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Towards a New Research Reactor in Slovenia

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ABSTRACT

In 2019, Slovenia has all the necessary knowledge and infrastructure to carry out nuclear projects. The education and training of nuclear professionals as well as nuclear research was made possible by the TRIGA Mark II reactor operated by Jožef Stefan Institute in Ljubljana. In addition to nuclear research, the research reactor has enabled the development in numerous other fields, such as nuclear medicine, chemistry, radio chemistry and computer science. Slovenia will also need nuclear expertise in the future; not just because of the energy sector, which is becoming more and more important because of environmental challenges, but also because of numerous non-energy applications, for example in medicine and environmental sciences. Today the existing research reactor is fully utilized and represents an indispensable resource, but a new research reactor will be required to keep the nuclear research relevant and allow new experiments. Slovenia has all the infrastructure necessary to accommodate a new research reactor, including an appropriate potential location and relevant operational experience. However, the nuclear community needs to establish research priorities and decide on appropriate research reactor capable of supporting research in the next 60 years. A traditional light water reactor would be easier to build and would support the European fleet of power plants, but a reactor with generation IV features would allow scientists to perform state of the art experiments. The next step is constructing a feasibility study and making a commitment towards building a new research reactor.

1 INTRODUCTION

The Jožef Stefan Institute (JSI) in Ljubljana, Slovenia is operating a TRIGA Mark II with a maximum steady state power output of 250 kW or maximum power of 1 GW for a short period of time during pulse operation. The reactor was built by General Atomics and achieved first criticality in 1966, only 11 years after the first ideas to build a reactor in Ljubljana and 24 years after the first man-made self sustained chain reaction was achieved at Chicago Pile 1. Nuclear energy was, together with radar, one of two big inventions resulted from the second world war. During this time, many countries were striving for access to the power of the atom, believed to change the world with the motivation of developing nuclear weapons or utilizing nuclear energy. It was a general consensus that nuclear fission and perhaps in the future nuclear fusion would provide a limitless source of electricity and thus that nuclear technology was crucial for the development of any country. Since then, the TRIGA reactor in Ljubljana has since then been a strong driving force for scientific and technological development in Slovenia. The Yugoslav government was supporting the project to enable the development of nuclear expertise and the reactor was attracting researchers from various fields, e.g. nuclear reactor physics, nuclear medicine, reactor technology, nuclear chemistry, computer science and analytical chemistry. A significant effect was the development of early expertise in computer science in Slovenia as computers were purchased and used for reactor calculations. A very important use case for the research reactor has been and still is support of all nuclear related activities in Slovenia. Practically all nuclear experts in the country have at some point been trained at the TRIGA reactor in Ljubljana. Furthermore, the research connected to the TRIGA reactor has allowed the development of multiple procedures and computer codes that have enabled Krško Nuclear Power Plant (NPP) to become more independent of the supplier (Westinghouse) and reduce outage and fuel management costs. Three such examples are core design package CORD, digital reactivity meter DMR043 and development of the rod-in method. In 2019, the research reactor continues to be the pillar stone of research and technology in the field of reactor physics, nuclear physics, nuclear chemistry and associated technologies in Slovenia and wider in the region.

In 2019, nuclear science is facing new opportunities as well as new challenges. On one hand, some countries are neglecting nuclear power due to political or economical reasons, on the other hand it is difficult to imagine an acceptable near-term solution to counteract climate change without nuclear power. In Slovenia, the nuclear expertise that was developed in the last 60 years puts the country in a great advantage regarding new projects in nuclear, but the lack of new developments in the future could jeopardise this situation. Furthermore, nuclear expertise in Slovenia will play an important role even if Slovenia decides not to build a new nuclear reactor in the near future. The Krško NPP operating life cycle is being continuously extended and decommissioning will take significant effort. Nuclear fusion, which is intended to provide electricity in the future requires a significant area of expertise in common with nuclear fission, meaning that a new research reactor would enable and foster both fission and fusion energy research. Furthermore, nuclear science plays a critical role in fields not related to energy production, such as nuclear medicine, carbon dating, agriculture, and hydrology, as well as helping to address problems of the future connected to the environment with techniques such as desalination.

The purpose of the article is to initiate a discussion about building a new research reactor among nuclear experts in Slovenia and in the region as well as connect potential stakeholders.

In the next chapter, the motivation for building a new research reactor in Slovenia is presented. The motivation serves as a basis for the justification of the need for a new reactor, which according to the IAEA document [1] is the first step towards the feasibility study needed to start a new research reactor project. The needs of the country and all nuclear related institutions in Slovenia and Europe, the current state and future plans for research reactors are reviewed. In chapter 3, a review of possible technologies is presented. Some possible systems and description of the issue of finding a balance between building a reactor with proven technology versus experimental systems is presented. We conclude the paper by proposing a discussion about building a new research reactor and providing an outlook for the future.

2 MOTIVATION AND JUSTIFICATION

The IAEA document [1] lists the feasibility study [2] as the first step towards starting a new research reactor project. The feasibility study is based on reactor justification done early in a new research reactor project and provides the following description:

> *The starting point for establishing the justification of a research reactor is the identification of stakeholders who have existing or potential interests in the facility and its capabilities [3]. A key stakeholder group will obviously be the potential users of the facility. These stakeholders are interested in the research reactor because it would potentially be able to provide solutions in the form of services not available otherwise (or possibly available elsewhere but at higher cost), or the research reactor could potentially provide products and services that add value to realize an economic or social benefit[4].*

Most of the potential stakeholders in Slovenia are already stakeholders at the TRIGA reactor in Ljubljana. In addition to the Slovenian government, who will be crucial in terms of financial support for this research, and whose interest is to increase the Slovenian research capabilities and support the industry, other potential stakeholders are:

Scientific organizations with Jožef Stefan Institute operating the reactor and performing research and research partners, such as CEA and CERN, which are already using the existing TRIGA reactor for irradiation and testing of detectors and would likely be interested in further collaboration and new capabilities provided by the new reactor.

Education sector with major universities in Slovenia and abroad.

Training sector including nuclear training centre at JSI, responsible for training nuclear reactor operators and international organizations such as IAEA that regularly utilize the TRIGA reactor for training.

Industry potential users are both domestic and international companies. The existing TRIGA reactor is constantly in use for various industrial projects, most commonly in support of development and testing of detectors or radiation hard products, such as LED lighting and processing electronics. The opportunities for such testing are expected to increase as the number of research reactors in Europe decreases further.

Perhaps the biggest motivation for the new reactor comes from the need to preserve nuclear research and know-how in Slovenia and set a foundation for development in this field for the next 60 years. The nuclear expertise in Slovenia that we have today is something that was being cultivated since the beginning of nuclear research in the 60s. The existing research reactor was the main driving force that allowed research to continue and attracted new generations of young scientists. A new reactor would allow research in nuclear and reactor physics to remain interesting and relevant. A developed nuclear field will provide Slovenia a significant advantage when a decision to build a second nuclear power plant will be necessary. A new research reactor will serve as a pilot project for legislation and minimize potential project related risks, since the licensing procedures for power reactors are similar. In 2017, Slovenia was a net importer of electricity. It generated $38\,\%$ [5] of electricity from Nuclear power, $32\,\%$ of power was generated from solid fuels, other electricity came mostly from hydroelectric power plants. By 2054, Slovenia is planning to shut down the only Slovenian nuclear power plant NEK and the coal power plant TEŠ 6. However, energy consumption is expected to increase in the future, due to economical growth, electrification of transport and electric heating. If we rule out new fossil fuel plant builds, which go against the climate goals set by the European Commission [6], it becomes difficult to imagine the next 50 years without electricity from nuclear fission.

Similar conclusions were drawn by research institutions from other countries. A report from MIT identified that options towards decarbonisation until the year 2050 are significantly less economical if they do not include nuclear power [7]. Another strong, energy related motivation for the continuation of research in nuclear energy is support of the existing nuclear fleet and supporting the decommissioning of nuclear power plants at the end of their lives. As of 2019, according to the IAEA database of research reactors, four research reactors are planned to be built in the European Union and Switzerland. Out of those only one is already under construction. None of these is flexible enough to be adapted to a wide array of different experiments or suitable for education activities. On the other hand, 35 research reactors are currently being decommissioned in Europe. European institutes, companies, and universities are already running short on facilities dedicated to research and education needed to support the research and development in the field of nuclear technologies. There are a few big nuclear projects in Europe that would benefit immensely from support projects based on research reactors [8]. They are the MYRRHA (Multipurpose Hybrid Research Reactor for High-tech Applications) accelerator driven system, the Jules Horowitz material testing reactor and the PALLAS reactor, which will be dedicated to isotope production. The report [8] also mentions ASTRID (Advance Sodium Technological Reactor for Industrial Demonstration) and ALFRED (Advanced Lead Fast Reactor European Demonstrator), which are meant to study Generation (Gen) IV concepts and would benefit immensely from support projects that can be carried out at a smaller research reactor. This situation provides Slovenia with an unique opportunity to become a leader in reactor physics research in Europe.

Research in nuclear physics also benefits fusion projects currently running in European Union through irradiation experiments and through scientific and technological exchanges or collaborations. Two such projects are ITER, International Thermonuclear Fusion Reactor in France and JET, a fusion reactor in United Kingdom.

In addition to nuclear energy, nuclear expertise supports several other fields, such as nuclear medicine and environmental sciences. The nuclear techniques are already indispensable in medical diagnostic and treatment of patients. In the future the environmental sciences are expected to become more important. Nuclear techniques can be used to track water sources, assist with agriculture and pest control. They can also be efficiently used for water desalination and hydrogen production.

3 REACTOR TECHNOLOGY

In chapter 2, we have identified that the main motivation for building a new reactor is supporting research. While for certain applications reactor characteristics directly follow their requirements, e.g. high flux and fast refueling in case of isotope production, designing a research reactor with a wide range of possible applications presents a different challenge. A question arises - what kind of reactor is best for research applications? The answer strongly depends on the primary research field it is intended to support, and moreover, most design choices will introduce some kind of trade-off.

3.1 Traditional or Gen IV

One choice that needs to be made is whether to design a traditional, light water reactor or go for a more experimental design, e.g. one using technology planned for generation IV reactors.

Building a light water moderated and cooled reactor has many advantages. Light water reactors are a well tested technology, so it would be easier to obtain approval for such reactor and there are many companies that can build and service them. A pool type light water reactor would also be especially easy to maintain and the core would be easily accessible, even during operation. Light water reactors with solid uranium fuel do not require any fuel processing by the organisation operating the reactor. Furthermore, a light water research reactor would be ideal to support the aging fleet of European power reactors whose lifetime is being continuously extended.

A new light water reactor would allow Slovenian scientists to implement some of the following changes compared to the current reactor:

- High density fuel, such as U-Mo/Al [9].
- A larger water pool to allow more space for experiments.
- Possibility of two reactor cores, one with higher peak flux than the current TRIGA reactor for irradiation experiments and the other as a zero power configuration.
- A fully digital, modern control system with scripting interface and advanced diagnostics.

On the other hand, the light water reactors have already been thoroughly researched in the last 60 years and a different concept could lead to much higher impact in the field. According to the European Sustainable Nuclear Industrial Initiative, the European Union is planning [6] multiple research projects with the goal of developing the generation IV reactors. The ultimate goal is to solve the issue of high level waste generated by the light water reactors currently in use. A research reactor with generation IV type technology would allow the nuclear community in Slovenia and abroad to support the European transition to new technologies and offer Slovenian scientists a platform where cutting edge research in reactor physics could be conducted. A generation IV type reactor would allow research in the following fields:

- Hard spectrum would allow experiments in burning heavy actinides, such as the ones that are present in spent nuclear fuel.
- High temperature would allow research in hydrogen production, which could be used for energy storage and transport.
- Research of safety parameters, physical parameters and processes for generation IV reactors.
- Support projects for MYRRHA, ASTRID, ALFRED and commercial designs.

The report prepared by the Generation IV International Forum and the U.S. Department of Energy [10] lists six technologies, listed in Table 1 as promising.

However, not every reactor listed in Table 1 is equally suitable for the needs of nuclear research in Slovenia. While all off the systems listed in the table can be passively safe, the Slovenian researchers would benefit the most from a reactor that can be operated efficiently on a small scale and would be flexible enough to support the education use cases in addition to a variety of science experiments.

In addition to the systems mentioned in Table 1, some variations of the six reactor types might be of special interest, two of which are mentioned in this article. One is the accelerator driven system. An external neutron source, such as an accelerator coupled with a spallation

Table 1: Generation IV reactor technologies rated by the Generation IV forum as most promising [10]. The reactors are depicted in Figure 1.

Reactor name	Acronym
Gas-Cooled Fast Reactor System	GFR
Lead-Cooled Fast Reactor System	LFR
Molten Salt Reactor System	MSR
Sodium-Cooled Fast Reactor System	SFR
Supercritical-Water-Cooled Reactor System	SCWR
Very-High-Temperature Reactor System	VHTR

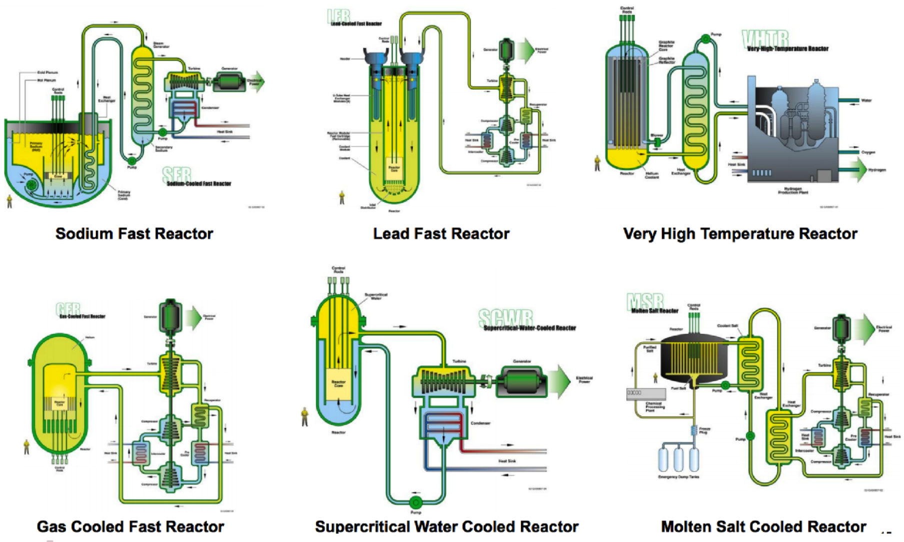

Figure 1: Drawings of six reactor systems listed in Table 1. Photo from `http://atomsforthefuture.org/general-information/about-gif`

target would allow researchers to conduct transmutation studies in a sub-critical configuration and support the MYRRHA project.

Another technology that could prove to be practical for a research reactor is a dual fluid system, like the one used by the Dual Fluid Reactor [11]. A reactor that has molten salt fuel in the fuel rods but does not have any fuel in the primary coolant could prove simpler to operate in a small scale environment like a JSI laboratory due to a lower volume of nuclear fuel.

3.2 Small modular reactor

The road to decarbonisation could be faster and cheaper with the introduction of small modular reactors (SMR) [12]. SMRs can be based either on widely used pressurized water technology or can employ Gen IV technology features, such as molten salt fuel/coolant. In contrast to the classical reactors, small modular reactors can be assembled in a factory and delivered on-site. The industrialized construction will allow the manufacturers to lower the construction cost and increase quality control. For the customer, the small modular reactors can be easier to finance thanks to the lower initial cost - when one reactor is being constructed, the previous one can already generate revenue. Introduction of a new technology, distinct from the classical nuclear reactors could help mitigate fears connected to nuclear reactors. One of the ways the nuclear community could help with the transition to energy generation with a low carbon footprint would be through support of small nuclear reactors. While the small nuclear reactors intended for power production will be closed systems and therefore comparatively less supportive of scientific research, Slovenia could adopt a mock-up version of a small modular reactor, where support projects would be carried out. The mock-up version would have a more accessible core designed to be fitted with advanced diagnostic equipment and irradiation channels.

Furthermore, the adaptation of a small modular electricity producing reactor would enable Slovenia to build a wider energy center that interconnects multiple fields with common goal of plotting the energy future of Europe. Slovenia already has sites that can host nuclear projects, a highly developed highway and large density of rivers in a relatively small area. These conditions would allow the country to build an energy research center that would connect nuclear technologies in a hybrid system with energy storage, hydrogen production and energy generations from renewable sources of energy.

4 SUMMARY AND OUTLOOK FOR THE FUTURE

It can be concluded that nuclear expertise in Slovenia forms an important part of the research and development community and will be needed regardless of the future of fission based nuclear power in the country. Slovenia has all the necessary infrastructure to lead Europe in a future where nuclear energy is utilised together with other emerging solutions designed to combat climate change, such as hydroelectricity, solar power and energy storage, becoming the European leader in clean energy. The location of the existing research reactor could potentially host another research reactor and the existing nuclear power plant near Sava makes it much easier to build a second nuclear power plant. A new research reactor will enable Slovenian researchers to perform cutting edge research in fields connected to nuclear technologies. The purpose of the article is to start a discussion about building a new research reactor. It is important to establish a framework based on which a decision about the reactor design could be taken. The authors of the article hope that in 3 years a plan for a new research reactor will be developed enough to proceed with project implementation.

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