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RESEARCH ARTICLE - SPECIAL ISSUE - CHALLENGES AND RECENT ADVANCEMENTS IN NUCLEAR ENERGY SYSTEMS

Advancing Nuclear Research and Education in Slovenia and EU: From Operating the TRIGA Reactor to Building a New Generation Facility

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Abstract
The TRIGA Mark II research reactor at the Jožef Stefan Institute in Slovenia achieved first criticality in 1966. Since then, the reactor has been playing an important role in developing nuclear technology. The reactor has been mainly used for research, education of university students, training of operators of the Krško nuclear power plant (start of operation in 1983) and other nuclear specialists, isotope production and beam applications. The reactor is experiencing a high level of activity today, engaging in a diverse range of experiments and studies across reactor physics, environmental research, radiation hardness testing as well training and education. The future of nuclear technology in Slovenia is focused on new NPPs, while the research community is looking forward to a possible new nuclear reactor. The basic initiatives are at a very preliminary stage: the primary choice is dual-core pool-type reactor, with a zero-power core and a separate MW-size core, cooled and moderated with light water. Such a dual-core configuration is designed to meet the varied requirements of the European Union member states. Another option would be hosting one or more micro-reactors with electrical and/or heating power producing capability that could offer stronger support toward demonstration of prototype small modular reactors in prototype future electrical grids.

Keywords Research reactor · Nuclear research · Nuclear education · European Union nuclear strategy · TRIGA

1 Past and Present–TRIGA Reactor

The TRIGA Mark II research reactor at the Jožef Stefan Institute (JSI) in Ljubljana, Slovenia, reached its first criticality on May 31, 1966, at 14:15. Since then, the reactor has played a vital role in the development of nuclear technology and safety culture in Slovenia. It is known as one of the country's few centers of modern technology, and its international cooperation and reputation contribute to the promotion of JSI, Slovenian science and Slovenia on a global scale.

The primary utilization of the reactor has been in training and education of university students, engineers and technicians who continue their careers in different fields of nuclear engineering. It also provides on-the-job training for staff working in public and private institutions. Additionally, the reactor is used for isotope production, neutron activation analysis (NAA), beam applications, neutron radiography, testing and development of a digital reactivity meter, as well as verification of computer codes and nuclear data, including criticality calculations and neutron flux distribution studies.

The TRIGA MARK II research reactor at the Jožef Stefan institute (JSI) is a typical 250 kW TRIGA reactor, moderated and cooled with demineralized water [1, 2]. During the long-time steady-state reactor operation, an external cooling system is operating, which cools the upper section of the

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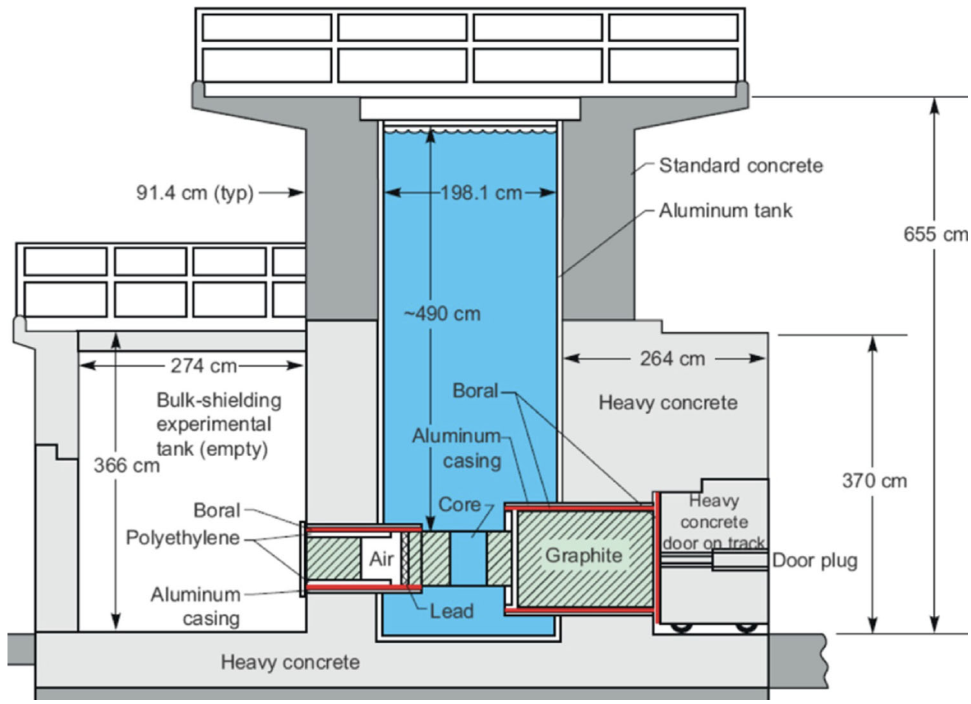

Fig. 1 Side view of the TRIGA MARK II reactor

pool through a forced convection; however, natural convection remains the driving force for the flow through the core. The core of TRIGA reactor is placed at the bottom of an open tank with 5 m of water column above it as presented in Fig. 1. The core has a cylindrical configuration with 91 designed locations to accommodate fuel elements or other components such as control rods, a neutron source and irradiation channels. Elements are arranged in six concentric rings. In recent years, the reactor has been extensively utilized for irradiating various components for the ATLAS [3] detector in the European Organization for Nuclear Research (CERN). Its precisely characterized irradiation channels have made it a reference center for radiation hardness studies of detectors developed for the ATLAS experiment. JSI has several ongoing projects related to reactor applications, with many more planned. The first section of this paper focuses on the current and planned utilization of the TRIGA Mark II reactor at JSI, highlighting that even small reactors like the 250 kW TRIGA at JSI can serve various purposes and significantly contribute to state-of-the-art achievements in nuclear science, technology and related fields. While some of the activities have been previously presented elsewhere, this paper specifically covers activities of the last decade.

1.1 Research Topics

The research activities at the JSI TRIGA reactor can be summarized as:

- Reactor physics (benchmarks, reactor physics parameters, pulse, digital meter of reactivity, rod insertion method);
- Radiation physics (radiation field characterization, nuclear instrumentation and detector development, testing and qualification);
- Safeguards;
- Neutron activation analysis;
- Radiation hardness (detectors at particle colliders, specialized nuclear equipment, material testing);
- Radiolytic chemistry;
- Environmental sciences;
- Nuclear data;
- Multi-physics;
- Radiation biology;
- COVID-19-related applications;
- Education and training;
- Development, verification and validation of computer codes.

Further in the text, some of the above-mentioned activities and their main results are briefly presented and discussed.

1.2 Reactor and Radiation Physics

The JSI TRIGA reactor has facilitated in a broad range of reactor and radiation physics studies. Through the comprehensive series of the benchmark experiments [4, 5], this research reactor has validated a various computational nuclear models and methodologies. Among the reactor physics parameters JSI TRIGA core criticality, control rod worth [6], power peaking factors [7], kinetic parameters [8, 9], fuel burnup [10] and pulse [11] were studied.

The JSI TRIGA was also a cornerstone in the development and testing process of the digital meter of reactivity (DMR) [12], which was developed in the 1980 s by the Department of Reactor Physics at the Jožef Stefan Institute and is used for real-time measurements of reactivity in a nuclear reactor core. The developed DMR is also crucial for the rod insertion method measurements. The rod insertion method [13, 14] represents a rapid, efficient and precise methodology for the assessment of control rod reactivity worth within nuclear reactors, facilitating the derivation of both integral and differential worth profiles. Suitable for application across research reactors and power generation reactors alike, this technique originated at the JSI TRIGA reactor toward the end of the 1980 s [15], marking its inaugural adoption within the operational protocols of the Krško nuclear power plant [16]. This marked the first instance of its application within a power-generating facility, significantly optimizing the duration of start-up testing procedures from multiple days to merely 12 h since its adoption in 1989. The efficacy and success of the rod insertion technique at Krško nuclear power plant have led to its widespread adoption across numerous global nuclear facilities [17].

The focus of the radiation field characterization is the precise measurement and comprehensive analysis of the gamma and neutron fields inside and outside the reactor core, using advanced detectors and simulation tools. The radiation field characterization studies at the JSI TRIGA included following measurements: neutron dosimetry [18], TLD [19] and RadFET [20] and water activation [21]. One of the main application fields of the JSI TRIGA reactor is also nuclear instrumentation and detector development, testing and qualification, where several experimental campaigns utilizing took place utilizing: fission and ionization chambers [22–25], self-powered neutron detectors [?], semiconductor neutron detectors [26], Cherenkov light detectors [27], robot [28] and submersibles [29].

Several experimental and computational campaigns using various nuclear detectors and sensors are the reason that the JSI TRIGA reactor is one of the best characterized and utilized research reactors in the world.

1.3 Neutron Activation Analysis

Shortly after its commissioning, the reactor became instrumental in neutron activation analysis [30]. Initially, the focus was on developing radiochemical procedures to determine trace elements in the environment and human health. Effective radiochemical NAA (RNAA) procedures were developed and successfully applied, enabling the determination of numerous elements. Presently, k0-based NAA serves as the primary analytical tool at the reactor, accompanied by RNAA as a specialized technique employed when its advantages outweigh other analytical methods.

1.4 Safeguards Activities

The purpose of particle analysis is to examine clothes or wipe samples collected from established nuclear facilities or locations suspected of clandestine nuclear material handling. These analyses aim to determine whether the particles originate from declared or undeclared activities. Particle analysis is a highly effective method for detecting proliferation activities, particularly uranium enrichment activities. One method used for non-proliferation detection is fission track-thermal ionization mass spectrometry (FT-TIMS) [31], developed by CEA in the late 1990 s. CEA is part of the Network of Analytical Laboratories accredited by the International Atomic Energy Agency (IAEA) for Safeguards analysis since 2001. FT-TIMS is also utilized by the French Defence Authority. The FT-TIMS method involves irradiating the collected sample under a thermal neutron flux. Fissile radionuclide particles (such as 235U and 239Pu) create fission tracks in a fission track detector. After irradiation, the fission tracks are etched and observed under an optical microscope. Particles that exhibit fission track clusters are precisely located and micro-manipulated onto a thermal ionization mass spectrometry (TIMS) filament. The TIMS instrument determines the isotopic composition of each individual particle. A bilateral collaboration project was carried out between the JSI and the CEA, which confirmed the possibility to use the JSI TRIGA reactor for irradiation of samples for the FT-TIMS method [31].

1.5 Radiation Hardness Studies

The JSI TRIGA reactor has emerged as an indispensable platform for conducting radiation hardness studies [32], playing a pivotal role in advancement of large accelerator technologies and beyond. Its utility spans a diverse range of applications, from the development of radiation-hard light-emitting diodes (LEDs), cameras and glasses to the irradiation of nanomaterials and ceramics for examining the impact of neutron fluence on their properties. This versatility has positioned the JSI TRIGA reactor as a vital facility for assessing the durability of materials and components under high radiation conditions.

Central to these studies is collaboration with the European Organization for Nuclear Research (CERN), where the JSI TRIGA reactor has been instrumental in investigating the displacement damage effects in silicone sensors and other detector components for the Large Hadron Collider (LHC) and its forthcoming upgrade to the high luminosity LHC (LH-LHC) [33, 34]. Since the initial experiments in 1996, the reactor's reliable source of fast neutrons and well-characterized neutron energy spectra have supported extensive research into the radiation hardness of sensors, electronics and support elements integrated into particle physics detectors. This research has led to significant discoveries, including insights into the radiation-induced effects in silicon, such as the increase in generation current and charge-trapping effects, which are critical for the development of low-gain advanced detectors (LGADs).

Moreover, the JSI TRIGA reactor has facilitated collaborations with industry partners, such as DITO lighting [35] and ISEC Monitoring Systems AB [36], for the development of heavy-duty lightning and radiation-tolerant surveillance cameras [37], respectively. These partnerships leverage the reactor's capabilities to test and validate products designed to withstand harsh radiation environments, demonstrating the reactor's broad applicability in nuclear technology and material science.

Additionally, the reactor has hosted material testing collaborations with the Azerbaijan Institute for Radiation Problems and the Electronic Ceramics Department at JSI, focusing in the neutron induced modification of nanomaterials and ceramics. These studies aim to understand how neutron exposure can alter the physical properties of materials at the nanoscale, contributing advancements in electronics and other applications [38–42].

During the shortage of personal protective equipment in the early stages of the COVID-19 pandemic, the reactor was used to study sterilization options for facepiece respirators using ionizing radiation [43].

In summary, the JSI TRIGA reactor's contributions to radiation hardness studies extend far beyond the particle physics, encompassing a wide array of fields and applications. Through its collaborations with CERN, industry and international research institutions, the reactor continues to play a crucial role in pushing the boundaries of material science, nuclear technology and high-energy physics instrumentation.

1.6 Development of Computer Codes and Models

At the JSI, the continuous development of computational codes and models for reactor analysis has significantly contributed to the optimization of reactor operation, safety assessment and educational purposes. The deterministic diffusion TRIGLAV [44] code, developed in the late 1990 s, marked a pivotal advancement from the older TRIGAC code, featuring enhanced capabilities for fuel element burnup, power and flux calculations and criticality predictions for the JSI TRIGA research reactor. The integration of a user-friendly graphical interface in TRIGLAV-W has facilitated its application in educational settings and international training courses [44].

Moreover, the perfection of the MCNP [45] model of the JSI TRIGA [4] over decades has allowed for precise simulation of various experimental setups and core reconfigurations. This versatility supports a wide range of irradiation studies and detector measurements, underpinning the model's extensive validation through experimental campaigns [24].

The adoption of the ADVANTG [46] model, coupled with MCNP for variance reduction, illustrates the institute's effort to tackle challenging calculations such as deep penetration and shielding. The extended MCNP model now encompasses the entire reactor building, enabling dose rate calculations for safety assessments and facility design optimization [47].

The Serpent and OpenMC models have further extended JSI's computational capabilities, offering detailed 3D reactor modeling and validation against experimental data. These tools have proven essential for analyzing criticality, reaction rates and neutron flux distributions with high accuracy [48, 49].

Lastly, the RAPID code system [10] and the thermal-hydraulics model [50] highlight JSI's commitment to multi-physics simulations (see Fig. 2), integrating neutron transport with thermal-hydraulic analyses to explore the intricate interplay between reactor core parameters and operational safety.

Collectively, these computational advancements underscore JSI's leadership in nuclear reactor analysis, demonstrating the institute's capability to develop and apply sophisticated tools for enhancing reactor safety, operation and education.

1.7 Education on JSI TRIGA Reactor

International courses: The TRIGA reactor has been actively utilized in numerous international training courses, primarily organized by the JSI Nuclear Training Centre (NTC) and the IAEA. To enhance the educational utilization of research reactors, a coalition was established, consisting of Austria, the Czech Republic, Hungary and Slovenia. This coalition operates under the framework of the Eastern European Research Reactor Initiative (EERRI), which was established in 2008 with the support of the IAEA [51]. Six-week training courses for participants from IAEA Member States have been conducted since then. In addition to EERRI, another international coalition focusing on education and training was formed within the IAEA programs. This coalition, known as the Mediterranean Research Reactor Network (MRRN), involves Mediterranean countries and was established in 2010. These initiatives highlight the collaborative efforts among various nations to promote education and training in the field of research reactors. Since 2009, the JSI TRIGA reactor has been equipped with a teleconference system and two full high-definition (HD) digital cameras, which serve as the foundation for remote training capabilities. The full HD

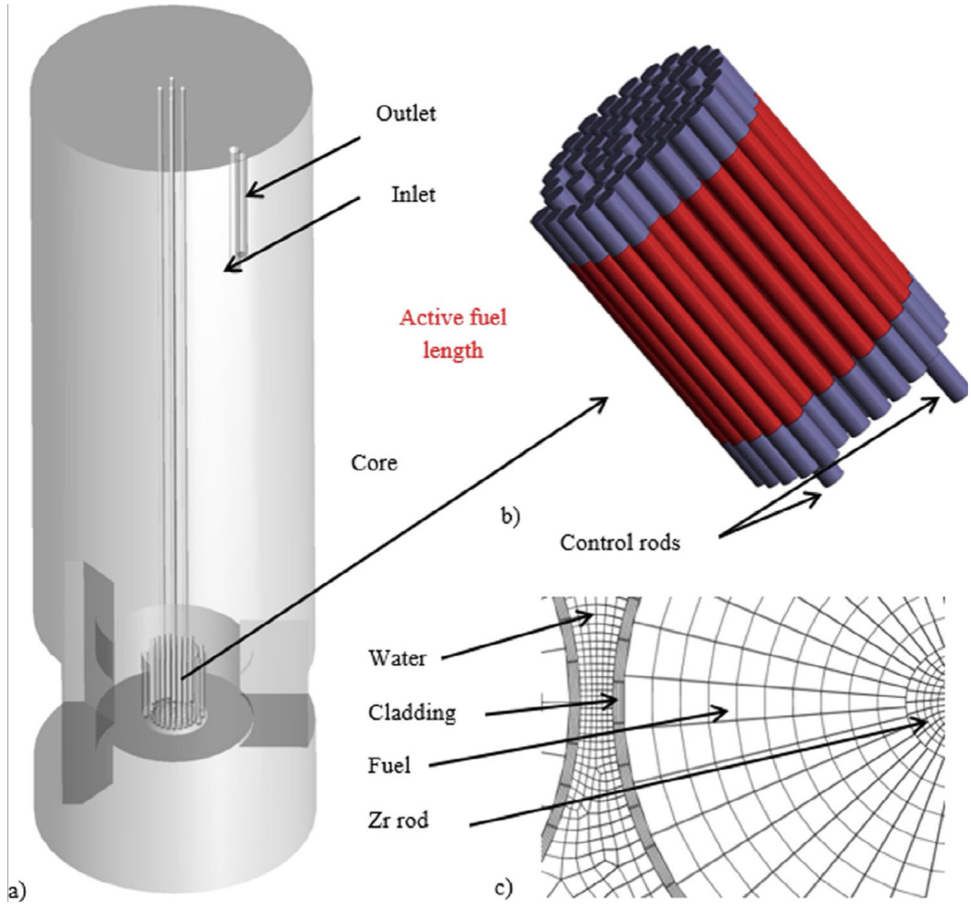

Fig. 2 Development, verification and validation of computer codes: geometry for coupled CFD/Monte Carlo analysis

camera is positioned just a few centimeters below the water level, enclosed in a specially designed leak-tight casing. It is equipped with a 10× optical zoom, allowing users to visually inspect the reactor core and individual fuel elements. The camera can be operated from the control room, with the feed displayed on a large 132 cm full HD screen. These new features have proven extremely valuable, particularly during practical exercises such as critical experiments, where fuel elements are manipulated and the source is withdrawn, and void coefficient experiments, where voids are inserted at various positions in the core and reactivity is measured. Our experience has shown that this system enhances the understanding of the experiments and makes all practical exercises more engaging in Fig. 3.

Advancements in fast and cost-effective computer clusters have facilitated the development and utilization of powerful computer codes for neutron transport, including Monte Carlo transport codes, as well as real-time 3D visualization of extensive data. By combining these codes and visualizing reactor physics data such as neutron flux and power distribution, a powerful tool for gaining rapid insight into reactor characteristics has been created. With the aid of advanced 3D visualization software, neutron flux and power distribution can be presented in a revolutionary manner. Various perspectives, including axial, radial and others, can be observed, allowing one to "walk" through the reactor core and witness changes in neutron flux and power across different components. Further details about these new methods can be found in [52, 53]. Human memory tends to retain information better when it is visualized. Therefore, this novel representation of the reactor and neutron transport parameters serves as an exceptional educational tool for future generations of nuclear power plant operators, nuclear engineers and other experts in the field of nuclear technology.

1.8 Research Reactor Simulator

The real-time research reactor simulator (RRS) [54], developed at the Jožef Stefan Institute in Slovenia, is based on the institute's long-standing experience with its TRIGA research reactor. It offers a platform for students and future reactor operators, particularly from institutions without access to a physical reactor, to gain practical insights into reactor physics and operations. The simulator is adaptable to various settings and features an intuitive graphical interface, making it a valuable educational tool. It is utilized in classroom settings, such as at the University of Ljubljana, and it supports the teach-

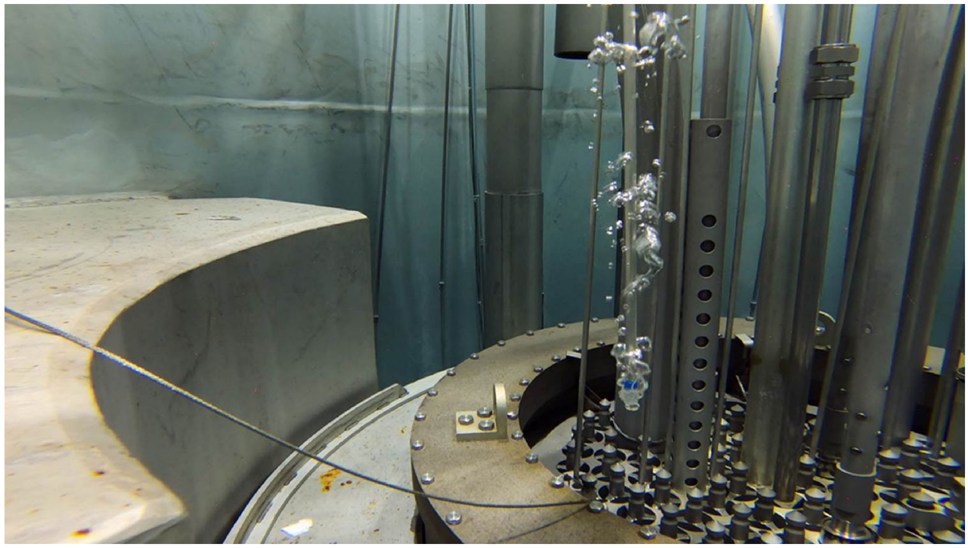

Fig. 3 Bubbles flowing through the core during the void reactivity coefficient experiment

ing of reactor behavior through simulations, bridging the gap between theoretical knowledge and practical application.

1.9 Hands-on Experiments on TRIGA

Since the 1990 s, the JSI TRIGA reactor has been extensively utilized for conducting reactor physics experiments for future nuclear power plant operators, as well as physics and nuclear engineering students. These experiments encompassed various areas, including:

- Subcritical multiplication
- Critical experiment (Fuel addition/control rod withdrawal)
- Reactor kinetics (reactor response to step reactivity changes)
- Reactivity coefficients (temperature, void, power)
- Control rod calibration (rod-in/rod swap)
- Pulse mode operation
- Thermal power calibration
- Primary water activation
- Reactor operation

Over the years, several upgrades were implemented to enhance existing exercises and introduce new ones. The pulse mode operation exercise saw improvements through the installation of a new data acquisition system and the development of a user-friendly graphical interface using LabVIEW software. The critical experiment exercise was enhanced by incorporating a new detector. Neutron population is now monitored using two independent fission chambers placed at different locations. Similarly, a new graphical user interface using LabVIEW software was developed for this exercise. To make the void reactivity coefficient experiment more realistic, a pneumatic system was installed to generate air bubbles just below the reactor core. The system includes valves, flow meters and aluminum tubes for conveying air under the core, allowing for a more accurate simulation of void reactivity changes.

2 The Status of Research Reactors in EU and W

Nuclear research reactors (RR) have been constructed in almost all countries implementing nuclear power plants or in those that intend to do so, as well as in many countries without a nuclear energy program. Their primary use was related to education, training and technological experiments necessary to develop commercial power reactors; however, many other important applications have emerged. Neutron beams soon became a powerful tool to study matter, high-performance RRs devoted solely to beam experiments have been constructed, and the world leading example is the high-flux reactor (HFR) [55, 56] at the Institut Laue-Langevin (ILL) in Grenoble, France. Production of isotopes for medical, industrial and scientific use is also a major application of RRs. Hence, a wide range of research reactors exist, from low power facilities suitable for education, training and some research applications (e.g., TRIGA) [57, 58], to large, specialized facilities, either focused in neutron beam experiments with limited core irradiation capability (e.g., HFR at ILL) or possibility of modifications for future isotope production capability (e.g., FRM II [59, 60] in Garching bei München), or focused in material irradiation but without beam facilities (e.g., the upcoming Jules Horowitz Reactor [61]).

Negative public attitudes toward nuclear energy based on Three Miles Island, Chernobyl and Fukushima accidents have caused an over 20-year crisis in the nuclear industry, especially in the USA an Europe. This made a devastating impact on the European research reactor fleet. Today, the number of RRs in Europe is decreasing, with only one being constructed since the Millennium - FRM II (1st criticality in 2004) and three under construction, the Jules Horowitz Reactor, the Pallas RR [62] and MYRRHA accelerator driven reactor [63, 64]. Furthermore, a significant number of research reactors have been closed in Europe in recent years. Most recent response to these challenges was the TOURR project [65] (available at "https://www.tourr.eu/") in which the status of the EU RR fleet was assessed and from it a strategy for optimized use and building of new RR devised.

The IAEA RR database [66] provides publicly available general information about research reactors, including details such as power, year of construction and type. To assess the age of the European research reactor (RR) fleet, TOURR researchers compared it to the world's average, as shown in Fig. 4. Notably, no new research reactors have been constructed in Europe since 2004, and the majority of existing research reactors were built during the 1960-1970 period. Consequently, the average age of European RRs in 2024 is 56 years, with a median age of 62 years. This indicates that the European RR fleet is relatively older than the global average of 48 years and its median of 51 years, emphasizing the need for proactive measures to address future requirements. The last built RR in the world is the Apsara-U reactor in Mumbai, India, in 2018, despite being constructed using the original Apsara reactor site, built in 1956 [67]. The last built research reactor on a new site is the Jordan Research and Training Reactor (JRTR) [68–70], finished in 2016. Based on these data, a clear conclusion can be given that the EU RR fleet is older than the world average and will face many challenges in the future, especially if no new RRs will be build.

2.1 Proposed Strategy for Upgrading the EU RR Fleet

Recently, several documents have been published that explore the use of research reactors, their future and potential opportunities for scientific and technological applications. One of such documents, titled "Strategic Planning for Research Reactors" [72], primarily focuses on enhancing the use of existing research reactors and offers guidance for developing and implementing a strategic plan for new research reactor projects. Another document, "Neutron scattering facilities in Europe, Present status and future perspectives" A publication "Strategic Planning for Research Reactors" published by the IAEA [73], provides a detailed overview of the current status of neutron scattering applications using RR and outlines various scenarios and perspectives for the future. Notably, the document identifies a crucial gap: the need for a reactor-based source in addition to the existing spallation source in Europe. Based on the analysis that was performed using the dedicated questionnaire that was sent to RR operators in Europe within the TOURR project [74], a strategy for upgrading the EU RR fleet was proposed [65].

An outline of the current and future situation regarding research reactors in Europe, including an indication of how these facilities would fit within it, is presented in Fig. 5. With the considerations, presented in [75], the view of the TOURR project was that in the short term (2030 s), these large facilities should be complemented by some small and medium ones. More specifically, we propose that the two following facilities should be integrated into the current European research reactor strategy:

1. At least one multipurpose medium-flux reactor, in the 20-30 MWth range. The required number of such reactors will largely depend on the success of other technologies currently under development, i.e., the above-mentioned CANS and alternative isotope-producing technologies. The need for a certain number of reactors will be much clearer by the end of this decade. This facility can be a fully newly built facility or a major refurbishment of an existing one (e.g., MARIA [76], LVR-15 [77, 78]). Such a facility can provide 15-20 neutron scattering instruments and will allow us to maintain the current four-reactor strategy for isotope production (this new RR + PALLAS, JHR and upgraded FRM II) and provide some additional material irradiation capability to complement JHR.
2. A flexible, zero-power facility for integral reactor physics experiments, possibly a multi-core facility. As stated above, while many zero and low power research reactors suitable for education and training still exist in Europe, only two facilities (VENUS-F and LR-0) offer sufficient flexibility to perform integral experiments. Hence, a facility to replace or complement VENUS-F and LVR-0 reactors should be included in a European strategy. Such a facility can also fulfill an education and training role. An example of such a facility can be the zero-power reactor testbed being built by the NRIC in the USA [79]. Given the very low power of such a facility, it should be relatively cheap to build and operate, although it is always difficult to provide cost estimates. For instance, the estimated construction cost of the ZEPHYR facility projected by CEA with a single reactor core was 80 million EUR [80].

An important fact to consider regarding the zero-power facility is that they use up virtually no fuel and they can reuse the fuel from previous zero-power reactors. Finally, co-locating a zero-power facility together with higher-power research reactors allows sharing the costs of such a facility.

In this sense, the JSI in Slovenia, in cooperation with the French CEA, is in the early stages of the planning of a new research reactor facility, accessible at the EU level. The initia-

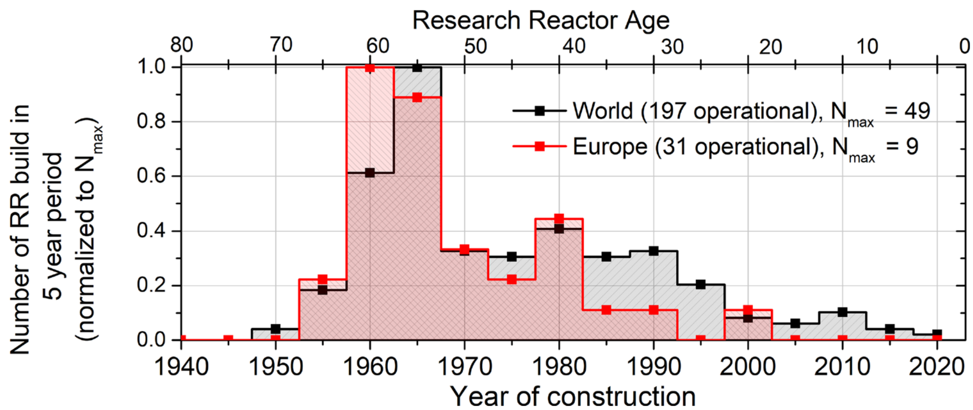

Fig. 4 Age profile of research reactors in Europe and the World (Europe included). The number of RRs built in 5-year period, normalized to the maximum number of RR built N_{max} in 5-year period, is presented for period of 1940-2024 [71]

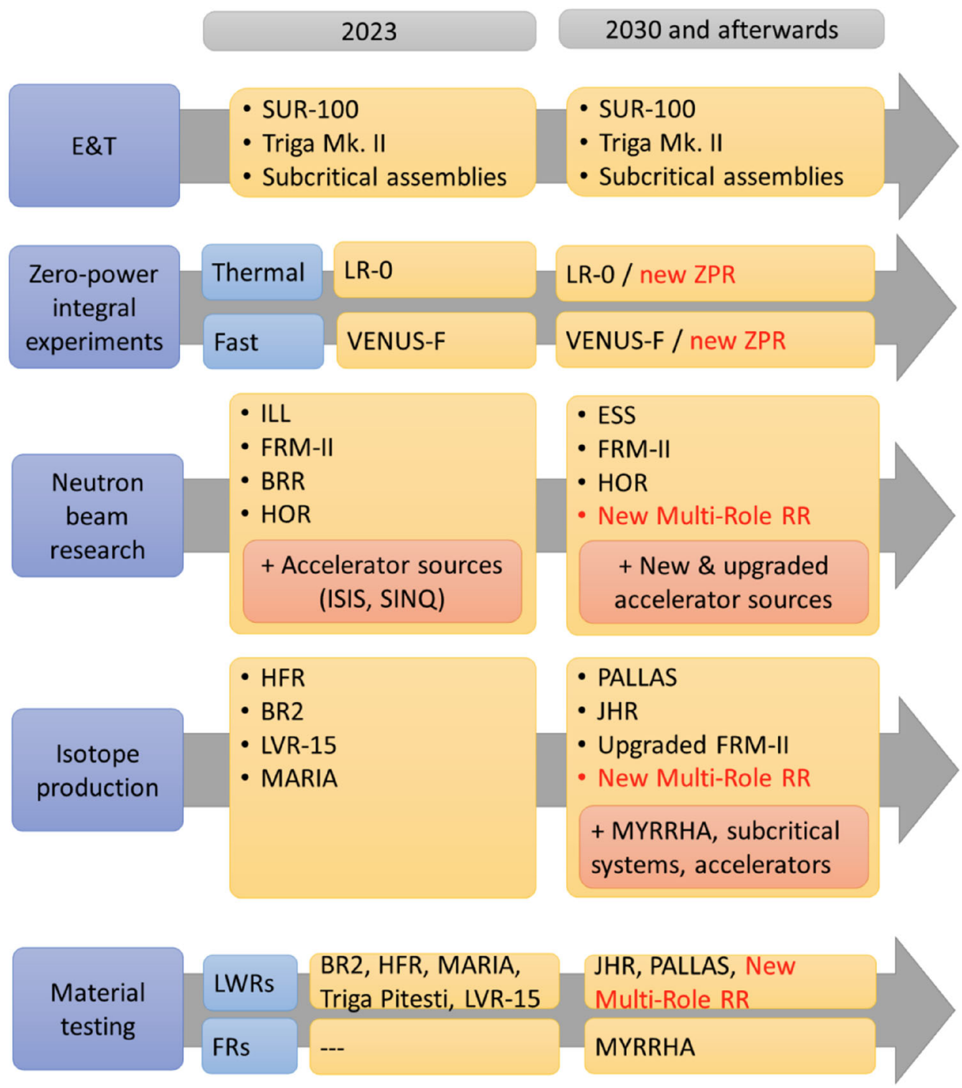

Fig. 5 Current and future European research reactor landscape with the strategy proposed in the scope of the TOURR project [65]. More information regarding the devised strategy can be obtained in project report [75], publicly available on "https://www.tourr.eu/documents"

tive aims to build a Versatile European Reactor fOr Neutron Irradiation and nuClear reseArch (VERONICA) which consists of two cores that will cover diverse needs of the member states of the European Union in domains of neutron irradiation, nuclear research and education. The preliminary plan is detailed in the following section.

3 New Research Reactor in Slovenia

Slovenia is currently in the process of developing a project aimed at constructing a state-of-the-art research reactor, which is foreseen at the existing TRIGA reactor site. The publications presented at the NENE Conferences in 2019 and 2022 [81, 82] discuss the rationale behind the initiative, provide an overview of the initial stages necessary to commence the project and enumerate the potential technologies that could be employed. Subsequently, we have successfully initiated preliminary discussions with prospective international collaborators for the research reactor venture. Planning a new research reactor project offers advantages and challenges distinct from those of a nuclear power plant. Research reactors are smaller and more affordable, simplifying budget allocation and fuel management. Public acceptance is generally easier to attain compared to power plants. However, economic viability and utilization pose significant challenges. The country hosting the reactor must commit to financing its entire lifecycle, demonstrating indirect benefits and support for nuclear power. Ensuring optimal utilization with diverse user requirements is crucial. To address these risks, JSI will conduct a feasibility study, identify stakeholders and secure commitments for reactor usage. The TRIGA reactor in Ljubljana currently covers training and research needs, including neutron transport calculations and radiation hardness testing. The new research reactor should cover all these needs, but should also support neutron beam users and contribute to the production of vital radionuclides for medicine. Additionally, it can aid in semiconductor chip manufacturing through neutron radiation-induced material changes.

3.1 Pilot Project for New Nuclear Builds

Slovenia has not commissioned a new nuclear reactor since the Nuclear Power Plant of Krško was commissioned in 1981. Over the decades, there has been a generational change in nuclear experts in the field and the introduction of new legislation, which has brought challenges for future nuclear projects. The new research reactor project will become an important pilot project for Slovenia's future nuclear projects, including the NEK2 nuclear power plant. This reactor will put the technologies and processes planned for larger projects through their paces and scrutinize the management of nuclear facilities, from compliance with regulations to cooperation with suppliers.

The inclusion of a small project, such as the research reactor, has one key advantage: issues that lead to delays and cost overruns are far less costly and easier to manage than in the construction of larger full-scale nuclear power plants. This proactive approach to the research reactor aims to pave the way for future large-scale nuclear power plant construction by ensuring that the necessary processes, technologies and regulatory frameworks are not only effective but also meet current standards. By identifying and addressing these challenges early on, Slovenia is preparing to tackle the complexities of modern nuclear energy development with confidence and minimize the financial and operational risks associated with the construction of new nuclear power plants.

3.2 Personal Development

According to the annual report, the Nuclear Power Plant of Krško with an installed capacity of 700 MW employed 648 full-time employees at the end of 2022[83]. An energy permit issued in 2021 anticipates the development of a power plant with a capacity of 1100 MW [84], but the information on the investor's website indicates that the capacity could increase up to 2400 MW [85]. Considering that staffing requirements increase with installed capacity [86], it can be assumed that a new power plant with such capacity will pose significant staffing challenges, not only for the direct employees of the power plant, but also for secondary support functions such as maintenance companies, regulators, government oversight functions and supporting industries. While only a portion of the new jobs will be filled by nuclear physicists and nuclear engineers, new infrastructure will be needed to attract new talents and increase training capacity.

3.3 Planning Considerations–Consortium Reactor

The planned new research reactor project is currently being examined in the form of a consortium initiative involving possible cooperation with several EU countries and international stakeholders. This concept is motivated by the success of similar nuclear cooperation projects such as MYRRHA, ESS and IFMIF-DONES, which illustrate the potential benefits of a collective approach to nuclear research and development.

Potential contributions from participating countries could include a range of options, including in-kind contributions such as reactor fuel or specialized equipment, financial investment or machine time allocation agreements. The proposed structure is intended to provide flexibility in the way countries, and institutions can engage with and support the project, tailoring participation to their capabilities and interests. As the consortium model is still in the planning phase, various governance and operational structures are currently being considered.

3.4 Technology Options: General Purpose Reactor

The new research reactor will be a multipurpose reactor accommodating a consortium of users. Light water reactors with open pools are suitable for training and research due to their ease of operation and accessible core. They can support power-generating reactors using similar fuel and coolant as European PWR reactors. Specifications have been developed to retain current use cases and expand to new ones. Increasing the thermal power enables broader applications, such as cost-effective production of radioisotopes and neutron transmutation doping. Higher flux attracts neutron beam users. The thermal power choice balances flux requirements and operating costs, aiming for a range around 5 MW without the need for active decay heat removal. To enhance flexibility, the reactor can provide regions with different neutron flux spectra and utilize uranium silicide fuel for increased power density and safety performance. A water channel connecting the reactor to hot cells simplifies material transport. The Jordan Research and Training reactor [87] serves as a comparable model with a 5 MW thermal power.

3.5 Technology Options: Additional Zero-Core R

Zero-power reactors, characterized by low burnup, are well suited for specific research tasks. Their core with minimal decay heat allows for greater flexibility in experimental setups, such as additional core loops, multi-physics experiments and investigations involving unique fuel types. The use of low-burnup fuel enables easier study with reduced radiation protection and decay heat removal requirements. Incorporating a second zero-power core alongside the multipurpose research reactor would enhance the flexibility of the research facility without significantly impacting construction and operating costs. This is because many overhead expenses, such as site preparation, radiation protection measures, fuel management and radioactive waste disposal, are already covered by the multipurpose reactor.

3.6 Technology Options: Research Reactor Producing Electricity

JSI is exploring the possibility of constructing a research reactor with electrical power generation capabilities. This reactor would serve as a pilot study for future nuclear power plants, including small modular reactors, and allow JSI to simulate various power generation and distribution systems such as electrical grids, district heating, hydrogen production and industrial heat utilization. The existing research reactor site is well suited for this purpose, offering ample land, proximity to Slovenia's capital, direct access to the ELES electrical power grid and availability of the Sava River for cooling. An example of a reactor that could align with JSI's objectives is the eVinci micro-reactor being developed by Westinghouse. This reactor employs TRISO fuel, graphite moderation and sodium-containing heat pipes for cooling. It features reactivity control through a rotating drum and horizontal channels equipped with control rods, which can also be used for sample irradiation. According to the provided leaflet [88], the eVinci reactor is designed to generate 15 MW of thermal energy and approximately 5 MW of electrical energy using an open cycle air turbine. The ultimate selection of the new research reactor technology is foreseen in the next year or so and will have to take into account the political and financial support for the new device.

4 Conclusions

In the past few years, we have identified the need for a new research reactor in Slovenia to advance nuclear science, attract talent, support the domestic nuclear power reactor and fill a gap in the diminishing European Union research reactor fleet. It could enhance the supply of vital radionuclides and improve electronic chip supply. The reactor is likely to be a consortium project with diverse partners, requiring a flexible technology. An open pool, light water reactor is suitable for education and research, expanding potential use cases. Adding a low-burnup fuel core or considering an electrical power-generating reactor is options to enhance research capabilities, despite trade-offs in flexibility. Our goal is to address critical needs and advance research within the European Union.

An open pool, light water reactor is ideal for education and research due to its user-friendly operation and accessible core. The new reactor has the potential to broaden its range of applications compared to the existing one, offering higher thermal power, increased fluxes and a pool connecting the reactor core to the hot cell facility.

We are considering adding a second, zero-power reactor core to accommodate research applications that require low-burnup fuel. This addition would not significantly raise project costs since many fixed expenses are covered by the general-purpose reactor. However, it would enhance the research capabilities of the facility. The working name of the new reactor is VERONICA—Versatile European Reactor fOr Neutron Irradiation and nuClear reseArch.

Alternatively, we are exploring the option of constructing a prototype or demonstration reactor that can generate electrical power instead of a general-purpose research reactor. This approach would enable research on power generation, load following, utilization of process heat for industry, district heating, hydrogen production and other energy-related applications. Nonetheless, it would involve sacrificing some flexibility of the reactor.

Building a new research reactor would mean also improving the experience of all nuclear entities that will be involved in construction of the large nuclear power plant: from utilities, to regulatory bodies, industry, research and educational institutions.

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