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New Research Reactor Developments in Slovenia

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ABSTRACT

The Jožef Stefan Institute is leading activities to build a new research reactor in Slovenia. The justification for the new research reactor was published in a NENE conference paper in 2019. It is still valid in 2022, after the European Union recognized nuclear power as sustainable in the Taxonomy Regulation and several member states and the United Kingdom announced plans to expand the nuclear fleet, but no plans for new research reactors.

The Jožef Stefan Institute, in collaboration with its international partners, has compiled a list of potential stakeholders, selected the reactor technology, and developed a preliminary timeline for the path to a new research reactor. It is likely that the new research reactor will be an international consortium project with many stakeholders. Therefore, the technology must be selected to cover a wide range of use cases in the European Union.

The primary choice for the new reactor is pool reactor, cooled and moderated with light water. In this way, the reactor will be able to support the European fleet of existing and future nuclear power plants, including small modular reactors based on pressurized water reactor technology. In addition, a water-cooled pool reactor has proven to be suitable for research and education because it provides easy access to the reactor core and is simple to operate.

One possibility would be to build a facility with two reactor cores. The first would be a multi-purpose research reactor with the thermal power output of a few megawatts and with thermal flux and high flux regions. Such a reactor would be cooled by forced cooling during operation, but passive cooling would be sufficient for decay heat. Such a facility could be used for training, radiation hardness studies, instrument testing and calibration, neutron radiography, neutron transmutation doping, testing of new additive materials, and a neutron source for cold and fast neutrons. The second core would be a zero-power reactor with a maximum power of a few kilowatts and would allow experimental setups such as water/salt loops inside the core, multiphysics experiments, and tests of different fuel types.

A third option would be building a micro-reactor with electrical power producing capability. Such reactor would enable JSI to carry out energy research as it could serve as a prototype for a small modular reactor or as a part of a prototype electrical grid for the future at a cost of sacrificing some of the flexibility of an open-pool reactor.

1 INTRODUCTION

Considering climate change and transition to low carbon society, there are discussions about building a second nuclear power plant (NPP) in Slovenia. As NPP is the only reliable and weather independent and sustainable energy source, this is practically the only option to reduce CO_2 emissions and at the same time maintain the same quality of life. Moreover, in July 2021 an energy permit for building a 1100 MWe NPP was issued by the ministry of infrastructure.

The first nuclear facility built in Slovenia was TRIGA Mark II research reactor (RR) built by General Atomics and commissioned in 1966. It was built for isotope production, research and educational purposes. In addition to nuclear research, the research reactor has enabled development in numerous other fields such as nuclear medicine, chemistry, radiochemistry, and computer science as well as education and training of students, researchers and other nuclear industry professionals in Slovenia and abroad. Practically all nuclear experts in Slovenia spent part of their career at the TRIGA reactor and the reactor centre of the Jožef Stefan Institute. The reactor is operated by the Jožef Stefan Institute and it presents an international hub for nuclear research allowing state of the art research to be performed at a well characterised and flexible nuclear facility.

Krško NPP [1] was built in 1983 when Slovenia was part of Yugoslavia. Since then a lot has changed; legislation, organisation of ministries, majority of people involved in construction got retired. Hence building a second unit will be a great challenge for Slovenia. It will be a challenge to attract and recruit enough experts to the field as well as to obtain all permits and construct the nuclear facility. In addition, the existing research reactor is aging and there is need for new one.

Both challenges could be met by building a new research reactor. On the one hand, the construction of a new research reactor would allow Slovenian researchers, in collaboration with scientists from around the world, to continue to be leaders in nuclear research and to expand existing research into other areas. On the other hand, the new reactor could serve as a platform to attract new talent to the field and train all those involved in the licensing process on how to commission a nuclear facility and prepare the system for licensing a more complex and expensive facility, i.e., the new NPP.

In the paper entitled "Roadmap to a new Research Reactor" presented at the 2019 conference NENE [2], we wrote about the motivation for building a new research reactor, outlined the initial steps needed to start a new research reactor project, and listed the possible technologies that could be used. Since then, we have organized initial discussions with potential international partners for a new research reactor project, outlined the next steps toward the new research reactor project, and identified which technological options best meet these requirements. According to the recommended milestones from "Feasability Study for New Research Reactor Programmes" [3] by IAEA (Figure 1), the current activities fall under the Phase 1 with the goal of producing a Feasability Study.

In particular, at the beginning of 2022, the JSI conducted an initial analysis with the support of the CEA and its expertise in research reactors, in order to identify the first elements that will determine the characteristics and performance of this new research reactor, as well as important points in the structuring of the project.

Present paper summarizes the activities in the last two years and presents plans including several possible reactor designs.

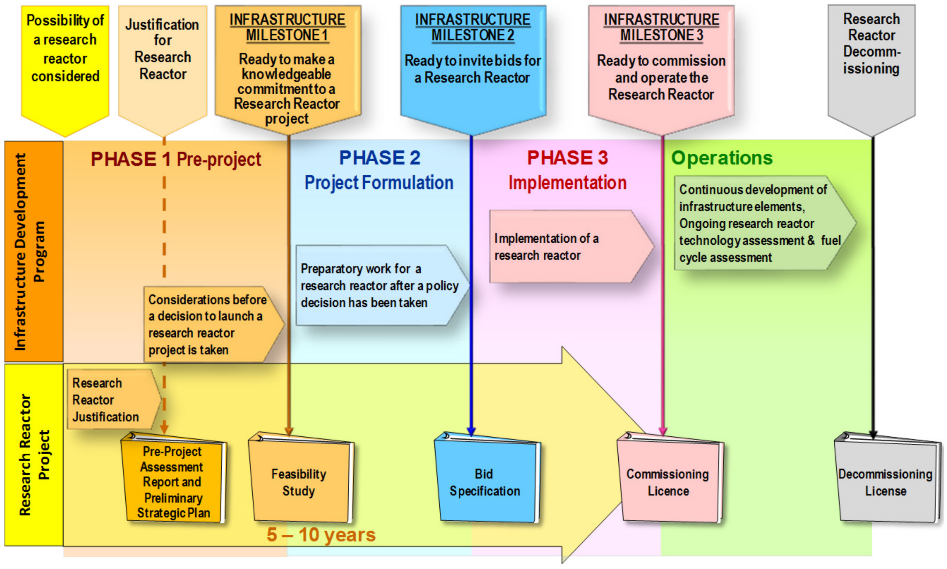

Figure 1 Recommended milestones from "Feasability Study for New Research Reactor Programmes"[3] by IAEA. The next goal of the project is the Feasability Study.

The paper is structured as follows: in section 2 planning considerations are presented. In section 3 we discuss possible designs. In the last section we summarise all finding and make conclusion.

2 PLANNING CONSIDERATIONS

Compared to planning a new nuclear power plant, planning a new research reactor project brings some advantages, but also some unique challenges that do not play a role in a new power plant project. The main advantage is that research reactors are smaller than nuclear power plants. A research reactor is typically cheaper than a nuclear power plant, so it may be easier to allocate a budget, and because research reactors operate at a much lower burnup, fuel management and radioactive waste disposal requirements are simpler. Research reactors generally do not face public acceptance issues to the same degree as nuclear power plants. The two major challenges that research reactors face are economic viability and utilization. Research reactors, like many projects needed for public health, education and research, rarely directly pay for themselves [4], which means that the country hosting the new research reactor will have to commit to financing the reactor through the entire life cycle, from the planning state to after the reactor has stopped operation. To obtain such a commitment from the government, the research reactor plan must demonstrate indirect financial or other benefits through the development of science, support of the nuclear power program, security of supply of medical isotopes, and development of personnel for the nuclear power program. The second challenge is to ensure optimal utilization during the life of the research reactor. While nuclear power plants are tasked with generating energy, research reactors typically have a diverse group of users with different requirements. The plan for a new research reactor must demonstrate that the research reactor must remain relevant throughout its lifetime.

To mitigate the risks described above, JSI will establish a working group to conduct a feasibility study that will identify future reactor users and use cases before a decision is made to build a new reactor. The working group will work to secure a commitment from stakeholders to use the research reactor. This may take the form of a financial contribution, in-kind contribution, a commitment of reactor time, or a letter of intent to use the research reactor.

In the paper presented at NENE2019 [2], we identified some of the basic use cases and key stakeholders for the research reactor project. Since then, the list of potential stakeholders and reactor use cases has expanded.

The new reactor needs to cover the use cases currently covered by the existing TRIGA reactor at the JSI, in particular training of new nuclear professionals and nuclear research applications. A typical nuclear research application requiring a research reactor is validation of neutron transport calculations for reactor physics and shielding, nuclear data, and multiphysics calculations. These use cases will become more important as time goes on, since in the European Union at the time of writing there are no plans to build new multipurpose research reactors and the existing fleet of research reactors is aging; on the other hand, several countries have announced plans to build new nuclear power plants. The stakeholders for these applications are Slovenian ministries, nuclear power plants and utilities from Slovenia and the European Union, national and international research organizations, universities, and educational networks such as ENEN [5] and ENEEP [6].

The existing TRIGA reactor in Ljubljana is also used for radiation hardness testing for detectors and other electronic devices used in particle accelerator facilities, fusion experiments, nuclear reactors, and space industry. With no new general-purpose reactors in European Union the demand for radiation hardness testing on the existing research reactors is expected to increase.

Another group of potential users in the scientific community are neutron beam users, including the cold neutron beam community. In this area, the research reactor competes directly with other neutron sources, such as spallation sources. The use cases where a research reactor has an advantage over other spallation sources need to be explored, and the potential users will be identified using the LENS network [7]. Moreover, new opportunities will also be investigated within the EU supported project TOURR [8]. JSI will use the TOURR project also to investigate complementarities with existing reactors and identify new stakeholders.

Radionuclides used in medicine are produced in nuclear reactors and particle accelerators. The nuclear reactors generally provide better economy of production due to large irradiation volume and simultaneous irradiation of multiple samples [9] and accelerators are used for radionuclides that cannot be produced by nuclear reactors. At the time of writing, the European Union is facing the potential shortage of radioisotopes, which could “potentially cause serious radioisotopes' shortages and jeopardise access to vital treatments for all European citizens” [10]. A new research reactor can help meet the demand of these vital isotopes. Most of the useful radionuclides cannot be stored and need to be produce regularly, so even if the supply capacity in the European Union improves, the research reactor could serve as a back-up in case of disruptions in the supply. The potential stakeholder that could support the capability for radioisotope production are the nuclear medicine community in Slovenia and ESA Euratom supply agency.

The semiconductor chips are the critical components in the technology that we use today, from smartphones to industrial processes and will remain a critical component in the transition to the greener economy. Research reactors can use neutron radiation to transmute silicon atoms in semiconductors to phosphorus, which causes a change in conduction characteristics of the material essential to the electronics industry. According to the technical document [11] published by the IAEA, neutron transmutation doping can achieve a more uniform dopant concentration compared to diffusion methods and is especially useful for production of semiconductors for power applications such as the ones used in production of electric cars, solar panels and windmills. A new research reactor capable of neutron transmutation doping in Europe will help meet the increasing demand and increase the independence of the supply chain of neutron transmutation doped semiconductors vital for the energy transition.

3 TECHNOLOGY OPTIONS

3.1 Multipurpose reactor

The new research reactor could be a multipurpose reactor that will have to satisfy a large consortium of potential users. Light water reactors with open pools are suitable for training and many research applications because they are easy to operate and have an accessible core. Another advantage is that they use a similar fuel and coolant as the PWR reactors used to generate electricity in Europe, so they can support power-generating reactors better than more specialized reactors. The authors of the article have developed specifications for the new reactor that would allow JSI to retain the use cases of the current reactor and expand to new ones.

A higher maximum thermal power in steady-state operation would expand the applications of the research reactor. Higher thermal power and flux increase the economics of producing radioisotopes for medicine and industry and improve the possibilities for doping by neutron transmutation. Higher flux also makes the reactor more attractive to neutron beam users. The exact thermal power is chosen based on a trade-off. Choosing a higher thermal power makes a reactor more competitive for applications requiring large neutron fluxes, but also increases fuel decay heat, which increases safety requirements and ultimately drives up operating costs. A thermal power in the range of 5 MW would make the reactor attractive for many applications whose effectiveness depends on neutron flux but is still low enough to allow passive decay heat removal. The target neutron flux (thermal and fast flux) is on the order of $10^{14}\ \mathrm{n/cm^2 s}$.

The new reactor could also increase flexibility by providing regions with different neutron flux spectra. In addition to high thermal flux in a heavy water reflector, the reactor should provide regions of fast flux for radiation damage and radiation hardness studies. Special channels should be devoted to epithermal applications.

Uranium silicide fuel has been identified as the most probable fuel. It features high level of reliability, proven safety performance, high security of supply and allows higher power density.

A water channel connecting the hot cells facilities to the reactor would simplify transport of irradiated material from the reactor core to the hot cells.

The Jordan Research and Training reactor [12] built in 2016 is an example of 5 MW multipurpose research reactor with similar requirements than the new Slovenian research reactor in terms of thermal power and fuel.

3.2 Zero-power core

A high-power multipurpose research reactor (MPRR) serves mostly as a neutron source to support many applications identified above. However, its main disadvantages are lower flexibility in terms of making changes to the core, inserting non-conventional samples into the core, more difficult access than in low power reactors, more demanding process for performing new experiments, less appropriate for education and training. Hence in addition to the high-power RR, a low or zero power facility is also needed to continue developing existing activities.

Zero-power reactors (ZPR) have low burnup and are more suitable for some research areas such as education and training and performing benchmark experiments. A reactor core with low decay heat offers great flexibility in setting up experimental setups, such as additional loops in the core and experiments with non-conventional fuel types. A low burnup fuel can be easily studied after irradiations with lower radiation protection and decay heat removal constraints. As the most viable and economic option we identified an option with one nuclear facility, i.e. one building, one containment with two cores, one MPRR and one ZPR. The second zero-power core in the same facility as the multipurpose research reactor would increase the flexibility of the research complex without significantly affecting construction and operating costs, since many of the overhead costs such as siting, radiation protection, fuel management, and radioactive waste disposal are covered by the multipurpose reactor.

Due to recent and upcoming shutdown of several zero-power research reactor in EU, a lot of fuel is available, hence we could utilise the fuel from those facilities thus reducing fuel supply cost and use existing uranium resources. For certain partners, fuel supply could be considered as an in-kind contribution to the new RR.

3.3 Research reactor with electrical power generating capability

JSI is also considering an option of building a research reactor with electrical power generating capability. Such reactor would be part of a pilot study for next generation of hybrid multipurpose nuclear power deployments including small modular reactors and would enable JSI and interested partners to study the power generation and distribution systems including electrical power networks, district heating, hydrogen generation and uses of process heat as well as nuclear driven chemical production [13]. The site of the existing research reactor, marked as a in the map given in Figure 2, is appropriate for such set-up as it has enough land, is in a proximity of the Slovenian capital, is in direct proximity of ELES electrical distribution utility (marked b) and has access to underground water and nearby Sava river for cooling (marked c).

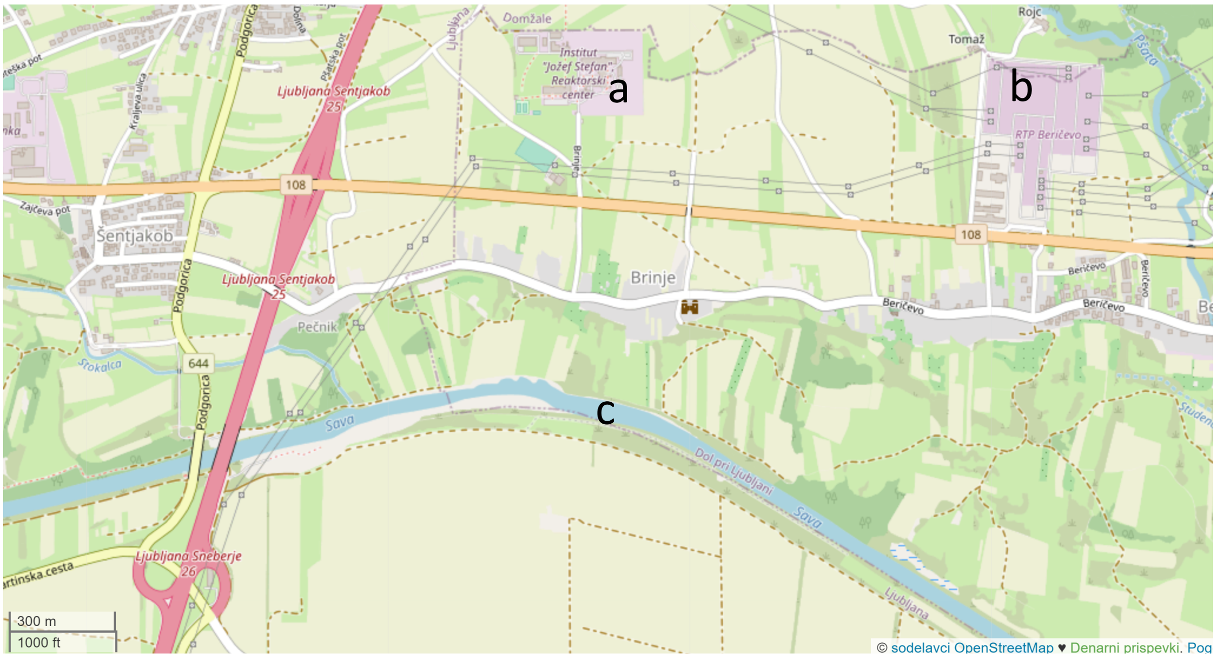

Figure 2 The existing Reactor Infrastructure Center a) is in close proximity to an electrical distribution center b) and Sava river c). It is located approximately 3 kilometers away from Ljubljana and has enough space for expansion. Map was exported from the OpenStreetMap project.

An example of a reactor that would allow JSI to study power generation and distribution, but still retain some of the capabilities for training and irradiation of samples, is the eVinci microreactor built by Westinghouse. The eVinci reactor uses TRISO fuel, is moderated with graphite, and cooled with sodium-containing heat pipes. Control of reactivity is achieved by both a rotating drum and control rods in horizontal channels that can also be used to irradiate samples. According to Westinghouse [14], the reactor will generate 13 MW of thermal energy and about 5 MW of electrical energy using an open-cycle air turbine.

4 SUMMARY AND CONCLUSION

Since the last paper on the new research reactor project published in [2], we have further explored the needs served by research reactors in European union and decided on the next steps towards building a new one. We have found out that a new research reactor in Slovenia is not only necessary to advance nuclear science, attract new talents, develop nuclear professionals, and support the nuclear power reactor in Slovenia, but also to fill a crucial gap in services offered by the aging fleet of research reactors in European Union. A new research reactor could also improve the supply security of radionuclides vital for patients in European Union and help us become more independent in terms of electronic chip supply.

As the EU and the world become more and more interconnected it would make sense that the new reactor will be a consortium reactor with partners from multiple countries with diverse interests. This means that in terms of technology we will have to choose a flexible reactor that can cover many use cases. An open pool, light water reactor is suitable for education and research applications since it is easy to operate and has an accessible core. The new reactor could expand the potential use cases compared to the existing TRIGA reactor by allowing for higher thermal power, higher fluxes, and a pool connecting the reactor core to the hot cell facility. To gain benefits of MPRR and ZPR the solution of having one nuclear facility with two cores is favourable. Hence, we are considering an option of adding a second, zero power reactor core to cover the research applications that require low-burnup fuel, e.g. education and training, benchmark experiments. This addition would not drastically increase the cost of the project since many of the fixed costs are covered by the general purpose reactor but would further increase the research capabilities of the facility.

We should consider also placing the new RR as part of the European Strategy Forum on Research Infrastructures [15].

Under the guidance of the NEA Nuclear Science Committee (NSC), the Working Party on Scientific Issues and Uncertainty Analysis of Reactor Systems (WPRS) has initiated a Task Force on Zero Power Reactor (ZPR) facilities with the twofold objective of

1. reviewing the projected needs for new reactor physics validation data and elaborating on the motivation, and
2. recommending a consensual course of action for acquiring such data, including minimal functional specifications of the needed facilities and expertise.

JSI has appointed one representative to the task force in order to use the knowledge from the task force to be used in planning the new RR.

In the next steps of feasibility study, we in collaboration with potential stakeholders will thoroughly investigate the above-mentioned options and identify the best option of Slovenia and EU. In the coming months we will search for financial and/or human resources for establishing the project team to perform feasibility study, including the quotation and letters of support from stakeholders. We plan to establish the team by end of 2022 and the feasibility report to be completed by end of 2024. This will include communication with other RR projects in Europe, to avoid duplication and competition risks.

A preliminary acronym of the JSI reactor project has already been made, i.e. VERONICA - Versatile European Reactor fOr Neutron Irradiation and nuClear reseArch.

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