Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Review of refueling methods in nuclear-powered ships

Kyung Rae Yook, Jeong Ik Lee*
Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
**Corresponding author: jeongiklee@kaist.ac.kr*
***Keywords:** Nuclear-powered ship, Refueling, shipyard*

1. Introduction

Major maritime nations such as China, the United States, and the United Kingdom are leading the push towards nuclear propulsion in response to the International Maritime Organization's (IMO) mid-century goals for substantial reductions in carbon and greenhouse gas emissions. This strategic shift underscores nuclear power's potential to diminish the environmental impact of maritime transport. The focus on transitioning from Highly Enriched Uranium (HEU), with its significant security risks, to Low Enriched Uranium (LEU), which offers a lower proliferation risk and is better suited for commercial reactors, supports safer, longer operating cycles and more secure waste management. This transition aligns with international directives from bodies like the International Atomic Energy Agency (IAEA), fostering compliance with the Nuclear Non-Proliferation Treaty (NPT) to ensure nuclear technology's peaceful use and prevent weapon proliferation [1].

The refueling process of a nuclear-powered ship is a coordinated procedure, encompassing several critical steps to ensure safety and operational efficiency. Initially, during the preparation phase, the ship is securely docked at a specially designed harbor, and the nuclear system is safely shut down to halt the nuclear fission reaction, setting a foundational layer for safety. Following this, the cooling and radiation reduction phase begins, where the spent fuel is cooled within the reactor to allow radiation levels to sufficiently decrease for safe handling, with continuous monitoring of radiation levels around the reactor to ensure a secure working environment. The next phase involves the precise removal and transfer of spent fuel using specialized equipment to transport it securely to a designated storage facility. After safely removing the old fuel, the new fuel is rigorously inspected and then carefully installed into the reactor, ensuring compliance with all safety and operational standards. The final step involves a comprehensive system check and the reactor's restart; after installing the new fuel and verifying that all systems function correctly, the nuclear reactor is reactivated, returning the ship to full operational status. This complex sequence is pivotal not only for extending the ship's service life but also for maintaining the highest safety standards throughout the operational lifecycle of the vessel.

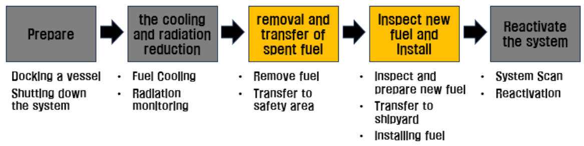

Fig 1. Refueling process

This paper analyzes nuclear-powered ships that have previously operated in the United States, Germany, Japan, and Russia. It reviews how each ship was fueled and what equipment was used. It also draws comparisons to onshore nuclear power plants and characterizes refueling at sea. This review can provide important information for the development of future nuclear-powered civilian ships.

2. Methods and Results

2. 1 NS Savannah (USA)

The NS Savannah was the first commercial nuclear vessel to operate in the United States, with a displacement of approximately 22,000 tons, measuring 182 meters long and 23 meters wide. The ship was fueled with low-enriched uranium enriched to 4.4% and used a Pressurized Water Reactor (PWR) manufactured by Babcock & Wilcox. The reactor had a design output of approximately 74 MW, which drove a steam turbine to generate approximately 22 megawatts of electricity. Savannah had a refuel cycle of approximately 3.5 years, during which time she was able to operate continuously. However, due to her high cost and operational complexity, she was decommissioned in 1972 and is preserved as a museum ship for tourism purposes [2].

The NS Savannah's refueling and maintenance operations are seamlessly coordinated between Todd Shipyard in Galveston, Texas, and the "Atomic Servant" Nuclear Servicing Vessel, constructed by the Electric Boat Division of General Dynamics at Todd Shipyards in Houston. Todd Shipyard takes charge of removing spent fuel and conducting comprehensive servicing tasks such as licensing, inspections, and training for over 20 nuclear vessels annually. After removal, the spent fuel was meticulously inspected and prepared at the shipyard before being reinstalled into the Savannah, followed by a detailed systems check to ensure the ship's readiness for recommissioning. In tandem, the "Atomic Servant," a specialized 129-foot long and 36-foot-wide non-propelled barge equipped with a robust 50-foot crane, played a crucial role in safely transferring and storing spent fuel in a specially designed, lead-lined pit that features extensive radiation shielding and advanced cooling systems. This arrangement facilitates the safe handling of heavy nuclear materials directly at the Savannah’s docking site, significantly enhancing safety and minimizing radiation exposure to personnel. This integrated approach not only maximizes operational efficiency and safety but also showcases a sophisticated and systematic method for handling the intricate processes of nuclear ship refueling and maintenance [3] [4].

Fig 2. NS Savannah refueling and "Atomic servant"

The refueling process at NS Savannah begins with the safe removal of spent nuclear fuel and its transfer to a "nuclear service vessel" known as the "Atomic Servant." The "Atomic Servant" plays a critical role in minimizing exposure to radioactive materials and facilitating the cooling process. Once aboard, the removed fuel undergoes ion exchange and mineralization processes to remove radioactive material and, if necessary, is placed in temporary storage. The new fuel is thoroughly inspected and all systems are verified before restarting. Spent fuel is then safely inspected and stored in shielded pits after prolonged cooling, and radioactive waste is properly packaged and disposed of. The "Atomic Servant" ensures that all these processes comply with strict environmental protection and worker safety regulations and are managed through continuous monitoring and advanced filtration systems. This system not only streamlines the refueling process but also enhances safety by reducing the risk of environmental contamination.

2. 2 NS Otto Hahn (Germany)

The NS Otto Hahn was a German nuclear-powered cargo ship and research vessel launched in the late 1960s, serving a pioneering role in maritime propulsion like the NS Savannah. With a displacement of about 15,000 tons and measuring approximately 160 meters in length and 21 meters in width, Otto Hahn was powered by an advanced pressurized light water reactor (APWR) manufactured by Siemens-KWU. The reactor, which utilized low-enriched uranium with an enrichment level between 3.5% and 6.6%, produced about 38 MW to generate around 10 megawatts of electricity, propelling the vessel. The ship had a refueling cycle of approximately 3.5 to 4 years. Despite its technological advancements, Otto Hahn faced high operational costs and complexity, which hindered its commercial [5].

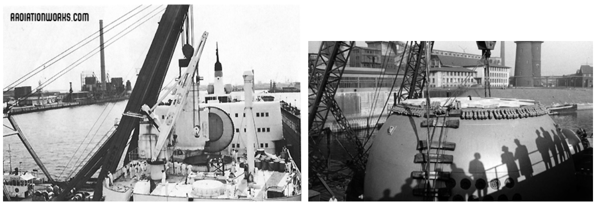

Fig 3. NS Otto Hahn refueling

The NS Otto Han received its first reactor refueling in 1972, after four years of operation, using 22 kg of uranium-235, and sailed approximately 250,000 nautical miles. It continued to operate until 1979, sailing a total of 650,000 nautical miles [6]. While there was insufficient publicly available data on refueling, there are lessons that can be learned. The experience gained from operating the first reactor core was also instrumental in planning the optimization of the second core. The first reactor core was made almost a trial run for the second reactor. In other words, the entire reactor was replaced. This initiative aimed to improve the reactor design to reduce fuel cycle costs and improve overall efficiency [7].

2. 3 NS Mutsu (Japan)

The NS Mutsu, Japan's first and only nuclear-powered civilian ship, was launched in the early 1970s to explore the feasibility of nuclear-powered shipping. With a displacement of approximately 8,200 tons, the ship measured 130 meters in length and 19 meters in width. The Mutsu was fueled by low-enriched uranium enriched to about 3-4% and utilized a Pressurized Water Reactor (PWR) designed by Mitsubishi Heavy Industries. The reactor had a design output of approximately 36 MW, which drove a steam turbine to generate about 10 megawatts of electricity. Mutsu had a planned refuel cycle of approximately 4 to 5 years, during which time it was expected to operate continuously. However, due to significant technical challenges, including a radiation leakage during its initial sea trial that led to public outcry, the ship faced operational delays and controversies, leading to its decommissioning as a nuclear-powered ship in 1982, subsequently being converted for use as a research vessel [8].

While NS Mutsu itself did not perform any refueling operations, its service site, located at Sekinehama Port in Mutsu City, Aomori Prefecture, is a 36,000-square-meter site with fuel exchange, fuel storage, waste treatment, and decontamination facilities, designed to meet the extensive service requirements of nuclear vessels, including shore-mobile cranes and laboratory, headquarters, and service buildings. The facility has been converted into a nuclear ship port. It provides space for storing new and spent fuel, accommodating up to two lots of total fuel assemblies. In addition, in 1989, the Japan Atomic Energy Agency installed a floating dock off the coast of Sekinehama Port for the safe berthing and inspection of the nuclear-powered vessel Mutsu. After being loaded onto the floating dock, it was towed into the harbor by a tugboat and docked at the pier [9].

The nuclear ship MUTSU, pivotal in evaluating the viability of nuclear propulsion for maritime applications, employed an advanced refueling system inclusive of specially designed shipping casks. These casks were engineered to handle spent nuclear fuel with utmost safety and efficiency. Following a necessary cooling period of over a year post-reactor operation, the spent fuel was transferred into these robust casks, crafted to exacting standards for leak-tightness and structural resilience. Key features of these casks included a robust stainless-steel body with a thickness sufficient to shield against radiation effectively, and dual lid systems with integrated double O-ring seals to ensure secure containment. Each cask was equipped with a sophisticated helium gas filling system to preserve the fuel's integrity during storage, and pressure transducers to continuously monitor the containment conditions. The MUTSU hosted an on-site storage facility where these casks were securely held on vertical skids, which not only facilitated safe handling but also supported efficient heat dissipation. The effectiveness of the casks in terms of their heat management and containment capabilities was thoroughly evaluated through a storage function demonstration test. Onshore facility was equipped with an on-site storage facility where these casks were securely stored on vertical skids, facilitating safe handling and containment. This process was complemented by rigorous testing, including a storage function demonstration test to validate the casks' performance in terms of heat dissipation and containment integrity [10] [11].

Fig 4. NS Mutsu refueling and cask

2. 4 NS Sevmorput (Russia)

The NS Sevmorput, a Russian nuclear-powered icebreaker and cargo ship, was launched in 1988 and is notable for its substantial role in Arctic maritime operations. This vessel stands out with a displacement of about 33,980 tons, measuring 260 meters in length and 32 meters in width. It is powered by a single KLT-40 nuclear reactor that utilizes enriched uranium with an enrichment level typically between 30% to 45%. The reactor has a thermal capacity of 135 MW, providing the ship with significant propulsion power to navigate through icy waters effectively. Sevmorput operates with a refueling cycle of approximately 7 to 10 years, showcasing its efficient nuclear design tailored for extended operations in harsh environments. Despite facing operational challenges and navigating complex international regulations concerning nuclear-powered vessels, Sevmorput continues to be an essential asset for Russia's commercial and military presence in the Arctic [12].

Fig 5. NS Sevmorput refueling

The Atomflot site in Murmansk, strategically positioned just 20 minutes from the city center, is an essential facility under the Russian Ministry of Transport. It serves as the central hub for the comprehensive management of nuclear-powered vessels, including seven nuclear icebreakers. Atomflot not only provides crucial repair and technical services but also handles the significant responsibilities of spent nuclear fuel management. The spent fuel, collected from various locations on the Kola Peninsula, is processed temporarily at Atomflot before being transported to Mayak in Chelyabinsk for further treatment, storage, and disposal [13]. This facility's role in the integrated management of nuclear-powered ships is vital, especially in the current global context where nuclear security is a paramount concern.

Table 1. Analysis of Nuclear-powered ship refueling

Ship Name	Fuel Cycle	Refueling Characteristics
NS Savannah (USA)	3.5 years	Refueled at Todd Shipyard using the dedicated servicing vessel "Atomic Servant."
NS Otto Hahn (Germany)	3.5-4 years	Refueling is replaced by a complete reactor overhaul.
NS Mutsu (Japan)	4-5 years	Refueling was used Cask, and there is a management facility in place.
NS Sevmorput (Russia)	7-10 years	Installed integrated refueling facilities at Atomfloat bases and comprehensive management of nuclear ships.

3. Design Consideration of NS Refueling

The design considerations of nuclear-powered ships refueling are discussed by examining the operational experience of nuclear-powered ships in the past. These experiences have led to lessons learned for refueling, including the necessary infrastructure and ship design.

3. 1 Support facilities and reactor design

The strategic placement of support facilities for nuclear-powered ships is crucial for maximizing operational efficiency and accessibility. Ideally situated near major shipping routes and in prominent port cities, these facilities significantly reduce logistics costs and enhance rapid access. Their proximity to existing industrial setups and shipyards is essential for conducting efficient maintenance operations and facilitating swift emergency responses. These facilities are comprehensively designed to manage all aspects of the operational lifecycle of nuclear-powered vessels, including nuclear refueling, routine maintenance, safety inspections, environmental monitoring, and waste management. By centralizing these functions within one facility, operations are streamlined and resource utilization is maximized. Drawing on historical operations like those of NS Savannah and NS Otto Hahn, these shipyards incorporate advanced nuclear fuel management and environmental safety technologies, adhering to stringent international safety standards.

To ensure the operational integrity and safety of nuclear fuel handling, the infrastructure includes dedicated tests areas, and thermal test chambers to ensure that fuel container can withstand high temperatures during transport and storage. Pressure and stress test rigs assess fuel body resistance under various conditions, while continuous radiation and contamination monitoring systems detect potential leaks. Environmental control systems maintain necessary climatic conditions for safe storage and transport. Facilities also feature rapid response containment and sophisticated venting systems to safeguard against accidental breaches or emissions. Certification centers facilitate compliance with stringent regulatory requirements through inspections and certifications that uphold safety standards. The design of these facilities prioritizes easy access for maintenance, monitoring, and emergency operations, ensuring efficient management of nuclear fuel container. Safety and environmental protection are paramount in the design and operations of these facilities. They comply with the highest international standards for radiation leakage protection and feature advanced emergency response systems. Continuous monitoring ensures adherence to environmental safety regulations, protecting personnel and marine ecosystems. For situations where traditional port facilities are inaccessible, support barges equipped for refueling and maintenance can operate at sea or in remote areas.

3. 2 Technical Differences in Refueling Between Onshore Power Plants and Maritime Operations

Onshore nuclear power plants handle spent fuel within a controlled environment, utilizing shielded and secured transport systems within containment buildings to mitigate any radioactive emissions and minimize environmental interaction. Robust safety protocols, including multiple containment layers and automated handling systems, significantly reduce accidental exposure risks. In contrast, maritime refueling operations face challenges due to limited space on ships, which restricts the size and type of safety equipment that can be used. This necessitates innovative design solutions to ensure safe handling of spent fuel without the extensive infrastructure found in onshore facilities. Moreover, transporting spent fuel from ships for disposal or reprocessing involves moving hazardous materials beyond initial containment, raising potential risks of environmental exposure if not meticulously managed.

One of the primary concerns with refueling nuclear-powered vessels is the potential exposure of spent nuclear fuel to the environment during onboard transport. This risk is absent at onshore nuclear power plants, where spent fuel is securely managed and stored within controlled facilities. To mitigate these risks at sea, offshore fuel supply facilities can adopt specialized containment systems, such as those inspired by NS Savannah's use of barges and NS Mutsu's casks. These systems are specifically designed for harsh ocean conditions with robust features that safely store spent nuclear fuel and prevent any leakage of radioactive materials during refueling. Utilizing advanced materials with superior radiation shielding and corrosion resistance is crucial to ensure that these containment systems can withstand prolonged exposure to the marine environment. Additionally, these systems must provide adequate cooling and exceptional heat resistance to maintain safety standards. Implementing refueling barges presents a strategic solution to the logistical challenges faced by nuclear-powered vessels, offering a safe, adaptable, and mobile refueling unit that delivers necessary infrastructure directly to the vessel, irrespective of its location. This approach not only significantly reduces downtime by enabling on-demand refueling but is also particularly beneficial for military or research vessels on extended missions in isolated areas. Refueling barges are outfitted with comprehensive safety and containment systems, including advanced shielding and emergency measures, ensuring the secure handling and transportation of spent nuclear fuel.

Addressing the reactor's cooling requirements during refueling and operational phases is critical. Building redundant systems that can utilize both seawater and onboard water tanks for cooling enhances safety with emergency options available if one system fails. Designing an emergency cooling strategy that activates swiftly in case of system failure is essential. This includes the installation of automatic cooling systems capable of detecting and responding to temperature spikes without manual intervention, further ensuring the reactor's operational reliability. While current International Maritime Organization (IMO) regulations may not fully support onboard storage of spent nuclear fuel, reevaluating this approach could significantly improve nuclear fuel management logistics at sea. Incorporating dedicated onboard casks for temporary storage, akin to those used in land-based nuclear facilities, requires innovative design to guarantee structural integrity and radiation safety in a dynamic marine environment. Additionally, implementing rigorous safety analyses to predict and mitigate potential accidents, alongside designing emergency containment features and redundant safety systems, is vital to address the risks associated with onboard fuel storage.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No.: RS-2024-00436693).

REFERENCES

[1] IAEA-TECDOC-1452 "Management of high enriched uranium for peaceful purposes: Status and trends" (IAEA, Vienna, Austria, 2005)
[2] Wikipedia contributors, "NS Savannah", Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/wiki/NS_Savannah
[3 P. Scordino and A. E. Allan, "NSV Atomic Servant: Nuclear Servicing Vessel, Design B2-MA-51a", in *International Shipbuilding Progress*, Vol. 7, No. 76, December 1960.
[5] Wikipedia contributors, "Otto Hahn (ship)", Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/wiki/Otto_Hahn_(ship)
[6] Gail H. Marcus and Steven M. Mirsky, "The history and future of civilian nuclear power afloat", Nuclear News, Dec 11, 2021
[7] Lukas Wulff, "Feasibility of the Implementation of Nuclear Reactors as Main Energy Source in Passenger Vessels", [Journal name, Volume, Pages, Year]
[8] Wikipedia contributors, "RV Mirai", Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/wiki/RV_Mirai
[9] Shuichi Sasaki, "General description of the first nuclear ship 'Mutsu'", Nuclear Engineering and Design, Vol. 10, Issue 2, 1969, pp. 123-125, ISSN 0029-5493, https://doi.org/10.1016/0029-5493(69)90035-1.
[10] Operation Report, "運転経験検討結果 Operation Report on Review Results of the Nuclear Ship 'MUTSU'", Japan Nuclear Ship Development Agency, 2023
[11] "Ishizuka, M., Umeda, M., Nawata, Y., Sato, H., Honami, M., Nomura, T., Ohashi, M., & Higashino, A. (Year). Development of the Nuclear Ship MUTSU Spent Fuel Shipping Cask. Tokyo: Japan Atomic Energy Research Institute; Mitsubishi Heavy Industries, Ltd."
[12] Wikipedia contributors, "Sevmorput", Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/wiki/Sevmorput#cite_note-imo-55
[13] Bellona Foundation, "Safe decommissioning work at Russia's Atomflot imperiled by the war in Ukraine", Dec 2023, https://bellona.org/news/arctic/russian-nuclear-icebreakers-fleet/2023-12-safe-decommissioning-work-at-russias-atomflot-imperiled-by-the-war-in-ukraine