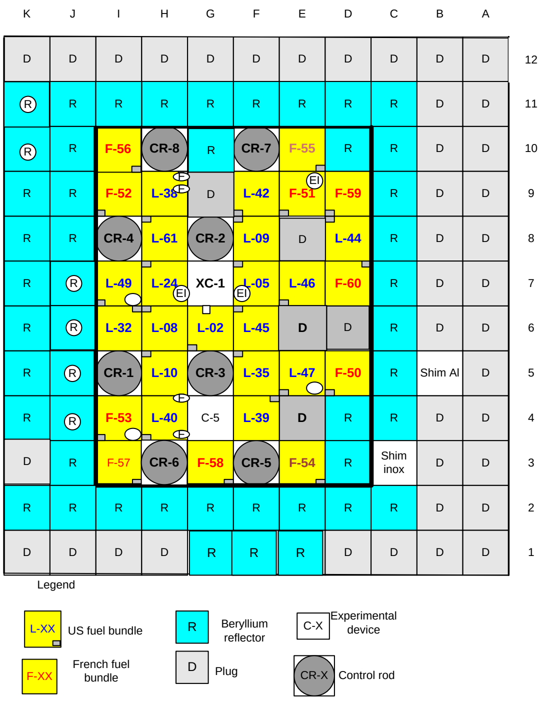

FIG. 3. Layout of TRIGA14MW reactor core.

It worth mentioning that INR staff has professional abilities for the following:

- neutron modelling and design of the irradiation conditions for in core material testing;
- irradiation devices design, manufacture and instrumentation to conduct the experiment with the support of the on-line data acquisition;
- to ensure the irradiation environment according to the customer's requirements;
- to ensure an effective irradiation volume of 1,500cm^3 with axial peak to average flux factor of 1.1-1.3.

For the TRIGA 14 MW reactor operation, maintenance and utilization, a specific organizational chart was prepared, including the reactor direct management. A clearly defined operational structure is available for the regulatory authority, institute management and the personnel, and is based on the description of duties and responsibilities of each post, understood and signed by the relevant personnel.

The compact structure of the organizational chart of Research Reactor department is based on three functions, each one associated to a group: (a) operation staff organized in shifts; (b) maintenance staff organized by special qualification (i.e., mechanical, electrical, instrumentation); (c) direct users staff for Research Reactor utilization, support for internal and external users/customers acting as an interface for user needs. All areas of activity and processes are continuously audited by the Regulatory Body, by Institute teams following an audit plan and by customers, mainly the Nuclear Power Plant – CNE Cernavoda.

3.2. Operation of TRIGA research reactor

The reactor operation is ensured by teams of licensed staff in shifts of 7 individuals, around-the-clock. The main support systems are under continuous operation, regardless of the status of core shut down, low power or at power. The continuous operating systems are the electrical systems, emergency power system, communication, ventilation, water purification, radioactive waste collection system, radiation monitoring system and physical protection. The operation team is coordinated by a licensed reactor operator and comprises 6 to 7 system operators.

Written operating procedures and written instructions have been used within TRIGA facility since 1977 – before commissioning.

3.3. Modification, modernization, ageing management

The main modifications in the history of the 14 MW TRIGA Reactor are related to the installation of irradiation devices loops and capsules for the irradiation testing of nuclear fuel and materials. Each irradiation device is subject to installation design and safety analysis report containing the safety of device and safety of overall reactor facilities.

Each irradiation facility operation is accompanied by its own OLCs. Some of them impose modifications of reactor OLCs. The core conversion from highly enriched uranium to low enriched uranium utilization has been seen as an initial core design modification. The process of conversion in this case was a gradual one, allowing the progressive replacement of HEU by LEU in order to obtain the maximum burn up of HEU and to accumulate experience in LEU fuel behaviour and safe utilization [3], [4], [5].

The chapters of Safety Analysis Report concerning the reactor core were subject to revision before each LEU fuel batch loading. The full conversion of the core was successfully accomplished in May 2006, as a result of international cooperation and support on behalf of the IAEA and of US-DOE [6].

The process of conversion started in 2002 with the assistance of Argonne National Laboratories. In 2001 a technical cooperation project concerning “Full conversion of 14 MW TRIGA Research Reactor” was successfully sustained by the IAEA. The last batch of TRIGA-LEU fuel was provided by CERCA, France, in March 2006.

The modernization of the 14 MW TRIGA Reactor in Pitesti, Romania, was accomplished between 2005 and 2009, subject to design modification approval by CNCAN, contractors accreditation for performing their activities in nuclear installations, systems commissioning following new procedures and quality plans for installation and commissioning.

Continuous revision and updating the SAR was performed to ensure conformity with the plant configuration due to modification following the development of the project of modernization.

The main goal of modernization was to extend the facility lifetime and to increase neutron flux performance in irradiation locations and in beam tubes for new applications.

The modernization actions concern:

1. Cooling tower refurbishment replaced the obsolete degraded system and increased the actual heat load by 50%.
2. Ventilation filtering system allowing utilization of new standard filters instead of the original ones, which are no longer manufactured.
3. Radiation monitoring system was modernized to allow utilization of new robust detectors and IT for operation ensuring on-line gamma spectrometry for continuous air
4. New fire alarm system.
5. New computer-aided supervision system for electrical network distribution, class 1, 2, 3.
6. Instrumentation of primary cooling system, secondary cooling system, purification system completely refurbished.
7. Some irradiation devices were refurbished to perform advanced fuel and materials irradiation.
8. Control rods were reconstructed using discrete absorbing materials, installed and commissioned.
9. Reactor safety instrumentation modernization, to replace the original electronic instruments, now out of order or obsolete, and to introduce the new concept of independence and separation between operating system and safety system, delivered by INVAP is not yet installed.

All the above projects are subject to design modification approval, construction by licensed suppliers, revision of associated safety report section and analysis, approval inspection and testing program by CNCAN.

3. UTILIZATION AND EXPERIMENTS

The 14 MW TRIGA R.R. is intensively used for a broad spectrum of experiments. The list of experiments, internal users or clients appears to be a long one, considering the 30 years of operation.

It is important to mention that the utilization of the reactor was oriented towards irradiation and testing of experimental fuel rods and assemblies, followed by post-irradiation examination, in order to gather data for the characterization of the Romanian technology of fuel for power plant qualification and determination of the limits in the utilization in steady-state condition of operation, anticipated transients and accident conditions, producing a large amount of data for the specific computer codes library. The safe and intensive utilization of the 14 MW TRIGA Reactor in Pitesti, enhanced the safety of CANDU-type fuel fabricated in Romania and used at the Cernavoda Nuclear Power Plant, without fuel failure in the last 10 years of operation.

The annual mean time of utilization of the reactor was 2000 – 2500 hours of operation in power for the 14 MW reactor. The top record was 6500 hours of operation/year, using four irradiation devices in core and several others in the reflector. About 120 experimental fuel rods were irradiated in both SSR and ACPR reactors, and for each irradiation licensing documentation was submitted to the regulatory authority in order to assent to the specific experiment and utilization of a dedicated irradiation device operating at CANDU-type core parameters. Four irradiation devices were in the process of modernization during the period of 2005–2009 in the frame of the project of reactor refurbishment.

The financial resources were allotted by the Government of Romania through the Ministry of Economy.

During the period of four years, 2005 – 2009, the reactor license was maintained for operational status, and, due to the extensive modernization work of different systems, the number of operating hours was of 200 to 800-1000 hours/year.

The following list of irradiation devices and experiments performed between 1980 –2009 will give the dimension of intensive and extensive utilization of the TRIGA R.R. in Romania:

1. Loop A – 100 kW thermal in core irradiation allowing installation of 3 to 6 experimental fuel rods per campaign; overpower test, ramp test. The irradiation facility loop A serves for investigating the behaviour of the CANDU type fuel at the INR-RR. Its main features are as follows:

- Total power 100 kW
- Water flow rate at the samples 3–7 m^3/h
- Maximum pressure in the primary circuit 135 bar
- Maximum water temperature 310°C
- Useful internal diameter 54 mm

Loop A allows the performance of overpower tests as well as ramp tests, for three or six fuel rods simultaneously. The high pressure primary circuit of loop A contains the elements of a power reactor primary circuit at reduced scale, allowing the simulation of thermal hydraulic parameters, a specified forced flow across the in-pile section and the water chemistry established through demineralizing bad resins , water purification by mixed bed ion exchange filters [7].

2. Capsule C1 – mechanical growing of fuel under irradiation, on line fission gas released from experimental fuel rods, thermal power 35 kW:

-- Dimensional measurement under flux in core of fuel elongation

-- On line fission gas composition measurement

3. Capsule C2 – 35 kW thermal, in core device CANDU parameters: on line fission gas pressure measurement and central fuel temperature in steady-state condition and transients;

4. Capsule C5 – 10 kW thermal: Capsule C5 was designed and used for the irradiation of steel samples and zirconium alloys in helium atmosphere at temperatures between 200 and 300°C. The C5 in-pile section was designed to irradiate several types of samples of cladding as well as pressure tubes. The specified test temperature is obtained by gamma heating and/or heating by an electrical furnace. The present capsule C5 is intended to be used for irradiation of samples of special materials for ITER project. Considering the future requirements for qualifications of candidate materials for new generation of reactors a new irradiation in core section will be designed and build to ensure an inert atmosphere and 600^0C on samples [8];

5. Capsule C6 operating in ACPR core in pulses, till 20000 MW amplitude: reactivity [9]. Other irradiation devices for RIA test using a special deign capsule with Pb-Bi eutectic for transient testing of MYRRHA fuel for determination of the pin failure threshold, in the framework of MAXSSIMA project is in the design phase and preliminary licensing and will be in operation at the end of 2014.

Insertion Accident (RIA) simulation, gathering data for nuclear safety computer codes;

6. Neutron activation analysis [10], [11].

7. Silicon ingot irradiation for doping till 52 mm in diameter;

8. Thermal column for flux spectrum characterization. Standard neutron flux for neutron devices calibration – will be subject of Metrology Recognition Agreement (MRA) [12];

9. Radioisotopes production: the Institute is licensed to produce and distribute sealed sources for industry and medical application;

10. Research for new medical radioisotopes – IAEA Regional Program EERRI;

11. Irradiation of electric and electronic equipment for environmental characterization for utilization in the safety system of Cernavoda NPP;

12. Neutron radiography under water installation;

13. Prompt Gamma Analysis for current samples from NPP;

14. Beam tube neutron-radiography for non-active objects under development;

15. Neutron powered diffractometer for stress and strain measurement [13];

16. Small angle neutron scattering diffractometer under installation.

The broad spectrum of utilization of the reactor is sustained by a dedicated team who perform all activities starting with client or user’s demands, specifications, installing experiments and licensing with CNCAN, operating and gathering the irradiation data for the customer's satisfaction.

The entire utilization of reactor and irradiation devices operation and specific maintenance is subject to licensing endorsing associated procedures, training and qualification of personnel.

4. RECENT ACHIEVEMENTS

Examples of research and development studies performed by Institute during the last year could be found on: www.nuclear.ro/programecercetare_en.htm.

Recent publication during annual Institute conference could be found on: www.nuclear.ro/arhiva_evenimente_stiintifice and www.jrnd-nuclear.ro.

5. FUTURE OF TRIGA 14 MW RESEARCH REACTOR

Referring to the previous activities developed for nuclear power plant and for nuclear energy in general since 1998 the Institute for Nuclear Research Pitesti Romania was nominated by law as Technical Support Organization (TSO) for nuclear energy in Romania. The main activities concern the behaviour of nuclear fuel and some reactor equipment as steam generators, pressure tubes, monitoring equipment, for these reasons the institute research programs are dedicated to technical support of nuclear power plant.

Testing of experimental fuel rods in accident conditions simulated in TRIGA Annular Core Pulsed Reactor in order to enriches the information and data base concerning nuclear fuel behaviour in severe accident are part of technical support.

Another institute program provides research and development for radioisotope production for industry and medicine.

International cooperation with IAEA TC programs for training of foreign country fellowships in to the broad aspects of research reactors neutron and thermal analysis till maintenance and refurbishment of research reactors is a continuous activities oriented to safety and security of utilization of research reactors.

Starting in the year 2000 the Institute for Nuclear Research and TRIGA reactor established a tight cooperation with Pitesti University and Bucharest Polytechnic University concerning practical training of students from nuclear energy classis. In this program 25-30 students are trained every year. The future of this activity we hope will increase due to continuation of construction of unit 3 and 4 from Cernavoda NPP and increasing motivation work for nuclear energy.

REFERENCES

[1] GENERAL ATOMICS, "Safety analysis report of the TRIGA steady-state research/materials and testing reactor", General Atomic Company, E-117-323, **II**, Feb. 1974.

[2] BARBOS, D., BUSUIOC, P., ROTH, Cs., PAUNOIU, C., **"**Neutron Flux Measurement in the Central Channel (Xc-1) of TTRIGA 14MW LEU Core", 4th World TRIGA Users Conference, 8-10 September 2008, Lyon, France.

[3] BRETCHER, M.M., SNELGROVE, J.L., "Transition from HEU to LEU fuel in Romania's 14MW-TRIGA Reactor", XIV 4-7 Nov.1991, Jakarta, Indonesia.

[4] BRETCHER, M.M., SNELGROVE, J.L., CIOCANESCU, M., "Analytical analysis of start-up measurements associated with the first use of LEU fuel in Romania's 14MW-TRIGA Reactor", XV International Meeting on Reduced Enrichment for Research and Test Reactor, September 27- October 1, 1992, Roskilde, Denmark.
[5] IORGULIS, C., PREDA, M., CIOCANESCU, M., "Pin power factor decrease and fuel economy during LEU refuelling of 14MW TRIGA core", SIEN'99, International Symposium on nuclear energy, Nov. 15, 1999, Bucharest, Romania.
[6] CIOCANESCU, M., "Full Conversion of the Pitesti 14MW RR Core from HEU to LEU Fuel", Technical Workshop on HEU Elimination, Oslo, Norway, June 17-18, 2006.
[7] HORHOIANU, G., SORESCU, I., PARVAN, M., "Irradiation tests on PHWR type fuel elements in TRIGA research reactor of INR Pitesti", Kerntechnik, **77** (6), (2012) pp.418-423.
[8] NEGUT, Gh, ANCUTA, M., RADU, V., "The irradiation effects on zirconium alloys", Journal of nuclear materials, **362** (2-3), (2007) pp.300-308.
[9] HORHOIANU, G., DOBREA, D., PARVAN, M., STEFAN, V., "Behaviour of CANDU fuel under power pulse conditions as the TRIGA reactor of INR Pitesti", Kerntechnik, **74** (1-2), (2009) pp.28-34.
[10] BARBOS, D., PAUNOIU, C., ROTH, Cs., "Determination of α and f parameters at the 14-MW TRIGA reactor at Pitesti, Romania", Nuclear Instruments. &Methods, A, 622(2) (2010), pp. 425-428.
[11] Cs. ROTH, Cs., BARBOS, D., GUGIU, D., DATCU, A., DOBREA, D., GLIGOR, M., PREDA, MWEETWA, M.B., **"**Irradiation and measurement devices and methods development for LSNAA applications at the TRIGA-ACPR core", Journal of Radioanalytical and Nuclear Chemistry, **291**(2), (2011), pp: 461-466.
[12] ROTH, Cs., GARLEA, I., DOBREA, D., AIOANEI, L., GARLEA, C., GUGIU, D., DATCU, A., PREDA, M., PAVELESCU, M., "The Sigma Sigma secondary intermediate-energy standard neutron field development at the Romania TRIGA Reactor", Nuclear Instruments. &Methods, A, **522**(3), (2004) pp. 462-469.
[13] IONITA, I., PAUNOIU, C., FLORESCU, V., "New trends in thermal neutron spectrometry getting high-resolution performances in thermal neutrons spectrometry by using inverse spacing focusing", Journal of Physics Conference Series 01/2012, 340(1).

THE PAST AND THE FUTURE OF THE TRIGA REACTOR VIENNA

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Abstract.

During the past five decades the TRIGA reactor Vienna has reached atop place in utilization among low power research reactors. This paper summarizes the research highlights of the past and offers an outlook to the years ahead.

1. INTRODUCTION

After the "Atoms for Peace" speech of President Eisenhower in December 1963 many low power research reactors were built all over the world, this was the boom-time for TRIGA reactors. Totally about 70 TRIGA reactors were built world-wide, later some other research reactors were converted to TRIGA type fuel, today about 35 TRIGA reactors are still in operation. The contract for the Vienna TRIGA was signed in 1958, the foundation was laid in August 27th, 1959, and the reactor reached first criticality after 2.5 years on March 7th, 1962, being located only 5 metro stations from the city center, a fact which would be totally impossible today. Other than the 10 MW ASTRA reactor in Seibersdorf, the TRIGA reactor was fully devoted to university education in the nuclear field, a mission which was strictly followed throughout the last five decades. All technical data of the TRIGA reactor Vienna were published at many conferences and can also be found in the Atominstitute's webpage (www.ati.ac.at).

2. MAJOR NEUTRON PHYSICS EXPERIMENTS

2.1. Interferometry

In 2011, 37 years have passed since the first perfect crystal neutron interferometer was tested by an Austrian-German cooperative group at the 250 kW TRIGA reactor in Vienna [1,2]. Since that time, neutron interferometry became a laboratory for quantum mechanical test experiments. The key feature of this technique are two widely separated coherent beams of thermal neutrons ($\lambda \sim 1.8$ Å, $E \sim 0.025$ eV) which are produced by dynamical Laue-reflection in a properly shaped perfect silicon crystal (see Fig. 1). Analogies exist to the Mach-Zehnder type interferometers used in light optics and to the Bonse-Hart interferometers developed for X rays [3].

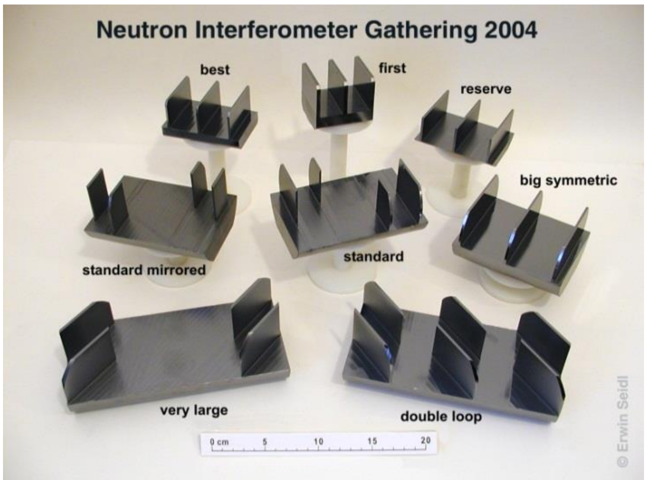

FIG. 1. All neutron interferometers used at the Vienna TRIGA reactor or at the high flux reactor of the ILL, Grenoble were manufactured and tested at the Atominstitut.

Neutron interferometry has been used for a series of quite spectacular fundamental quantum mechanical experiments, a most complete synopsis of results is given in [4]. Recent achievements are the demonstration of Bell's inequality with single neutrons [5], measurement of topological phases [6], and of confinement induced quantum-phase [7]. One remarkable experiment with the neutron interferometer was the determination of the coherent neutron scattering length of gaseous natural krypton and its isotope ^{86}Kr [8]. While the result for natural krypton was in excellent agreement with existing literature, the result for the isotope represented the first experimental value, and in fact the first experimental value for any of the krypton isotopes. During data analysis it was found that the accuracy of the results was mainly determined by the stability of the setup and not by the limited neutron flux. These results obtained at the small reactor proved that competitive neutron interferometric results may be obtained also at small neutron sources provided that a stable setup is used. It may be added that for these measurements the reactor was unconventionally operated 24 hours a day.

Although the majority of these experiments had to be performed on the High Flux Reactor of the Institute Laue-Langevin (ILL), Grenoble, simply because of intensity reasons, it was essential to conceive and to prepare them at the TRIGA reactor Vienna as well as to test the functionality of the various components of the final setup.

2.2. Ultra small-angle neutron scattering (USANS)

Ultra-small-angle neutron scattering (USANS) is a technique which enables to follow neutron diffraction to extremely small angles, and when cleverly done, even into the forward direction where it overlaps with the non-scattered transmitted incident beam. It relies on the very narrow angular reflection width of perfect single-crystals and is realized as a multi-bounce perfect silicon double crystal diffractometer. While primarily designed for materials characterization in the µm-range – which follows from the use of thermal neutrons and widths of a typical instrument resolution function of the order of µrad – these instruments may also be used for fundamental investigations related to the coherence properties of neutron beams and the macroscopic limits of neutron diffraction. A beautiful example of such measurements was diffraction and multi-beam interference from artificial lattices [9]. Corresponding experiments were performed at the USANS facilities of the Atominstitut and of the S18 instrument at the ILL in Grenoble. There, we observed diffraction patterns from samples being periodically structured in one and two dimensions. These measurements took advantage of the extended coherence function of the setup and the high quality of the manufactured silicon sample lattices. The diffraction pattern of a line grating with 32 μm lattice constant was obtained at both instruments in Grenoble and Vienna. Due to the much narrower resolution function, resulting from the (331) silicon reflections employed, the interference orders were completely resolved with the Viennese instrument while the diffraction pattern recorded at S18 was a superposition of several interference orders. This showed that, given the proper experimental context, neutrons may be coherently diffracted by structures whose size is of the order of 0.1 mm. It is clear, specifically at the small reactor, that all these phenomena are related to multi-beam self-interference of the neutrons.

Ultra-small-angle neutron scattering (USANS) has been extended to the study of magnetic structures by using polarized neutrons in recent years (USANSPOL). The initial instrument arrangement and first experimental results are closely connected with the Vienna TRIGA reactor [10]. The neutrons are loss-free polarized by permanent magnetic prisms located between the monochromator crystal and the sample. Neutrons with opposite spin state are separated by the diffraction angle of the prisms and their different scattering behavior may be studied in a single measurement without additional manipulation of the neutron spin. In this manner we are able to separate the magnetic and nuclear contribution to the scattering. In [10], we presented first exemplifying measurements on ferromagnetic rods and wires, and on soft-magnetic ribbons. Again, these experiments were performed at the USANS facilities in Vienna and at the combined neutron interferometer/USANS instrument S18 at the ILL, Grenoble. With the measurements in Vienna, e.g., we could beautifully demonstrate the birefringent nature of magnetic lens refraction.

The use of polarized neutrons in neutron optical instruments like neutron interferometers and USANSPOL diffractometers relies on the practically loss-free polarization of the incoming neutron beam. Spin-dependent birefringence of neutrons upon passage through the air gap of a prism-shaped permanent magnet yoke can be used to split a thermal neutron beam in two polarized sub-beams with slightly different directions. Using then a sequential arrangement of two such prisms, a splitting larger than twice the width of the instrument resolution function is achieved and yields a maximum beam polarization of about 97-98%. This was first demonstrated at the Vienna TRIGA reactor [11]. Such polarizes are now routinely employed in the neutron optics instruments in Vienna and Grenoble.

Model samples with known parameters, especially silicon phase gratings will help to better understand the basic features of the USANS technique and clarify the performance of the instruments involved [12-14]. Corresponding measurements were performed at the USANS facility of the Atominstitut. These experiments are of fundamental interest as well since the diffraction patterns result after quantum mechanical multiple-beam interference of the neutron particle waves.

3. OTHER MAJOR REACTOR APPLICATIONS

3.1. Radiochemistry

The radiochemistry group of the Atominstitut has a long tradition in neutron activation analysis. Some highlights of this work illustrate the wide applicability of this method. The geological event at the Cretaceous-Tertiary Boundary had caused global environmental as well as climatic changes. It’s traces have been found in geological formations in the Gosau Basin (Austria) and could be characterized by neutron activation analysis (NAA). The abundance of geomarkers such as iridium – an element that can be determined by NAA with extreme sensitivity – makes a “meteorite hypothesis” most likely for this *galactic* event [15].

Since many years, the radiochemistry group is working in the field of archaeometry. Originally, this work was primarily focused on provenance studies of pumice (a volcanic rock) – more than 500 pumice lumps could be provenance over the past decade – however, the group is constantly expanding the focus of analytical techniques for archaeometric challenges. Recent topics are provenance of obsidian, ceramics, clay tablets and still pumice. The data obtained by the radiochemistry group allow the establishment of chronologies, trade routes and relative age determination and hence are of great importance for archaeologists and historians [16-19].

Our main future focus will be environmental analysis, especially the environmental impact of the Fukushima reactor accident. In this project information will be gathered from official statements and measurements to provide a sound chronology and identify the seismic and nuclear reasons for the accident. The current scientific prognosis of long-term health- and environmental consequences will be explored, focusing on the effects attributable to radionuclide release and dispersion. Advice will be provided for implementation of future programs on disaster management and mitigation.

3.2. Education and training

Since the mid-1980ies the Atominstitut is engaged in training and educational courses not only for national students but also for international course participants. The first institution taking advantage of the TRIGA reactor Vienna was the International Atomic Energy Agency (IAEA) starting with a Safeguards Traineeship program carried out in a two years cycle since 1984. Up to now the Atominstitut has trained over 90 junior safeguards inspectors. Parallel to this courses the Atominstitut hosted more than 125 IAEA fellows from all over the world being attached to one of the researchers as coordinator for a period between one to twelve months. Since the early 1990ies an increasing number of courses for external participants were organized such as retraining of Nuclear Power Plant (NPP) staff from NPP Bohunice and Mochovce, retraining for Mol research reactor operators and regular courses for the UK Nuclear Technology Educational Consortium (NTEC) with two courses per year. Another Central European initiative is the Eastern European Research Reactor Initiative (EERRI) under the coordination of the IAEA where junior technicians and engineers from nuclear emerging countries are trained at several research reactors in this region. The duration of the training program is 6 weeks and covers about 30 topics ranging from theoretical lectures to practical experiments at the reactors grouped into three main areas; organizational matters, research reactor operation and maintenance and radiation protection. Currently the following institutes are involved in this project.

- Vienna University of Technology/Atominstitut (VUT/ATI), Austria
- KFKI Budapest, Hungary
- Budapest University of Technology, Hungary
- Institute Jozef Stefan, Ljubljana, Slovenia
- Technical University of Prague, Czech Republic
- Research Centre Rez, Czech Republic

Beyond academic education also education and early information at the college level is very important to attract the young generation to basic nuclear knowledge which may later lead towards further academic nuclear education. Due to these factors, besides its regular academic programs, the ATI has recently established a new program for college students just before their certificate for university studies (17 to 18 years of age). In co-operation with dedicated physics teachers, two full day courses have been carried out in December 2010 to interest potential future university students in nuclear physics and nuclear technology.

3.3. Safeguards and security

Another important cooperation with the IAEA is Nuclear Safeguards and Nuclear Security research. As closest nuclear facility to IAEA the ATI has a number of samples of special nuclear material (SNM) stored for the IAEA which is regularly used for test measurements, re-calibration of various safeguard instruments and for IAEA retraining of their safeguards inspectors. These samples are also used to test and improve hand-held radioisotope identifiers used as anti-smuggling devices. At the ATI about 10 Master Thesis projects and 3 PhDs have been carried out in this field with special focus on environmental effects on these detectors and on tests and improvement of the installed software. A typical example is the suppression of medical isotope signals in hand-held portable gamma spectrometers to avoid unnecessary alarms at ports of entry, in this case trespassing patients with incorporated radionuclides can be distinguished from malevolent smugglers. Another interesting experiment was the detection of SNM behind several tons of fertilizer on a truck to determine the minimum detectable amount of SNM by hand-held radioisotope identifiers.

4. POTENTIAL FUTURE USE AS NEUTRON SOURCE

4.1. Neutron optic experiments

Quite recently, the station neutron interferometry station (NIS) is renovated by modifying and re-adjusting a focusing monochromator [20]. Now an optical bench is completely renewed, which is much more compacted than the old one and equipped with new anti-vibration and thermal insulation systems, more intensity with higher stability is expected. This interferometer setup is essential for students to directly access a matter-wave interference instrument on a macroscopic scale: a number of practical courses as well as Master Thesis were carried out recently. It should also be emphasized that the interferometer setup has also been used for preparation and test of individual optical elements, which were used for measurements at the high flux interferometer setup S18 at the Institut Laue Langevin (ILL), Grenoble in France. Major neutron interferometer experiments are performed at the ILL and it is essential to develop optical elements “at home” in advance due to limited beam time at the ILL.

New developments and application is expected in the field of ultra-small-angle neutron scattering both in the non-polarized USANS and the polarized USANSPOL versions. Due to the limited neutron flux, specifically with neutron beams monochromatized by perfect single-crystal reflections, large diffracted or scattered intensities are necessary for application at the Vienna TRIGA reactor. Phenomena related to this include multi-beam interference [21], refraction [10] and strong nuclear/magnetic contrast combined with intermediate structure size [22]. The issue of coherence properties of thermal neutron beams holds still potential for a considerable amount of future work and artificial lattice microstructures in one and two dimensions represent one of the proper keys to tackle this topic. These structures may be manufactured as phase gratings, partly absorbing entities or from magnetic materials to produce birefringent phenomena. The investigation of domain sizes in novel magnetic materials of technological relevance, often with exceptional magnetostriction properties [22], can profit from the ultra-high resolution of the Viennese instrument. Application of external parameters like magnetic field and mechanical stress is indispensable for a complete neutron characterization of these materials. With increasing magnetic order within the sample the domains evolve towards macroscopic dimensions which concentrates neutron scattering increasingly around the forward direction and compresses the scattering signal around the instrument resolution function [23]. The very-low scattering vector limit of our instrument allows to follow the evolution to the largest domain sizes which are possible by this technique. An overlap with imaging techniques is the ultimate goal which would connect real space measurements with traditional SANS investigations and provide for a complete picture from atomic clusters to macroscopic sample structure. The development of an appropriate sample environment for related USANSPOL studies is currently underway [24]. These studies may be complemented by 3D neutron depolarization measurements where a corresponding experimental setup is also available at the Vienna TRIGA reactor. Related studies for an implementation of this scheme are currently carried out by our group.

The development of new experimental methods in polarized neutron physics and instrumentation has always been at the forefront of neutron research activities at the Atominstitut. Such new techniques will be of particularly renewed interest in the context of the upcoming European neutron spallation source ESS. A recent project which shows prospects in that direction but offers also exciting possibilities at reactor-based continuous neutron sources is the revival of the concept of spatial magnetic spin resonance [25], a concept which dates back to the 1960s and was invented by Drabkin in Russia. By this method, wavelength selection of polarized neutrons becomes possible based on the fast electronic switching of magnetic fields. When combined with travelling magnetic waves very versatile polarized neutron instruments are feasible that may change their key parameters in an instant. It was shown recently at the Atominstitut where a prototype resonator was realized and tested experimentally with µs resolution that this technique actually works [26]. This development has created immediate interest for triple axis spectroscopy and the beta decay instrument PERC which is built at the FRM-II in Munich. Considering the millisecond long neutron pulses foreseen for the ESS such a resonator could be easily employed for arbitrary pulse shaping at various polarized neutron instruments. This resonator is but one example for the development work that is foreseen in the near future at the TRIGA reactor in Vienna.

Following in this respect, there is rapid international development in the field of polarized neutron imaging [27, 28]. Since the neutron physics group at the Atominstitut has a long tradition in both polarized neutron physics as well as neutron radiography and tomography imaging the setup of an polarized neutron imaging instrument is an important issue for future activities at the Vienna TRIGA reactor, especially since fundamental methodic work from our group has contributed to this field in recent years [29].

A particularly attractive addition to the instrument suite of the Atominstitut would be the installation of a beam line for ultra-cold neutrons (UCN). The successful implementation of a UCN source into a TRIGA beam port was demonstrated at the Mainz 100 kW TRIGA reactor [30]. This UCN source, again at a small reactor, is competitive in ultra-cold neutron phase space density with much larger installations that defined the best achievable UCN density values so far. Such a facility may be used for fundamental investigations [31] as well as methodical development [32] as demonstrated in Mainz. This methodical work could directly influence the development of new projects, having again the ESS in mind.

4.2. Neutron polarimetry

The neutron polarimeter apparatus turned out to be used for quantum interference experiments by taking a spinor rotation as a consequence of interference between up and down spin eigenstates, in contrast to the interference between the beams in path I and II in the interferometer. It is a big advantage of polarimetry that high intensity and high stability of the system is easily attainable also with a small reactor like a 250kW TRIGA-reactor. Needless to mention educational use, typically for practical courses, the neutron polarimeter setup for advance studies of quantum mechanical phenomena: i.e. a peculiar property of quantum in Physical Review Letters [33]. Quite simple configurations and easy access of the setup allows students to develop and improve individual optical elements by themselves, which is a reason why the setup is almost ideal for the use of Master- and PhD students. Recent works cover investigations of an alternative model of quantum mechanics with high precision [34] and a new form of Heisenberg's uncertainty relation [35], both give significant insight in the field.

Both neutron interferometer and polarimeter setups at the Atominstitut exploit the dual nature of neutrons, sometimes a particle and sometimes a wave, this enables wonderful manifestation of entanglement in addition to superposition in quantum physics. Such studies – not only on coherent interactions but also topological, non-local, gravitational, effects as well as contextual models of quantum mechanics – will be carried out further.

5. CONCLUSIONS

As it was shown above there are many interesting projects to further increase the basic and applied research around the TRIGA reactor Vienna. International cooperation with powerful neutron sources and with international organizations are of utmost importance, the past five decades have shown the obvious benefits, this positive symbiosis is expected to continue beyond the US spent fuel return program**.**

REFERENCES

[1] Atominstitut, Vienna, Austria; web page http://www.ati.ac.at

[2] RAUCH, H., TREIMER, W., BONSE, U., Phys. Lett. A **47** (1974) 369.

[3] BONSE, U., HART, M., Appl. Phys. Lett. **6** (1965) 155.

[4] RAUCH, H., WERNER, S.A., "Neutron Interferometry", Clarendon Press, Oxford (2000).

[5] HASEGAWA, Y., LOIDL, R., BADUREK, G., BARON, M., RAUCH, H., Nature **425** (2003) 45.

[6] HASEGAWA, Y., LOIDL, R., BADUREK, G., BARON, M., MANINI, N., PISTOLESI, F., RAUCH, H., Phys. Rev. A **65** (2002) 052111-1-10.

[7] RAUCH, H., LEMMEL, H., BARON, M., LOIDL, R., Nature **373** (2002) 630-632.

[8] TERBURG, B.P., VERKERK, P., JERICHA, E., ZAWISKY, M., Nucl. Instr. Meth. A **324** (1993) 247.

[9] JERICHA, E., BARON, M., HAINBUCHNER, M., LOIDL, R., VILLA, M., RAUCH, H., J. Appl. Cryst. **36** (2003) 778.

[10] JERICHA, E., BADUREK, G., TRINKER, M., Physica B **397** (2007) 88.

[11] BADUREK, G., BUCHELT, R.J., KROUPA, G., BARON, M., VILLA, M., Physica B **283** (2000) 389

[12] JERICHA, E., BARON, M., HAINBUCHNER, M., LOIDL, R., VILLA, M., RAUCH, H., J. Appl. Cryst. **36** (2003) 778.

[13] Hainbuchner, M., Villa, M., Kroupa, G., Bruckner, G., Baron, M., Amenitsch, H., Rauch, H., J. Appl. Cryst. **33** (2000) 851.
[14] TREIMER, W., STROBL, M., HILGER, A., Phys. Lett. A **289** (2001) 151.
[15] PREISINGER, A., ZOBETZ, E., GRATZ, A.J., LAHODYNSKY, R., BECKE, M., MAURITSCH, H. J., EDER, G., GRASS, F., RÖGL, F., STRADNER, H., SURENIAN, R., The Cretaceous/Tertiary boundary in the Gosau Basin, Austria Nature **322** (1986) 794-799.
[16] STEINHAUSER, G., STERBA, J.H., BICHLER, M., HUBER, H., Neutron activation analysis of Mediterranean volcanic rocks – an analytical database for archaeological stratigraphy. Appl. Geochem. **21** (2006) 1362-1375.
[17] STERBA, J.H., MOMMSEN, H., STEINHAUSER, G., BICHLER, M., The influence of different tempers on the composition of pottery. J. Archaeol. Sci. **36** (2009) 1582-1589.
[18] STERBA, J.H., FOSTER, K.P., STEINHAUSER, G., BICHLER, M., Old pumice in a new light: On the origin of pumice from egyptological museum collections. J. Archaeol. Sci. 36 (2009) 1738-1744.
[19] STEINHAUSER, G., STERBA, J.H., OREN, E., FOSTER, M., BICHLER, M., Provenancing of archaeological pumice finds from North Sinai. Naturwissenschaften 97 (2010) 403-410.
[20] BOTH, M., Diploma work, TU Wien (2010).
[21] TRINKER, M., JERICHA, E., BOUWMAN, W.G., LOIDL, R., RAUCH, H., Nucl. Instr. Meth. **579** (2007) 1081.
[22] JERICHA, E., BADUREK, G., GÖSSELSBERGER, C., Physica B **406** (2011) 2401.
[23] BADUREK, G., JERICHA, E., GRÖSSINGER, R., SATO-TURTELLI, R., J. Phys.: Conf. Ser. **211** (2010) 012027.
[24] JERICHA, E., BADUREK, G., GÖSSELSBERGER, C., SÜSS, D., J. Phys.: Conf. Ser., Proc. of the ECNS 2011 (in print).
[25] BADUREK, G., GÖSSELSBERGER, C., JERICHA, E., Physica B **406** (2011) 2458.
[26] GÖSSELSBERGER, C., et al., J. Phys.: Conf. Ser., Proc. of the ECNS 2011 (in print).
[27] KARDJILOV, N. et al., Nature Phys. **4** (2008) 399.
[28] STROBL, M., et al., Physica B **404** (2009) 2611.
[29] JERICHA, E., SZEYWERTH, R., LEEB, H., BADUREK, G., Nucl. Instr. Meth. A **586** (2008) 119.
[30] FREI, A., et al., Eur. Phys. J. A **34** (2007) 119.
[31] ALTAREV, I., et al., Phys. Rev. Lett. **100** (2008) 014801.
[32] SOBOLEV, Yu., et al., Nucl. Instr. Methods A **614** (2010) 461.
[33] KLEPP, J., SPONAR, S., FILIPP, S., LETTNER, M., BADUREK, G., HASEGAWA, Y., Phys. Rev. Lett. **101** (2008) 150404.
[34] SCHMITZER, C., Diploma work, TU Wien (2009).
[35] ERHART, J., Diploma work, TU Wien (2010).

THE RESEARCH REACTOR TRIGA MAINZ

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Abstract.

The TRIGA Mark II-reactor at the Johannes Gutenberg-Universität Mainz is one of three research reactors in Germany. The TRIGA Mainz became first critical on August, 3rd 1965. It can be operated in the steady state mode with a maximum power of 100 kW_{th} and in the pulse mode with a peak power of 250 MW_{th} and a pulse length of 30 ms. The TRIGA Mainz is equipped with a central thimble, a rotary specimen rack, three pneumatic transfer systems, four beam tubes and a graphite thermal column. The TRIGA Mainz is intensively used both for basic and applied research in nuclear chemistry and –physics as well as for education and training purposes. For the latter, various courses in nuclear and radiochemistry, radiation protection and reactor operation and rector physics are held at the Institut für Kernchemie for scientists, advanced students, teachers, engineers and technicians utilizing the TRIGA Mainz reactor.

1. INTRODUCTION

Founded already in 1477 and named after the famous fifteenth-century printer who revolutionized printing with movable letters, the Johannes Gutenberg-Universität Mainz, with nowadays about 35,000 students from more than 130 nations, is one of the largest universities in Germany. About 500 professors and 2,300 academic staff members are involved both in research and teaching in eleven faculties comprising 150 different institutes. The university offers a wide research area, including the natural sciences, humanities, social studies, law, economics and medicine. The campus also hosts the electron accelerator facility MAMI and a research reactor type TRIGA Mark II [1,2]. The latter was built on the initiative of Fritz Strassmann, at that time the Director of the Institute for Anorganic Chemistry and Nuclear Chemistry (Institut für Anorganische Chemie und Kernchemie) at Mainz University.

On the 3rd of August 1965, the TRIGA Mainz became first critical with the insertion of the 57th fuel element in the reactor core. April 3rd 1967 marks the official inauguration of reactor operation with Nobel Prize Laureate Otto Hahn as guest of honour at the opening ceremony. Figure 1 shows a picture of Otto Hahn in the TRIGA Mainz reactor control room.

Since this time the TRIGA Mainz has operated failure-free during about 200 days per year except a short break for a complete refurbishment of the cooling and purification circuits and the cooling tower in 1995. Since almost 50 years the reactor is intensively used for basic research in nuclear chemistry and -physics, applied science as well as for educational purposes. The broad educational program is fully integrated into the curriculum of the faculties of Chemistry and Physics.

On the occasion of the 100th anniversary of Fritz Strassmann on February 22nd 2002 the Institut für Kernchemie became a so-called “Historical Landmark of Science” (Historische Stätte der Wissenschaft) and a plaque was installed at the entrance of the institute to remember the work of Lise Meitner, Otto Hahn and Fritz Strassmann that led to the discovery of nuclear fission in 1939. Figure. 2 shows a picture of the plaque.

FIG. 1. Otto Hahn (right) as reactor operator of the TRIGA Mainz on the occasion of the official opening ceremony April, 3rd 1967. First criticality was reached already August, 3rd 1965 with the insertion of the 57th fuel element in the reactor core.

FIG. 2. Plaque at the entrance of the reactor to remember the work of Lise Meitner, Otto Hahn and Fritz Strassmann that led to the discovery of nuclear fission.

2. CURRENT TECHNICAL STATUS

The TRIGA Mark II reactor at the University of Mainz is a light water-cooled swimming pool reactor with a graphite-reflected core placed inside an aluminum tank with a diameter of 2 m and a height of 6.25 m. The surrounding concrete biological shield and the de-mineralized water in the pool provide the required radiation shielding. The fuel-moderator elements are fixed in the core with a top and bottom grid plate containing 91 positions loaded with the fuel-moderator elements, control-rod guide tubes or irradiation channels and graphite dummy elements. Currently, the reactor core is equipped with 76 fuel elements, concentrically arranged by means of a lower and upper grid plate. The fuel used at the TRIGA Mainz is composed of an alloy of uranium, zirconium and hydrogen containing 8 weight% U, 91 weight% Zr, and 1 weight% H, respectively ($U_{0.03}Zr_1H_1$). Each fuel element contains about 200 g of U, enriched 20 % in U^{235}. The UZrH -fuel matrix forms a circular cylinder about 35.5 cm long and approx. 3.5 cm in diameter. Graphite slugs at each end of the cylinder act as top and bottom reflectors. Each fuel element contains about 36 g of U^{235} [3,4]. The elements are cladded either with aluminum or stainless steel. Under the typical operation conditions of the TRIGA Mainz, the burn-up is in the order of 4 g of U^{235} per year only. Thus, the TRIGA Mainz actually has a life-time core. However, a fresh fuel element is introduced about every four years in order to overcome the slow decrease of the reactivity over time.

2.1. Irradiation facilities

For irradiations the TRIGA Mainz is equipped with a central experimental tube (central thimble), three pneumatic transfer systems (rabbit systems) and a rotary specimen rack with 40 positions which allows the irradiation of 80 samples at the same time. In addition, the TRIGA Mainz includes four horizontal beam ports penetrating the concrete shielding and extending inside the pool towards the reflector. A graphite thermal column provides a source of well-thermalized neutrons suitable for physical research or biological/medical irradiations. Figure 3 shows a vertical cross section view of the TRIGA Mainz and a photo of the reactor pool indicating the position of the core, the reflector and of various irradiation facilities. Figure 4 shows the actual core configuration.

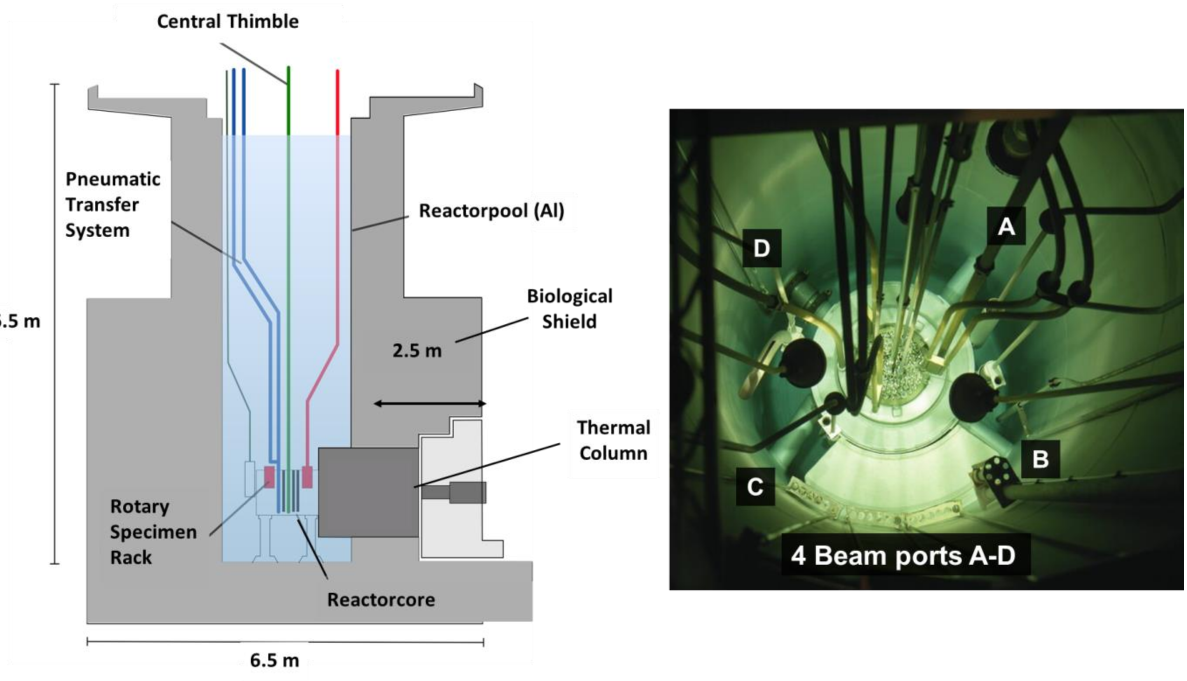

FIG. 3. Vertical cross section view of the TRIGA Mainz and photo of reactor pool indicating the position of the four beam ports A-D.

In the steady state mode the TRIGA Mainz can be operated at power levels ranging from about 100 mW_{th} up to 100 kW_{th}. Pulse-mode operation is also possible, corresponding to a maximum pulse peak power of up to 250 MW_{th}, a neutron flux in the order of 10^{15} cm^{-2} per pulse and a pulse width (FWHM) of about 30 ms. Here, the large prompt negative temperature coefficient of the TRIGA-reactor - an inherent characteristics of the fuel-moderator elements - reduces the power of the reactor within a few thousandths of a second, faster than any engineered device can operate [5]. For pulse mode operation, the reactor is operated at a low steady state power, normally 50 W, and then a control rod is shot out of the reactor core with compressed air. Due to this sudden insertion of excess reactivity the power rises sharply with a reactor period of only a few milliseconds. The pulses have a shape that can be approximated by a Gaussian function with a width at half maximum in the millisecond range. The ratio of the pulse-generated activity A_p to the saturation activity A_S, which is rapidly reached for short-lived nuclides under steady state conditions, is given by Eq. (1):

$$A_P/A_S = (0.737 \cdot t_P \cdot R_P)/T_{1/2} \qquad (1)$$

Here, t_P is the pulse width at half maximum and R_P is the ratio of the pulse peak power to the maximum steady state power output (100 kW_{th}). For a pulse peak power of 250 MW_{th}, t_P is ~30 ms leading to an activity ratio A_P/A_S = 55 s/$T_{1/2}$. Thus, for a 55 s-nuclide the activity produced with a 250 MW_{th} pulse is equal to the saturation activity obtained by steady state irradiation. With equation 1 one can estimate for which short-lived nuclides activation by pulsed irradiation is advantageous [5]. The average operation time of the TRIGA Mainz is about 200 days per year. In recent years, approx. 80% of the time is used for reactor operation at the nominal power of 100 kW_{th} and the rest for pulses, as well as for steady state operation with thermal powers ranging from 100 mW_{th} up to 100 kW_{th}. The operation licence allows the insertion of an excess reactivity up to 2 dollars (250 MW_{th} pulse peak power).

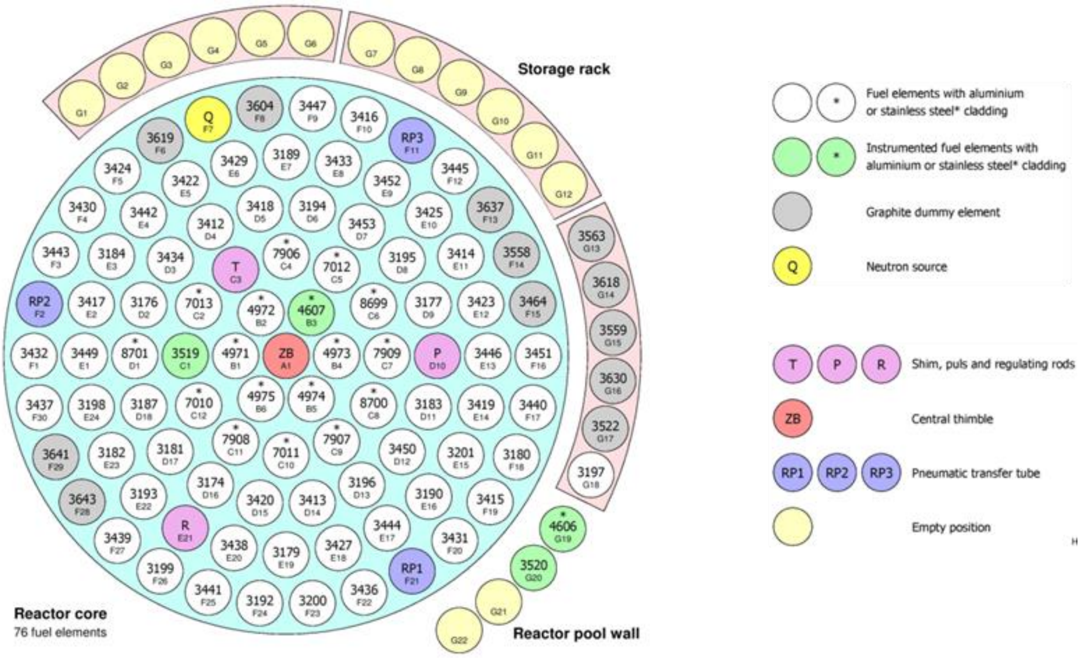

FIG. 4. TRIGA Mainz core configuration with 76 fuel elements in-core.

For long-term irradiations the rotary specimen rack with 80 irradiation positions and the central thimble are used. Here, the samples are transferred manually. Furthermore, for the production of nuclides with short half-lives (up to a few minutes), three transfer systems (so called “rabbit” systems) are available. From a terminal located in the reactor hall or in a radiochemical laboratory the samples are transferred pneumatically to the irradiation position and back. With these systems transport times of 1 to 5 seconds can be achieved. In addition to that, the TRIGA Mainz is equipped with four beam tubes where transport times of about 0.5 seconds are possible by means of special rabbit systems. The thermal column is a further irradiation unit that provides well thermalized neutrons. It consists of a boral-lined aluminum container filled with blocks of graphite (see Fig. 1). For irradiations in the thermal column up to five graphite blocks (102 mm × 102 mm × 1270 mm) can be removed to introduce the sample. Table 1 summarizes the neutron fluxes at the various irradiation positions [6].

TABLE 1. THERMAL AND EPITHERMAL NEUTRON FLUXES AT THE DIFFERENT IRRADIATION POSITIONS OF THE TRIGA-MAINZ AT A POWER OF 100 KW_{TH}

Irradiation Position	Thermal flux[1)] [$cm^{-2}s^{-1}$]	Epithermal flux[2)] [$cm^{-2}s^{-1}$]
Rotary specimen rack	7×10^{11}	4×10^{10}
Rabbit systems	$1.6 - 1.8 \times 10^{12}$	$4.6 - 5.6 \times 10^{10}$
Beam tubes	$1.0 - 5.4 \times 10^{11}$	$7.6 \times 10^{8} - 1.6 \times 10^{10}$
Central thimble	4.2×10^{12}	1.4×10^{11}
Thermal column (hot end)[3)]	3.1×10^{10}	2.1×10^{8}
Thermal column (cold end)[3)]	2.6×10^{7}	6.8×10^{2}

[1)] $E_n \leq 0.4$ eV [2)] $E_n \geq 0.4$ eV [3)] Central irradiation channel

2.2. Organizational structure

Figure 5 shows the organizational chart of the TRIGA Mainz. Reactor operation is supervised by the Reactor Manager (RM), the Deputy Reactor Manager and the Radiation Protection Officer (RPO). The Nuclear Security Officer (NSO) acts independent from RM and RPO and reports directly to the President of JGU who actually is the holder of the operational licence. In addition to that, there are seven rector operators, including the head of the operator crew and four RP technicians. RM, deputy RM and NSO can act as deputy RPO in the case of his absence. Currently, the staff of the Institut für Kernchemie includes 15 scientists and 24 technicians in permanent positions. In addition, about 40 students are working on their master- or doctoral thesis in third-party funded projects. The educational opportunities offered by the institute cover all areas of research and are fully integrated into the curriculum of the Faculties of Chemistry and Physics.

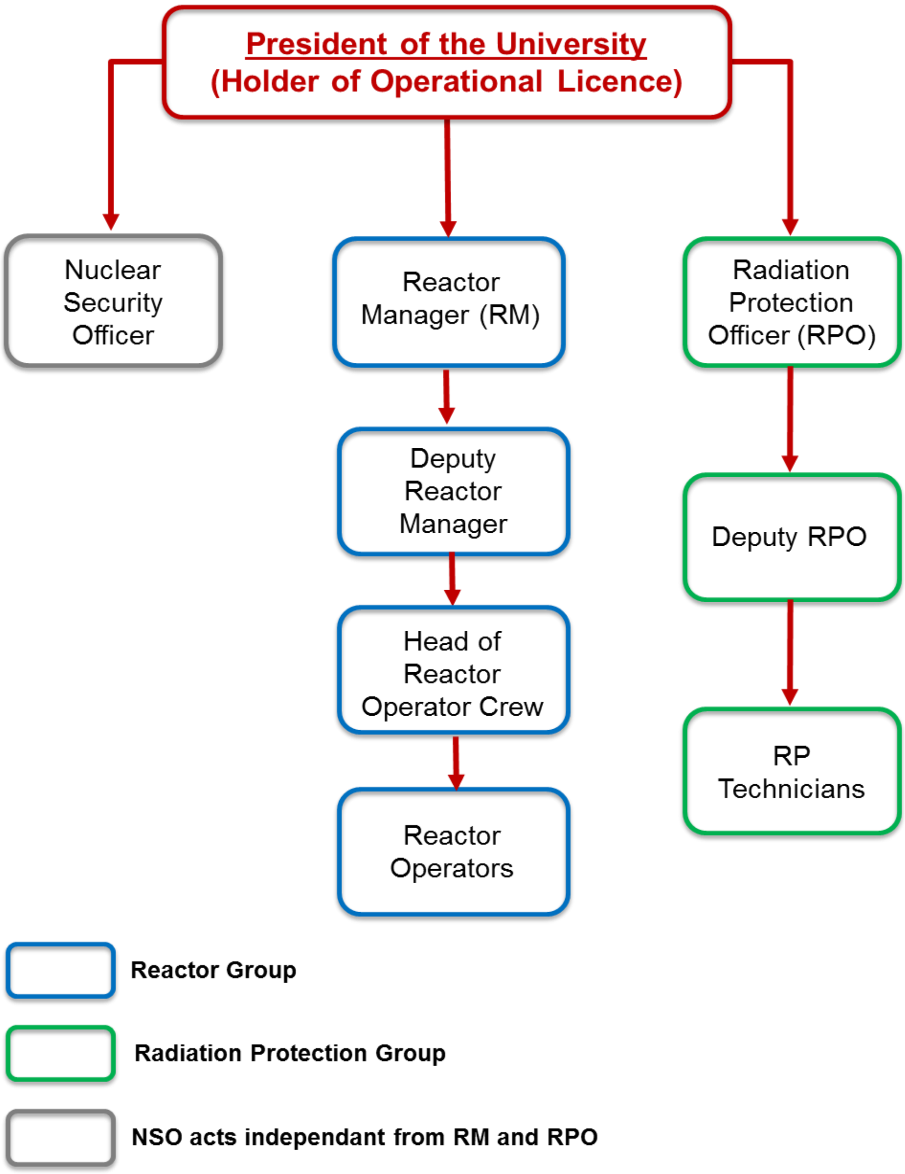

FIG. 5. Organizational structure of the TRIGA Mainz.

3. UTILIZATION OF THE TRIGA MAINZ

The TRIGA Mainz is used for fundamental and applied scientific research as well as for education, and training.

- TRIGA is part of the so-called Cluster of Excellence "Precision Physics, Fundamental Interactions and Structure of Matter“ (PRISMA). PRISMA consists of leading research groups that work primarily in the areas of astroparticle, high-energy, and hadron physics, nuclear chemistry and precision physics with ultra-cold neutrons and ion traps. Beam ports C and D are reserved for the production of ultra-cold neutrons (UCN) to determine fundamental neutron properties with very high precision. Another high-precision experiment (TRIGA-SPEC) is installed at beam port B for the determination of ground-state properties of neutron-rich nuclei by means of Penning trap mass spectrometry and collinear laser spectroscopy.

- Fast chemical separation procedures combining a gas-jet transport system installed in beam port A with either continuous or discontinuous chemical separation are being developed for the investigation of the chemical properties of the heaviest elements.
- Neutron Activation Analysis (NAA) and isotope production for various applications in research and industry are also applications of the TRIGA Mainz. For this, the rotary specimen rack, the central thimble and the rabbit systems are most often used.
- For education and training, various courses in nuclear and radiochemistry, radiation protection, reactor operation and -physics are held for scientists, advanced students, teachers, engineers and technicians.

Figure 6 shows a scheme comprising the current utilization of the TRIGA Mainz.

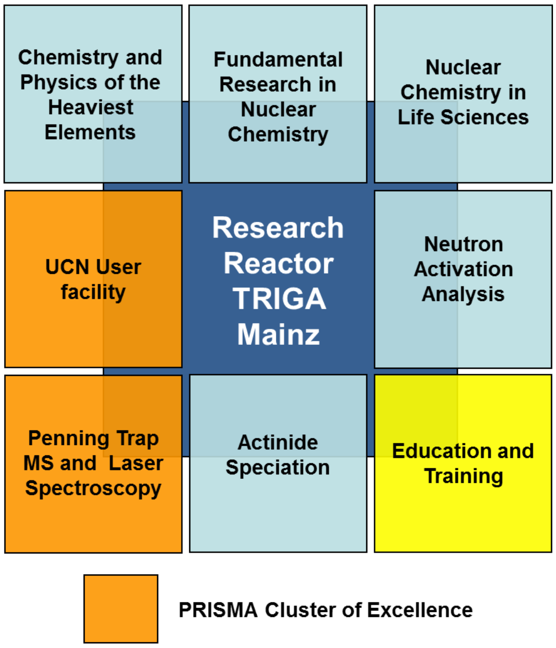

FIG. 6. Utilization of the TRIGA Mainz.

3.1. Production of ultra-cold neutrons

Ultra-cold neutrons (UCN) offer unique opportunities for studying the properties of the free neutron with exceptionally high precision. Properties as its lifetime can be measured with unprecedented accuracy. Sources for UCN are under construction at different research centers worldwide in order to tackle the existing count-rate limitations in these kinds of experiments. UCN posses very low kinetic energies (<10 m/s) and hence are storable in certain material bottles or in magnetic fields over hundreds of seconds in such traps and their fundamental properties can be measured with ultra-high precision. Experiments with UCN aim, among others, to measure the neutron lifetime, to detect a non-zero permanent electric dipole moment or even a non-zero electric charge of the neutron.

Even a low-power reactor such as the TRIGA Mainz is strongly competitive for UCN production due to the possibility to pulse the reactor every five to ten minutes with a maximum pulse peak power as high as 250 MW to produce a high density of UCN. Pulse mode operation ideally meet the requirements of storage experiments, where the trap has to be filled in similar periods in time. With a recently installed super-thermal UCN source [7] at TRIGA a density of 10 UCN per cm^3 in a 10 liter storage volume has been achieved [8].

Background interference during data taking is essentially zero since the reactor is off during the measurements. Low magnetic noise is another quality feature of this reactor. Within PRISMA the TRIGA reactor is transformed into a world-leading user facility, which will be open to researchers from all over the world who want to perform new high-precision experiments with UCNs. Our goal is to reach a UCN density of ~100 per cm^3.

3.2. High-precision measurements of nuclear ground state properties with TRIGA-SPEC

High-precision measurements of nuclear ground state properties of short-lived, neutron-rich nuclei are fundamental for the improvement of nuclear models and a better understanding of the nucleo-synthesis process in stars. The research reactor TRIGA Mainz is an ideal facility to provide neutron-rich nuclides with production rates sufficiently high for mass spectrometric and laser spectroscopic studies. Nuclear mass directly reflects the binding energy in the nucleus and thus precise mass measurements can provide important data for astrophysical calculations of the so-called rapid neutron-capture process (r-process) and also serve as test cases for nuclear mass-models in the heavy mass region. Independent of a particular nuclear model, laser spectroscopy yields information on properties such as nuclear moments and charge-radii of neutron rich nuclides far from stability, which are extracted from the observed hyperfine structure and isotope shift.

The TRIGA-SPEC experiment [9] at beam port B, consists of two branches: (i) the Penning trap mass spectrometer TRIGA-TRAP and (ii) a set-up for collinear laser spectroscopy called TRIGA-LASER. Currently, TRIGA-SPEC is world-wide the only facility of this type installed at a nuclear research reactor. Short-lived nuclides are produced by neutron-induced fission of an actinide target located in a specially designed recoil chamber near the reactor core. For extraction of fission products from the production site to the TRIGA-SPEC set-up, a gas-jet transport system is used. The fission products – attached to aerosols particles– are guided through the biological shield of the reactor by means of a thin capillary. Transport times of less than 500 ms and transport efficiencies up to 70 % have been achieved with this technique [10]. By means of an aerodynamical lens the transport gas is removed and the aerosol particles are guided into an ion source. Here, the aerosol particles are destroyed and a beam of radioactive ions is extracted at kinetic energies of 30 keV. In a subsequent magnetic separator, the nuclides of interest are selected and then enter a quadrupole lens unit where the continuous ion beam is stopped and focused. Bunches of radioactive ions enter a subsequent electrostatic deflector which guides the ion beam either to TRIGA-TRAP or to TRIGA-LASER.

3.3. Development of fast chemical separation procedures for the investigation of the heaviest elements

The heaviest elements known in the periodic table are the trans-actinide elements or so-called super-heavy elements (SHE, $Z > 103$). SHE elements can only be produced at ion accelerator facilities. For this, an intense ion beam is shot onto a thin actinide target. The production rate of the SHE is extremely low and varies between a few atoms per hour down to only one or two atoms per month. For chemists, these elements are exciting, since relativistic effects might alter the energy of the valence electrons in such a way that the chemical behaviour of the SHE might be significantly different from the chemistry of their lighter homologues. In this way, SHE chemistry is a probe to map out the architecture of the Periodic Table of the Elements in its uppermost region.

Due to the low production rates and the short half-lives, there are special requirements for a SHE chemistry experiment, since one performs chemical separations on a one-atom-at-a-time basis. Thus, separations must be performed as fast as possible, fully automated and the decay of the SHE must be detected with high efficiency [11].

The TRIGA reactor gives us a unique possibility to develop and test chemistry set-ups. Short-lived isotopes of the lighter homologues of the SHE can be produced in the neutron induced fission of actinides and used for experiments. Systems to study the chemical properties of single atoms by means of ion-exchange chromatography, liquid-liquid-extraction, and electro-deposition on various metals [11-13] have been invented in Mainz. Furthermore, the synthesis of new volatile compounds of SHE are under development. Very recently an international collaboration led by research groups from Mainz and Darmstadt has achieved the synthesis of a new class of chemical compounds for SHE at the RIKEN Nishina Center for Accelerator-based Research (RNC) in Japan. For the first time, a chemical bond was established between a super-heavy element – seaborgium (Sg, Z=106) in the present study – and a carbon atom. A total of 18 Sg atoms were converted into Sg- hexacarbonyl complexes, which include six carbon monoxide molecules bound to the seaborgium. Its gaseous properties and adsorption to a silicon dioxide surface were studied and compared with similar compounds of neighbors of seaborgium in the same group of the periodic table [14]. A series of preparatory experiments were carried out at the TRIGA Mainz and were shown to work exceptionally well with short-lived atoms of molybdenum, the lighter homologue of Sg.

3.4. Neutron activation analysis and isotope production

Neutron activation analysis (NAA) is a versatile method for various analytical problems due to its simplicity, multi-element capacity, and sensitivity. Instrumental neutron activation analysis (INAA) is performed without any chemical separation steps, whereas the radiochemical neutron activation analysis (RNAA) applies chemical procedures either prior to or after the neutron irradiations. NAA in combination with high-resolution γ-spectrometry can simultaneously determine up to 30-40 elements, down to a range of 0.01 ppb (10 pg/g) for some elements. The selectivity and the detection limit can further be improved by applying coincidence or anticoincidence systems reducing the Compton-background [15]. Delayed neutron activation analysis (DNAA) is a special version and uses the counting of ß-delayed neutrons emitted from very neutron-rich fission products as obtained by the irradiation of fissile material.

At the TRIGA Mainz INAA is applied for trace element determinations in a variety of different sample matrices such as solar grade silicon, dye pigments and glass samples of reverse paintings, as well as for provenance analysis of limestone samples from ancient roman temples and settlements. Irradiations are normally performed in steady state mode at a thermal power of 100 kW using the central thimble, a rabbit system, or the rotary specimen rack. Subsequent to irradiation the activated samples are analyzed using low-level γ-spectroscopy [16].

- *Solar grade silicon*: Due to the growing demand for the production of high efficiency solar cells for electricity production, the availability of high purity silicon - which is also used in the semiconductor industry in huge quantities - is limited due to increasing costs. An alternative might be the so-called solar grade silicon (SG-Si). SG-Si is defined as silicon with acceptable concentration of impurities e.g. from the 3d transition metals since they reduce the energetic efficiency of solar cells. The 3d transition metals perform recombination centres and reduce the life time of the charge carrier produced by light irradiation. In order to investigate the different purification procedures the NAA is used to determine the 3d metal content for solar grade silicon. Other investigations focus on the determination of phosphorous in n-type Si-semiconductors. N-type multicristalline silicon is regarded as a promising candidate for the production of low-cost, high-efficiency solar cells [17]

- *Reverse glass paintings:* In reverse glass paintings of the 18th and 19th century quite different dye pigments and also different glasses were used. By analysing several paintings from different European countries and different periods by INAA it could be shown that it is possible to distinguish pigments of different areas of origin. Dating is also partly possible. Their supposed period of origin was between the middle of the 18th and the end of the 19th century [18].

- *Provenance analysis of limestone:* The region along the river Moselle is characterized by rich limestone deposits which were mainly formed during the Jurassic period. The Romans appreciated the high quality of this material for the construction of representative buildings and artwork. Knowledge of its provenance can reveal e.g. details of ancient trade routes. INAA was used to determine concentration profiles of more than 30 elements. For sampling a few millimetre of the surface was removed to avoid cross contamination of the material. High-purity drill bits were then used to sample about 100 mg of limestone material. Irradiations were performed using the pneumatic transfer systems and the rotary specimen rack. By applying different irradiation times and different subsequent sample cooling times it was possible to obtain concentration profiles of more than 30 elements present in the limestone. Multivariate statistics helped to distinguish between different objects and thus allowed provenance analysis of the samples. This work is performed in collaboration with different museums and archaeological research institutes in France, Belgium and Germany [19].

- *Delayed Neutron Activation Analysis (DNAA):* Delayed neutron activation analysis is used for the fast determination of fissile nuclides, such as ^{233}U, ^{235}U and ^{239}Pu by measuring the delayed neutron emission of some fission products. From the nuclides produced in nuclear fission, about 110 are known precursors of ß-delayed neutrons emission with half-lives ranging from milliseconds to minutes. Furthermore, this technique was also applied for the determination of thorium in samples containing uranium. ^{232}Th fissions only with neutrons of an energy of 1 MeV and above and therefore a cadmium cover for the absorption of thermal neutrons is used. At the TRIGA Mainz the fast neutron flux is much lower than the thermal flux and thus the sensitivity for thorium is decreased compared to uranium and plutonium.
  Under conditions of the TRIGA Mainz the detection limits are 10^{-11} g for ^{235}U and ^{239}Pu and 10^{-6} g for ^{232}Th. Typically, the samples are irradiated for 2 min using one of the rabbit systems for fast sample transfer and after a delay time of 15 to 20 s, they are counted for 1 min with ^{3}He proportional tubes in a circular arrangement. The delayed neutrons thermalized by paraffine and polyethylene are detected with an efficiency of about 30% [16].

- *Production of radioactive tracer isotopes:* At low flux reactors, such as the TRIGA Mainz, radioisotopes with short decay times can be produce easily. For applications in the chemical industry radio-tracers such as ^{24}Na, ^{41}Ar, ^{56}Mn, ^{113m}In, ^{82}Br, ^{140}La are applied for on-line measurements of flow rates (gaseous and liquid), dwell times and volume determinations.

3.5. Education and training

Education and Training is a main utilisation of the TRIGA Mainz. There is a demand in Germany for education and training not only in nuclear engineering and radiation protection but – equally important – in the fields of nuclear chemistry and –physics for students in undergraduate and graduate level. For this, various courses in reactor operation and –physics, in nuclear and radiochemistry as well as in radiation protection are held at the Institute for Nuclear Chemistry utilizing the TRIGA Mainz reactor.

- *Reactor operation and reactor physics:* This course consists of a lecture in reactor physics and practical training in reactor operation at steady state power as well as in the pulse mode. The course is focused on education and practical training to understand the general behaviour of a nuclear reactor. The main object of this course is to introduce in the basics for reactor operation, reactor techniques and physics in practical examples at the research reactor TRIGA Mainz. The participants receive practical experience in operation of a nuclear reactor which can be perfectly executed at the TRIGA Mainz. The complete course takes five days and is held at least two times per year. The number of participants is limited to 8-10 to assure proper mentoring. The requirements for participation are basic theoretical knowledge in nuclear chemistry and –physics, nuclear reactions, including nuclear fission and related phenomena. The students must have passed the basic course in nuclear chemistry. This includes a related lecture in nuclear and radiochemistry. One additional course per year is conducted for training of Swiss reactor operators from the reactor training school (Reaktorschule) at the Paul-Scherrer-Institut in Villigen, Switzerland.

- *Basic course in nuclear chemistry:* This training course is based on the course “Praktische Radiochemie” (Experimental Radiochemistry) previously held by Otto Hahn at the Kaiser-Wilhelm-Institut für Physikalische Chemie in Berlin to teach his students in the handling of radioactive isotopes. Fritz Strassmann established this course in Mainz soon after he joined the Johannes Gutenberg-Universität in 1946.The complete course takes two weeks (10 days) and is held at least four times per year. The number of participants is limited to 18 students, mainly due to the available laboratory space and the necessity for intense mentoring of the student handling radioisotopes in solution. For participation the students must have successfully attended the related lecture “Introduction to Nuclear- and Radiochemistry” held at the Institut für Kernchemie. The course gives a broad overview of the production, the properties and the applications of radioisotopes in chemistry, physics and life sciences.

- *Advanced course in nuclear chemistry:* This course is focused on research and takes four weeks. The participants work in one of the institutes research groups under the supervision of a PhD Student. Subjects include the development of chemical separation procedures to study the chemistry of the heaviest elements, high precision mass measurements in a Penning-Trap and collinear laser-spectroscopy of fission products, production and application of ultra-cold neutrons (UCN), ultra-trace analysis of plutonium and other actinides with Resonance Ionization Mass

Spectroscopy (RIMS), trace element analysis of various samples using Neutron Activation Analysis (NAA), irradiation of cell cultures for studies in Boron Neutron Capture Therapy (BNCT). When the practical work is finished, the participants have to prepare an extensive research report as well as to deliver a talk in the weekly institute seminar.

- *Courses in radiation protection:* Training courses of different levels in radiation protection are frequently offered for firemen, technicians, teachers, students and scientists of various fields e.g. chemistry, physics, life sciences, pharmacy and medicine. All courses fulfill the requirements of the German Radiation Protection Decree (Strahlenschutzverordnung). The experimental program carried out comprises measurements of neutron- and γ-dose rates at the biological shield and the near-surface of the reactor pool. The reactor is operated at different thermal power levels from a few Watt up to the maximum steady-state power of 100 kW allowing dose rate monitoring at different power levels. Furthermore, subsequent to the irradiation experiments samples of the pool water are taken and investigated using γ-spectroscopy to monitor pool water activity.

4. MAJOR ACHIEVEMENTS

In June 2012, the funding for the Cluster of Excellence "Precision Physics, Fundamental Interactions and Structure of Matter (PRISMA)" has been approved by the Joint Commission of the German Research Foundation and the German Council of Science and Humanities. PRISMA is one of two clusters in Germany dedicated to research into basic questions about the nature of the fundamental building blocks of matter and their importance for the physics of the Universe. The Cluster is funded by the German Research Foundation (DFG) and the State of Rhineland Palatinate. PRISMA is a joint initiative involving Johannes Gutenberg- University Mainz, the Helmholtz Institute Mainz (HIM), and the GSI Helmholtz Center for Heavy Ion Research in Darmstadt. The TRIGA Mainz is one of the key facilities of PRISMA, besides the electron accelerator facility MAMI.

Within the frame of PRISMA two intense sources of ultra-cold neutrons (UCN) are operated and further developed. Currently, the TRIGA reactor in Mainz has one of the strongest UCN-sources world-wide. In the past few years a Penning trap and a laser-spectroscopy setup for the investigation of short-lived fission products - TRIGA-SPEC - has also been installed at TRIGA for high-precision measurements of ground-state properties of short-lived, neutron-rich isotopes of astrophysical relevance. TRIGA-SPEC is also part of PRISMA.

At TRIGA the development of chemical separations of a one-atom-at-a-time basis is performed since many years. Separation procedures e.g. for Rf, Db, Sg, and Bh (Z=104-107) have been developed with fission products as the lighter homologues of the SHE. Recently, a method applied to synthesize the first organic compound of Sg has been developed at TRIGA using short-lived Mo isotopes as provided by nuclear fission.

5. FUTURE PROSPECTS

PRISMA strengthens the research in the area of low-energy precision experiments by upgrading the TRIGA research facility to provide one of the world’s strongest pulsed source of ultra-cold neutrons. PRISMA provides the infrastructure to sustain long-term experiments at a facility well suited for UCN-storage experiments. The conversion to a full user facility is ongoing: A He-liquefier with a capacity of 14 l/h has been commissioned in autumn 2014. New staff for user operation has been hired. In parallel the upgrade of the UCN-source from its present 10 UCN per cm^3 is ongoing. A UCN density of ~50 per cm^3 in the near future is expected. The central experiment at this UCN-source is the τSPECT experiment that is currently being set-up at beam port D. *τSPECT* will measure the lifetime of the free neutron using magnetic storage of the neutrons. It will determine the lifetime using an in-situ measurement of the decay curve by detecting the decay products of the neutron decay, the proton and the electron. A rapid development is expected since *τSPECT* is based on the successful *aSPECT* experiment and reuses many of its components.

Mass Measurements of heavier trans-plutonium actinides up to Bk-249 are planned with TRIGA-SPEC. For this an off-line ion source based on laser ablation in combination with a miniaturized quadrupole lens for efficient ion extraction will be used. Measurements with Bk-249 are planned for 2015.

REFERENCES

[1] KOUTZ, S.L., TAYLOR T., MCREYNOLDS, A., DYSON, F., STONE, R.S., SLEEPER, H.P., DUFFIELD, R.B., “Design of a 10 kW Reactor for Isotope Production, Research and Training Purposes”, Proc. 2nd U.N. Intern. Conf. Peaceful Uses Of Atomic Energy (1958) 1017.

[2] TONE, R.S., SLEEPER, H.P., STAHL, R.A., WEST, G., “Transient Behaviour of TRIGA, a Zirconium-Hydride, Water - Moderated Reactor”, Nuclear Science and Engineering 6 (1959) 255.

[3] MERTEN, U., DIJKSTRA, L.J., CARPENTER, F.D., HATCHER, A.P., LA GRANGE, L.D., “The Preparation and Properties of Zirconium-Uranium-Hydrogen Alloys”, Proc. 2nd U.N. Intern. Conf. Peaceful Uses Of Atomic Energy (1958) 789.

[4] MCREYNOLDS, A.W., NELKIN, M.S., ROSENBLUTH, M.N., WHITTEMORE, W.L., “Neutron Thermalization by Chemically-bound Hydrogen and Carbon”, Proc. 2nd U.N. Intern. Conf. Peaceful Uses Of Atomic Energy (1958) 1540.

[5] MENKE, H., TRAUTMANN, N., KREBS, W.-J., “Irradiations by Means of Reactor Pulses”, Kerntechnik 17 (1975) 281.

[6] EBERHARDT, K., TRAUTMANN, N., “Neutron Activation Analysis at the TRIGA Mark II Research Reactor of the University of Mainz”. In: IAEA Technical Reports Series No. 455 “Utilization Related Design Features of Research Reactors: A Compendium“ (2007) 537-545.

[7] FREI, A., SOBOLEV, YU., ALTAREV, I., EBERHARDT, K., GSCHREY, A., GUTSMIEDL, E., HACKL, R., HAMPEL, G., HARTMANN, F.J., HEIL, W., KRATZ, J.V., LAUER, TH., LIZON AGUILAR, A., MÄLLER, A.R., PAUL, S., POKOTILOVSKI, YU., SCHMID, W., TASSINI, L., TORTORELLA, D.,TRAUTMANN, N., TRINKS, U., WIEHL, N., “First production of ultracold neutronswith a solid deuterium source at the pulsed reactor TRIGA Mainz”, Eur. Phys. J. A 34 (2007) 119.

[8] KARCH, J., SOBOLEV, YU., BECK, M., EBERHARDT, K., HAMPEL, G., HEIL, W., KIESER, R., REICH, T., TRAUTMANN, N., ZIEGNER, M., “Performance of the solid deuterium ultra-cold neutron source at the pulsed reactor TRIGA Mainz”, Eur. Phys. J. A50 (2014) 78.

[9] KETELAER, J., KRÄMER, J., BECK, D., BLAUM, K., BLOCK, M., EBERHARDT, K., EITEL, G., FERRER, J., GEPPERT, C., GEORGE, S., HERFURTH, F., KETTER,

J., NAGY, SZ., NEIDHERR, D., NEUGART, R., NÖRTERSHÄUSER, W., REPP, J., SMORRA, C., TRAUTMANN, N., WEBER, C., TRIGA-SPEC: A setup for mass spectrometry and laser spectroscopy at the research reactor TRIGA Mainz“, Nucl. Instr. Meth. A 594 (2008) 162.

[10] EIBACH, M., BEYER, T., BLAUM, K., BLOCK, M., EBERHARDT, K., Herfurth, F., GEPPERT, C., KETELAER, J., KETTER, J., KRÄMER, J., KRIEGER, A., KNUTH, K., NAGY, SZ., NÖRTERSHÄUSER, W., SMORRA, C., “Transport of fission products with a helium gas-jet at TRIGA-SPEC” Nuclear Instruments and Methods A 613 (2010) 226.

[11] “The Chemistry of Superheavy Elements”, SHAUGHNESSY, D., SCHÄDEL, M., (Eds.), Springer, Berlin, 2nd. Ed. (2014).

[12] ALSTAD, J., SKARNEMARK, G., HABERBERGER, F., HERRMANN, G., NÄHLER, A., PENSE-MASKOW, M., TRAUTMANN, N., “Development of New Centrifuges for Fast Solvent Extraction of Transactinide Elements”, J. Radioanal. Nucl. Chem. 189 (1995) 133.

[13] HILD, D., EBERHARDT, EVEN, J., K., KRATZ, J.V., WIEHL, N., LÖB, P., WERNER, B., HOFMANN, C., “MicroSISAK: continuous liquid-liquid extractions of radionuclides at 0.2 ml/min”, Radiochim. Acta 101 (2013) 681.

[14] EVEN, J., YAKUSHEV, A., DÜLLMANN, CH.E., HABA, H., ASAI, M., SATO, T.K., BRAND, H., DI NITTO, A., EICHLER, R., FAN, F.I., HARTMANN, W., HUANG, M., JÄGER, E., KAJI, D., KANAYA, J., KANEYA, Y., KHUYAGBAATAR, J., KINDLER, B., KRATZ, J.V., KRIER, J., KUDOU, Y., KURZ, N., LOMMEL, B., MIYASHITA, S., MORIMOTO, K., MURAKAMI, M., NAGAMA, Y., NITSCHE, H., OOE, K., QIN, Z., SCHÄDEL, M., STEINER, J., SUMITA, T., TAKEYAMA, M., TANAKA, K., TOYOSHIMA, A., TSUKADA, K., TÜRLER, A., USOLTSEV, I., WAKABAYASHI, Y., WANG, Y., WIEHL, N., YAMAKI, S., “Synthesis and detection of a seaborgium carbonyl complex”, Science 345 (2014) 1491.

[15] MAUERHOFER, E., “Improvement in the Counting Statistics and in the Limit of Detection with Compton Suppression Spectrometers – a Contribution to Instrumental Neutron Activation Analysis”, Appl. Radiat. Isot. 47 (1996) 649.

[16] EBERHARDT, K., TRAUTMANN, N., “Neutron Activation Analysis at the RIGAMark II research Reactor of the University of Mainz, in: “Utilization Realated Design Features of Research Reactors - A Compendium”, International Atomic Energy Agency Technical Report Series No. 455, Vienna (2007).

[17] FERREIRA, J., PALAIS, O., PASQUINELLI, M., BARAKEL, D., “Is n-type multicristalline silicon the best candidate for short-term high-efficiency lower-cost solar cells?“ Proceedings of the International Conference on renewable Energies and Power Quality, Granada (2010).

[18] CONEJOS-SANCHEZ, I., HAMPEL, G., ZAUNER, S., RIEDERER, J., “Reverse paintings on glass—A new approach for dating and localization”, Applied Radiation and Isotopes 67 (2009) 2113.

[19] STIEGHORST, C., HAMPEL, G., ZAUNER, S., PLONKA-SPEHR, C., „Archäometrie mittels instrumenteller Neutronenaktivierungsanalyse am Forschungsreaktor TRIGA Mainz“ METALLA, Sonderheft 5: Archäometrie und Denkmalpflege (2012).

APPENDIX: TECHNICAL DATA OF THE TRIGA MAINZ

1. FUEL ELEMENTS	
fuel-moderator material	8 wt% uranium 91 wt% zirconium 1 wt% hydrogen
uranium enrichment	20% Uran-235
fuel element dimensions	3.75 cm in diameter 72.24 cm in length
cladding	0.76 mm aluminum or 0.51 mm steel
active core volume	max. 49.5 cm diameter, 35.56 cm high
core loading	2.7 kg of uranium-235
2. REFLECTOR	
material	graphite with boral cladding
radial thickness	30.5 cm
3. CONSTRUCTION	
reactor shielding	heavy and standard concrete 6.55 m high, 6.19 m wide, 8.76 m long
reactor pool	1.98 m in diameter 6.40 m in depth
4. RADIATION SHIELDING	
radial:	30.5 cm of graphite; 45.7 cm of water and at least 206 cm of heavy concrete
vertical:	above the core 4.90 m of water underneath the core 61.0 cm water and about 90 cm standard concrete
5. IRRADIATION DEVICES	
(1) four beam ports (2) one central irradiation tube (center of core) (3) a rotary specimen rack with 40 irradiation positions (4) three pneumatic transfer systems (near core edge) (5) a thermal column with cross section 1.22 x 1.22 m and a length of 1.68 m	

ITU TRIGA MARK II TRAINING AND RESEARCH REACTOR

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Abstract.

ITU TRIGA Mark-II Training and Research Reactor is a nuclear research reactor located in Istanbul Technical University, Turkey. It is a light water reactor, the 54th TRIGA in the world designed and manufactured by General Atomics. The facility was opened on March 11, 1979. There are 5 members of the reactor staff. Beam ports, central thimble and pneumatic rabbit system are available irradiation facilities in the reactor. The field of utilization concerns education and training and neutron activation analysis. Another purpose of the reactor is to remove public concern about nuclear energy. As a result of some actions, the number of visitors is increased significantly during the recent years. In the future, reactor will be electronically modernized and utilization of the reactor is expected to be increased.

1. BRIEF HISTORY

ITU TRIGA Mark-II Training and Research Reactor is a nuclear research reactor located in Istanbul Technical University, Turkey. It is a light water reactor, the 54th TRIGA in the world designed and manufactured by General Atomics. The facility was opened on March 11, 1979. It is the one of three installed nuclear research reactors in Turkey, another two reactors known as TR-1 and TR-2 have been established in Çekmece Nuclear Research and Training Center. TR-1 started operation on May 27, 1962 with its 1 MW nominal power. After 15 years of operation, TR-1 was upgraded to the 5 MW reactor known TR-2. TR-2 reached criticality in the same building and the existing pool on December, 1981. Since TR-2 has been shut down to meet the re-licensing requirements, ITU TRIGA Mark-II Training and Research Reactor is the only operational research reactor in Turkey now.

ITU TRIGA Mark II was continuously operating till 2002. After the 1999 earthquake which occurred near Istanbul, and despite no real damage done to the ITU-TRR, the institutions responsible for the status of the research reactor decided to reinforce the reactor building. This feature has been also suggested by the Turkish Atomic Energy Authority. Necessary funds could be made available at the end of 2005. Then a new wall of the reactor facility was built from reinforced concrete after existing wall had been demolished. The cooling tower of the secondary cooling system has been evaluated and found worn out with the need to be replaced with a new one. Old cooling tower has been replaced with a new more powerful tower. At the end of these works, the reactor was subsequently undergone another very careful inspection. Furthermore, the health physics and monitoring equipment has been renewed and neutron activation analysis and also low-background radiation laboratories were constructed in the same time. There was no long standing interruptions in the operation of the reactor except this 4 years of shut down period of the reactor.

2. CURRENT TECHNICAL STATUS

The ITU TRIGA Mark II Training and Research Reactor is a low power pool type research reactor. It is used currently to carry out training and research activities, irradiation of samples for neutron activation analysis (NAA) and examination of properties of different materials and education.

The various services of the ITU TRIGA Mark II Training and Research Reactor, all have relevant priorities within the 2012-2016 strategic programme. This programme was developed based on the IAEA-TECDOC-1212 which provides guidance for the reactor managers to develop a strategic plan [1]. Reactor facilities such as the beam port and in-core irradiation facilities are also selectively made available as a service to the community e.g. for industrial benefit and in particular to academic organisations as an institutional benefit.

The TRIGA MARK II is an above-ground fixed core research reactor as shown in Figure 1. The reactor pool is 6.4 m deep by 1.98 m in diameter. Surrounding water and approximately 2.44 m of concrete provide radial shielding.

FIG. 1. ITU TRIGA Mark II Training and Research Reactor.

The reactor is operated in two modes: steady-state and pulsing. Reactor power levels in the steady-state mode are range up to and include 250 kW. Pulsed mode operation will take place by step reactivity insertions with the reactor initially at a power level less than 1 kW. Reactor can reach 1200 MW pulsing peak power in 20 milliseconds in the pulse mode.

The reactor core components are contained between top and bottom aluminum grid plates surrounded by the graphite reflector, and consist of a lattice of fuel-moderator elements, graphite reflector elements, 3 control rods, Am-Be neutron source and in-core experimental devices such as the central thimble, pneumatic system terminus and in-core irradiation positions. Other reactor experimental facilities include horizontal irradiation channels which are called as radial, piercing and tangential beam tubes, and horizontal graphite thermal column.

Reactor cooling is provided by natural circulation of pool water which is in turn cooled and purified. Coolant is returned to the reactor pool through a discharge pipe which terminates in a diffuser nozzle approximately 183 cm above the reactor core. Operation of the diffuser pump significantly reduces the nitrogen-16 contribution to the surface dose rate. Secondary cooling system consists of heat exchanger and cooling tower. This system transfers heat from the primary side of the heat exchanger to the cooling tower by conduction through the tube walls.

Purification is performed by circulating coolant from the reactor pool through a pool surface skimmer, a small pump, a filter and mixed bed demineralizer, and back to the reactor. The filter removes particulate matter not retained in the surface skimmer while the demineralizer removes dissolved material to maintain proper conductivity and radioactivity levels. The effectiveness of the demineralizer is measured by conductivity probes on the inlet and outlet side of the demineralizer.

The ventilation system is designed such that it will maintain a slight vacuum inside. Any uncontrolled and unnoticed leakage will be inward rather than outward. If a sensor in the chimney detects excess radioactivity in the air, it shuts down the ventilation, automatically. In this case an emergency blower, bypassing the main blower maintains the vacuum.

NAA is a quantitative and qualitative method for the measurement of elements in different types of samples. ITU TRIGA Mark II Training and Research Reactor is used as the source of neutrons during the irradiation of the samples. Subsequent to irradiation, radiation from the samples can be measured instrumentally by a high resolution semiconductor detector. A gamma ray spectrometer with semiconductor detector is used for the measurements in the NAA laboratory. The NAA laboratory has two laboratory rooms for sample preparation and radiation counting. Equipment in the sample preparation laboratory includes drying oven, shaker bath and analytical balance. In the other room, qualitative and quantitative measurement of radioisotopes is made at radiation counting laboratory by using the gamma ray spectrometer consisting of a detector, digital spectroscopy system and gamma spectrum analysis software.

There are several in-core and in-pool facilities in the reactor tank. Two vertical irradiation channels are located in the core: Pneumatic transfer system permits irradiations to produce shortlived radioisotopes. The in-core terminus of this system is normally located in the outer ring of fuel element positions. Also, the reactor is equipped with a central thimble for conducting experiments or irradiating samples in the core. It is at the centre of the reactor core. It is the nearest irradiation point to the core maximum flux among other irradiation facilities.

Fuel storage racks each capable of containing 10 fuel elements, are located underwater along the walls of the reactor tank to provide temporary storage of fuel-moderator or graphite dummy elements. Also, Am-Be neutron source is stored in one of the racks. Fuel element inspection tool is another in-pool facility. It is used to accurately inspect a fuel element for longitudinal growth and bowing.

The beam ports provide tubular penetrations through the concrete shield and the reactor tank water, making beams of neutrons and gamma radiation available for a variety of experiments. ITU TRIGA Mark II Training and Research Reactor has three 15.24 cm diameter horizontal beam ports, extending through the shielding to the face of the reflector; permit the extraction of core radiations. One of the beam tubes extend radially to the reflector, a second penetrates the reflector to the core's edge, and the third is tangent to the core.

Radial beam port terminates at the outer edge of the reflector can. Radial beam can be used for the Boron Neutron Capture Therapy (BNCT) experiments on rats. For this purpose, a setup has been designed in front of this beam tube and experiments were performed. Second radial port pierces the graphite reflector and terminates at the inner edge of the reflector can. Fast neutrons can be produced using this port. Third beam port is oriented tangentially to the outer edge of the core and penetrates the concrete shield structure and the reactor water, terminating at the outer edge of the reflector can. A hole is drilled in the graphite tangential to the outer edge of the core. A bismuth crystal is placed in front of this beam port as the gamma ray filter. This port is used for neutron radiography.

A graphite thermal column, measuring 1.22 m × 1.22 m × 1.68 m and extending from the reflector through the concrete structure, provides a source of well-thermalized neutrons suitable for physical research or biological irradiation. A 107 cm thick rolling door with a removable 15.24 cm concrete plug shields the outer face of the column.

Fuel Element Handling Tool: It is used for repositioning the fuel-moderator and graphite elements. Made of stainless steel, this tool consists of a grapple mechanism, a weight, a handle and grapple release, and a flexible control cable.

Reactor is frequently used for education and training. In order to train supervisor and operator candidates, training programmes are available for ITU TRIGA Mark II Training and Research Reactor. They are written both in Turkish and in English. Short (5 days) and long (20 days) internship programmes in ITU TRIGA Mark II Training and Research Reactor has been prepared for students from other universities. Reactor experiments can be designed and performed for the nuclear engineering students, operator and supervisor candidates and interns. Mostly conducted experiments are measurement of the reactor period, control rod calibration, determination of temperature and void coefficient of reactivity, reactor power calibration, determination of neutron source strength in the subcritical reactor, determination of reactivity value of uranium fuel and graphite element in different core positions, approach to criticality and NAA experiment.

There are 5 members of the reactor staff. One operator has the facility-specific operator license. He is responsible to operate the reactor. During the period of assignment, operator is authorized and responsible to operate the reactor in compliance with the operational limits and conditions within the frame of licensing conditions. Other duties of the operator are to control startup and shutdown for safely operation, to operate the reactor according to daily programme and to keep the operational records. Within the period of assignment operator is responsible to supervisor.

The supervisor has been delegated direct responsibility and authority by the operating organization for the operation of the reactor. He has an operating license belong to facility. He has overall responsibility to operate the reactor within the operational limits and conditions pursuant to licensing conditions in accordance with the regulations and to ensure safe operation. Other duties of the supervisor are the implementation of emergency procedures, management of fuel handling and industrial and academic utilisation of the beam ports.

There are two radiation protection personnel in the reactor. They are responsible for the protection of the people from radiation during operation and assigned by the operating organization in accordance with the rules and procedures. Radiation protection personnel are authorized and responsible to provide the required conditions, to operate the reactor according to principles of radiation protection, to take measures in accordance with the regulations during the normal operation and emergency conditions, to carry out the decontamination processes and to keep the all records relating with the health physics.

Operating manager who is responsible for operation of the reactor is a manager of the reactor unit and is assigned by the director of the ITU Energy Institute. Operating manager is responsible to know all information in detail which is required duties and responsibilities. Operating manager is assigned to establish (perform) all technical and administrative arrangements and its implementation and monitoring/inspecting the staff in the ITU TRIGA Mark II Training and Research Reactor, in order to operate the reactor in safely manner in compliance with the licensing conditions and related legislations. Establishment physical security system of the reactor and application of operating limits and conditions of the reactor are examples of manager's responsibilities. Figure 2 shows the organization chart of the ITU TRIGA Mark II Training and Research Reactor.

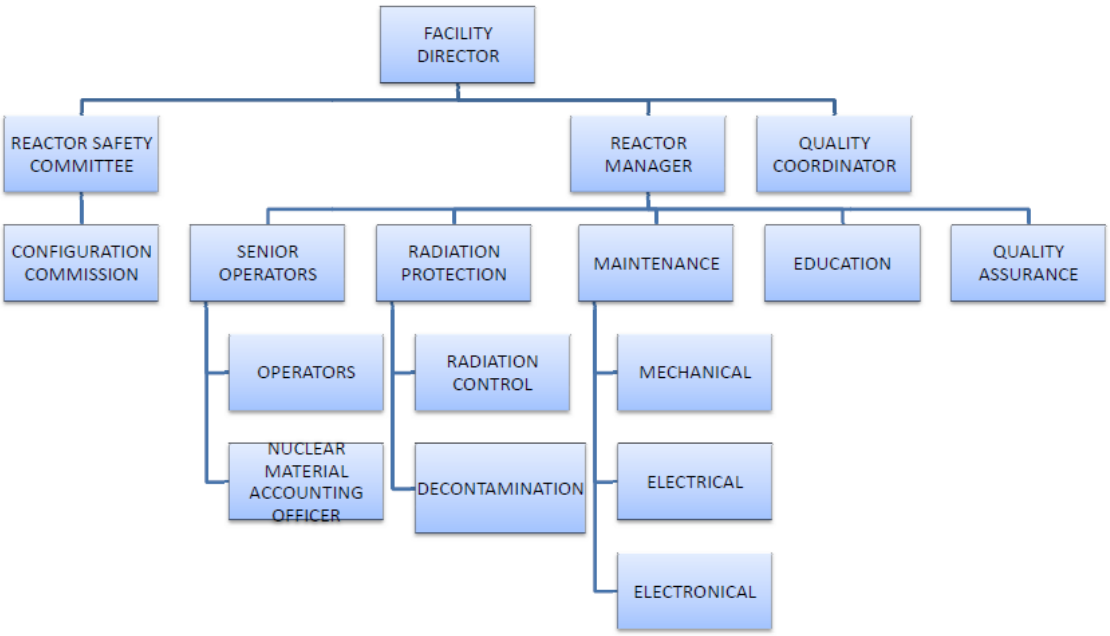

FIG. 2. Organization chart of ITU TRIGA Reactor.

3. APPLICATIONS AND UTILIZATION EXAMPLES

ITU TRIGA Mark II Training and Research Reactor rendered services to ITU and other universities and institutions within the scope of operation purposes in 2013. The main applications in the reactor are education and training, and NAA.

It is possible to perform 10 reactor physics experiments using the reactor for the graduate students of ITU Energy Institute. There is a course called "Nuclear Engineering Laboratory" including these experiments in energy science and technology programme.

In the summer seasons, students from other universities (especially nuclear engineering students) come to the reactor for the reactor experiments. Last year, 4 experiments were performed for graduate students in one week period. Similarly, reactor experiments were carried out for intern students.

Every year many high school and university students are introduced to the reactor. Also domestic and foreign visitors are informed about the reactor. Another purpose of the reactor is to remove public concern about nuclear energy. Turkey has plans to build nuclear power plants and reactor is used to change public perception of nuclear energy. As a result of some promotional activities, the number of visitors is increased significantly during the recent years. Also a new nuclear energy information center was opened on March 2014. It is expected that 20 000 people will visit the center every year.

Irradiation requests from ITU and other universities are realized in the reactor. Another research activity was the BNCT experiments in radial beam last year. Also neutron flux measurement at the irradiation channels were carried out several times.

NAA is the field of main research in the reactor. Investigation of selenium elimination in aqueous environment by radiotracer technique, optimization of k_0 standardization in neutron activation analysis using LVR-15 reactor in Řež and TRIGA Mark II reactor in Istanbul, determining spatial distribution of industrial pollution in terms of ecological risk levels in Marmara region are examples of recent research activities [2]. Reactor was used to irradiate samples such as boron composites, selenium, potassium, rubidium, sodium etc.

In order to increase international collaboration, participation was provided some International Atomic Energy Agency (IAEA) supported meetings. Strategic and action plan of the reactor was renewed and updated in 2013. Then participation was provided to the IAEA workshop “Regional Workshop on Development and Implementation of Strategic Plans at Research Reactors”. Also ITU TRIGA Mark II Reactor took part in Mediterranean Research Reactor Network (MRRN).

4. SUCCESS STORIES

There are a few successful utilization examples of the ITU TRIGA MARK II Training and Research Reactor, and these are briefly described below.

After writing a letter provincial directorate for national education to encourage high school visitors to the ITU TRIGA reactor in Istanbul, the number of student visitors has been increased significantly. They satisfy their curiosity by visiting the reactor and learn more about the nuclear energy by listening the related presentation.

Cooling tower has been relocated recently. Now external cooling circuit has higher performance in heat transfer process. After this change, annual operation hours of the reactor increased from 30 hours/year to approximately 90 hours/year.

ITU TRIGA Mark II Training and Research Reactor was used for the first time in the field of medicine research last year. BNCT experiment on rats was carried out using radial beam tube.

After the long period of shut down, reactor building has been strengthened against earthquakes in Istanbul. Then, reactor could start its operation successfully and safely. This is an essential progress in the reactor, since future earthquakes are the major threat for the safe operation of research reactors in Istanbul.

Older quality and configuration management systems has been renewed recently. Both of them are important for the safe operation of the reactor. Now the quality management system includes new and detailed procedures. Some of the operational procedures of ITU TRIGA Mark II Training and Research Reactor are:

- Radiation protection procedure,
- Emergency situation procedure,
- Operational records procedure,
- Sample irradiation procedure,
- Maintenance procedure,
- Nuclear material accountability and control procedure,
- Reactor visitors' entrance and exit procedure,
- Education and training procedure,
- Safety procedure in external works for the reactor,
- Device, material and service purchase procedure,
- Inspection and acceptance procedure for purchased device and materials,
- Calibration procedure of all device used in the reactor,
- Procedure for permanent changes in the reactor,
- Procedure for temporary changes in the reactor,
- Failure report procedure,
- Incident report procedure,
- Accident/event report procedure,
- Documentation control procedure,
- Reactor experiments procedure,
- Radioactive waste management procedure,
- Core management procedure,
- Fuel movement procedure,
- Operational experience feedback procedure,
- Material movement and storage procedure,
- Entrance control in the sections of the reactor,
- Nuclear fuel storage procedure,
- Inspection of reactor systems procedure.

In addition to the operational procedures, quality management system of ITU TRIGA Mark II Training and Research Reactor contains other quality management procedures, quality policy, organization, duties and responsibilities. Quality management document of IAEA have been used in the preparation of reactor quality management system [3]. Quality control procedures are applied to all services of the reactor.

The physical protection system of the reactor has been improved recently. According to the international rules (IAEA), the ITU TRIGA reactor belongs to the Category III from the point of view of its fuel amount and enrichment [4]. After the recent improvement in the physical protection system of the reactor, the level of protection surpassed the necessary requirements for Category III material and now it corresponds to the requirements for Category II level nuclear material.

After the disaster at the Fukushima Daiichi nuclear power plant on March 11, 2011, public concerns about nuclear energy has greatly increased. During those days, many media organs visited the ITU TRIGA reactor to give information to public about nuclear energy. ITU reactor played a role to remove public concerns about the nuclear energy and nuclear reactors. Also ITU TRIGA reactor is an important tool to raise public awareness about nuclear energy since Turkey is building its first nuclear power plant.

2012-2016 strategic programme of the ITU TRIGA reactor has been prepared following precisely the IAEA guidelines, reviewed by IAEA experts and therefore could serve as a successful example for other facilities interested in the development of a similar document [5]. An action plan is also included in the strategic plan. It consists of a number of action steps, objectives, responsibilities and deadlines to enhance the utilization of the reactor. Some of the actions have been already carried out. One of such actions is the development of computational capability of ITU-TRR using Monte Carlo codes [6].

ITU TRIGA Mark II Training and Research Reactor has been continued to operate without encountering any safety problem since its commissioning in 1979.

5. FUTURE PROSPECTS

Demand for nuclear professionals is expected to be increased in the future, since Turkish government has nuclear power plant construction plans. Hence, government related activities might be possible to meet this demand in the future. Training of regulatory body staff, nuclear engineering students and power plant personnel can be possible in the future. Development and validation of new computer codes using the reactor are also possible.

Another expectation to increase the utilization of the reactor is the development and implementation of digital neutron radiography facility. Current system is film based system and not efficient. Tangential beam tube is used for this purpose. The main problem is to find funding for this project.

There is a refurbishment, replacement and modernisation project at the reactor. A considerable part of this project is related with the modernization of the reactor control console. It is expected that the original analog console will be changed with a digital control console within the next two years. The analog control console was facing ageing and obsolescence problems as it frequently failed and parts could not be purchased. Some components used in the console were manufactured in the late 1970's or early 1980's. New control rod drive assemblies were also required so that it will be compatible with the digital console. Necessary funding is now available and the project starts nowadays. New electronical system of the reactor will be home product which is desirable.

There are some issues and challenges to enhance the sustainable utilization of the reactor. One of them is the lack of student and researcher interest. In order to overcome this issue, the promotional activities such as distribution of booklets, introductory seminars to the other faculties etc. are ongoing.

Another issue is the necessary improvements in the reactor, such as in NAA laboratory and neutron radiography, in order to perform fully implemented actions. NAA is the most important research activity in the reactor. But rabbit system needs some adjustments and renovation. It is necessary to establish sample changing automation for the rabbit system. Lack of funding when necessary to refurbish reactor facilities is the main concern for the operation of the reactor efficiently.

Another challenge is the aging of the reactor. Commissioning date of the ITU TRIGA Mark II Reactor is 1979 and some parts of the reactor need refurbishment.

Challenges facing TRIGA community are also valid for ITU TRIGA reactor. They include back-end options related to the spent nuclear fuel return to the country of origin programme; potential shutdown of the TRIGA fuel fabrication facility; weakening of technical support from General Atomics; and challenges for an enhanced utilization [7].

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Strategic planning for research reactors, IAEA TECDOC Series No 1212 (2001).

[2] ERENTÜRK, S., HACIYAKUPOĞLU, S., CAMTAKAN, Z., KIZILTAŞ, S., OKKA, M., GENCELİ, M., MERCİMEK, M., GENCELİ, E., YUSAN, S., GÜR, F., OLGEN, K., TANBAY, T., Determining spatial distribution of industrial pollution in terms of ecological risk levels, International Conference Ecology-Interdisciplinary Science and Practice, (25-26 October 2012), Sofia (Bulgaria).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Quality Assurance in Operation IAEA Safety Series: 50-C-SG-Q-13 (1996).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear security recommendations on physical protection of nuclear material and nuclear facilities, IAEA Nuclear Security Series No. 13, INFCIRC/225/Rev. 5. (2011).

[5] MERCİMEK, M., CAMTAKAN, Z., OKKA, M., TANBAY, T., GENCELİ, M., TUĞRUL, B., ÇOLAK, Ü., ERENTÜRK, S., REYHANCAN, İ., HACIYAKUPOĞLU, S., Strategic and action plan of ITU TRIGA MARK II Research and Training Reactor, IAEA Technical Meeting on Research Reactor Coalitions: Concerted actions in the Mediterranean Region, (10-13 July 2012), Istanbul (Turkey).

[6] TÜRKMEN, M., ÇOLAK, Ü., Analysis of ITU TRIGA Mark II research reactor using Monte Carlo method, Progress in Nuclear Energy, 77, (November 2014), 152–159.

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Technical Meeting on Research Reactor Coalitions: global issues of TRIGA research reactors; Vienna, Austria; 4–8 November 2013, meeting report as a working material, IAEA, Vienna (2014).

TRIGA RC-1 AT ENEA C.R. CASACCIA

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Abstract.

The TRIGA Mark II reactor of ENEA Casaccia Research Center (in Italy named RC-1) reached first criticality in 1960 and, after an upgrade completed in 1967, its power was increased to 1 MW. The reactor, that represents one of the three nuclear experimental facilities in Italy, is still running at this power level mainly for education and training of students, operators and researchers, and also for short half-life radioisotopes production, activation analysis, neutron radiography and tomography.

1. HISTORY

The TRIGA RC-1 nuclear research reactor (Training, Research, Isotopes, General Atomic Reactor Casaccia 1) is a source of thermal neutrons sited in the ENEA Casaccia Research Centre.

FIG. 1. ENEA Casaccia Research Centre.

The Casaccia Research Centre is ENEA's largest complex of research and development facilities (Fig. 1).

Located around 25 km (15 miles) northwest of Rome, near the Bracciano Lake. It was named by a farm called "La Casaccia", around which were born the first laboratories. Employing a few dozen researchers the facilities were set up in 1959 and originally, completely devoted to NUCLEAR RESEARCH.

Today the Casaccia Centre hosts most of ENEA's programmatic units, which operate in the following fields:

- Bio-technologies and protection of human health and ecosystems;
- Renewable energy sources and innovative energy cycles;
- Protection and development of the environment and the territory, and environmental technologies;
- Materials and new technologies;
- Advanced physics technologies;

- Generation of high-temperature heat with concentrating solar systems;
- Hydrogen and fuel cells;
- Global climate;
- Protection from ionizing radiation;
- Computing and modelling;

ENEA, in the role of an agency, provides also support to public administrations and to small and medium-sized enterprises.

The remaining research activities in nuclear field is linked to the presence of 2 research reactors: Triga RC-1 and Tapiro.

TRIGA RC-1 (Fig. 2-5) was built in 1960 in its first version with power in steady state of 100 kW as part of the U.S. Atom for Peace initiative. The first criticality at 100 kW was reached at 2:20 a.m. of June 11, 1960.

FIG. 2. TRIGA RC-1 at 100 kW.

The reactor has been working at this level of power until 1965 and during that period it played a key role for Italy as it has contributed to the formation of a large number of nuclear scientists and technicians.

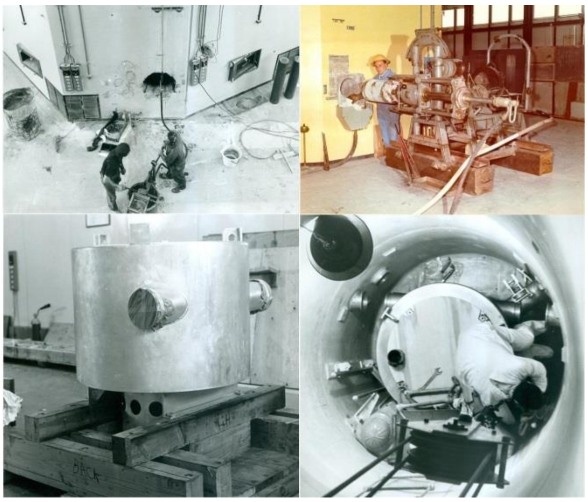

FIG. 3. Tangential Channel and new Core structure.

FIG.4. Installation of the aluminum liner.

The experience gained during the construction and the operation at 100 kW even allowed the reactor personnel to develop a project to upgrade the reactor power at 1 MW.

In 1965 TRIGA RC-1 was shut-down and upgrading works began. Were increased thicknesses of shielding and the value of the water level. An aluminum liner inside the reactor pool was also installed. A new experimental channel (Piercing Tangential Channel) was added by drilling the concrete reactor structure. The entire core, with the addition of another fuel elements ring (Ring G), was redesigned and replaced.

All the old fuel elements (Aluminum cladded) were replaced with fresh ones (SS cladded) and a new type of control rods (Fuel Follower) was installed. Even auxiliary systems were redesigned and replaced: cooling circuits, air circulation systems, environmental monitoring systems etc.

The C.R. Casaccia electronic laboratories designed and realized most of the control instrumentation.

All this was done in 2 years. At 4:20 p.m. of July 28, 1967, the reactor was again critical in its new configuration. After few days of tests and experiments, the reactor reached for the first time the power of 1 MW. From that day until now, the reactor worked regularly and without any major malfunction.

In the first years after its entry into operation, the reactor operated strongly at full capacity (‘70, ‘80), especially because Italy was projected into a strong program of nuclear technology development. In the last period (’90, ’00, ‘10), mainly because of the abandonment of nuclear power from Italy and of the general crisis, the utilization of the reactor is not at the same levels. In the period 2001-2004 a very strong impulse at the activities around the reactor was given by the TRADE (TRiga Accelerator Driven Experiment) project that was unfortunately stopped in 2004 because of financial problems. During this period TRIGA RC-1 became a point of reference for many scientist all over the world working on ADS projects [1-5]. It was constitute an international working group and a lot studies, projects and experiments were carried out and a very large amount of publications was done.

Nowadays the reactor continues to be an important point of reference for research, education and provision of services in the nuclear field.

2. THE TRIGA RC-1

The TRIGA core consists of an annular structure immersed in water which serves as primary coolant (Fig. 6). The core is arranged in a circular array forming an annulus with seven coaxial cylindrical rings of fuel elements

FIG. 5. TRIGA RC-1 reactor.

The reactor and the experimental facilities are surrounded by a concrete shield structure. The core and the reflector assemblies are located at the bottom of an aluminium tank (190.5 cm diameter). The overall height of the tank is about 7 m, therefore the core is shielded by about 6 m of water.

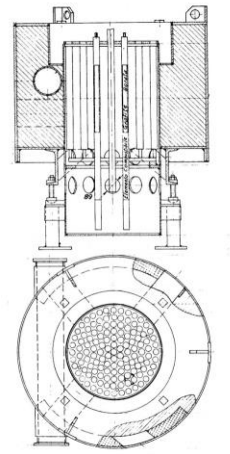

FIG. 6. Schematic view of the core structure.

The core which is surrounded by the graphite reflector, consists of a lattice of fuel elements, graphite dummy elements, control and regulation rods. There are 127 channels divided in seven concentric rings (from 1 to 36 channels per ring). The channels are loaded with fuel rods, graphite dummies and regulation and control rods. One channel houses an Am-Be source, while two fixed channels, the central one and a peripheral, are available for irradiation or other experiments.

The diameter of the core is about 56.5 cm while the height is 72 cm. Neutron reflection is provided by graphite contained in an aluminium container which is surrounded by 5 cm of lead acting as a thermal shield. An empty aluminium tube (15 cm diameter and 0.6 cm thick) traverses the graphite reflector tangentially to the reactor core for thermal flux irradiations. The core components are contained within a top and bottom aluminium grid plates: the top grid has 126 holes for fuel elements and control rods and a central thimble for high flux irradiations. The reactor core is cooled by natural convention of the water in the reactor pool.

The fuel elements consist of a stainless steel clad (AISI-304, 0.05 cm thick, 7.5 g/cm^3 density) characterized by an external diameter of 3.73 cm and a total height of 72 cm end cap included (Fig. 7). The fuel is a cylinder (38.1 cm high, 3.63 cm in diameter, 5.8 g/cm^3 of density) of a ternary alloy uranium-zirconium-hydrogen (H-to-Zr atom ratio is 1.7 to 1; the uranium, enriched to 20% in ^{235}U, makes up 8.5% of the mixture by weight: the total uranium content of a rod is 190.4 g, of which 37.7 g is fissile) with a metallic zirconium rod inside (38.1 cm high, 0.5 cm in diameter, 6.49 g/cm^3 of density). There are two graphite cylinders (8.7 cm high, 3.63 cm in diameter, 2.25 g/cm^3 of density) at the top and bottom of the fuel rod. Externally two end-fittings are present in order to allow the remote movements and the correct locking to the grid.

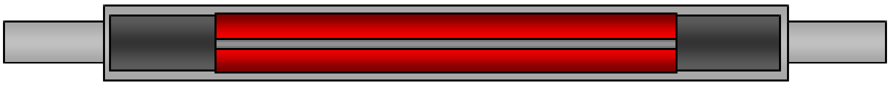

FIG. 7. Schematic fuel rod section.

The regulation rod has the same morphological aspect as the fuel but instead of the mixture of the ternary alloy U-ZrH$_{1.7}$ there is the absorber (graphite with powdered boron carbide). Some control rods are "fuel followed": the upper section of the rod is graphite; the next 381 mm is the neutron absorber. The follower section consists of 381 mm of U-ZrH$_{1.7}$ fuel and the bottom section of 165 mm of graphite. The graphite dummies are similar to the fuel rod but the central volume is filled by means of graphite.

A typical core loading is shown in Fig. 8.

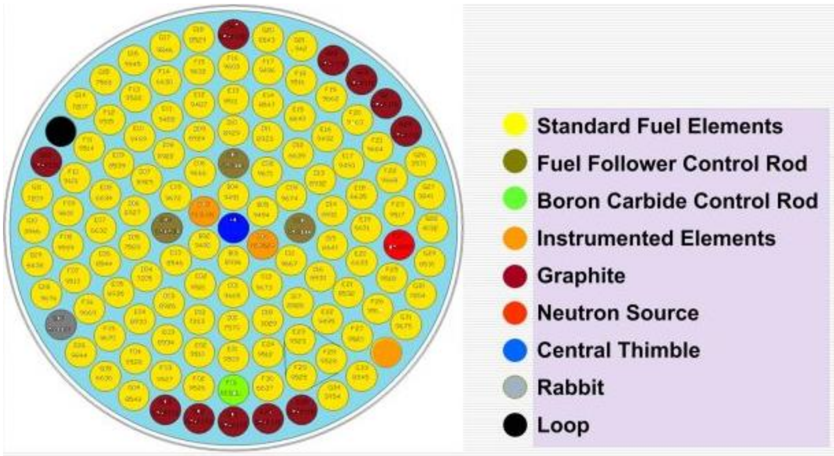

FIG. 8. TRIGA RC-1 core configuration.

The reactor's main features are:

- maximum power: 1 MW;
- maximum neutron flux: 2.7 × 10^{13} cm^{-2}·s^{-1};
- core cooling by natural convection;
- irradiation facilities:
  - 1 central channel;
  - 40 positions in rotating rack;
  - 1 pneumatic transfer system ("Rabbit”);
  - 1 loop for irradiations of liquids;
  - 1 thermal column;
  - 1 thermalizing column;
  - 6 horizontal neutron channels;
  - Irradiation cavity in the core (3 el. space);

- Irradiation cavity in the thermal column inside the reactor pool.

In Table 1 are shown the characteristics of the core.

TABLE 1. CHARACTERISTICS OF THE TRIGA CORE

Core	Cylindrical diameter	535 mm
	Height	670 mm
Fuel	Type	Uranium – ZrH alloy (8.5 wt% U)
	Enrichment	20% ^{235}U
	Moderator	H_2O, ZrH
	Coolant	Demineralized water in natural convection
Control Rods	Type	n°3 B_4C Fuel Follower n°1 B_4C Regulating Rod
Reflector	Cylindrical Inner Reflector diameter	543 mm
	Outer Reflector Diameter	1098.5 mm
	Overall Height	733.4 mm
	Radial thickness	214 mm
	Material	Graphite

3. EXPERIMENTAL FACILITIES

3.1. General description of experimental and testing facilities

An overview of the TRIGA RC-1 experimental facilities is shown in Fig. 9 and in Fig. 10 is shown, in a 3D representation, a transparency of the radial channels. The facilities are described furthermore in the following subsections.

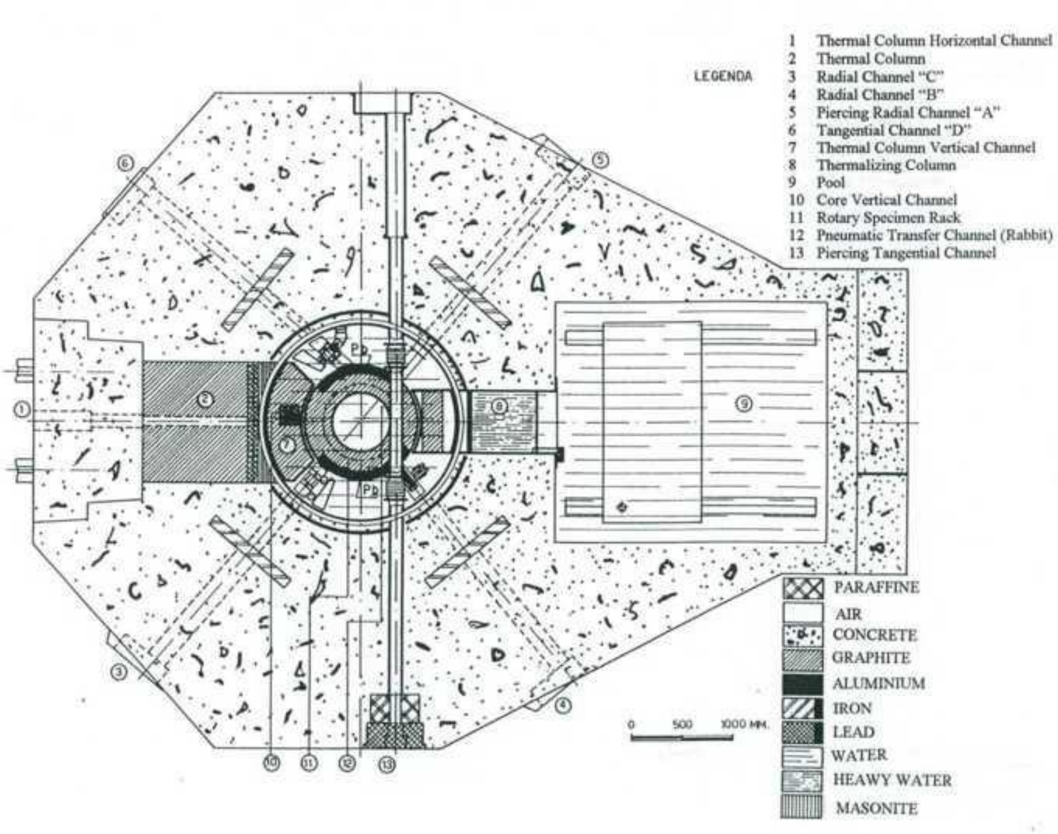

FIG. 9. Irradiations facilities.

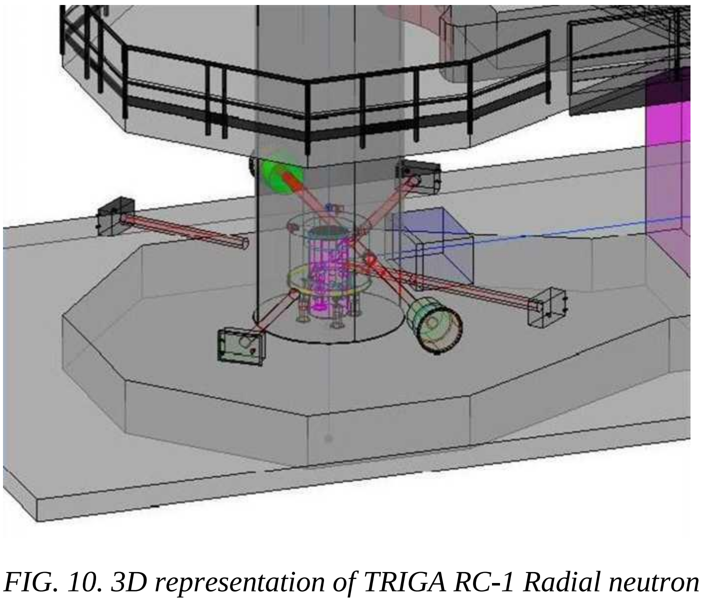

FIG. 10. 3D representation of TRIGA RC-1 Radial neutron channels.

3.1.1. Thermal column horizontal channel

The thermal column is crossed by a cylindrical hole (Fig. 11, in red) which collimates the neutron beam. The channel, just outside the concrete shield, is provided with a mobile pneumatic shutter allowing its opening and closure (Fig. 12). This device can be driven remotely from the reactor hall. The whole zone in front of and around the channel is shielded by concrete and paraffin blocks to reduce exposition for researchers and workers. The thermal column is suitable for neutron imaging applications [7, 9].

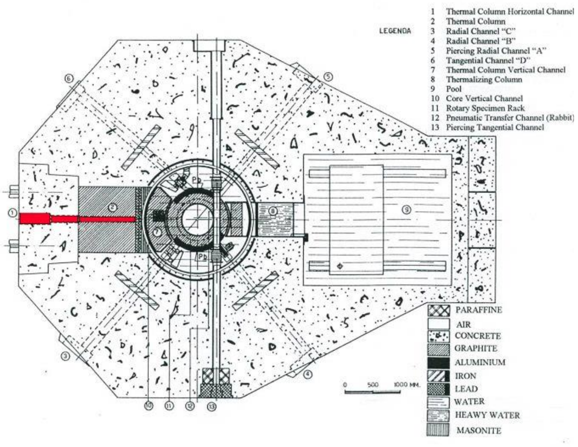

FIG. 11. Horizontal channel at the Thermal Column.

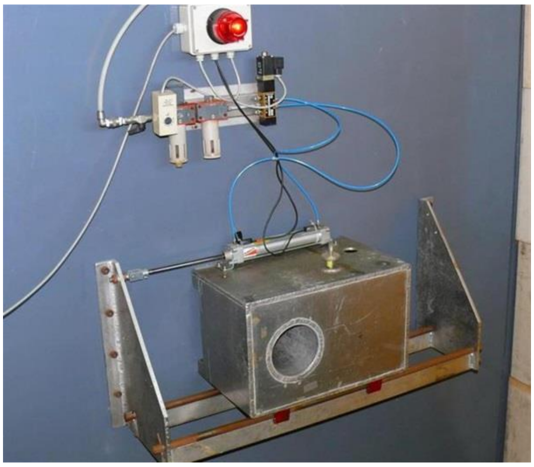

FIG. 12. Thermal column shutter.

3.1.2. Thermal column

It is formed by two parts (Fig. 13), internal and external to the tank. The internal part constitutes the thermal column vertical channel. The outer part is constituted by an aluminium box of square section 1.2 m × 1.2 m containing lead, graphite and a mobile part in concrete. The outer part is crossed by a cylindrical hole that collimates the neutron beam and constitutes the thermal column horizontal channel.

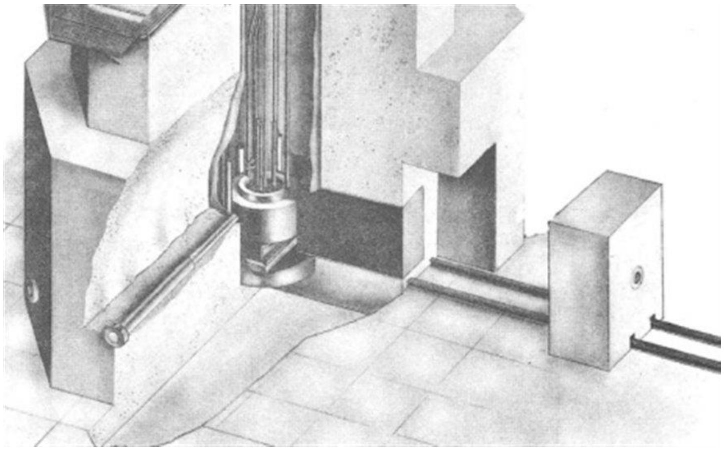

FIG. 13. Thermal column.

3.1.3. Radial channels "B" and "C"

Consist of an aluminium inner cylindrical tube of internal diameter 152 mm. The radial channel C allows the introduction of experimental samples from the outside to the outer surface of the tank.

3.1.4. Piercing radial channel "A"

Consists of an aluminium inner cylindrical tube of internal diameter 152 mm. The piercing radial channel allows the introduction of experimental samples from the outside to the outer surface of the reflector.

3.1.5. Tangential channel "D"

Consists of aluminium inner cylindrical tube of internal diameter 152 mm. The tangential channel D allows the introduction of experimental samples from the outside to the outer surface of the tank.

3.1.6. Thermal Column Vertical Channel

Consists of an aluminium box containing graphite (202 mm × 178 mm) to which it is possible to connect a cylindrical tube collimator having vertical axis (internal diameter 56 mm out of the tank).

3.1.7. Thermalizing column and shielding tank

- **The thermalizing column**

  Its vertical section size is 608 × 608 mm^2, and it is divided into two parts: the first one enclosed between the shielding tank and the external wall of the reactor pool, the second one between the internal wall of the reactor pool wall and the core reflector (Fig. 14).

  The first part is an aluminium box filled with heavy water and the second one consists of a sealed box of aluminium alloy shaped in such a way as to leave the minimum thickness of water toward the reflector and into the reactor vessel, and it is filled with graphite and air.

- **Shielding tank**

  The shielding tank (Fig. 14) that was originally designed for shielding measurements has the following dimensions: 4.65 m in depth, 2.44 m wide, 2.74 m in length. Impermeability is achieved by applying a layer of epoxy (epoxy white) on the concrete of the bottom and of the walls.

  On the bottom of the tank are located two rails to allow, in the origin, the translation of a trolley for experimental devices. On top of the tank, just over the security wall which surrounds it (90 cm height), there are other two rails allowing the translation of the special equipment for the positioning of a new irradiation device [10].

  The main physics peculiarity of the thermalizing column, in the shielding tank, is a large, uniform and well thermalized neutron flux.

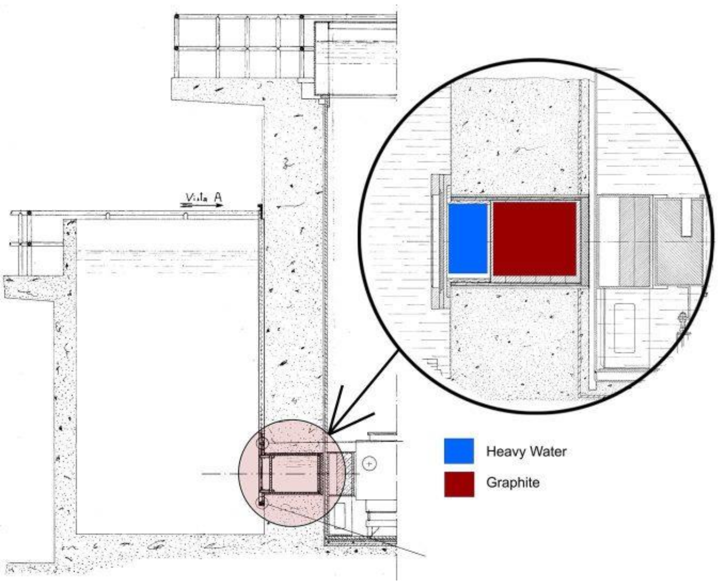

FIG. 14. Sections of the shielding tank and of thermalizing column.

3.1.8. Central thimble

The central thimble (see Fig. 8), in the center of the reactor core, allows the irradiation of small samples at locations of maximum flux and to extract a collimated beam of neutrons and γ ray. The channel is constituted by an aluminium tube of 7.10 m in length and internal diameter of 34.04 mm which can be filled with air or water.

3.1.9. Rotary specimen rack (Lazy Susan)

The rotary specimen rack (Fig. 15) consists of an aluminium ring mounted on a steel bearing, contains forty aluminium cups evenly spaced. These cups serve as holders for the radioisotope specimen containers. The rotary specimen rack can be rotated manually, automatically (continuous rotation or step). A single removal tube is used for inserting and removing irradiation specimen. The specimen containers, which fit into the cups, are cylinders 188 mm high and 30 mm in diameter. The Lazy Susan is located in an anular guide, between the top of the core and the radial graphite reflector so the tops of these containers are approximately at the same level of the top of the core. The specimen is used for the production of isotopes of average half-life in useful quantities.

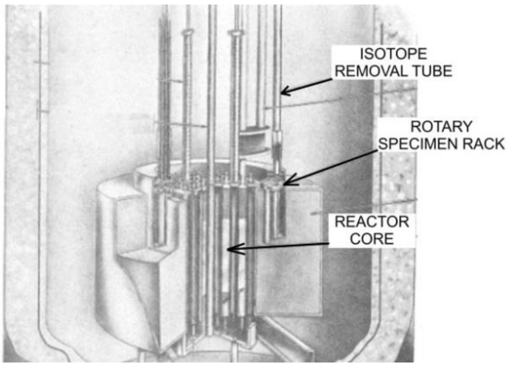

FIG. 15. Rotary Specimen Rack.

3.1.10. Pneumatic transfer channel (Rabbit)

A pneumatic transfer tube, located in the outermost ring of the core (Fig. 8), is provided for fast insertion and removal of irradiated specimens into the core. The Rabbit allows the production of radioisotopes with extremely short half-lives which are transferred from the reactor to a counting room. Special containers (inner diameter of 14.2 mm, length 100 mm), made of nylon or aluminium, can be accommodated in this facility.

3.1.11. Piercing tangential channel

This channel (Fig. 16, in purple) crosses all the length (east-west direction) of the biological shield. It is tangential to the inner surface of the reflector, just 113 mm above respect to the core mid-plane. One of the outlet of the channel (the east one) is equipped with a collimator [6] and a shutter (Fig. 17) designed also to minimize the gamma and neutron streaming due to structure discontinuities. The collimator filter and geometry are optimized, using Kobayashi method, in order to maximize the neutron flux and the beam diameter. The substitution of the inner part of the collimator allows to try collimator's response for different configuration: graphite, bismuth and air. The scope is to obtain an optimization of the n/γ ratio for neutron radiography and tomography [6, 9].

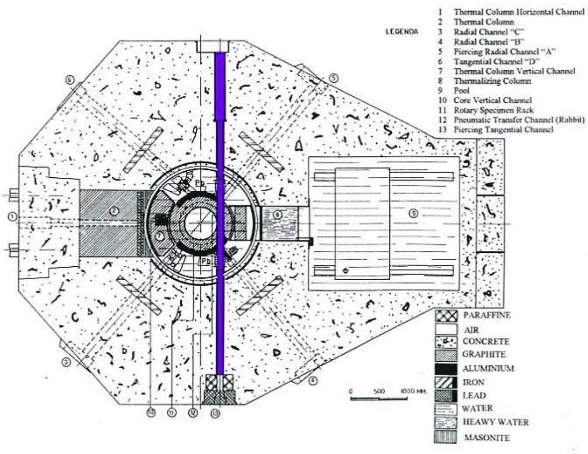

FIG. 16. Piercing Tangential Channel.

FIG. 17. Piercing tangential channel shutter.

3.1.12. Removable grid cavity

On the upper grid (Fig. 18-19) of the core is provided a removable part structured into three contiguous holes arranged in a triangular fashion. Removing three fuel elements, the spacer and the removable grid become available for irradiations of specimens having a diameter up to 60 mm.

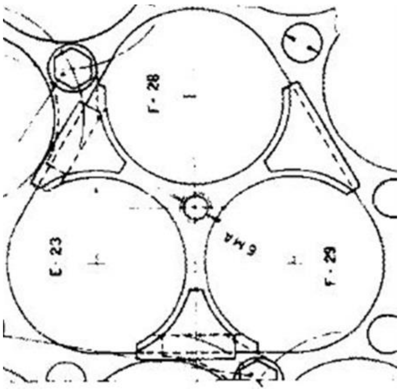

FIG. 18. Removable grid cavity.

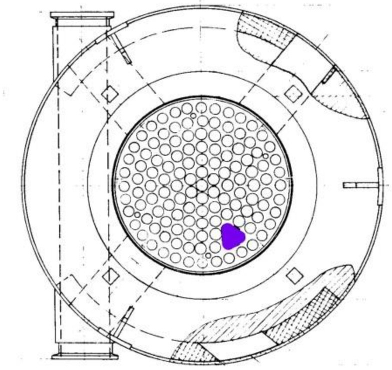

FIG. 19. Core position of the Removable grid cavity.

3.1.13. Irradiation facility for liquid samples (LOOP)

In the peripheral zone of the core (ring G) it is possible to place a special capsule, stainless steel (SS) made, in which can flow the liquid solution to be irradiated. The position of the LOOP capsule is evidenced in Fig. 8. The capsule is connected by means of a small SS pipe with a special receiving station placed in the radiochemistry laboratory. A pneumatic system injects and extracts the liquid into and from the capsule. The SS capsule is faced with the axial center of the core and it is contained into an aluminium pipe filled with demineralized water which ensures, by means of a forced circulation, the removal of the thermal power produced by the capsule. The water also ensures the shielding from radiations in the axial direction. Figure 20 shows the layout of the circuit. The irradiation of liquids can be done in continuous or in batch mode.

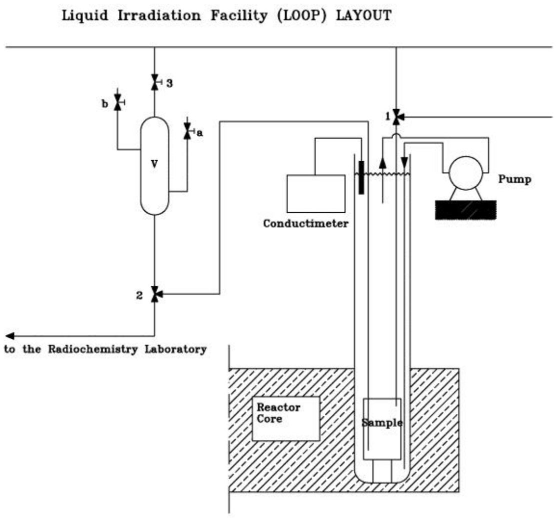

FIG. 20. Layout of the Liquid Irradiation Facility (LOOP).

In Table 2 is provided an overview of the main characteristics of the experimental facilities.

TABLE 2. TRIGA RC-1 MAIN CHARACTERISTICS OF EXPERIMENTAL FACILITIES

EXPERIMENTAL FACILITY	THERMAL FLUX ($n \cdot cm^{-2} \cdot s^{-1}$)	R_{Cd}*	SHAPE	DIMENSIONS (mm)
A - Radial Channel	$4.8 \cdot 10^{12}$	~ 2.2	CYLINDER	Ø INT. = 152
B - Radial Channel	$4.3 \cdot 10^{10}$	~ 3	CYLINDER	Ø INT. = 152
C - Radial Channel	$4.3 \cdot 10^{10}$	~ 3	CYLINDER	Ø INT. = 152
D - Radial Channel	$5.4 \cdot 10^{10}$	10.4	CYLINDER	Ø INT. = 152
Tangential Channel	$1.1 \cdot 10^{6}$	2.22	CYLINDER	Ø INT. = 152
Piercing Tangential Channel	$1.1 \cdot 10^{6}$	1.24	CYLINDER	Ø INT. = 180
Thermal Column Horizontal Channel	$2.2 \cdot 10^{6}$	3.2	CYLINDER	Ø INT. = 40
Thermal Column Vertical Channel (with plug of graphite)	$1.9 \cdot 10^{10}$	4.3	SQUARE	SIDE = 100
Thermal Column Vertical Channel (without cap of graphite)	$4.2 \cdot 10^{9}$	~ 4	SQUARE	SIDE = 100
Central thimble	$2.68 \cdot 10^{13}$	1.73	CYLINDER "S" SHAPED	Ø INT. = 34.04
Thermalizing Column	$1.3 \cdot 10^{8}$	> 100	PARALLELEPIPED	608 x 608 x 155
Rotary Specimen Rack	$2.0 \cdot 10^{12}$	2.7	CYLINDER "S" SHAPED	Ø INT. = 32
Removable grid cavity	$1.25 \cdot 10^{13}$	2.21	TRIANGULAR PRISM	Ø INT. = 60 h = 650
RABBIT (Pneumatic transfer tube)	$5.1 \cdot 10^{12}$	2.00	CYLINDER	Ø INT.. = 14 Ø INT. TUBE = 27
Loop for irradiation of liquids	$\sim 5.0 \cdot 10^{12}$		CYLINDER	V ~ 150 ml

*R_{CD} = Cadmium ratio

3.2. Experimental devices

3.2.1. Irradiation device at the thermalizing column

It is a plexiglas cylindrical (diameter 170 mm, length 330 mm) waterproof cavity (Fig. 21-22) that can be moved in the water and placed in front of the thermalizing column neutron beam, deeply in the shielded tank [10]. The cylinder is equipped also with a tube allowing the connection of the cavity, by wires or cables, with the external of the pool. It's possible to introduce a wide type of objects: from gold foils to ampule or others containers of sufficient dimension to test irradiation on various materials. It is provided with a positioning system to facilitate operations.

FIG. 21. Cavity placed in front of thermalizing column.

FIG. 22. Detail of the cavity.

3.2.2. Neutron radiography and tomography device

Neutron fluxes provided by the thermal column and the piercing tangential channel are utilized to obtain a radiography image of objects and, with a time dependent image acquisition, a tomography reconstruction of such objects [9]. The device is composed by:

- a support for object able to rotate and translate so that the operator can reach the optimal object interaction with neutron flux;
- a neutron converter provided with efficiency parameters;
- a system equipped with an optical system used to focus the light produced;
- a CCD camera connected with an acquisition and analysis system composed by hardware and software;
- a software tool for tomography reconstruction.

3.3. Experimental ancillary facilities for applied research

3.3.1. Neutron activation analysis

Neutron activation analysis (NAA) has been widely employed by means of TRIGA reactor since 1963.

In the TRIGA reactor NAA is mainly performed by pile irradiations using either a vertical channel passing through the core center (Central Thimble), a second vertical channel characterized by a pneumatic tube to transfer the irradiated samples (Rabbit), a rotating rack with forty holes for samples introduction (Lazy Susan), and a water pool, separated from the reactor core, with a thermalizing thickness of D_2O (Thermalizing column).

Gamma spectrometry measurements are performed by mean of HPGe detectors supplied from Canberra and ORTEC, equipped with adequate instrumentation and software. The laboratory is also equipped with an anti-coincidence measurement system utilizing a NaI 300 × 300 mm annular single crystal Bicron detector characterized by a relevant spectral background reduction. Another useful detector is constituted by a HPGe planar detector with high efficiency in measuring X and γ rays of energy < 100 keV and for XRF counting.

By exploiting the instrumental analysis (INAA) potentials it is possible to study analytically and determine, either by thermal, epithermal, or fast neutrons, or by the radiochemical separation, the majority of the macro constituents, minor constituents, trace, and ultra-trace elements in a very wide set of matrices and materials. The samples that may be analyzed and the applications of the INAA range from alloys to soils; from sediments and suspended matter to the atmospheric particulate matter; from archaeological materials to the materials for the study of the physics of sub atomic particles; from radiotracers to the execution of forensic studies.

3.3.2. Radiological characterization

During the last years the activities carried out at the TRIGA Reactor by Nuclear Materials Characterization Laboratory's personnel has been aimed to the radiological characterization of drums containing wastes produced in the routine activities of the Plant.

The characterization was carried out using mobile equipment:

ISOCS (In Situ Object Counting System): radiological characterization system for assaying objects of any shape and nature containing γ emitting radionuclides; the measurement system operates with a Germanium detector, whose response to a series of point sources or distributed in predefined arrays was characterized using Monte Carlo codes.

Portable Multi-Channel, equipped with neutron probe and gamma radiation detector. This instrument is characterized by high accuracy and speed in response and was used for preliminary inspections of the drums.

4. ENGINEERING AND RESEARCH INFRASTRUCTURES

TRIGA RC-1 facility has a section devoted to design and manufacture experimental devices (mechanicals, hydraulics and electronics). Some examples of this capability are:

- Neutron collimators [6];
- Channel shutters;
- Irradiation devices [10];
- Optical bench for neutron imaging [9];
- “Ad hoc” Hydraulics loops;
- Ancillary systems for experiments;
- Electronic control panels;
- Neutron activation analysis by k_0-method.

5. EDUCATION AND TRAINING

TRIGA RC-1 facility is an Italian point of references for all the people working on nuclear activities and offers the following services:

- Training for university students;
- Experiment design (with Monte Carlo and deterministic codes);
- Neutronic characterization of irradiation channels;
- Hands-on educational experiences for university students;
- Integral control rod worth measurement by positive period method;
- Neutron flux measurement;
- Training for reactor operators.

6. SOME RELEVANT EXAMPLES OF R&D EXPERIENCES OCCURRED IN THE LAST TEN YEARS

In the TRIGA RC-1 facility, during more than 50 years of operation, a lot of research activities were carried out. Below some examples:

- Test and utilization of a special instrumented TRIGA fuel element;
- Multiplication factors measurements by means of Deuterium - Tritium tubes;
- Investigation by neutron tomography and by a volumetric 3D display for visualization of archaeological samples;
- Neutron imaging tests of archaeological samples;
- Neutron imaging tests of electronic/mechanical equipment;
- Neutron imaging tests of biological samples;
- Environmental (neutron/gamma) tests of electronic components;

- Design and characterization of neutron collimators;
- Tests and development of innovative neutron detectors [11];
- Irradiations and neutron activation of many kind of solid/liquid samples for several purposes;
- Developing of a digital console for control room parameters supervision [8, 12].

7. THE TRADE (TRIGA ACCELERATOR DRIVEN EXPERIMENT) EXPERIENCE

2002 - 2010 - The TRADE program [1-5] was planned to investigate the static and dynamic behavior of ADS at power in thermal neutron spectrum. Because problems in financial backing, the program was interrupted at the end of 2004. In spite of these unlucky circumstances, a huge experimental data bank has been set up during the time period prior to the program interruption. In 2007 IAEA endorsed this experimental campaign, and an experimental benchmark, named “pre-TRADE experimental benchmark”, was launched in the frame of the Coordinated Research Project “Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems (ADS)” coordinated by IAEA [12]. The benchmark was focused on the evaluation, via computation, of the correction factors to be applied to the PNS Area-ratio and MSA results for the selected reactivity estimates to take into account the role of the spatial/energy effects on the rough experimental data.

REFERENCES

[1] RUBBIA, C., MONTI, S., SALVATORES, M., CACUCI, D. G., D’ANGELO, A., BIGNAN, G., BURGIO, N., CAHALAN, J., CARTA, M., FOUGERAS, P., GRANGET, G., IMEL, G., JAMMES, C., KADI, Y., NABEREJNEV, D. G., PHILIBERT, H., RAVETTO, P., TRADE: A Full Experimental Validation of the ADS Concept in a European Perspective, American Nuclear Society, Accelerator Applications Division, AccApp’03, "Accelerator Applications in a Nuclear Renaissance”, San Diego, California – June 1-5, 2003.

[2] RUBBIA, C., CARTA, M., BURGIO, N., CIAVOLA, C., D'ANGELO, A., DODARO, A., FESTINESI, A., MONTI, S., SANTAGATA, A., TROIANI, F., SALVATORES, M., DELPECH, M., KADI, Y., BUONO, S., FERRARI, A., HERRERA MARTÍNEZ, A., ZANINI, L., IMEL, G., Preliminary Neutronic Analyses of The TRIGA-ADS Demonstration Facility, Nucl. Sci. and Eng. **148**, (2004), 103-123

[3] BURN, K.W., CARTA, M., CASALINI, L., KADI, Y., MONTI, S., NAVA, E., PALOMBA, M., PETROVICH, C., PICARDI, L., RUBBIA, C., TROIANI, F., "The TRADE Experiment: shielding calculations of the building hosting the subcritical system", ICRS-10, Funchal, Madeira Island (Portugal), May 9-14, 2004.

[4] RUBBIA, C., AGOSTINI, P., CARTA, M., MONTI, S., PALOMBA, M., PISACANE, F., KRAKOWIAK-AILLAUD, C., SALVATORES, M., KADI, Y., HERRERA-MARTINEZ, A., MACIOCCO, L., "The TRADE Experiment: Status of the Project and Physics of the Spallation Target", PHYSOR-2004, Chicago, Illinois, April 25-29, 2004.

[5] STANCULESCU, A., LOPASSO, E. M., KIYAVITSKAYA, A., AÏT-ABDERRAHIM, H., ARIEN, B., MAIORINO, J.R., XIA, H., CHABERT, C., BILLEBAUD, A., BROEDERS, C., NOACK, K., CARTA, M., RAVETTO, P., OIGAWA, H., SASA, T., PYEON, C., SZIEBERTH, M., DA CRUZ, D. F., IQBAL, M., SZUTA, M., TACZANOWSKI, S., JANCZYSZYN, J., TITARENKO, Y., PONOMAREV, L., GRIBKOV, V., ABÁNADES, A., PEÑA, A., GONZALEZ-ROMERO, E. M., GUDOWSKI, W., PERSSON, C. M., FOMIN, S., GOHAR, Y., SHVETSOV, V., “IAEA Coordinated Research Project (CRP) on analytical and experimental benchmark analyses

of Accelerator Driven Systems", PHYSOR'08 International Conference on the Physics of Reactors, Interlaken, Switzerland, September 14–19, 2008.
[6] PALOMBA, M., ROSA, R., "Characterization of a Neutron Collimator for Neutron Radiography Applications", International Conference on Research Reactors: Safe Management and Effective Utilization, Sydney, Australia, November 5 – 9, 2007.
[7] FIASCONARO, V., ANDREOLI, F., PALOMBA, M., PAPALEO, A., ROSA, R., "Volumetric 3D display for visualization of archaeological samples investigated with neutron tomography", SPIE optical metrology, Munich, Germany, 17-21, 2007.
[8] MEMMI, F., FALCONI, L., CAPPELLI, M., PALOMBA, M., BOVE, R., SEPIELLI, M., "A preliminary user-friendly, digital console for the control room parameters supervision in old-generation Nuclear Power Plants", ICAPP '12 Chicago, USA, June 24-28, 2012.
[9] PALOMBA, M., FALCONI, L., MANCO, D., BOVE, R., SEPIELLI, M., "Neutron radiography and tomography equipment at ENEA C.R Casaccia TRIGA RC-1 reactor", 7th International Topical Meeting on Neutron Radiography, Kingston, Canada, 16– 24 June 2012.
[10] PALOMBA, M., FALCONI, L., GROSSI, A., SEPIELLI, M., BOVE, R., "A new irradiation device at the Thermalizing Column RC-1 TRIGA reactor", RRFM 2013 – European Research Reactor Conference, Saint Petersburg, Russia, 21 – 25 April, 2013.
[11] BEDOGNI, R., BORTOLOT, D., POLA, A., INTROINI, M., GENTILE, A., ESPOSITO, A., GOMEZROS, J., PALOMBA, M., "A new active thermal neutron detector", submitted Radiation Protection Dosimetry, 2013.
[12] CAPPELLI, M., MEMMI, F., FALCONI, L., PALOMBA, M., BOVE, R., SEPIELLI, M., "The role of FPGA-based architecture in the control room modernization process: preliminary results of a case-study", ICONE20, Anaheim, California, USA, July 30-August 3, 2012.

TRIGA UTILIZATION EXPERIENCES AT THE UNIVERSITY OF PAVIA

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Abstract.

The Laboratory of Applied Nuclear Energy (LENA, University of Pavia) operates a TRIGA reactor with numerous results in the field of applied research, education, international development programs. The Laboratory was established and became operational in 1963 as forward-looking intention of the Department of Chemistry (Radiochemistry group) and continues its activities supporting and promoting collaborations with the various departments of the University, including the Physics Department. Multidisciplinary activities in collaboration, or as a provider, with several institutions, industries and research centres both at national and international level represent the main activities. We present an overview of TRIGA utilization experiences gained through years of activity at the University of Pavia. In particular we emphasize that research reactors facilities require expertise team (continuously updated) present before installation and licensing in order to support the new and incoming activities and to deal with and manage the development and coordination of the activity in many scientific fields; in particular, in a University centre, with different Departments. Through our experience, we strongly suggest that Education and Training programs should be one of the driving activities for this kind of installation. Furthermore, being involved in national and international networks, is also fundamental to be updated in terms of operation experiences and new possible forthcoming utilizations of the reactor facility.

1. HISTORY

The Laboratory of Applied Nuclear Energy (LENA) is located on the campus of the University of Pavia, which is the operating organization of the reactor; wanted by Prof. Mario Rollier, Director of the Institute of General and Inorganic Chemistry of the University of Pavia, the reactor reached its first criticality on November 15, 1965 and was officially opened in December 16, 1966. The reactor is a TRIGA Mark II research reactor authorized to operate at a maximum steady state power level of 250 kW. Although the reactor was originally licensed to operate also in pulse mode, it has not been pulsed for nearly 20 years and there are currently no plans to resume pulse mode operation. The reactor is typically operated at full power between 300 and 400 hours per year. The facility has been operating with significant results in the field of applied research, education, international development programs as well as providing services to institutions and enterprises, other universities, industries and research centres both at national and international level.

2. CURRENT TECHNICAL STATUS (STATUS OF AVAILABLE INFRASTRUCTURE AND UTILIZATION CAPABILITIES, INCLUDING STAFF)

The reactor core, characterized by cylindrical symmetry, consists of 80 standard TRIGA type fuel elements (uranium enriched at 20 % charged at 8 %) clad in stainless steel or Alloy 800, 5 graphite elements (dummies), 1 Radium-Beryllium source, 3 control rods (REGULATING, TRANSIENT and SHIM) and irradiation positions (Central Thimble, Pneumatic Transfer System Thimble) arranged in five concentric rings and held in place by lower and upper grid plates. Upon the current core configuration, fuel elements on the 1st, 2nd rings have stainless steel cladding those on the 3th and 4th rings have aluminium cladding while the 5th ring is a combination of the latter. In the tank, just outside the graphite reflector, is installed a thermal irradiation channel. The core is completely surrounded in the radial direction by an annulus of graphite which provides neutron reflection. The core is located near the bottom of a cylindrical aluminium tank that is 6 meters deep and 2 meters in diameter and is open to the reactor building atmosphere at the top. The aluminium tank is surrounded by thick concrete which functions as the primary biological shield for personnel working on the experimental level in the reactor hall. The tank is filled with light water which provides neutron moderation, natural convection cooling of the fuel and radiation shielding for personnel at the reactor top area. Currently, the only horizontal channel in use is the piercing channel.

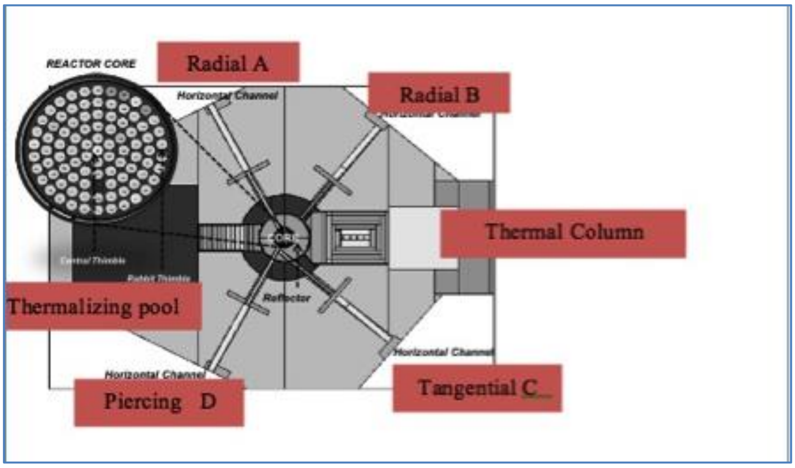

FIG. 1. Cross section view of the TRIGA reactor. The vertical irradiation channels and the core map are on top left of the figure; horizontal channels and out-core irradiation facilities are with red labels.

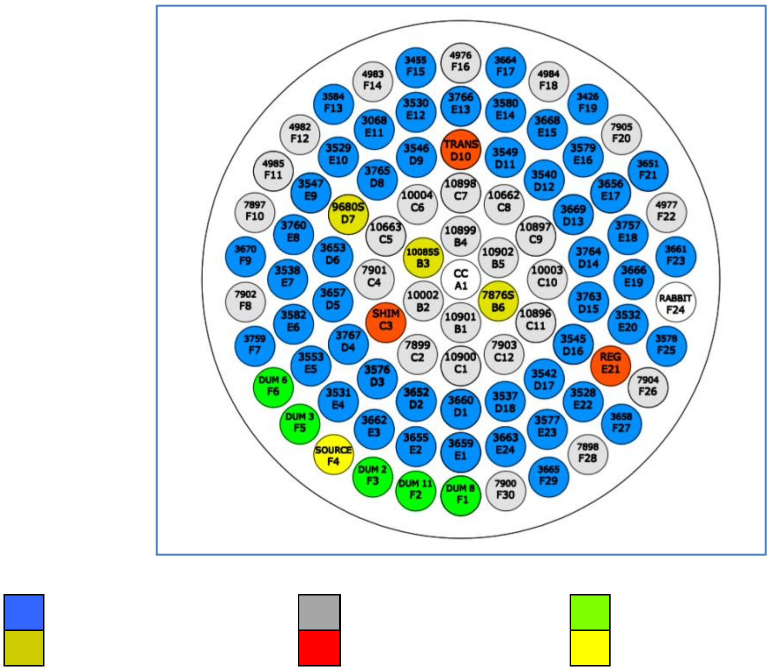

FIG. 2. TRIGA Mark II core, as configured in September 2013.

TABLE 1. MEAN VALUES AND STANDARD DEVIATIONS OF THE INTEGRAL NEUTRON FLUX RESULTS IN THE FOUR IRRADIATION FACILITIES [26]

Irradiation Facility	Measured Flux [N/(S Cm^2)]	**RELATIVE ERROR**
Central Thimble	(1.72 ± 0.17) 1013	10 %
Rabbit Channel	(7.40 ± 0.95) 1012	13 %
Lazy Susan	(2.40 ± 0.24) 1012	10 %
Thermal Channel	(2.52 ± 0.36) 1011	14 %
Thermal Column [27]	(1.19 ± 0.08) 1010	------------

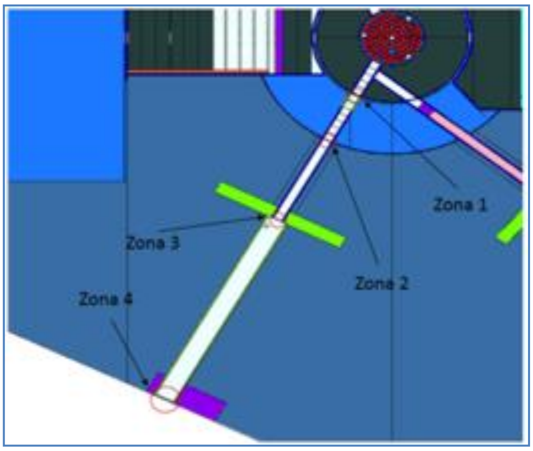

FIG. 3. Graphical output of MCNP simulation of the piercing channel D.

TABLE 2. THE INTEGRAL NEUTRON FLUX IN THE PIERCING CHANNEL D [25]

	ZONE 1	ZONE 2	ZONE 3	ZONE 4
NEUTRON FLUX [1/(CM^2 S)]	$1.14 \cdot 10^{12}$	$1.12 \cdot 10^{11}$	$9.07 \cdot 10^{9}$	$1.10 \cdot 10^{9}$

2.1. Central Thimble, Rabbit and Lazy Susan

These channels are positioned along the vertical axis of the core, where the neutron flux is maximum. The central thimble can is a dry tube that can host up to 3 samples in cylindrical containers (130 mm-height; 30 mm-diameter made by polyethylene or aluminium), and the position of the channel in the core can be conveniently adjusted based on the irradiation needs.

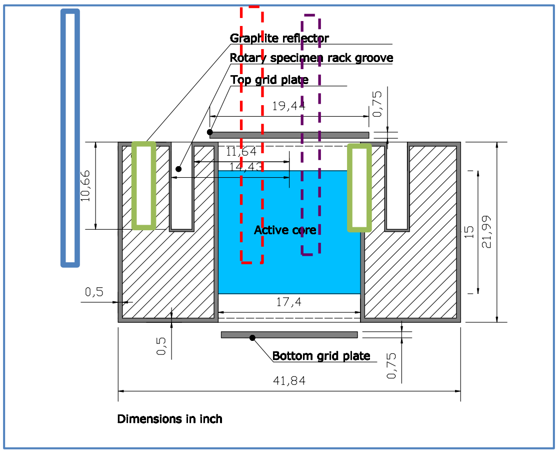

FIG. 4. Vertical irradiation channels: central Thimble (in red), Lazy Susan (green), Thermal Channel (blue) and rabbit Channel (magenta).

The “Lazy Susan” is a rotary specimen rack made of aluminium provided with 40 holes with inner diameter of 38 mm. The specimen rack is placed in an annular groove in the upper part of the reflector body. The loading capacity is up to 80 samples in cylindrical containers (130 mm-height; 30 mm-diameter). The rabbit system is a vertical channel positioned in the outer core ring and can be operated remotely by a pneumatic sample transfer system. Samples are sent and received directly from the radiochemical laboratory. The utilization of these channels is mainly dedicated Instrumental Neutron Activation Analysis (INAA) and Isotopes Production as described in the following Chapter 3.

2.2. Thermal channel

Recently installed, the channel is made of an aluminium cylinder (38 cm-height; 7 cm-diameter) just out of the reflector. Currently it’s being used to perform the fine tuning of Si doping devices.

2.3. Thermal column facility

The thermal column facility of the reactor has been modified along the years. An additional shutter system was installed to allow insertion and extraction of larger sized samples without to shut down the reactor. One of the most frequent applications is the BNCT (Boron Neutron Capture Therapy).

2.4. Horizontal piercing channel D

The irradiation position is shielded with concrete blocks and the samples are moved with an automatic system that can be connected to power supply and signals treatment, for online data acquisitions. The main utilization is for performance tests on electronic devices and large target irradiations (up to 20 cm^3).

2.5. Other irradiation facilities and devices available

- IBA Cyclotron (18 MeV proton, 9 MeV deuterons) facility for radioisotope production
- X-Ray industrial generator (250 kV, 12 mA, 825 Gy/h @ 10 cm; 350 kV, 6 mA 920 Gy/h @10 cm gamma-ray cobalt source (210 Gy/h @ 12 - 2013)

- Radiochemistry laboratory equipped with hoods, glove box and devices for manipulation and analysis of any kind of radionuclides
- Low-background gamma spectrometry laboratory
- Radioprotection instrumentation
- Electronic devices for experiments and for training
- SM1 subcritical multiplying complex for low neutron flux irradiation (10^4-10^5 n/(cm^2·s))

2.6. Operational data

In Table 3 we report the main operational data of the Pavia TRIGA reactor from 2008 to 2013. It is important to underlying that less operational days in specific years are due to reactor planned maintenance period or particular operation related to experimental facility setup that required the reactor in a shutdown condition for days or weeks. On the contrary, years with more operating hours match with the beginning of new experiments that require, as an example, long period of sample irradiation and/or neutron field measurements.

TABLE 3. OPERATIONAL DATA FOR THE TRIGA MARK II OF LENA

	Year 2008	Year 2009	Year 2010	Year 2011	Year 2012	Year 2013
Days in operation	99	106	95	72	107	107
Hours at 250 kW	390.9	317.5	229.9	376.4	324.9	337.7
MWD	4.07	3.30	2.35	3.92	3.38	3.52
Burn-up (U-235, g)	4.29	3.47	2.52	4.13	3.56	3.70

2.7. Performance indicators

Performance indicators are data that provide a measurement of some aspect related to process efficiency and effectiveness. They are an indispensable tool to manage, assess and improve the operation and maintenance of the reactor as well as the management system. For each process involved the organization identified a set of parameters to benchmark the process itself as well as the whole system. Each indicator can be represented as a numerical calculation of a specific formula. Input data are collected from the records from a predefined period of time onwards and, depending on the results of the measurement, the organization determined the proper actions or strategies in order to achieve the desired targets. The following table (Tab. 4) summarizes the main performance indicators relate to the operation of the reactor. Calculated values are based on the IAEA Nuclear Energy Series No. NP-T-5.4 titled “Optimization of Research Reactor Availability and Reliability: Recommended Practices”.

TABLE 4. PERFORMANCE INDICATORS FOR THE REACTOR TRIGA MARK II OF LENA

Process	Indicator*	Expected value	Calculated value 2013
Reactor operation	Reactor availability	70 – 80 %	79 %
	Reliability	70 – 80 %	73 %
	Reactor Utilization	>50 %	57 %

**Availability:* The fraction of time for which a system is capable of fulfilling its intended purpose

$$Availability = \frac{\text{actual operating time}}{\text{planned operating time}} \cdot 100$$

**Reliability:* The probability that a system or component will meet its minimum performance requirements when called upon to do so

$$Reliability = \frac{\text{actual operating time}}{(\text{actual operating time } + \text{ duration of unplanned shutdowns})} \cdot 100$$

**Utilization:* measure of a facility's planned operation

$$Utilization = \frac{\text{planned operating time}}{\text{total duration of reporting period}} \cdot 100$$

2.8. Human resources

As is typical for smaller research reactors, the number of personnel is limited and therefore the various tasks and functions in the organization must be combined. Currently, staff on duty at the LENA reactor consists of 12 employees.

Staffs are organized in section or units with different functions, usually made up of a head of section or unit and one or more employees (Tab. 5). This enables every staff member to be involved in more than one task, namely the allocation of multiple responsibilities to the same person, at the same time, making sure to avoid conflicts of interest. The hiring of personnel is performed according to the national regulation for public employment. LENA has developed a clear positional description including identification of necessary knowledge and skills required for each position to be filled and the training programme for new personnel is described documented procedures. As a part of a bigger organization, LENA is supported, for tasks not strictly related with the reactor operation or radioprotection, by other university staff or external contractors.

TABLE 5. HUMAN RESOURCES AT LENA

Specialization	Function	Appointed
Administrative		2
Technicians (Total number 10)	Top Management (Direction)	2
	Reactor Operation & Management	6
	QA	2
	Radiation Protection Advisor	1
	Health Physics Section	4
	Mechanical Maintenance	2
	Electrical Systems & Instr. Maintenance	1
	Analysis	3
	Marketing & Customer	1
	Educational	1

TABLE 6. LICENSED REACTOR STAFF

Year 2013	
Technical Directors	2*
Reactor Supervisors	7
Reactor Operators	7

*Currently other 3 licenses applications are in progress

3. APPLICATIONS AND UTILIZATION EXAMPLES, INCLUDING COLLABORATIONS

Currently, the core business related to the operation of the reactor is the design and delivery of irradiation services and nuclear measurements, both operated under ISO 9001:2008 standard. Basically, usual LENA customers can be grouped in the following categories:

- Customers from Departments of the University of Pavia;
- Other national and international universities;
- National and international institutions;
- Private companies.

In the following we present the main research fields in which the Pavia TRIGA reactor is involved both directly and as technical support to these activities.

3.1. Boron Neutron Capture Therapy (BNCT)

Since several years the facility has been involved in applied research for medical applications of neutron irradiation using different techniques of analysis; in particular, Boron Neutron Capture Therapy (BNCT), takes up a substantial share of the reactor operating time. BNCT, is an experimental form of binary radiotherapy based on the neutron capture reaction of boron via the reaction $^{10}B(n,\alpha)^{7}Li$. The BNCT thermal neutron irradiations are carried out in a small chamber housed in the modified thermal column of the reactor and that was used to perform BNCT on the explanted liver of patients affected by multiple metastases. For further details see for example Refs. [1, 2, 3].

3.2. Reactor physics and nuclear engineering

Currently, LENA offers technical support to research activities in two research projects funded by INFN and performed in cooperation with other universities (University of Milano Bicocca and of Politecnico di Milano), concerning the reactor physics and nuclear engineering: ARCo (Analysis of Reactor Core) and Nuc-Smile (Nuclear Subcritical multiplying complex for lead experiments) [4]. Basically, the research line concerns the key issues concerning the design of new generation nuclear power plants and related fuel cycles for the development of flexible computational methods for determining the core-critical parameters, the distribution of neutron fluxes, the time evolution of nuclear fuel composition (i.e. kinetics of poisons, burn-up, production and transmutation of actinides and fission fragments, isotopes decay). The aim of the two projects is a sound validation of specific computational codes by comparison with direct measurements performed at the TRIGA reactor and sub-critical multiplicative complex SM1 of the University of Pavia. Another scientific collaboration was carried on with ENEA (National agency for new technologies, Energy and sustainable economic development), within the framework on the "New Nuclear from Fission: international collaboration and development of skills in the nuclear field". The main goal was the measurements of macroscopic quantities for testing of models, codes and nuclear data in research reactors. The activities carried out using the TRIGA Mark II reactor, provided a validation of a methodology for studying the temporal evolution of the composition of nuclear fuel, against the benchmark simulations carried out with the Monte Carlo codes and direct measurements of macroscopic quantities (e.g. as the assessment of the rates of production and transmutation of transuranic elements (TRU) and fission products (FP) by irradiation of fissile material / fertile in the reactor).

Recently the Politecnico of Milano has also carried out a study on the reproduction of the dynamic behaviour of the TRIGA Mark II on the entire operative power range (i.e., 0 - 250 kW) using a zero dimensional approach [5]. In this work the coupling between neutronics and thermal-hydraulics in natural circulation has been considered.

3.3. Neutron activation analysis

The LENA runs quality control on the content of sodium and chlorine in batches of ion exchange resins on behalf of companies that are suppliers of the nuclear industry. The analyses are routinely carried out with the method of neutron activation (INAA) and allow the achievement of a relative high instrumental sensitivity with quick-to-manage irradiation time in reactor. The technique is used as tools in several research& development fields for example as quality test and materials characterization [23], study of industrial processes in steel industry [24] and others dedicated at the activities described here.

3.4. Environmental analysis

Environmental measurements, radioprotection expertise consultancy and investigations in the field of natural and artificial radioactivity are services provided daily by LENA (see for example Ref. [21]). The services are performed both as nuclear site monitoring and also side by side with national institutions or private companies. The main areas of interest are:

- Waste management including radioactive wastes;
- Land reclamation and environmental recovery from oil & gas activities;

- Agricultural products;
- Certification of building materials;
- Monitoring of water and leachate in the phosphate industry;
- Monitoring of radioactivity in air dust.

The LENA laboratory successfully participates annually to intercomparison exercises in a network of international laboratories promoted by the International Atomic Energy Agency (IAEA) with the aim to strengthen the proficiency and reliability of the participant laboratories.

3.5. Electronic devices response to radiation

The CMS group of Pavia (Department of Physics and INFN) started a set of measurements on the front-end electronics used by the muon detector of the CMS (Compact Muon Spectrometer) experiment at CERN (European Center for Nuclear Research) [6]. The purpose is to understand the average life and the behaviour of the front-end of the detectors subjected to high radiation flux, in particular in view of future upgrades. It is intended to realize both measurements of comparison between magnitudes characterizing the system studied before and after irradiation to derive information on the average life of the device is direct measurements of the cross section associated with transient phenomena generated in the devices for effect of irradiation.

3.6. Geosciences

The research activity in the field of fission tracks dating method (see for example Refs. [7, 8]) of the C.N.R Institute of Geo-sciences and Geo-resources (University of Pisa, Italy) is carried on through sample neutron irradiation in the experimental channels of the reactor. With this method it is possible to measure the effect, rather than the product, of radioactive decay. In this case, the radioactive decay is the spontaneous fission of ^{238}U which produces, through its high-energy fission fragments, damage linear (tracks) in the crystal lattice of the mineral. The age of fission tracks is calculated from the number of tracks per unit area observed on the polished surface of the mineral (density of spontaneous tracks). The same method can be applied to measure the concentration in uranium ore, in which ^{238}U is contained as a trace element, and this is done through a second set of fission tracks that are induced through a thermal neutron irradiation provided by the reactor. The research activities of the Laboratory of Geochronology (University of Pisa - Italy) also regard the age determination of minerals through neutron irradiation, flux measurement and isotopic concentrations (^{40}Ar, ^{39}Ar, ^{38}Ar, ^{37}Ar, ^{36}Ar) for mass spectrometry (see for example Refs. [9, 10, 11, 12, 13]).

3.7. Metrological research

The Pavia Radiochemistry and Spectroscopy Unit of INRIM (National Institute of Metrological Research) deals with the study, development and application of radio-analytical, nuclear and spectroscopic methods of measurements of the amount of substance for intercomparison, certification and applied research in various fields (e.g. human health, environment, energy and materials) (see Refs. [14,15,16,17]). The research activities of INRIM are carried on with the Pavia TRIGA reactor. In particular, a methods of Neutron Activation Analysis for the determination of major and trace elements in different types of matrix was developed. In metrology, the activation procedure is used for the certification of reference materials distributed by institutions such as NIST (National Institute of Standards and Technology, USA), IAEA and IRMM (Italian Institute for Reference Materials and Measurements). All measurement activities and researches carried out by INRIM include a sample irradiation stage at LENA.

3.8. Radiochemistry

The Radiochemistry Area of the Department of Chemistry of Pavia, carries on different research activities, such as the development and application of neutron activation analysis techniques, both instrumental and destructive. New separation methods for the determination of trace elements in geological, cosmological and environmental matrices are just few examples of the on-going activities (see for example Refs. [18, 19, 20]).

Another field is the application of neutron activation analysis to archaeological investigations as for provenance studies by using trace element determination and statistical data treatment (multivariate methods and cluster analysis). Typical investigated materials are: marbles, granites, obsidians, pottery, bronze and coins. Neutron activation analysis is also used for the determination the neutron spectrum in the TRIGA Mark II reactor for dating methods in archaeology and geology. The applied experimental part of the Radiochemistry Course of the Chemistry Degree at the University of Pavia, is carried out at the LENA Laboratory in particular:

- preparation of radio-nuclides,
- INAA and laboratory best-practice,
- optimization of electronic parameters and calibration of γ ray detectors,
- surface contamination measures (e.g. using smear test),
- LSC measurements and radiochemical separation of ^{99m}Tc from Mo activated using MEK technique.

Results are in terms of about 25 students attending the course and 2 master thesis works per year.

3.9. Radioisotope production

Metastable technetium-99 (^{99m}Tc) is the most important and widely radioactive marker in nuclear medicine. Since 2009 the international scientific community has highlighted the critical problem about possible near-future shortage, asking to find out for different production routes from the common production via nuclear reactors. One of the possibilities is to replace the current reactor-based method with accelerator-based systems. In this context, the LENA Laboratory participates with technical support to the APOTEMA INFN research project, in order to find out alternative accelerator-driven ^{99}Mo/^{99m}Tc production routes; in particular for the radiochemical separation of ^{99m}Tc from Mo activated using MEK technique in collaboration with the Radiochemistry Unit of the Pavia Chemistry Department. The APOTEMA INFN project also involves the INFN sections of Legnaro, Padova, Milano and Ferrara. Beside the above mentionedproject, the LENA also prepares some radionuclides to use them as tracer for research experiences in the field of waste treatment. The main radionuclides produced are ^{134}Cs, ^{110m}Ag, ^{24}Na, ^{60}Co.

3.10. Education and training

Nowadays, the nuclear field (industry, government authorities, R&D organizations and educational institutions) has a constant need for specialized, highly trained and motivated workforce for its sustainability. High standards of performance are expected for the workforce employed in this field and their specialization is a key issue in order to grant and maintain efficiency and high safety levels. Universities can offer, with such facilities, training, laboratories and experiences in different degree courses. Thanks to the deep expertise gained in more than 45 years of operation of the reactor and to the academic context in which it is operated, LENA can offer a wide range of education and training programs covering most of the topics related to the nuclear field: from safety culture and radioprotection to research reactor maintenance and quality assurance. Training courses are held by qualified professionals working at LENA, or by professors from the University of Pavia, or are a part of the educational path from other universities or institutions contributing to courses for Nuclear Engineering, Physics Master Degrees and for post-graduated International Masters in the subjects of Reactor Physics, Radiochemistry, Radiation Protection and Nuclear Instrumentation. In the academic year 2012/2013 the laboratory has hosted the practical part of the following courses:

- Course of Radiochemistry (University of Pavia) where teaching exercises are expected in the radiochemistry laboratory (an overview of the typical equipment and activities);
- Practical exercises on reactor kinetic for the course on Nuclear Plant in Nuclear Engineering (University of Milan);
- Course of Cellular Radiobiology (University of Pavia) overview on the facility and its utilization;
- Experiences and student stages of the Institute for Advanced Study of Pavia (IUSS) within the International Master on Nuclear and Ionizing Radiation Technologies – NIRT;
- Lessons on neutron physics for course organized by the Physics Department for the Radiobiology course;
- Lessons for the Master in Hadrontherapy (organized by CNAO foundation - National Center of Oncological Hadrontherapy) on various topics related to neutron physics and their application.

In the field of education it’s also included the Radiation Officer personal preparation of candidates to the “Radiation Protection Advisor" exam at the Ministry of Labour.

Besides the above described activities addressed to university students and professionals, since many years, LENA has been promoting the information about the nuclear field providing guided visits to the reactor facility. This activity is particularly addressed to students from high schools, in order to promote nuclear energy and give adequate information to those that aims to get a higher education in the nuclear field. In fact, promoting a proper skill transfer avoiding possible losing in the specific competences needed in the nuclear field is a strong commitment for LENA. The average visitor number per year is about 1500 students; LENA provided teaching activities for about 600 hours during the past three years.

3.11. The Pavia TRIGA research reactor within international networks

The IAEA promotes networking, coalitions and regional collaboration to improve the efficient and sustainable utilization of Research Reactors (RRs). The coalition/network concept involves putting in place cooperative arrangements among research reactor operators, user entities and other stakeholders. A strong partnership is formed leading to increased utilization of individual RRs through collective efforts, including improved self-sustainability and self-reliability. In this context, the Pavia TRIGA reactor is present in the Mediterranean Research Reactor Network (MRRN) created by the IAEA.

IAEA CRPs (Coordinate Research Programs) are another important aspect in the field of international cooperation and knowledge sharing. LENA is currently involved in the following on-going projects:

- "Accelerator-based alternatives to Non-HEU Production of Mo-99/Tc-99m": Lena Laboratory, with the Radiochemistry Unit, carries out research activities that rely on the large experience in the technique of separation and purification of isotopes produced by the nuclear research reactor. The main objective of this research project is to investigate efficient and fast methods for separating ^{99m}Tc from the ^{100}Mo target and for recycling the residual highly expensive ^{100}Mo.

- “Improved I&C Maintenance Techniques using the Plant Computer” aiming to enable the replacement of time based calibrations with condition based calibrations for the reduction in personnel radiation exposure (ALARA), improvement in calibration costs, and adding to plant safety and reliability. LENA actively contributes with tests and benchmarks on actual data retrieved by the automatic data acquisition systems supervising the reactor operation.

In mid-2013, LENA hosted a peer review mission, held by IAEA and international experts, regarding the Operation and Maintenance Assessment of the reactor (OMARR). That was a pathfinder mission for a small sized RR as LENA’s, and resulted very useful as a chance to assess the operation and maintenance processes and share experience and best practices with the other participants. Based on the positive outcomes of the above mentioned mission, LENA received a IAEA INSARR (Integrated Safety Assessment for Research Reactors) mission aiming to assess the facility under the nuclear safety point of view, with the overall goal to continuously improve the efficiency and effectiveness of all processes related to the safety management of the facility.

4. SUCCESS STORIES, MAJOR ACHIEVEMENTS

4.1. NADIR

During the 80’s the fundamental physics experiment NADIR was carried out at LENA laboratory for the study of free neutron-antineutron oscillations. This experiment was characterized by a wide collaboration between different Universities (Pavia, Roma “Tor Vergata”, Sassari, Politecnico di Milano) and the INFN. Further detail can be found in Z. Phys.C Particle and Fields **43**, (1989)175-179.

4.2. Euracos

Euracos II was a specially constructed irradiation facility with a high intensity fission neutron source ($6.1\cdot10^{11}$ n/s). The irradiation system consisted of a disk having a diameter of 80 cm and made of an alloy of Al with highly enriched ^{235}U. The disk was placed in front of the thermal column of the TRIGA MARK II reactor operating at LENA laboratory of the University of Pavia (Italy). Dedicated radiation protection were installed. It was a joint research between JRC Ispra Establishment and University of Pavia. The source had a well defined geometry and a neutron spectrum very close to that of fission. Euracos II was designed for studies of neutron and γ penetration, providing both experimental validation of material characteristics, e.g. cross sections, and also of computer codes. In particular, experiments have been done on Fe and Na. [29, 30]

4.3. BNCT

For the first time in the world, Boron Neutron Capture Therapy (BNCT) has been applied with a challenging protocol of auto-transplantation at the TRIGA reactor in Pavia. The idea was to treat a whole organ affected by multiple unresectable metastases, in order to hit all of them without the need to know their precise number or location. This is possible with BNCT, because the principle is to enrich tumour with ^{10}B by administrating to the patient a suitable carrier able to selectively accumulate into the tumour cells, and then irradiate the target with low energy neutrons. The selectivity of this therapy is thus ensured by boron biodistribution rather by the irradiation field. The idea was to exploit this mechanism by irradiating the whole liver affected by metastases from colon carcinoma, a pathology that causes the death of the patients in few months due to liver failure even if the primary tumour is easily removed and no other metastases are present. After boron administration, the liver was explanted and irradiated for about 10 minutes in the thermal column of the reactor in order to ensure the best possible neutron flux uniformity inside the organ. After irradiation the liver was re-implanted in the patient. Two treatments were performed in 2001 and 2003. This protocol has inspired other international research groups in order to apply it in other facilities and to other explantable organs.

4.4. Implementation of an Integrated Management System (IMS)

In order to continuously improve the quality of reactor management and the accomplishment of the requirements of interested parties, LENA decided to implement an integrated management system in accordance with The Management System for Facilities and Activities (IAEA Safety Standards Series No. GS-R-3, IAEA, Vienna 2006) and the International Quality Standard ISO 9001. An independent Body certified the management system in 2010, and periodically reconfirmed. The main objective of the quality management system is the provision of irradiation services and nuclear measurements. The graded approach utilized during the implementation process, allowed to consider also all the safety constrains related to the operation of a small sized nuclear research reactor. The implementation of the Integrated management System at LENA was chosen, as a case study, for the IAEA SAFETY REPORTS SERIES No. 75 “Implementation of a management system for operating organizations of research reactors”.

5. FUTURE PROSPECTS (INCLUDE ISSUES AND CHALLENGES)

5.1. Fast beam facility: ARCO-FAST (Analysis of Reactor COre – Fast neutrons Analysis with Simulations and Tests)

Starting from the results obtained in ARCO experiment that led to a complete characterization of the TRIGA Type reactor of Pavia using different analysis devices, a new research program (currently under evaluation), for the next years 2014 - 2015 and 2016 will transfer these tools on topics like fast reactors (GEN-IV) and Accelerator Driven Subcritical complex (ADS). For experimental applications will be characterized and used the fast component of TRIGA flux for cross-sections study and burn-up in these new reactors type. Neutron and thermos hydraulic studies will be adopted to foreseen the static and dynamic behaviour of such complexes. In order to achieve these results is on study a new facility using the channel D with thermal flux cut neutron fast reactions.

5.2. Neutrons beam facility for radiobiology study

A feasibility study on the generation of a monochromatic neutron source of energy around 1 MeV from one of the TRIGA reactor horizontal channels is currently on-going at LENA Laboratory, in collaboration with the Radiobiology group of the Department of Physics of the University of Pavia. This facility will be dedicated to the study of Neutron Relative Biological Effectiveness (RBE) and its energy dependence, being maximal for neutron energy energies of about 1 MeV. This topic is widely under investigation in the international scientific community for radiation protection purposes.

5.3. Feasibility study for a neutron diffractometer facility

Recently, a feasibility study by the Pavia Department of Physics on a collimated monochromatic neutron beam (coming from the penetrating channel of the TRIGA reactor) for diffractrometry was performed. The simulations were performed by means of MCNP5 in order to test the different elements necessary to achieve a sufficient neutron flux in the sample position. The best configuration (neutron guides, materials) allows to obtain a neutron flux of 8 x 10^5 n/(cm^2·s) in samples of typical dimensions in powder diffractrometry experiments. For further detail see Ref [22].

5.4. Prompt gamma

A preliminary study about the realization of prompt gamma facilities was carried out in 2011. Among the above-mentioned horizontal channels, the most suitable for this activity resulted the radial channel B, where the graphite reflector thermalizes neutrons, making the epithermal and fast components lower than compared to the other channels. The thermal neutron flux at the beam port, in the original configuration of the channel, was equal to $1.07 \cdot 10^8$ n/(cm^2·s) and the thermal-to-total neutron flux equal to almost 0.8. The insertion of proper filters was studied in order to obtain a neutron beam suitable for Prompt Gamma Neutron Activation Analysis (PGNAA) purposes; with a high thermal neutron component low epithermal, fast neutrons and γ ray contaminations. The construction of the facility is scheduled for the near future; most of the materials required to build the facility were purchased (saphire crystal and bismuth blocks). Some practical aspect of the facility construction are still under study, for example, the sample positioning system and the implementation of a shutter, as long as work schedule and shop drawings. This device system, in particular concerning the turning on and off the beam, will allow replacing the sample without the need to shut down the reactor.

REFERENCES

[1] ZONTA, A. et al., Extra-corporeal liver BNCT for the treatment of diffuse metastases: What was learned and what is still to be learned, Appl. Radiat. and Isot. **67**, (2009) 67-70.

[2] ALTIERI, S. et al., Neutron autoradiography imaging of selective boron uptake in human metastatic tumours, Appl. Radiat. and Isot **66**, (2008) 1850-1855

[3] GENINATTI-CRICH, S. et al., Magnetic Resonance Imaging guided Neutron Capture Therapy by a dual Gd/B agent targeted to tumor cells via upregulated LDL transporters, Chemistry-A European Journal, **17**(30), (2011) 8479–8486.

[4] ALLONI, D. et al., Neutron flux characterization of the SM1 sub-critical multiplying complex of the Pavia University, Prog. Nucl. Ener., **67** (2013) 98-103.

[5] CAMMI, A. et al., A zero dimensional model for simulation of TRIGA Mark II dynamic response, Prog. Nucl. Ener. **68**, (2013), 43–54.

[6 ABBRESCIA, M. et al., Neutron-induced Single Event Upset on the RPC front-end chips for the CMS experiment, NIM A, **484** (2002) 494–502.

[7] OLIVETTI, V. et al. Tectonic and climatic signals from apatite detrital fission-track analysis of the Cape Robert Project core records, south Victoria Land, Antarctica. Tectonophysics, **594** (2013), 80–90.

[8] BALESTRIERI, M.L. et al, Detrital fission-track-compositional signature of an orogenic chain-hinterland basin system: The case of the late Neogene Quaternary Valdelsa basin (Northern Apennines, Italy). Sedimentary Geology, **289**, (2009) 159–168.

[9] DI VINCENZO, G., PALMERI, R., An^{40}Ar–^{39}Ar investigation of high-pressure metamorphism and the retrogressive history of mafic eclogites from the Lanterman Range (Antarctica): evidence against a simple temperature control on argon transport in amphibole. Contributions to Mineralogy and Petrology, **141** (2001), 15–35.

[10] DI VINCENZO, G. et al., Evidence of a close link between petrology and isotope records: constraints from SEM, EMP, TEM and in situ ^{40}Ar–^{39}Ar laser analyses on multiple generations of white micas (Lanterman Range, Antarctica). Earth and Planetary Science Letters, **192**, (2001) 389–405.

[11] DI VINCENZO, G. et al., The effect of chlorite interlayering on ^{40}Ar–^{39}Ar biotite dating: an^{40}Ar–^{39}Ar laserprobe and TEM investigation of variably chloritisedbiotites. Contributions to Mineralogy and Petrology, **145**, (2003), 643–658.

[12] LAURENZI, M.A. et al., New constraints on ages of glasses proposed as reference materials for Fission-Track dating. Geostandards and Geoanalytical Research, **31**, (2007) 105-124.

[13] BIGAZZI, G. et al., Multi-method approach to dating glass: the case of Basiluzzo Islet (Aeolian archipelago, Italy). Journal of Volcanology and Geothermal Research, **177**, (2008) 244-250.

[14] BERGAMASCHI, L. et al., Determination of trace elements by INAA in urban air particulate matter and transplanted liches, J. Radioanal.Nucl. Chem., **263** (3), (2005) 745-750.

[15] GIORDANI, L. et al., Neutron activation analysis in forensic investigations: trace elements characterization of cigarettes, J. Radioanal. Nucl. Chem., **263** (3), (2005) 739-744.

[16] D'AGOSTINO, G., et al., Instrumental neutron activation analysis of an enriched ^{28}Si single-crystal, Journal of Radioanalytical and Nuclear Chemistry, *accepted* (25.07.13).

[17] D'AGOSTINO, G. et al., Elemental characterization of the Avogadro silicon crystal WASO 04 by neutron activation analysis, Metrologia **49** (2012) 696–701.

[18] BIGAZZI, G. et al., The Italian obsidian sources. ArcheometriaiMűhely **1** (2005)1-12.

[19] BOTTO, M. et al., Caratterizzazione di anforefenicie e puniche mediante analisi archeometriche Mediterranea, Quaderni annuali dell'Istituto di Studi sulle Civiltà italiche e del Mediterraneo antico, **2** (2005)28-56, Pisa (2006).

[20] ARIAS, A., New data for the characterisation of Milos obsidians" J. Radioanal. And Nucl. Chem. **268** (2006) 371-386.

[21] MANERA, S. et al., Japanese Green Tea radioactivity measurments, radiochemical extraction yield determination and some radioprotection considerations". NRC8 - International Conference on Nuclear and Radiochemistry - Session 13 - radioactive

elements in the environmental Como Sept. 2012 (*submitted* to Journal of Life Sciences and Biotechnology (ISSN 2155-8019)).

[22] REVERSI L., Studio computazionale per la realizzazione di unfascio di diffrattometrianeutronicapressoilreattore TRIGA di Pavia., MSc Thesis, University of Pavia (2012).

[23] CLEMENZA, M. et al., Ultra Sensitive Neutron Activation Measurements of 232-Th in Copper", Topical Workshop on Low Radioactivity Techniques - LRT 2010, AIP Conference Proceedings 1338, 37-43; doi: 10.1063/1.3579557; 2011 American Institute of Physics; ISBN 978-0-7354-0892-0 (2011).

[24] GRASSI, B. et al., Determination of trace elements in metallic materials by neutron activation analysis, Journal of Physics: Conference Series **41** (2006) 288-295).

[25] REVERSI, L., "Studio computazionale per la realizzazione di un fascio di difrattometrianeutronicapressoilreattore TRIGA di Pavia" Master Degree Thesis – University of Pavia (2013).

[26] BORIO DI TIGLIOLE, A. et al., TRIGA reactor absolute neutron flux measurement using activated isotopes, Progr. Nucl. Ener. **70**, 249–255 (2014).

[27] PROTTI, N. et al., Neutron Spectrometry for the University of Pavia TRIGA Thermal Neutron Source Facility" Transactions of the American Nuclear Society, **107**, San Diego, California, November 11–15 (2012).

[28] STELLA, S., Design of a Prompt Gamma Neutron Activation Analysis (PGNAA) System form Boron Neutron Capture Therapy (BNCT) using Monte Carlo code" PhD Thesis, Pavia (2011).

[29] NICKS, R. et al., Ann. Nucl. Ener., **15**, (1988) 457-469.

[30] PERLINI, G. et al., Ann. Nucl. Ener., **16**, (1989)189-201.

THE JSI TRIGA MARK II REACTOR, SLOVENIA

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Abstract.

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 extensively 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 aforementioned activities proving that even such small reactors are still indispensable in nuclear science and technology.

1. INTRODUCTION

The 250 kW TRIGA Mark II research reactor at the Jožef Stefan Institute (JSI), located near a small village Podgorica near Ljubljana, Slovenia, achieved its first criticality on 31st of May 1966 at 14:15h. It is a light water reactor, with solid fuel elements in which 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 system, as well as 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 thermalizing column. In 1991 the reactor was almost completely reconstructed (new grid plates, 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.

With the maximum neutron flux in the central thimble of 10^{13} $n{\cdot}cm^{-2}{\cdot}s^{-1}$ and many sample irradiation positions the reactor serves as an important research tool which is in many fields competitive with the reactors in the higher flux region. The acquisition and installation of the reactor has mainly been aimed at producing isotopes, supporting basic and applied research in various fields and as tool for training in the nuclear science. 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. Besides these, applied research around the reactor has been conducted, such as doping of silicon monocrystals, a 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 middle 80's.

Since its first criticality the reactor has been playing an important role in developing nuclear technology and safety culture in Slovenia, at the same time being one of a few centres of modern technology within 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 the 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 [1].

The reactor is presently organised 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. APPLICATIONS, UTILIZATION AND ACHIEVEMENTS

2.1. Production of radioactive 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} $n \cdot cm^{-2} \cdot s^{-1}$ 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.

2.2. 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 TRIGA fuel, applications in metallurgy and inspections in aviation and metal industries. Present activities to utilize thermal 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. In the year 2010 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 was successfully completed. Recently, several discussions with Slovenian companies to use neutron radiography as a method to investigate their products were initiated.

2.3. Neutron activation analysis

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} $g \cdot g^{-1}$ to virtually 10^{0} $g \cdot g^{-1}$). The reactor has been utilized for NAA soon after its commissioning in 1966 [2]. 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 the semi-empirical k_0-based NAA [3] 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 [4]. The k_0-NAA is amply used for the analysis of environmental samples including biological materials, as well as for new materials and industrial samples. About 1,000 samples per year are analyzed by this method [5]. 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.

Some parameters indicating utilization of the JSI's TRIGA research reactor during the last ten years are shown in Table 1.

TABLE 1. SOME PARAMETERS RELATED TO UTILIZATION OF THE JSI'S TRIGA REACTOR

Year	No. of samples irradiated in the rotary specimen rack	No. of samples irradiated in the pneumatic transfer rabbit system	Operating days	Energy produced	No. of pulses
2004	1164	431	188	282	26
2005	940	766	176	258	10
2006	838	1025	218	210	0
2007	1300	257	155	225	0
2008	1071	224	128	179	0
2009	818	183	123	170	0
2010	624	168	106	140	0
2011	676	61	127	125	0
2012	1307	37	147	124	23
2013	825	16	136	104	0

2.4. Irradiation of materials for research purposes

During the last years, 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 the

European Organization for Nuclear Research (CERN) [6, 7]. 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 *E*uropean *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 Research 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 [8];
- Irradiation of potential future first wall and breeder blanket structural materials for the planned fusion reactor [9, 10];
- Irradiation of various materials in gamma radiation field for research on polymerization and sterilization processes.

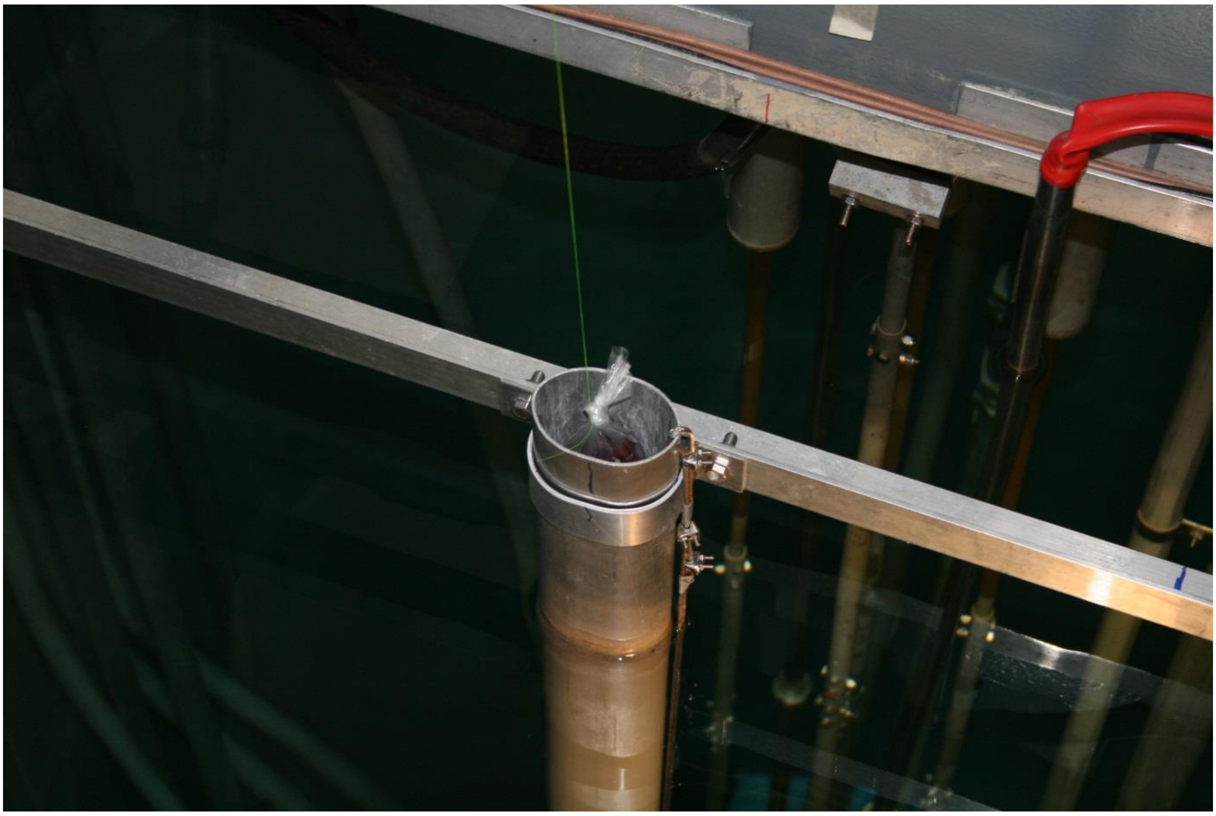

FIG. 1. Insertion of a sample into the "triangular" channel to be irradiated for a research experiment.

2.5. 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 using the most advanced Monte Carlo neutron transport codes such as MCNP, the Monte Carlo N-Particle Transport Code [6]. 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 [11, 12]. 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 [13]. A series of pulse experiments is candidate for a TRIGA kinetic parameters benchmark.

Recently, two bilateral projects with the French Alternative Energies and Atomic Energy Commission (CEA) have been started as part of an agreement between the CEA and the Slovenian Ministry of higher education, science and technology. Objective of the first project 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 aim is also 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 experiments carried out 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. In Fig. 2 experimental and calculated reaction rates are compared for irradiated Au monitor in three channels. Good agreement between experimental and calculated values can be observed.

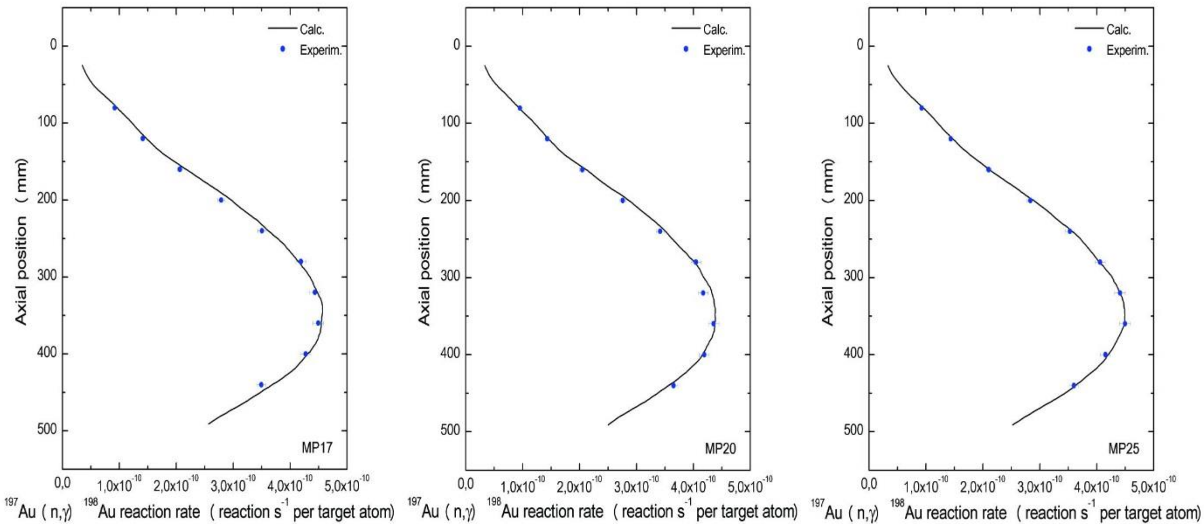

FIG. 2. Experimental and calculated ^{197}Au (n, γ) ^{198}Au reaction rates in the measuring positions MP17, MP20 and MP25.

The second joint project with the CEA 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.

Objective of the projects are to analyze and improve the power calibration process of the TRIGA reactor (procedural improvement and uncertainty reduction) by using absolutely calibrated CEA fission chambers. The experiments are one of the few available power density distribution benchmarks for testing not only the fission rate distribution but also the absolute values of the fission rates. Preliminary calculations indicate that the total experimental uncertainty of the measured reaction rate is sufficiently low so that the experiments could be considered as benchmark experiments.

2.6. Education and training

The 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 and the Slovenian Nuclear Safety Administration. 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 Centre (NTC) located at the reactor site. In addition, on average more than 1,400 people visit the reactor yearly as part of improving general knowledge on nuclear technology among population. For training purposes, many practical reactor physics exercises are performed each year. In the year 2012 a project, financially supported by the Krško NPP, was initiated to upgrade some of the existing and to introduce some new exercises outlined below.

2.6.1. Critical experiment

Critical experiment and study of subcritical multiplication is one of the basic experiments in reactor physics. At the JSI TRIGA reactor critical experiment is performed in two different ways, either by adding fuel elements or by withdrawing control rods. Until recently the neutron population in the reactor was measured only by using the fission chamber that is part of the reactor instrumentation, the so called start-up channel. As the critical experiment should be performed with at least two independent neutron sensitive detectors, we installed the second fission chamber with autonomous electronic into one of the irradiation channels in the core. This allows for demonstrating the dependence of $1/M$ curve shape versus detector position. For the start-up channel the nuclear instrumentation is used, and dedicated control and data acquisition software by using the LabVIEW software was developed. This allows the trainee to control counting time of both fission chambers. In addition $1/M$ diagram is plotted and for each step the software automatically calculates reactivity required to reach criticality. In order to study reactor kinetics around criticality the software features a possibility of observing count rate versus time. The latter feature is especially convenient to study the level of critically close to $k = 1$ when criticality is estimated by inserting and withdrawing the neutron source.

2.6.2. Pulse mode

The JSI TRIGA reactor features pulse rod, which is equipped with pneumatic mechanism that can shoot the pulse rod out of the core in a couple of milliseconds. In pulse mode all control rods except the pulse one are completely withdrawn and the reactor is slightly subcritical. Then pulse rod is pneumatically shot out of reactor core till a predefined limit. This sudden increase in reactivity causes the reactor to go supercritical with a period of a few milliseconds. Reactor power sharply increases for a few decades and at the same time also the fuel temperature increases. Due to prompt negative temperature reactivity coefficient the reactivity is decreased and reactor shuts down. The full pulse length depends on inserted reactivity and is typically in the order of 100 ms. This experiment demonstrates inherent safety of the reactor and is very useful for verification of reactor kinetics models.

The data acquisition system that logs the signal on the pulse channel was upgraded and is now capable of very fast simultaneous sampling of reactor power and fuel temperature. The new software calculates basic parameters of a pulse such are peak power, peak temperature, released energy etc. immediately after the pulse. The TRIGA pulsing was also shot by using high definition and high speed cameras. The video clips are available at the JSI TRIGA webpage [14].

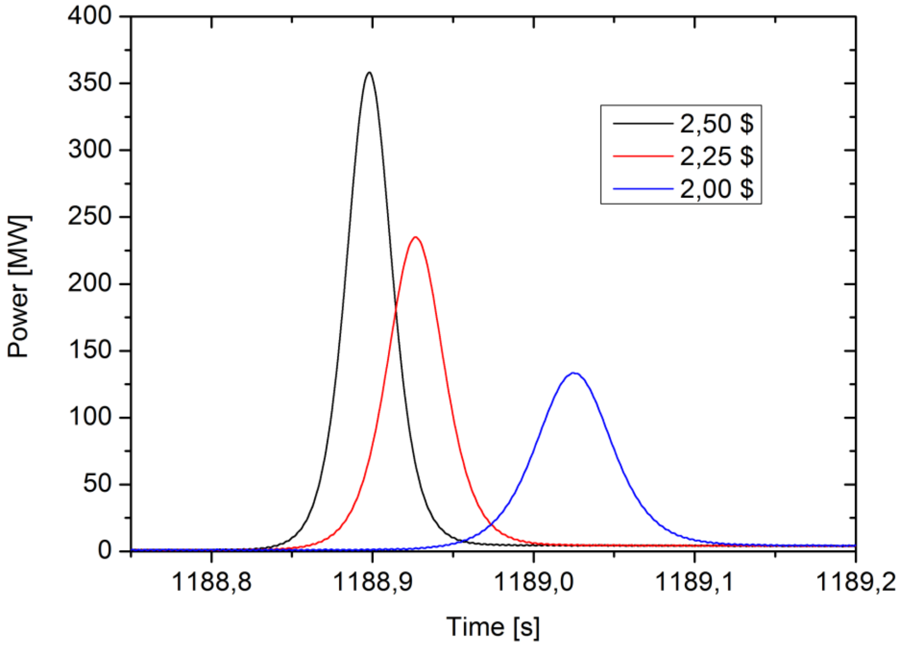

FIG. 3. Three different pulses with inserted reactivity of 2.00 $, 2.25 $ and 2.50 $.

2.6.3. Void reactivity coefficient

Voids in nuclear reactor are usually formed as a result of primary coolant boiling and as such affect reactivity and thermo-hydraulic characteristics of the reactor. Consequently the void coefficient of reactivity is one of the key safety parameters in nuclear reactors.

In the past the void reactivity coefficient exercise was performed by inserting small Al batons at various places in the core and measured reactivity changes versus location and size of the void. The advantage of such approach is that the location and volume of the void is very well defined. The disadvantage, however, is that Al baton does not resemble bubbles and is not so illustrative.

Therefore a system for simulating water boiling (generation of voids/bubbles) in the reactor we designed. For this purpose a pneumatic system was built which generates air bubbles under the core. The system consists of controller, pressure regulators, valves, air flow meters, Al tubes and nozzles for producing air bubbles. Al tubes with nozzles are inserted in the reactor core on different radial locations so the nozzles are located just under the core. Each Al tube is individually connected to its own valve, choke and air flow meter so that air flow through each individual tube can be independently adjusted and measured. Alongside with the pneumatic system a LabVIEW-based application for controlling pneumatic system and acquiring data with implemented digital reactivity meter was developed.

By using the graphical user interface (GUI) in LabVIEW one can adjust air pressure and set location in the core where the voids are formed. By adjusting the air pressure the air flow rate and consequently volume of the voids in reactor core is changed. Location of the voids is controlled by switching on or off each individual valve and thereby air flow through each individual tube. They are all controlled independently.

It is important to note that installation of this exercise was considered as temporary modification of the reactor. Hence a thorough safety screening and safety evaluation had to be performed prior to installation and is thoroughly described in [15].

The aim of the exercise is to measure reactivity changes versus flow rate and void position. Therefore a digital reactivity meter was integrated into the package. Dedicated software allows trainee to control the air flow, observe reactivity changes and acquire data all with one application. This way trainee can focus to reactor physics and not to the implementation of the exercise.

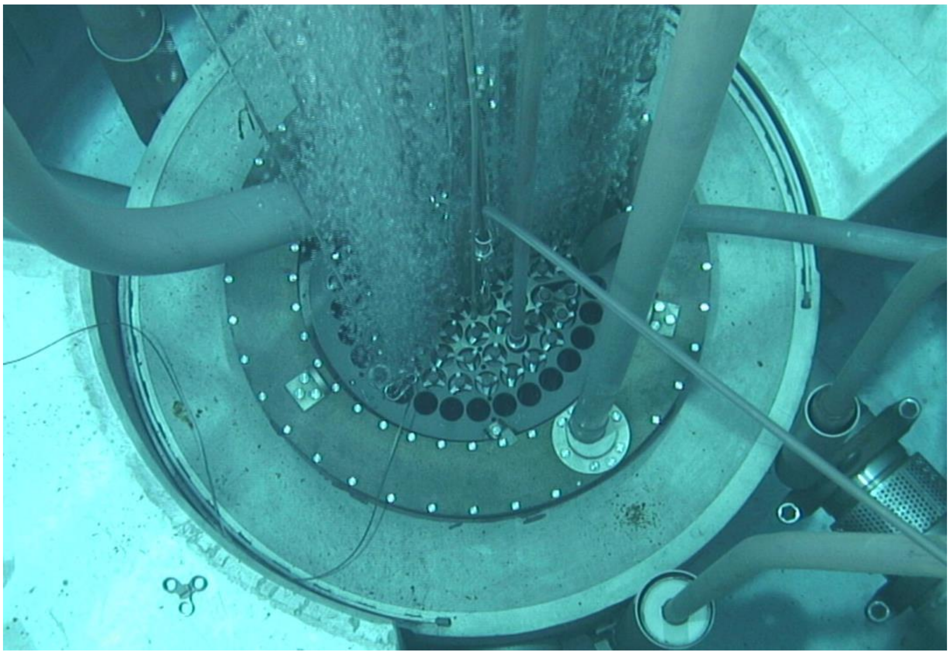

FIG. 4. Simulation of water boiling in nuclear reactor. Air is fed just under the core where air bubbles (voids) are generated. Here air bubbles are generated across the reactor core.

2.6.4. Primary water activation

Coolant in water cooled reactor gets activated by neutrons causing elevated dose rates in the vicinity of primary circuit, mostly due to ^{16}N, that emits gamma rays with relatively high energy (Table 2). The purpose of this practical exercise is to get familiar with methods for primary water activation measurements and to measure primary water activation versus reactor power level.

TABLE 2. THE MOST IMPORTANT ACTIVATION PRODUCTS IN WATER

Nuclide	Isotopic abundance	Reaction (neutrons)	Activation product	$T_{1/2}$	Gamma-ray energy
^{16}O	99.76	n, p (fast) E > 9 MeV	^{16}N	7.13 s	6.129 MeV 7.117 MeV
^{18}O	0.20	n, γ (thermal)	^{19}O	26.9 s	0.197 MeV 1.357 MeV

The setup for this exercise is composed of a pump which pumps primary water through reactor core to reactor platform, where water activity is measured. Primary water is pumped below the core and is guided by the aluminium tube through the core to the platform at a constant flow rate, which can be adjusted. On the reactor platform primary water tube is fed through a lead shield where detectors are located, so the detectors measure only activation of primary water and not background radiation of working reactor. Water activity is measured with portable GM tube for measuring dose rate and two types of spectrometers, a semiconducting HPGe and a scintillating LaBr crystal. Signal from spectrometers is analysed with Amptek PX5 multichannel analyzer and acquired with DppMCA software.

In the first part of the exercise the trainees learn how to calibrate the spectrometers with Cs source before the exercise and how to search the gamma line peaks. In the second part they monitor intensity of selected gamma lines corresponding to water activation products, versus reactor power level measured on the linear channel. In addition they monitor the dose rate.

2.6.5. In-core flux mapping

In-core flux mapping at a nuclear power plant is performed regularly in order to verify the power profile calculations. As the in-core flux mapping system at the NPP is usually not suitable for training, an analogous practical exercise was developed. The aim of the exercise is to get familiar with the in-core flux mapping system and to get familiar with the axial power profile in a nuclear reactor. A special experimental set-up was made in order to measure the axial fission rate profile in the reactor.

A fission chamber (FC) containing approximately 10 μg of 98.49% enriched ^{235}U is used to perform axial measurements of the fission rate along the complete core height at various radial measurement positions. The FCs are deployed into the reactor core by using a specially designed FC positioning system, composed of Al guide tubes, drive mechanism and data acquisition system. Figure 5 shows a schematic view of the system where FC integrated cable is also used for inserting and withdrawing the FCs into and out of the reactor core.

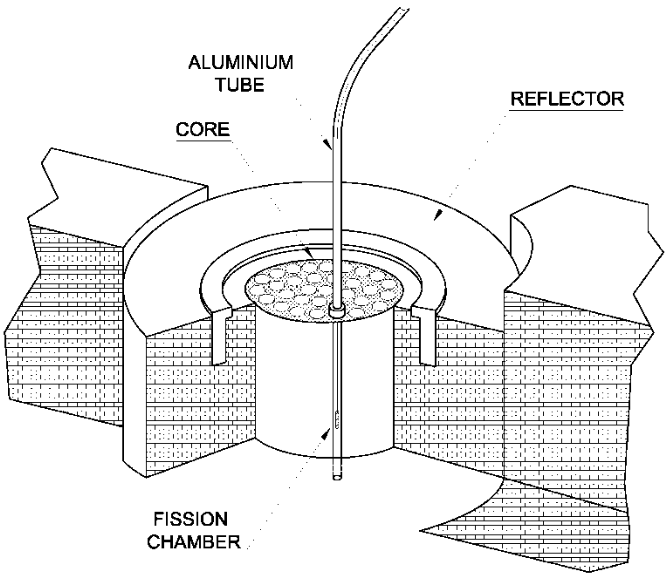

FIG. 5. Schematic figure of the FC positioning system.

The FC position is regulated by a commercially available pneumatic drive consisting of a series of valves and pistons, all controlled by a microcontroller (Fig. 6). The axial positioning is ensured by an incremental system which measures the FC position relative to the reference position at the end of the guide tube. The accuracy of the FC positioning system is ~ 0.1 mm and the repeatability of the FC position is within 0.3 mm.

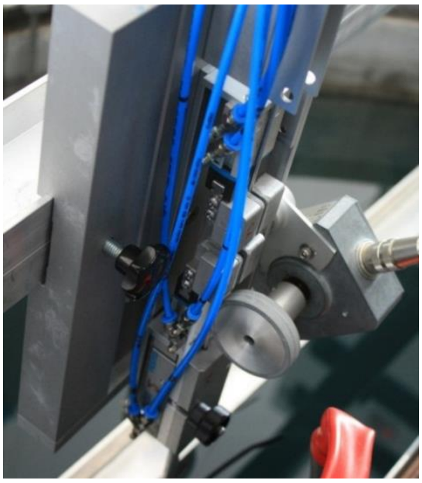

FIG. 6. Pneumatic system with fixed and moving jaw, which can move fission chamber in both directions: System is mounted above the reactor pool. On the right one can see incremental positioning encoder which provides accurate axial position. The system was developed and manufactured at the JSI.

Fission rate in the fission chamber is measured using Amptek PX5 MCA which is configured so that it generates 5 V TTL pulse for each detected fission. Response from fission chamber is measured by counting those digital pulses with NI-6356 DAQ and at the same time accurate axial position is provided by incremental positioning encoder.

A dedicated software was developed in the LabVIEW environment in order to control movement of fission chamber, adjust counting time and acquire data. Actual measurement of axial fission rate distribution is done by moving fission chamber in steps from the lower end stop, which is slightly below the core, to few centimetres above the core. On each step response from fission chamber and current position is recorded. Measurement of a power profile can be done manually or automatically with adjustable axial resolution and speed.

2.7. Regional and international cooperation

The Reactor infrastructure centre of the Jožef Stefan Institute acts as a recipient institution for numerous trainees coming through IAEA – TC (International Atomic Energy Agency – Technical Cooperation), ICTP/IAEA STEP (International Centre for Theoretical Physics/IAEA Sandwich Training Educational Programme), NATO – SPS (North Atlantic Treaty Organization – Science for Peace and Security) mechanisms, as well as within frameworks of bilateral agreements.

Furthermore, the institute participates in a number of international collaborations. The role of the particular collaborations and the JSI participation are briefly described in the following paragraphs.

2.7.1. Eastern European Research Reactor Initiative (EERRI)

The EERRI was established in 1998 by the initiative of the International Atomic Energy Agency (IAEA). It organizes regular training courses on utilization of research reactors for educational purposes and so far, eight training courses were organized. The training is usually organized as a six weeks course implemented at research reactors in four countries, one of them being the JSI's TRIGA. Countries participating in the EERRI coalition are shown in Fig. 7.

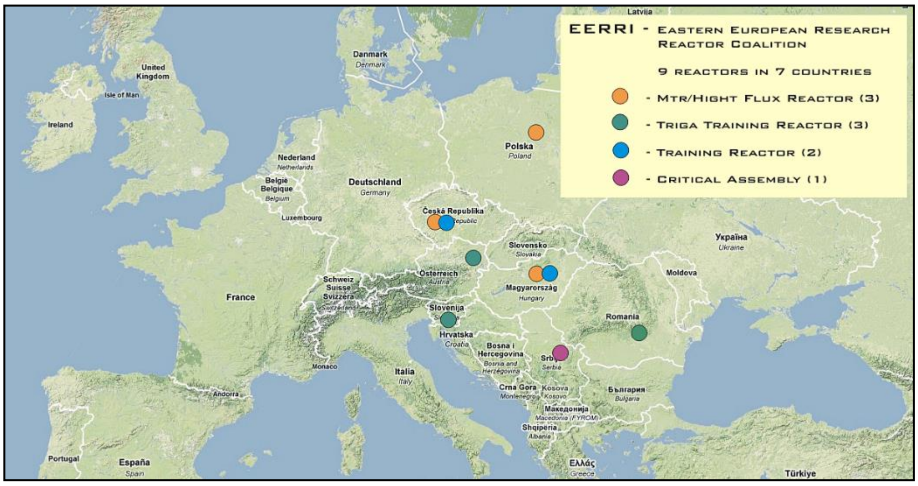

FIG. 7. Countries participating in the Eastern European Research Reactor Initiative (EERRI).

2.7.2. Mediterranean Research Reactor Network (MRRN)

The MRRN, established in 2008, comprises institutions from 14 IAEA Member States located on both European and African sides of the Mediterranean Sea (Fig. 8). The harmonized activities are focused on three main topics:

- Nuclear education and training,
- Neutron activation analysis, and
- Neutron radiography and tomography.

The Reactor infrastructure centre of the Jožef Stefan Institute acts as a coordinator for the nuclear education and training.

FIG. 8. Countries participating in the Mediterranean Research Reactor Network (MRRN).

2.7.3. European Advisory Safety Committee for Research Reactors in Europe (EURASC)

The EURASC was established upon the IAEA initiative in 2010. Presently consisting of 11 European IAEA Member States meeting on a yearly basis, it aims at enhancing the safety of research reactors in Europe and acts mainly as an advisory group to deliberate upon important safety issues in the region and to strengthen the effectiveness of the operating organizations' safety committees. It also provides for facilitating the use of qualified human resources to address specific safety issues in the region, and to exchange information and share knowledge and experience on research reactor safety, including application of the IAEA Code of Conduct on the Safety of Research Reactors and safety standards. The Head of RIC/JSI acts as a chairperson of EURASC for the next two years, till 2016.

2.7.4. European Atomic Energy Society – Research Reactor Operators Group (EAES – RROG)

The RROG unites operators of the European research reactors from 23 countries that meet annually since 1988. JSI staff regularly participates at these meetings where practices and operational experiences are critically discussed and assessed.

2.7.5. Global TRIGA Research Reactor Network (GTRRN)

The TRIGA-type research reactors by General Atomics have become the most widely used model around the world, and with common advantages and challenges, its users aim to strengthen ties and formulate strategies and solutions within a global network. In July 2012, joint agreement among 11 TRIGA reactor representatives from 9 Member States, including Slovenia, concluded that a number of important global issues, in particular back-end options related to the spent nuclear fuel return to the country of origin programme and potential shutdown of the TRIGA fuel fabrication facility, could best be addressed by a coalition/network. Therefore, a relevant Memorandum of Understanding was adopted to be signed by the interested reactor operators and a five-member steering committee established. The global network presently consisted of 14 members, has potential to include and coordinate regional sub-groups such as operational TRIGA facilities in Africa (2), Asia-Pacific (7), Europe (8), Latin-America (3), in a manner comparable to the existing US-located TRIGAs (18).

3. FUTURE PROSPECTS

It might be concluded that 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 preserve the knowledge of nuclear energy.

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.

The existing activities in the field of research will be maintained and the activities in reactor physics experiments and benchmarks, as well as in the field of irradiation of samples under well-defined conditions will be further expanded.

It is planned that the TRIGA reactor, along with the Nuclear Training Centre would become an 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. It is written in the strategy that TRIGA reactor will receive 20 million EUR for complete refurbishment and 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 shut down, 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. TRIGA would then be closed and decommissioned. During decommissioning of the TRIGA reactor, involved people would get operational and theoretical experience, which could later be used in decommissioning the Krško NPP. Additionally, a company could be established that would provide services and practical training on decommissioning worldwide.

REFERENCES

[1] SNOJ, L., SMODIŠ, B., 45 Years of TRIGA Mark II in Slovenia, Proceedings 20th International Conference Nuclear Energy for New Europe 2011, Nuclear Society of Slovenia (2011).

[2] SMODIŠ, B., Forty-five years of neutron activation analysis in Slovenia: achievements towards improved quality of measurements results, J. Radioanal. Nucl. Chem., **291** (2012) 543–548.

[3] DE CORTE, F., et al., Installation and calibration of Kayzero-assisted NAA in three Central European countries via a Copernicus project, Appl. Radiat. Isot., **55** (2001) 347–354.

[4] OSTERC, A., et al., Development of a method for ^{129}I determination using radiochemical neutron activation analysis, Acta Chim. Slov., **54** (2007) 273–283.

[5] BUČAR, T., et al., Quality assessment of k_0-NAA by statistical evaluation of CRM results, Acta Chim. Slov., **55** (2008) 166–171.

[6] KRAMBERGER, G., et al., Annealing studies of effective trapping times in silicon detectors, Nucl. Instrum. Meth. A, **571** (2007) 608–611.
[7] KRAMBERGER, G., et al., Impact of annealing of trapping times on charge collection in irradiated silicon detectors, Nucl. Instrum. Meth. A, **579** (2007) 762–765.
[8] SNOJ, L., et al., Experimental Verification of Radiation Dose in Mixed Neutron/Gamma Radiation Fields, International Conference Nuclear Energy for New Europe 2007, Proc. Int. Conf. Portorož 2007, Nuclear Society of Slovenia (2007) 602.1–602.8.
[9] SNOJ, L., et al., Long Lived Activation Products in Eurofer, International Conference Nuclear Energy for New Europe 2007, Proc. Int. Conf. Portorož 2007, Nuclear Society of Slovenia (2007) 905.1–905.8.
[10] LENGAR, I., et al., Evaluation of Activation Characteristics of Silicon Carbide in a Fusion Spectrum, International Conference Nuclear Energy for New Europe 2008, Proc. Int. Conf. Portorož 2008, Nuclear Society of Slovenia (2008) 810.1–810.9.
[11] JERAJ, R., RAVNIK, M., TRIGA Mark II Reactor: U[20] – Zirconium Hydride Fuel Rods in Water With Graphite Reflector, IEU-COMP-THERM-003, ICSBEP Handbook, NEA/NSC/DOC[95]03, Paris (1999).
[12] RAVNIK, M., JERAJ, R., Research reactor benchmarks, Nucl. Sci. Eng. **145** (2003) 145–152.
[13] SNOJ, L., et al., Analysis of neutron flux distribution for the validation of the computational methods for the optimization of research reactor utilization, Appl. Radiat. Isot., **69** (2011) 136–141.
[14] INSTITUT JOŽEF STEFAN REAKTORSKI CENTER, http://www.rcp.ijs.si/ric/pulse-s.html (last accessed February 2014)
[15] JAZBEC, A. et al., Analysis of a Void Reactivity Coefficient of the JSI TRIGA Mark II Reactor, International Conference Nuclear energy for new Europe 2013, Bled, Slovenija, Nuclear Society of Slovenia (2013) 606.1–606.9.