RESEARCHING NUCLEAR REACTORS DEPLOYED AT SEA FROM A 3S PERSPECTIVE

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Abstract

In 2024, an interdisciplinary research project on marine nuclear reactors was initiated at Uppsala University. The overall goal of the project is to perform research related to the safety, safeguards and security of such systems, and to support Safeguards and Security by Design. The project, which will run for 3.5 years, will investigate mainly challenges associated with equipping ships with nuclear reactors. In this publication, we use the term “ship” to denote any boat or floating marine vessel used for carrying cargo, passengers or a nuclear reactor no matter if it is self-propelled or not. Such challenges could be a concern for e.g., nuclear infrastructure and transports of nuclear material, technical research on different reactor concepts and their intended operation; and research related to legal and regulatory issues associated with the ownership, licensing, operation and maintenance of the ships and reactors.

The project is divided into three phases. The first phase includes an overview of marine reactor concepts, identification of common challenges, assessments of to what extent existing safeguards and security practices can be applied, and the identification of gaps for further research. In the second phase, proliferation resistance studies and nuclear material assessments will be performed, together with research on the legal frameworks. In the third phase, recommendations on regulatory pathways for ship-based reactors will be presented, together with suggestions concerning physical protection and the verification of nuclear material for safeguards purposes. In this paper we will describe the project in more detail, and elaborate on results from the first months of execution.

1. INTRODUCTION

Nuclear reactors on land have been operated for over 80 years, and have been in commercial use for some 70 years. Before the larger commercial reactors were put into operation, small nuclear reactors were operated for various civilian and military purposes, including reactors placed on ships - a topic that was recently revisited [1]. However, already in 1995, the International Atomic Energy Agency (IAEA) issued a report following a technical meeting on floating nuclear energy plants for desalination purposes [2]. It was followed up by another report by the IAEA in 2002, assessing market opportunities for non-electric uses, where shipping applications were highlighted [3]. Today, the placement of nuclear reactors at sea, for example on barge ships and platforms, is again discussed for providing remote or sea-based locations with electricity [4-8]. Researchers have studied marine nuclear propulsion in recent years, from revisiting the topic of the potential use of small modular reactors (SMRs) on ships [1], to limitations posed by safety considerations such as route restrictions in national territorial waters and the risk of accidents with severe consequences [8]. It has also been suggested that nuclear reactors for propulsion purposes could be an alternative to fossil-fuelled icebreakers [9] or ships, and calculations taking financial cost and greenhouse gas emissions into account have been performed [10].

2. PROJECT DESCRIPTION

This project concerns research on the topic on nuclear safety, security, and safeguards related to nuclear reactors on (mainly) ships for either nuclear propulsion or the production of electricity and/or heat. Exchange of information and research results are anticipated with the recently established nuclear competence centre ANItA in Sweden [11].

The project has two goals. One goal is to identify the challenges and solutions related to safeguards and security issues for civilian marine nuclear reactors under development or consideration, in agreement with safeguards-by-design (SBD) and security-by-design (SeBD). Another one is to investigate the legal and regulatory aspects of such reactors, which can be coupled to both safety assessments and feasibility evaluations in the short- and long-term perspective. The project is divided into three phases:

- Phase I will study common issues for nuclear reactors on ships. The objective is to assess the applicability of current safeguards and security practices and identify gaps where further research is needed. Different deployment and operation scenarios will be identified and safeguards and security issues will be analysed.
- Phase II includes technical case studies, where two main reactor types will be studied in further detail using simulations. One of them will be a near-term deployable light-water reactor (LWR) concept, and the other a Generation IV (Gen IV) concept. The objective is to characterize the nuclear material and draw conclusions about the technical means to safeguard it. Proliferation resistance studies will be performed to identify mainly safeguards or security concerns (since safety assessments are performed by vendors to a much larger extent). Phase II also contains non-technical research on the legal frameworks around 3S for marine reactors in general, and specifically for the reactor concepts chosen in the case studies.
- Phase III concerns recommendations. The recommendations will concern technical solutions to the safeguards and security challenges such as verification of the nuclear material (NM) and prevention of unauthorized access to the NM. Non-technical recommendations will concern regulatory pathways for ship-based reactors in Sweden, the EU and internationally.

3. FINDINGS OF PHASE I

The project is currently partway through phase I, and the initial findings are reported here. Floating nuclear power plants (FNPPs) are a subset of marine-based reactors, which also include immersible reactors (such as reactors placed on the seabed) and reactors used for nuclear propulsion. Reference [12] accounts for marine-based SMRs developed and pursued by different countries. Although this project does not include immersible reactors, we note that a French concept includes placement of the reactor on the seabed, including SBD studies for the proposed concept [13] and that Australia is planning to operate uranium-fuelled submarines. Technical nuclear non-proliferation and safeguards assessments of the nuclear material in the submarines have been performed in [14].

Marine reactors currently operating or under development can provide insights on SBD and SeBD issues that have already been identified. Such reactors are for instance Russian icebreakers and Akademik Lomonosov. There are also investigations around, or efforts to place, pressurized water reactors (PWRs) on ships in countries such as China [15], South Korea [16] and the US [17]. Investigations are also being conducted about placing non-PWR ship-based reactors on ships, such as thorium reactors in the USA, and the molten salt barge ship proposed in Denmark. In addition to reactors mounted on ships, there are also proposals for reactors placed on floating platforms [18]. Such reactors could be small and modular, but also large-scale reactors are proposed.

3.1. Previous experience of operating nuclear reactors on ships

Although marine reactors may seem to be a novel invention, both civilian and military experience exists of operating such reactors. Four civilian ships have relied on nuclear propulsion and were intended to demonstrate this applicability for either cargo or person transport. The civilian ships were intended as experiments and technology demonstrators, in anticipation of a more widespread application of naval propulsion. Each ship was of a different origin (NS Savannah from the US, NS Otto Hahn from Germany, NS Mutsu from Japan and NS Sevmorput from the Soviet Union) and was constructed as a one-of-a-kind demonstrator. In addition, a total of nine Soviet/Russian icebreakers, relying on nuclear propulsion, have been constructed. Much of the technical characteristics, operation and construction of these ships can be found, but very little information is available on the associated nuclear infrastructure including construction, maintenance, fuel cycle, and intermediate and long-term storage of the irradiated fuel, except that most of the necessary equipment for operation and maintenance was found on-board. On the military side, the United States Army operated several nuclear reactors under the Army Nuclear Power Program (ANPP). This program was focused on the development of small PWRs and boiling water reactors (BWRs) with the aim of powering military sites and settlements in remote locations as well as producing heat. The program ran from 1954 and was eventually phased out in 1977. The program covered the development, operation and eventual shutdown and decommissioning of in total of eight nuclear installations. A brief account of these reactors and their operational experience can be found in [19]. Worth pointing out is that while the military experience covers different reactor types and fuels, it does not include any civilian security or safeguards considerations.

Civilian experience in modern times, comes mainly from the Russian floating nuclear power station Akademik Lomonosov, which is a 35 MWe co-generation plant, operated in the eastern regions of Russia since 2018. The plant is placed on a barge which is not self-propelled, and was towed to its destination. Upon its commission, it was destined to provide 35 MW of electric power and up to 300 MW of heat for around 200,000 people for the next 40 years in the far-flung eastern settlements of Russia. Experience is also available from placing nuclear reactors such as the OK-150, OK-900, and KLT-40 systems on civilian ships (ice breakers) as documented in [20].

3.2. Ongoing efforts related to nuclear reactors on ships

Recently, the interest in investigating the possibility of placing nuclear reactors on ships has grown, motivated largely by the need to move away from fossil fuels, which will have other positive environmental effects such as reduced oil-spills and sulfur dioxide emissions. LWR concepts are being considered for near-term deployment, and Generation IV (Gen IV) nuclear reactor concepts are being explored for not-so-distant deployment. Interest in this topic is demonstrated by researchers and stakeholders such as nuclear reactor designers and vendors, and the shipping industry as detailed below.

3.2.1. Research studies

From a research perspective, much effort is put into investigating advanced, or Gen IV, nuclear reactor concepts compared to LWR concepts (see latter half of this section where references are available). The reason is that LWR concepts are mature and available to learn from and build on, although that does not necessarily mean that it is straight-forward to put a nuclear reactor on a ship or a floating platform. Examples of recent efforts to closely study challenges and opportunities around placing LWRs in a maritime environment include the SMART (system-integrated modular advanced reactor) reactor, a 330 MWt integral PWR being developed by KAERI for seawater desalination and electricity generation [21] and the Offshore Floating Nuclear Plant (OFNP-300) [18].

Several researchers have studied the operation of advanced, or Gen IV, reactors on ships. Reference [22] performed a feasibility study for a nuclear-powered commercial merchant (container) ship and concluded that liquid metal reactors such as sodium-cooled fast reactors (SFRs), molten salt reactors (MSR) and lead-cooled fast reactors (LFR) were good options for this application. Another reference [23] studied Gen IV systems and MSRs for merchant ship propulsion purposes, and found MSRs very promising after comparing them to PWRs and considering weights, volumes, costs and nuclear safety. Reference [24] also studied different reactor concepts for nuclear propulsion and power generation, and concluded that very-high-temperature reactors (VHTR) and MSRs seem promising.

There are also examples of larger collaborative projects, initiated to investigate nuclear reactors on ships; NuProShip (Nuclear Propulsion of Merchant Ships) is an example of this. This is a research collaboration between the Norwegian maritime authority, universities, shipbuilders, and shipping companies. The first phase of NuProShip [25, 26] was started up in 2023 with the main purpose of developing Generation IV SMRs for marine purposes and international shipping, motivated by reducing emissions from the shipping industry. NuProShip argues that realistic solutions to this problem are either nuclear propulsion or the production of synthetic fuel using large-scale land-based nuclear reactors. [27].

3.2.2. Development work by nuclear designers and reactor companies

Over the past few years, many small- and medium-sized reactor concepts have been put forward. Some reactors were originally proposed to be placed on ships, while other reactor concepts originally planned for land use have found new applications with time. One example of the former is the barge ship concept developed by Seaborg in Denmark [6], and one example of the latter is the recently announced collaboration between NuScale and Prodigy Clean Energy [17] to make the NuScale reactor concept suitable for a marine-based environment.

3.2.3. Investigations led by the shipping industry

The shipping industry, with no prior experience of nuclear reactor operation, has also initiated several projects, and a few of them are mentioned here. The company Newcleo is collaborating with the Italian shipbuilding Fincantieri and RINA (the Royal Institute for Naval Architects) to study nuclear propulsion using a 30 MWe LFR running on mixed-oxide (MOX) fuel, and a refueling interval of every 10-15 years [28]. Newcleo aims to launch a 30 MWe LFR demonstrator and a MOX fuel fabrication unit in partnership with the French Alternative Energies and Atomic Energy Commission (CEA) and to have a LFR for maritime applications ready for the market by the early 2030s. Onomichi Dockyard and Imabari Shipbuilding in Japan collaborate with TerraPower [29] on the Molten Chloride Fast Reactor (MCFR) producing 30-300 MWe. Online refueling, ie fueling of the reactor during operation, is planned and the first criticality of a 300 kW research reactor is expected in 2025. Finally, we mention that both a consortium of industry organisations within the South Korean shipping industry [16] and the American Bureau of Shipping (following a request by the U.S. Department of Energy) [30] independently investigate the use of MSRs.

3.3. Safeguards and security concerns around marine reactors

Despite the growing interest, there is surprisingly little research on SBD and SeBD for marine reactors including FNPPs. In terms of safeguards concerns, one effort that could be mentioned in this context is the symposium on FNPPs arranged by the IAEA in 2023 [31], with dedicated sessions on challenges and the potential use of existing safeguards measured [32]. In addition to this event, there are a number of published works. Reference [12] studies unique safeguards challenges and opportunities associated with FNPPs and SMRs, including transportation issues, processing of MSR fuel salts, limited access to the nuclear material and measurement technologies and verification techniques for SMRs/FNPPs. Reference [33], written in 2010, discusses proliferation and security concerns related to Russia’s planned FNPPs, with many concerns being still relevant today such as risks for material diversion while the FNPP is stationed in another state’s territorial waters. More recent publications from the Russian side include [34] and [35] and focus on Akademik Lomonosov. While reference [34] is very brief, it proposes a model where a floating nuclear power unit is manufactured, fueled and delivered to the host State where it then operates. Reference [35] further elaborates on the applicability of existing safeguards measures to a floating power unit. The authors highlight that, unlike today’s nuclear safeguards practice, verification of nuclear material quantities and properties will not be possible on board as the material is contained in the sealed reactor vessel which is only possible to open at a dedicated service station. This raises questions about how the verification should be done and what data should be transmitted to the IAEA. The authors also propose a model referred to as ”manufacture-own-deliver-operate-return”, which could remove some of the proliferation concerns raised in [33], such as the transfer of ownership of the FNPP and its nuclear material, and potential development of additional front- and back-end parts of the fuel cycle, although physical access for IAEA inspectors to verify the design information and correctness of declarations remain problematic for sealed cores.

In terms of security, the IAEA covered security concerns in the 2023 symposium on FNPPS [31], and has in addition published recommendation and implementation guide documents on the security of nuclear facilities [36], nuclear material under transport [37] and institutional issues related to transportable nuclear power plants

[38]. However, there are no additional International Maritime Organisation (IMO) regulations on the security of nuclear material or facilities at sea. A few researchers raise concerns related to maritime security [39]. Others acknowledge some of these issues, but push them to the future (e.g. reference [1]). In [40] a survey with input from 65 experts and industry representatives from the maritime shipping and nuclear sectors was conducted, to identify barriers against adopting nuclear propulsion technology. Results showed that security concerns were ranked very high among all participants, and that licensing and regulatory challenges are hurdles in the development and implementation of commercial nuclear propulsion ships [41],[42]. With respect to SeBD, reference [43] identifies regulatory requirements for the physical protection of FNPPs, and addresses gaps in physical protection between IMO and the IAEA. Nuclear security considerations are also included in [44], where are number of potential challenges are identified. Security concerns have also been raised around FNPPs during transit, while on lease to a state and also when stationed in Russia [33]. From this reference it remains clear that matters concerning security arrangements around spent fuel and radioactive waste remain open. In the same reference, threats have been identified including piracy, sabotage and hostage situations, and attacks while being in operation. Some solutions have been proposed, such as armed guards on the ships, but these raise new concerns related to rights and responsibilities in the territorial waters of another state.

4. CONCLUSION AND OUTLOOK

This relatively new research project, initiated in 2024, has so-far focused on gathering information on the potential deployment and operation of nuclear reactors on ships, in order to set the stage for future research related to 3S research on marine reactors including FNPPs. There seems to be a great interest in placing reactors on ships for various purposes, but so-far few research results related to safeguards verifications or security measures for FNPPs are available.

The next phase of the project will be devoted to case studies, where technical safeguards and security assessments for selected concepts are being made. A number of concepts to study in more detail will be selected in connection to this, they should cover both LWR concepts and reactors of a more advanced type such as MSR concepts. The irradiation of the nuclear fuel in the reactor will be modelled using simulation codes. The results of the simulations will be used to make assessments related to the overall safeguards approach, the verification of nuclear material and evaluations related to material attractiveness and physical protection. In parallel, studies related to the applicable regulatory frameworks will be initiated, shedding light also on rights and responsibilities with respect to, for example, safety aspects around the concepts. In the end, we aim to arrive at recommendations that concern the safety, security and safeguards aspects of marine nuclear reactors.

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