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Review

A Review of Maritime Nuclear Reactor Systems

Keith E. Holbert

School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, AZ 85287, USA; holbert@asu.edu

Abstract: Marine reactors have been applied to floating nuclear power plants, naval vessels such as submarines, and civilian ships such as icebreakers. Nuclear-powered shipping is gaining increased interest because of decarbonization goals motivated by climate change. Enhanced reactor safety can potentially reduce regulatory and liability challenges to the adoption of nuclear propulsion systems for merchant ships. This gives strong impetus for reviewing past use of nuclear reactor systems in marine environments, especially from the perspective of any accident scenarios, lest planners be caught unaware of historical incidents. To that end, a loss of coolant accident (LOCA) in a *Lenin* icebreaker reactor in 1965 and disposal at sea of some of its damaged fuel and reactor vessel as well as the entire tri-reactor compartment is recounted.

Keywords: floating nuclear power plant; icebreaker; Lenin accident; marine reactor; naval nuclear propulsion; nuclear-powered merchant vessel; nuclear ship

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1. Introduction

This review is motivated by multiple factors, including goals to decarbonize shipping and ongoing efforts to update regulations related to nuclear-powered merchant vessels. This increased interest in marine nuclear reactors also serves as an impetus to examine potential lessons learned from mishaps of the past.

Moore et al. (2016) make the point that the "differences between naval reactors and civilian power reactors are often not understood even by nuclear engineers who have not been exposed to naval propulsion reactors" [1]. Proposals to utilize nuclear reactors to decarbonize maritime shipments [2–5] and the fact that the individuals who designed the nuclear merchant ships are no longer practicing professionals motivate a review of some history associated with naval reactors and the differences between shipborne reactors and shore facilities. Noteworthy is that the International Maritime Organization (IMO), which is the United Nations' specialized agency responsible for safe, secure, and efficient shipping and the prevention of pollution from ships, has a goal of reducing greenhouse gas emissions from international shipping to net-zero around 2050 [6]. Furthermore, some individuals seem to discount the possibility of future civilian nuclear ships; for instance, a 34-page peer-reviewed journal article in 2022 dedicated only a single paragraph to the possibility of using nuclear-powered ships to reduce CO_2 emissions [7].

This review is a survey of maritime nuclear power and propulsion systems. In this context, "maritime" not only encompasses ships but could also include nuclear reactor systems in or near the sea. That said, there are many coastal nuclear power plants with characteristics not differing significantly from inland facilities, and those generating stations have ample coverage in other publications such that they are not of interest here. However, the present sparsity of and plans for floating nuclear power plants makes them worthy of consideration herein. Furthermore, information on naval nuclear propulsion systems for ships such as submarines tends to be more closely guarded such that less attention will be devoted to those systems.

Other related reviews include those of Freire et al. (2015), who examined the four historical nuclear-powered merchant ships (*Savannah*, *Otto Hahn*, *Mutsu*, and *Sevmorput*) [8], and Schøyen and Steger-Jensen (2017), who also reviewed those four merchant ships [5]. The present review expands the field of view to also encompass icebreakers and some naval vessels to broaden our understanding of the potential challenges and opportunities for maritime reactors.

2. Background Information

Compared to baseload shore systems, shipborne reactors require greater operational flexibility and rugged construction. In addition, leaks from the tertiary saltwater coolant into the secondary (steam) system must be monitored [9]. As shown in Figure 1, ship reactor systems are placed centrally for multiple reasons. First, the weight of the nuclear steam supply system (NSSS) and its radiation shielding motivates the midship placement of the reactor compartment (RC) to maintain boat stability [10]. Second, collisions, grounding, etc., are statistically more likely to occur at the bow or stern of the ship [11,12]. Third, the central location experiences less movement [13]. Such ship movement in three dimensions, as seen in Figure 1, will challenge passive safety approaches depending on the natural circulation of coolants. With that in mind, researchers have performed both computer simulations and laboratory tests of natural circulation under such conditions [14,15].

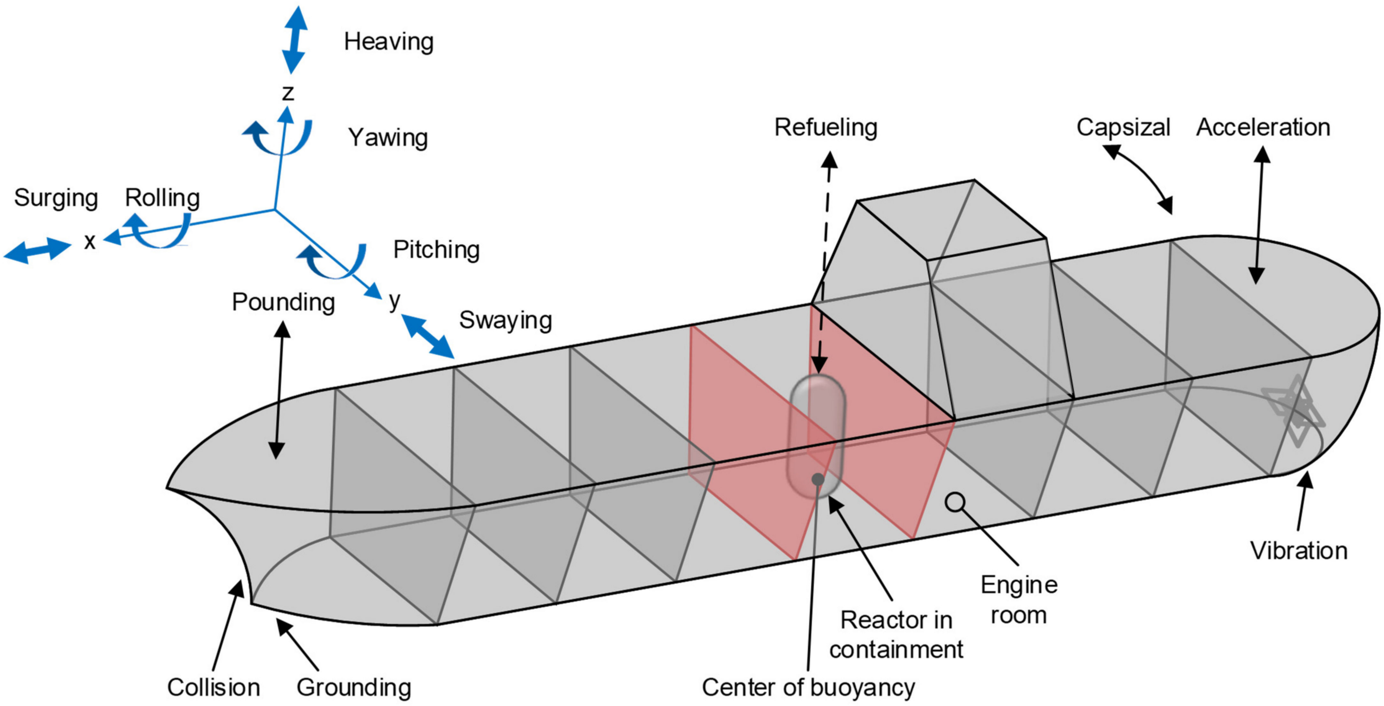

Figure 1. Central placement of a nuclear propulsion power plant in a ship. After [16] (p. 244).

In 1967, West and Roland wrote that the "two aspects of nuclear ship design which set it apart from the conventional [ship] design are collision protection and containment" [17]. Although the existing 125-page IMO Code of Safety for Nuclear Merchant Ships dates to 1981–1982 and is restricted to pressurized light-water reactors [18] (p. 6), a 350-page gap analysis was submitted to the IMO in 2024 [19]. The IMO Code lists four successive physical barriers to prevent the release of radioactive material: (1) fuel cladding, (2) primary pressure boundary, (3) containment structure, and (4) the safety enclosure. A nuclear engineer would recognize the nature of many of the IMO requirements such as reactivity control and engineered safety features but might be less familiar with the NSSS collision protection structure, which is neither the containment structure nor the safety enclosure, which can be the ship hull, as depicted in Figure 2. Primary shielding of gamma rays and neutrons from the reactor would permit short-term entry into the containment vessel after shutdown, while the secondary shielding would reduce personnel exposure from any radiation emitted by radioactive material in the containment vessel, for instance, due to the release of radioactivity in the event of an accident [20]. Typical primary biological shielding includes water and lead, while secondary radiation shielding comprises concrete, lead, and polyethylene. Dry docking and underwater hull inspections motivate employing shielding above the keel [21] including temporarily flooding bottom sections of the ship, as was possible in the *Otto Hahn* [22].

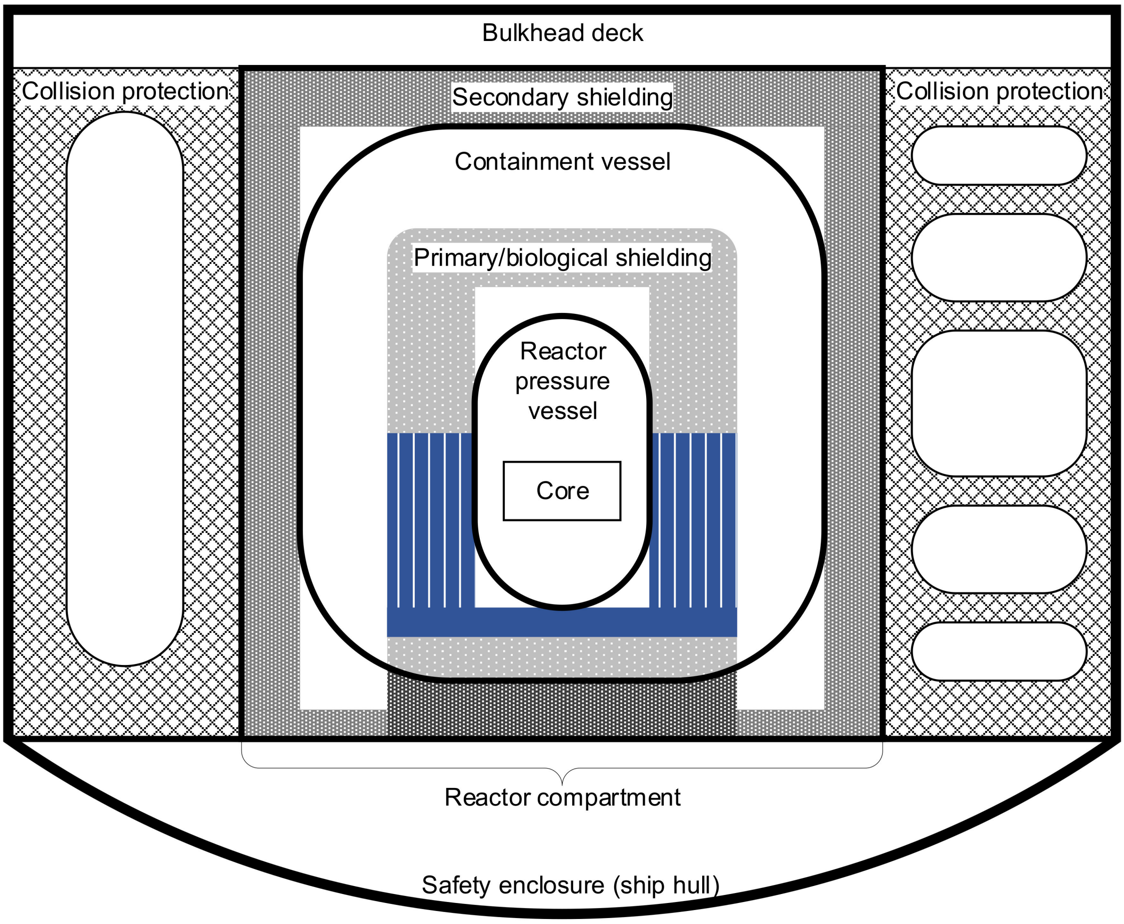

Figure 2. Diagram of notional nuclear ship radioactivity containment, radiation shielding, reactor compartment, and collision protection systems (e.g., barriers and crumple zones).

A nuclear-powered ship must be designed to meet the usual maritime safety requirements, as well as address the unique requirements for reactor safety. The reactor must not be adversely affected by the propagation of normal ship accidents such as collision, grounding, sinking, flooding, storm damage, fire, and explosion. Unlike land-based nuclear units, shipborne reactors must consider what might be a worst-case scenario for safety—capsizing. For instance, the NSSS vendor Babcock & Wilcox (B&W) analyzed reactor safety in the event of the N.S. (nuclear ship) *Savannah* capsizing, with the major concerns being reactor shutdown, core heat flux burnout, and primary coolant system integrity [23]. Although collision normally concerns interaction with another ship or fixed/floating objects, Dietrich (1972) analyzed the impact of an aircraft on a nuclear ship [24], and Paik and Park (2020) examined a terrorist attack carried out with a Boeing 777 against a nuclear unit floating offshore [25].

The challenges to nuclear merchant ships include liability/indemnification and regulations [26], which are directly tied to reactor safety. These are not new issues, for Winall and Esleeck wrote in 1979 that technology and economics are not the problem, but rather three challenges existed then (as they do today): (i) port entry, (ii) indemnification or insurance, and (iii) first-of-a-kind and startup costs [27]. Despite attempts to lessen such issues, some efforts have been for naught; for instance, the Brussels Convention on the Liability of Operators of Nuclear Ships of 1962 has never entered into force [28,29]. Although these challenges are seemingly non-technical in nature, others have recognized that the use of inherently safer nuclear reactors would alleviate the basis of some concerns being expressed. Even in the former Soviet Union, its own nuclear-powered container ship *Sevmorput* was denied entry to some Soviet harbors due to the Chernobyl accident [30].

Thus far, all the nuclear-powered merchant ships and icebreakers have utilized pressurized water reactors (PWRs), but a few submarines have employed liquid-metal-cooled reactors (LMRs). The USS *Seawolf* submarine of the 1950s originally used General Electric's S1G liquid sodium reactor. In the 1960–1970s, the Soviets built five lead–bismuth-cooled reactors including a prototype [31,32], although others tally up to eight LMRs [33]. Challenges with the 44% Pb–56% Bi coolant included its melting point of about 125 °C and the creation of Po-210 via beta decay after the $^{209}Bi(n,\gamma)^{210}Bi$ reaction [34]. Today's naval reactor systems worldwide exclusively utilize PWRs. The use of gas-cooled reactors has been considered since at least 1958 [35–40]. Other reactors contemplated for marine applications include boiling water reactors [41] and organic moderated reactors [42]. In terms of core thermal power, all these units would be categorized as small reactors.

More recently, small fourth-generation reactors using molten salt are being proposed as potentially safer alternatives to PWRs [43,44]. Some of the small modular reactor (SMR) designs being pursued utilize high-assay low-enrichment uranium (HALEU), which has already received ire from a proliferation standpoint [45]. There have certainly been proponents of nuclear power for merchant shipping [46,47], but economics continues as a prime consideration [48,49]. Besides economic viability, present challenges to adopting nuclear power for shipping include emergency planning zone (EPZ) size issues, in that the EPZ may be as large as the entire port. The Maritime Nuclear Application Group notes that advanced reactors may have an EPZ as small as the ship hull [50]. Another proposal to address harbor entry is to have dedicated ports for large bulk carriers [51], but those infrastructure costs are obviously a hindrance to economic viability.

A timeline of major nuclear ship deployments is shown in Figure 3, which reveals that most nuclear ships have been military naval vessels. The exact dates for inaugural events are subject to the defining moment for a ship, whether it be christening, launching, or commissioning. Normally, after being christened/launched, the ship must still be fitted and sea trials carried out before commissioning occurs when the vessel enters active service. The period between launching and commissioning may be as much as three years for a nuclear-powered aircraft carrier [52]. We find that for the USS *Nautilus*, these events are not in that order, as the world's first nuclear submarine was commissioned in September 1954 to demonstrate that the project schedule had been met, but sea trials did not take place until January 1955 [53] (p. 58).

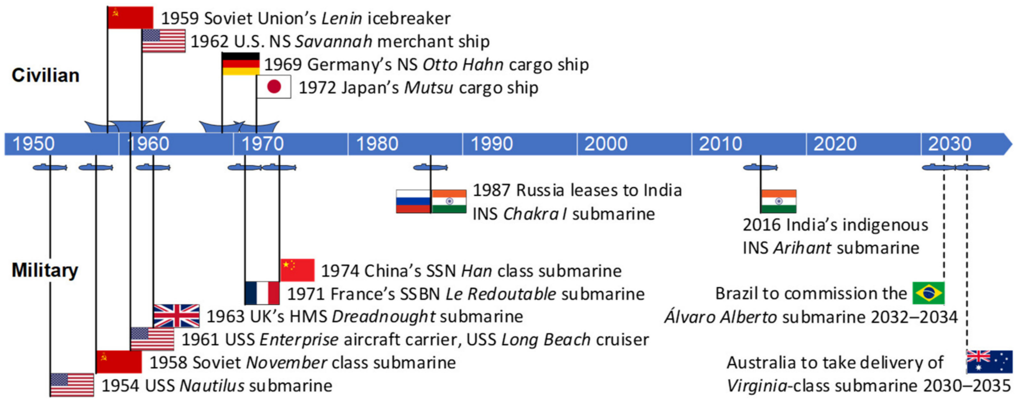

Figure 3. Timeline of mostly firsts in marine nuclear propulsion systems.

3. Naval Nuclear Propulsion Systems

It is instructive to examine naval nuclear power systems due to their impact on commercial nuclear power plants and merchant shipping, as well as their role as the inaugural nuclear propulsion systems. Known as the Father of the Nuclear Navy, then-Captain (later Admiral) Hyman G. Rickover would lead the U.S. Naval Nuclear Propulsion Program (NNPP) for more than 33 years (1948–1982) [54]. On 17 January 1955, USS *Nautilus* (SSN 571) Commander Wilkinson signaled the message "underway on nuclear power" as the first vessel to achieve that feat [53]. Without a doubt, nuclear propulsion systems had a revolutionary impact on naval options, allowing previously submersible ships to truly attain submarine status [55,56] (p. 41). In the meantime, air-independent propulsion (AIP) systems have become an alternative to nuclear reactors in submarines [57,58].

The quintessential (qualitative) technical paper on the *Nautilus* may well remain that of Roddis and Simpson (1954) [59]. The *Nautilus* employed the submarine thermal reactor (STR) Mark II system, also designated as the S2W (i.e., Submarine reactor number 2 Westinghouse). The S2W employed hafnium control rods [59,60] as Hf does not require cladding in water to prevent oxidation [61] (p. 61), and it has good dimensional stability [62]. In addition, hafnium is said to be "particularly suitable for control rods because it has a relatively high capture cross-section and because several daughter products after neutron capture are stable isotopes which also have good capture cross-sections" [63]. Reportedly, the *Nautilus* reactor outlet temperature was approximately 500 °F (260 °C) [64] (p. 207), and the estimated 60–70 MWt core [65] (p. 238) delivered 13,400 horsepower to the dual screws [53]. The recirculation-type steam generator employed a horizontal straight tube-and-shell heat exchanger with riser and downcomer pipes connected to a separate steam drum [66].

The *Nautilus* STR Mark II and those U.S. naval reactor systems that followed were housed in a shielded reactor compartment (RC) designed to contain accidents and protect the crew from radiation exposure (e.g., from 6.1-MeV gamma-ray emission by N-16 produced in the $^{16}O(n,p)^{16}N$ reaction in the primary water coolant). As seen in Figure 4, the prototype STR Mark I (S1W) constructed in Idaho had its RC (hull) placed in a 40 ft (12 m) deep × 50 ft (15 m) diam. [67] (with about one million liters of water [54]) sea tank to make measurements of the shielding effectiveness for radiation backscattered by the sea [64] (pp. 121–122), [68] (p. 33). Radiation shielding measurements were made of the gamma-ray dose rate distributions, thermal neutron flux distributions, and fast neutron dose rate distributions over much of the shielded surface, outside the hull with and without water in the sea tank, in the shielded reactor compartment, and in the reactor shield tank [69] (pp. 220–221). The attention paid to radiation shielding in these first PWRs resulted in Rockwell's 1956 publication of the nearly 500-page *Reactor Shielding Design Manual* [69]. The

S1W RC was directly connected to an engine compartment that transferred the developed shaft power to a water brake that simulated tortional resistance [70].

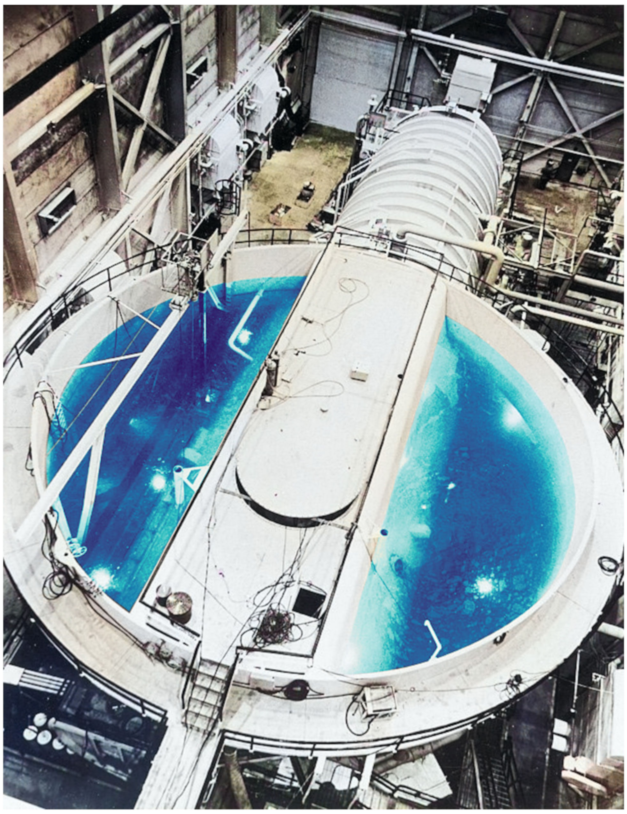

Figure 4. Prototype submarine thermal reactor (STR Mark I or S1W) at the then-named National Reactor Testing Station (NRTS) in Idaho. The reactor compartment in the foreground is surrounded by a 300,000-gallon sea tank, with the engine compartment behind. Photo courtesy of the U.S. Navy.

Ebersole (1957) details the radiation exposure for the *Nautilus* crew—an average of 106 men—for 1955 [71,72]. The average dose was 173 mrem/y for the entire crew but 2.7 times higher at 468 mrem/y for the engineers with a maximum exposure of 1438 mrem/y. Interestingly, Schaefer (1959) calculated the radiation exposure at the control stations of a German submarine in that era to be 38.5 mrem per week due to dials painted with radioactive paint [73], which is significantly larger than the afore-cited measurements for the *Nautilus*. Today, each U.S. naval reactor plant—surface ship and submarine—contains over 100 tons of lead (Pb) shielding [74] (pp. S–3, 1–5). During 2010–2022, the average annual radiation doses for U.S. naval fleet and shipyard personnel were 10 mrem and 17 mrem, respectively [75] (pp. 31–32).

In the United States, development of the first commercial power reactors was inextricably linked to the early naval reactors. In particular, the U.S. Atomic Energy Commission (AEC) charged the NNPP and concomitantly Westinghouse with (literally) porting the naval reactor technology to the development of the four-loop Shippingport Atomic Power Station, which, with commercial operation in 1958, became the first utility-scale nuclear plant in the world dedicated solely to electricity generation [76,77]. In fact, the first seed-and-blanket core design at Shippingport was that of the canceled Carrier Vessel Reactor (CVR) [78] (p. 324), [79], with the annular seed region having an enrichment of 93% [77]. Consequently, the Shippingport reactor shared several features with naval reactors that are not found in present commercial power plants, including the use of plate-type fuel elements [62] and hafnium control rods [76]. The plate-type fuel elements permit high power density and compact cores [62]. For the Osiris pool-type experimental reactor and

Rubis class submarines, the French have utilized "caramel" fuel plates—so named because the fuel is composed of high-density low-enrichment uranium (LEU) platelets of UO_2 embedded in zirconium alloy [61] (pp. 61–62). Compared to a cylindrical rod, the caramel fuel configuration is said to reduce primary coolant contamination in the event of fuel degradation [61] (p. 61). Similarly to present-day PWRs, *Nautilus* reactor control was based on maintaining a constant average temperature in the primary coolant system [80].

Meanwhile, Westinghouse was also developing reactors for surface ships as part of the AEC's Large Ship Reactor (LSR) program. The A1W (Aircraft carrier reactor number 1 Westinghouse) prototype comprised two reactors (A and B) and associated steam generating equipment to drive one shaft of an aircraft carrier. Like the Shippingport reactor, coolant entered the A1W reactor pressure vessel (RPV) below the core and exited the RPV above the core [70,76]. Commissioned in September 1961, the cruiser USS *Long Beach* with two C1W reactors (based on the A1W) was the world's first nuclear-powered surface warship; the *Enterprise* would follow two months later. The first nuclear-powered aircraft carrier, the USS *Enterprise*, launched in September 1960, would boast eight A2W reactors supplying four steam turbines and shafts [54]. Simpson reflects that only a single reactor per shaft would have been sufficient, but Rickover insisted upon two reactors per propeller [68] (p. 79). Subsequent U.S. aircraft carriers would utilize only two reactors.

Other early naval reactors worth mentioning include the S2G (Submarine reactor number 2 General Electric) LMR installed in the USS *Seawolf*. Launched in July 1955 as the second nuclear-powered submarine, the *Seawolf* operated for about 2 years using the LMR [54]. The S2G reactor was partially moderated by an array of solid beryllium reflectors [81] (§12.50), [82] (p. 102), and was thus originally referred to as the submarine intermediate reactor (SIR). Rickover et al. (1957) reported that a sodium-cooled core can produce the same shaft horsepower as a typical PWR with only about 85% of the reactor power [80]. This can be deduced from the fact that the reactor coolant temperature rise and outlet temperature of 850 °F (454 °C) in the SIR were significantly greater than those of the STR, the exit temperature of which was about 500 °F (260 °C) [64] (p. 207). Unfortunately, sodium leakage in the steam generator resulted in the entire LMR system being replaced by a PWR at the first refueling [54,56] (p. 273). The leaks were detected by means of a sodium-potassium monitoring fluid in the annulus of the double-tube steam generator design [53,66]. An additional drawback of the sodium LMR (besides the Na melting temperature of 98 °C) was its higher levels of neutron-induced radioactivity in the coolant compared to a PWR [80]. Although the half-lives of N-16 and N-17 in activated water are 7.1 s and 4.2 s, the 14.96 h half-life Na-24 from the $^{23}Na(n,\gamma)^{24}Na$ reaction delivers its 1.37 MeV and 2.75 MeV gamma rays over a much longer period. Table 1 provides a stark contrast between the radiological conditions for an LWR and LMR.

Table 1. Typical radiological considerations for water and sodium coolants.

Condition	Water	Sodium
During Operation		
Radioactivity of coolant in reactor system	1 kCi (37 TBq)	3 MCi (110 PBq)
Radiation near coolant system (inside shield)	200 R/h	500,000 R/h
Shielding required around coolant system, average thickness of lead (or equivalent)	6 in. (15 cm)	14 in. (36 cm)
One Minute After Shutdown		
Radioactivity of coolant in reactor system	1 Ci (37 GBq)	3 MCi (110 PBq)
Radiation near coolant system (inside shield)	0.2 R/h	500,000 R/h

Table 1. *Cont.*

Condition	Water	Sodium
Closest permissible approach to hull in water	Contact	10 ft (3 m)
System accessible for maintenance	Yes	No

Data source: Rickover et al. (1957) [80]. The roentgen (R) is a legacy unit of exposure, which for photons is approximately equal to a rad (1 R ≈ 1 rad = 0.01 Gy).

The U.S. was not the only nation to construct land-based prototypes for naval reactors. The British developed the Dounreay Submarine Prototype (DS/MP) PWR on the north coast of Scotland [83,84]. While developing its PWR1, the UK would purchase a S5W reactor system for installation in the Royal Navy's first submarine, the HMS *Dreadnought* that was launched in 1960 [85].

In the 1960s, General Electric's S5G submarine reactor for the USS *Narwhal* would become the first to use natural circulation [86]. At low and medium speeds, the natural circulation provided sufficient heat transfer, with primary pumps only being needed for high-speed operation [82] (p. 135). In a land-based plant, the reactor orientation is constant, but in a marine application, the reactor tilts at various angles with the ship's roll and pitch. Hence, a 54 ft wide × 240 ft long (16 m × 73 m) concrete test basin for the S5G prototype was built at Idaho [67] (p. 92), and gyro stabilizers were incorporated to rock the prototype to a roll angle of 15° to each side to simulate sea conditions [87]. The SG5 prototype included the 21 ft long × 33 ft diam. (6.4 m × 10 m) RC, as well as an engine compartment with a control room and a forward end compartment that housed the gyroscopes [88].

Warship reactor design entails ensuring operation under adverse conditions including battle shock [89]. As such, dead time caused by xenon-135 poisoning is unacceptable. To compensate for this, some navies have utilized high-enrichment uranium (HEU) fuel to provide sufficient excess positive reactivity. The use of HEU provides a smaller core, high specific power (kW/kg), and long core life [62]. Although the first and second *Nautilus* cores had enrichments of 18–20% and 40%, respectively [82] (p. 134), U.S. naval reactor cores were later enriched from 93% to 97.3% [90]. The utilization of HEU, and especially weapons-grade uranium, in naval reactors has elicited proliferation concerns [90,91]. In contrast, China, France, India, and Russia reportedly use enrichments of 3–5%, 7–90%, 40%, and 20–45%, respectively [90,92]. Thus far, nuclear naval systems have been operated only by nations possessing nuclear weapons; however, this status quo may be upset with plans by Australia via the AUKUS (Australia, United Kingdom, United States) trilateral security partnership [93] and Brazil's indigenous nuclear-powered submarine *Álvaro Alberto* [94]. AUKUS's plans include delivery of a *Viriginia*-class nuclear-powered but conventionally armed submarine to Australia sometime in the early 2030s [95].

Naval propulsion systems have two design options for driving the propellor: either (a) directly from the steam turbine or (b) by using an electric motor that derives power from a turbogenerator [10]. Even in the former case, a turbogenerator is needed to produce electricity to supply pumps and other equipment on board the ship. After Short (1961) [96], the first truly representative diagrams of a PWR in a submarine seem to have appeared publicly in 1984 from Rolls-Royce, which designs the UK's submarine PWRs [10,82,97]. Many of the naval PWR system schematics found in the literature today, such as that in Figure 5, can probably be traced back to the UK's PWR1 diagram. Modern submarines may utilize a pump-jet propulsion system that pushes the vessel by sucking in and then expelling the seawater. Less well publicized is that Welsh (2009) of Rolls-Royce shows a passive design for residual heat removal from the submarine PWR2 [98], as replicated in Figure 5; however, the submarine has water above and below the hull, permitting natural circulation of the seawater through the boat from the bottom to the top—a situation unavailable to a surface ship. (Technically, a submarine is a ship; however, for historical reasons submariners traditionally refer to their vessel as a boat [99,100].)

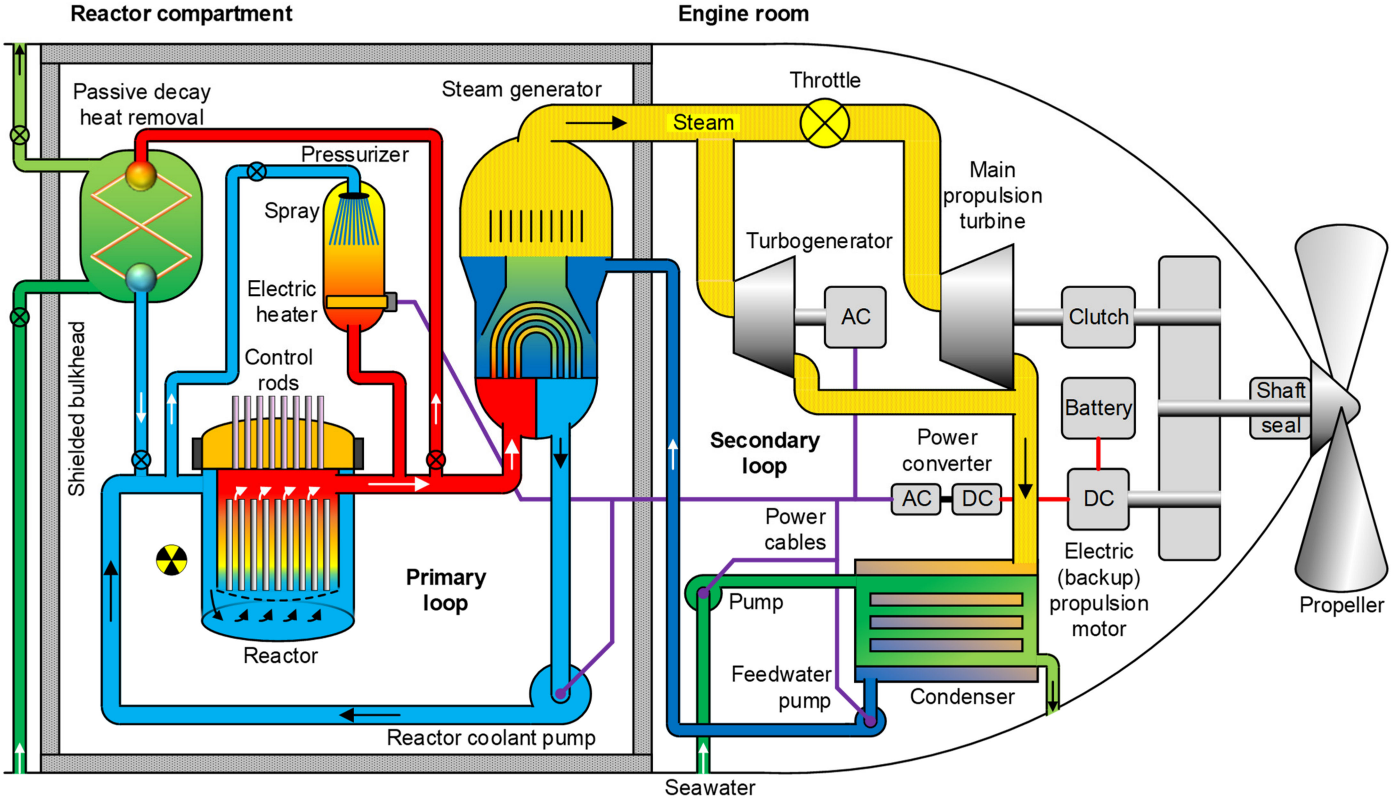

Figure 5. Representative naval nuclear propulsion system using a pressurized water reactor. Note the decay heat removal tank that could permit passive core cooling indirectly using seawater in the event of loss of electric power to active decay heat removal systems. Diagram after [10,82,97,98].

Kostin et al. (2007) describe four generations of Soviet Russian submarines [101]. More recently, Zverev et al. (2020) refer to five generations of Russian ship reactors [32]. Except for the USS *Triton*, Western submarines have employed a single reactor, whereas many Soviet submarines housed dual reactor systems [102]. The *Triton* is famous for having retraced Magellan's three-year voyage to circumnavigate the globe underwater [103].

Unfortunately, there have been several instances of reactor-related accidents on Soviet submarines. Mian et al. (2019) state that "of the 14 nuclear reactor-related accidents on submarines, 13 occurred with Soviet/Russian vessels. Six suffered loss of coolant accidents, five had uncontrolled startup due to operator errors, while in nine of the accidents, the reactor core was damaged" [104]. Ølgaard (2001) tallied five criticality accidents, nine loss-of-coolant accidents (LOCAs), and three other uncharacterized reactor accidents in the USSR/Russian Navy [105]. Those early Soviet submarine accidents include the following [104,106]:

- 1961: K-19 LOCA, from which at least eight people suffered acute radiation syndrome (ARS) due to repairing/welding a pipe in the RC;
- 1968: K-27 LMR LOCA that resulted in nine deaths from ARS;
- 1985: K-431 criticality accident during refueling that killed 10 workers.

In the last case, a steam explosion occurred that hurled new fuel and started a fire [107]. Sarkisov and Vysotskii (2021) describe that 1985 nuclear submarine accident as being the largest naval incident globally, reaching Level 5 (i.e., an accident with wider consequences) on the International Nuclear and Radiological Event Scale (INES) [108]. They indicate that all the atomic fleet accidents occurred in the first- and second-generation nuclear submarines of 1960–1990 and that, subsequently, no accidents transpired on submarines of the third and fourth generations [108].

4. Floating Nuclear Power Plants

Floating nuclear power plants (FNPPs) are not naval nuclear propulsion systems, but it is important to be cognizant of their existence in the realm of marine nuclear systems. Floating nuclear reactor systems may be used for more than one purpose, including electricity generation, process heat production, and desalination [109]. Large-scale offshore power plants have been considered as far back as the 1970s. The Atlantic Generating Station was to have been an approximately 1000 MWe floating nuclear plant moored within a massive D-shaped breakwater [110]. The U.S. Nuclear Regulatory Commission (NRC) staff undertook a study that found, except for a core-melt accident, that "the risks and impacts via the liquid pathway from postulated accidents at [floating nuclear plants] at representative sites are expected to be substantially the same as that expected for [land-based plants]" [111]. Unsurprisingly, the concerns then about an offshore nuclear plant remain today—in particular, the release of radioactivity in a water environment. The advantages of the offshore approach included alternative siting options where land tracts are unavailable, insensitivity to seismic disturbances, and more than ample condenser cooling water [112]. More recent safety analyses for floating nuclear power plants include [113].

Buongiorno et al. (2016) provide a tabular comparison of nine civilian offshore nuclear power plants built or designed [114,115]. Of those nine proposed plants, only one—the Russian *Akademik Lomonosov*—has been built and deployed as a floating nuclear power plant. Absent from that tabular comparison was the world's first floating nuclear plant, the *Sturgis*, from the 1960s. Thus far, all these moored nuclear facilities have utilized PWRs to generate electricity and/or heat.

4.1. Sturgis

During 1968–1976, the *Sturgis* barge served as the world's first floating nuclear power plant [61] (pp. 142–144), [116]. The *Sturgis*, shown in Figure 6, was a World War II Liberty ship converted in the 1960s for this purpose. The midbody of the original Liberty ship was entirely replaced with a new midsection designed to protect the reactor system from external impacts such as severe grounding or a broadside collision with another vessel [117]. The *Sturgis* LEU reactor was developed as part of the U.S. Army Nuclear Power Program (ANPP) and designated MH-1A (mobile high-power number 1A) [116]. Predating the U.S. Nuclear Regulatory Commission (NRC), the Atomic Energy Commission reviewed the project at specific milestones.

With a design pressure of 1500 psia (10 MPa), this 45 MWt single-loop PWR supplied 10 MWe to shore facilities with a thermal efficiency of 22%. The core was fueled with 32 fuel elements composed of 5% enriched UO_2. Twelve cruciform control rods of enriched boron provided regulating capability. Unlike the Shippingport power station and the N.S. *Savannah*, the reactor inlet nozzle was placed above the top of the core. The single steam generator had normal inlet and exit temperatures of 510° and 470 °F (266° and 243 °C). In the event of pump failure, the MH-1A primary system was designed such that natural circulation could gradually reduce the primary coolant from the maximum design temperature of 617°F (325 °C) to a safe level of 120°F (49 °C) over 5 days [117]. The MH-1A NSSS was housed in an ovoid containment vessel, with a spent fuel tank nearby [117]. The 320-ton stainless steel containment vessel, which was 43 ft (13 m) long and 31 ft (9.4 m) diameter, was designed to accommodate the maximum credible accident pressure [117]. Water surrounding the reactor pressure vessel served as primary shielding, and secondary shielding was supplied by up to 4 ft (1.2 m) thick reinforced concrete, 5 in. (13 cm) of lead, and 8 in. (20 cm) of polyethylene surrounding the containment vessel and the spent fuel storage cask [117].

Figure 6. *Sturgis*, floating nuclear power plant operating in the Panama Canal Zone. The electrical substation is seen on the bow. Photo credit: U.S. Army Corps of Engineers (circa 1970).

Beginning in 1967, the *Sturgis* MH-1A initially supplied power to Fort Belvoir in Virginia [117]. The Sturgis turbogenerator could supply either 50 Hz or 60 Hz ac power. In July 1968, the *Sturgis* was deployed to the Panama Canal Zone (PCZ), which at that time was a territorial unit of the U.S., to generate electricity for military and civilian use because the output capacity of PCZ hydroelectric plants was curtailed due to drought and the dry season [117] and other factors [118]. The *Sturgis* arrived at the PCZ in August 1968 and began delivering power two months later. Before shutting down the MH-1A in July 1976, the reactor would be refueled four times while in the PCZ [117]. Reasons given for discontinuing its use include the completion of the Panamanian government-backed 150 MW Bayano Hydroelectric Plant, the costs for the small output plant, and the need to upgrade the NSSS to comply with the latest NRC requirements; for instance, the MH-1A lacked an emergency cooling system [117].

4.2. Akademik Lomonosov

Moored in Pevek, Chukotka (Russia's far east), the *Akademik Lomonosov* began generating electricity in December 2019. Fully commissioned in May 2020, the Russian floating power unit (FPU) *Akademik Lomonosov* contains two 150 MWt PWRs that supply both electric power and heat to meet coastal needs [119]. Besides serving as a cogeneration facility, this FPU has also been envisioned to desalinate seawater [120].

Figure 7 shows the barge that houses the two KLT-40S reactors, which are a derivative of the 135 MWt KLT-40 reactor used on the container/carrier icebreaker *Sevmorput* [121,122] presented in Section 5.4. Together, the two KLT-40S reactor units onboard can generate a maximum power of 70 MWe while supplying 50 Gcal/h of heat or supply a maximum thermal power of 146 Gcal/h while producing 38.8 MWe [120].

Figure 7. The start of towing of the (unpainted) floating power unit *Akademik Lomonosov* to Murmansk on 28 April 2018. Photo credit: ROSATOM (https://www.rosatom.ru/en/, accessed on 16 August 2024).

The KLT-40S modular NSSS places four steam generators and four reactor coolant pumps near the RPV with short, large-diameter pipes connecting this equipment [123]. The fuel enrichment is reportedly 14.06% [124], thereby making it HALEU. The service life of the reactor is expected to be 40 y with 2.5–3 y between refuelings [121]. Additional specifications of the KLT-40S reactors are given in Table 2.

In performing a Level 1 probabilistic risk assessment (PRA), Antipin et al. (2020) found a total probability of less than 10^{-6}/y for a severe accident with core damage for a FPU with a KLT-40S reactor installation [125]. For 2020, the average radiation dose (internal and external) for the 255 personnel of the *Akademik Lomonosov* was 0.24 ± 0.21 mSv with 52 people receiving a zero dose [126]. Sarkisov et al. (2008) provide estimates of external and internal exposures from the *Akademik Lomonosov* under normal and accident conditions [127].

Although the *Akademik Lomonosov* operates domestically, Lysenko et al. (2019) provide an interesting analysis of legal regulations related to the export and operation of FNPPs under international law, including some gaps and gray areas [128]. Fialkoff (2020) states "existing international legal regimes for both nuclear and maritime security do not explicitly address or account for FNPPs" [129]. Such uncertainties in the law have been expressed by others since at least the 1980s [130], and there has been an uptick in publications on the subject [131,132]. Even though the 1980s IMO Code is intended for nuclear-propelled ships, some have utilized its requirements for FNPPs [133]; however, in October 2024, the American Bureau of Shipping released a 70-page set of requirements for the design, construction, and survey of vessels such as FNPPs having onboard nuclear power system installations [134]. One can imagine that as a revival of nuclear marine propulsion becomes more likely, there will be a similar increase in legal analyses and what-if scenarios.

4.3. Planned FNPPs

Besides Russia, other nations have plans for implementing FNPPs. Table 2 compares some of the marine based reactors being investigated. China's two state-owned nuclear corporations are developing FNPPs to supply power to oil rigs and artificial (and in some cases contested) islands in the Pacific [135,136]. The China General Nuclear Power Group

(CGN) has proposed the ACPR50S floating reactor with a 200 MWt, 50 MWe output, whereas China National Nuclear Power (CNNP) has plans for the ACP100S reactor, a marine version of its ACP100, which would generate 385 MWt, 125 MWe [137]. Korea Electric Power Corp. (KEPCO) has proposed the development of a FNPP using the BANDI-60 200-MWt PWR [138,139]. In addition, Korea Hydro & Nuclear Power (KHNP), which is a subsidiary of KEPCO, is part of a consortium that plans to develop molten salt-reactor-based FNPPs in the range of 200–800 MWe (recall that KHNP operates and exports the APR 1400 PWR [140]).

While not wishing to wade into politics, we must be alert to the possibility that the efforts of some entities to deploy FNPPs may be called into question for nationalist rather than technical reasons. For example, the safety or proliferation risk of a deployed power unit may be challenged as a diversion to the actual reason for objecting to its installation.

Table 2. Characteristics of floating PWR power systems.

Parameter	China ACPR50S	China ACP100S	South Korea BANDI-60	Russia KLT-40S
Nominal reactor power, MWt	200	385	200	150
Electric power output, MWe	50	125	60	35
Reactor coolant pressure, MPa	15.5	15	15.5	12.7
Core inlet/exit temperature, °C	299.3/321.8	286.5/319.5	290/325	280/316
Number of fuel assemblies	37	57	52	121
Fuel enrichment, %	<5	<4.95	4.95	18.6
Discharge burnup, GWd/t	<52	<52	29.4	45.4
Refueling cycle, months	30	24	48–60	30–36
RPV height/diameter, m	7.2/2.2	10/3.35	11.2/2.8	4.8/2.0

Data source: IAEA (2022) [141].

5. Nuclear-Powered Merchant Ships

In 1957, the Soviet Union's icebreaker *Lenin* became the world's first nuclear-powered surface vessel launched. Not including Russian icebreakers (which are explored in the next section), there have been four nuclear-powered civilian ships, as listed in Table 3. A marine reactor must be designed to accommodate more rapid changes in load compared to land-based reactor systems [10,142]. The *Savannah* NSSS was designed to increase load from 20% to 85% in 10 s and decrease power from 100% to 20% in 3 s [143,144]. Thus far, all the civilian ships, including the icebreakers, have utilized PWRs. The first three ships in Table 3 were intended more so as demonstration vessels to obtain technical data and practical knowledge [20], and, in fact, we find that both the *Otto Hahn* and *Mutsu* were eventually refitted with diesel engines. Although commercial nuclear power plants achieve thermal efficiencies of around 33% using equipment such as feedwater heaters, the overall efficiency of a nuclear ship is significantly lower; however, we also note that determining the overall efficiency η requires including the mechanical (P_m) and electrical (P_e) outputs, respectively, of the main propulsion turbine and the turbogenerator of Figure 5, that is, from the reactor power (P_{Rx})

$$\eta = (P_m + P_e)/P_{Rx} \quad (1)$$

We must be mindful that deployed marine personnel may be confined to their ship 24 h per day, 7 d per week, unlike individuals employed in an onshore job. In contrast to a simple 50 mSv (5 rem) annual occupational dose limit, the IMO sets dose rate limits according to the area on the ship as listed in Table 4. Except for Russia's *Sevmorput*, these merchant ships predated the IMO's 1982 Code of Safety for Nuclear Merchant Ships and instead needed to adhere to the International Convention on Safety of Life at Sea (SOLAS, 1962), which contained rules and recommendations on nuclear ship safety in Chapter VIII and in Annex C [145]. Wilkinson et al. (1970) observed at that time that neither Germany nor Japan was allowed by treaty to have a nuclear warship program such that any experience with marine nuclear propulsion would have to originate from merchant ships [146].

Table 3. Nuclear-powered merchant vessel characteristics and specifications.

Nuclear Ship	*Savannah*	*Otto Hahn*	*Mutsu*	*Sevmorput*
Country	United States	West Germany	Japan	Russia
Ship type (purpose)	Cargo and passenger	Cargo (ore carrier)	Cargo	Icebreaking freighter
Operational period	1962–1970	1968–1979	1974, 1991–1992	1988–present
Reactor power (MWt)	70→80	38	36	135
Reactor coolant pressure (MPa)	11.96	6.33	10.9	13
Reactor coolant average temperature (°C)	264	273	278	295
Enrichment (wt%)	4.2–4.6 (average: 4.4)	2.80–4.86	3.24–4.44	90
Core life (full power days)	760	500	375	417
Shaft power (hp)	22,000	10,000	10,000	39,400
Shaft power (MW)	16.4	7.46	7.46	29.4
Speed (knots)	21	17	17	20.8
Maximum load increase rate (% steam flow)	10% to 80% in 10 s (6%/s)	10% to 100% in 90 s (1%/s)	18% to 90% in 30 s (2.4%/s)	See text
Maximum load decrease rate (% steam flow)	100% to 20% in 3 s	100% to 10% in 1 s	100% to 18% in 1 s	See text

Data sources: B&W 40th edition of *Steam* (1992) [144], Freire and Andrade (2015) [8], Schoyen and Steger-Jensen (2017) [5], Higson (1971) [147], Bünemann et al. (1972) [148], Ishida et al. (1993) [142].

Table 4. Limiting dose-equivalent rates for different areas and spaces.

Area or Space	Dose-Equivalent Rate
1. In the navigating bridge	0.75 µSv/h (0.075 mrem/h)
2. In accommodation spaces	0.15 µSv/h (0.015 mrem/h)
3. On upper deck and in cargo spaces	0.50 µSv/h (0.050 mrem/h)
4. On ship's sides above the waterline	0.50 µSv/h (0.050 mrem/h)
5. On ship's bottom where "in water" maintenance or survey is contemplated with the reactor at 10% power	7.5 µSv/h (0.75 mrem/h)

Source: IMO (1982) [18] (p. 121). These dose-equivalent rates are from ship sources only; they do not include natural background radiation.

5.1. Savannah

The NS (nuclear ship) *Savannah* was named after the SS (steam ship) *Savannah*, which was the first vessel to use steam power on an Atlantic crossing [149] (p. 125). Launched in July 1959, the NS *Savannah* was a passenger and bulk cargo vessel, as showcased in Figure 8. As part of U.S. President Eisenhower's (December 1953) Atoms for Peace initiative, the *Savannah* merchant ship program was absent of military involvement. Instead, the *Savannah*'s development was jointly directed by the Atomic Energy Commission (AEC) and the Maritime Administration (MARAD) [149]. As the only merchant ship to transport passengers, construction of the civilian *Savannah* passenger–cargo ship provided the opportunity to demonstrate the safe conveyance of the public using nuclear power. In fact, passengers were provided with a viewing gallery to observe the reactor operators.

Figure 8. NS *Savannah* enroute to the 1962 World's Fair. Photo from U.S. Atomic Energy Commission via U.S. National Archives NAID 542141.

The Babcock & Wilcox Company (B&W) designed and built the 70 MWt nuclear reactor, which was later uprated to 80 MWt [23]. Reactor criticality was first reached on 21 December 1961 [9,150]. Figure 9 shows that *Savannah*'s reactor was a two-loop PWR, with each loop comprising two primary coolant pumps and a steam generator producing saturated steam. The steam generator consisted of a lower section with horizontally oriented U-tubes with a U-shell housing above which the heated secondary water passed through boiler risers into a steam drum upper section. The risers and downcomers were designed to ensure natural circulation at all loads and attitudes of the ship within the design pitch and roll conditions [151]. Two gate and two check valves were provided in each loop such that either loop could be isolated from the reactor if needed. The steam turbine drove a single screw for propulsion.

Unlike present PWRs, the coolant was said to undergo a triple pass through the core. Similarly to the Shippingport reactor, the inlet nozzles from the cold leg were located near the bottom of the RPV such that the first coolant pass was up through the three stainless steel thermal shields, the second pass was down through the exterior half of the core (16 fuel elements), and the third pass was up through the remaining central 16 fuel assemblies [149] (p. 153), [151]. As seen in Figure 10, the core comprised 32 fuel elements of either 4.2% or 4.6% enrichment. The UO_2 fuel pellets were placed in type 304 stainless steel fuel rods; this use of stainless steel is unusual compared to today's PWRs, as the stainless steel contained boron that served as a burnable poison [16,152]. Each of the 32 fuel assemblies consisted of 164 fuel rods. Twenty-one cruciform-shaped control elements (rods) made of enriched boron were employed [16,149] (p. 165), to maintain an average reactor coolant temperature of 508 °F (264 °C) [66]. At 80 MWt, the core inlet and outlet temperatures were 494.6 °F and 521.4 °F (257 °C and 272 °C), respectively [151]. Kramer (1962) [149] and Rev. III (1968) of the equivalent to a final safety analysis report (FSAR) [143] provide additional quantitative details on the thermal, hydraulic, and nuclear design and performance characteristics of the *Savannah* NSSS. Per FSAR performance data at 70.0 MWt reactor operation, the propulsion shaft power was 22,000 hp (16.4 MW), and the total electric load was 2.4 MW, yielding an overall thermal efficiency of 26.9%. Twin 1.5 MWe turbogenerators fed ship electric power needs.

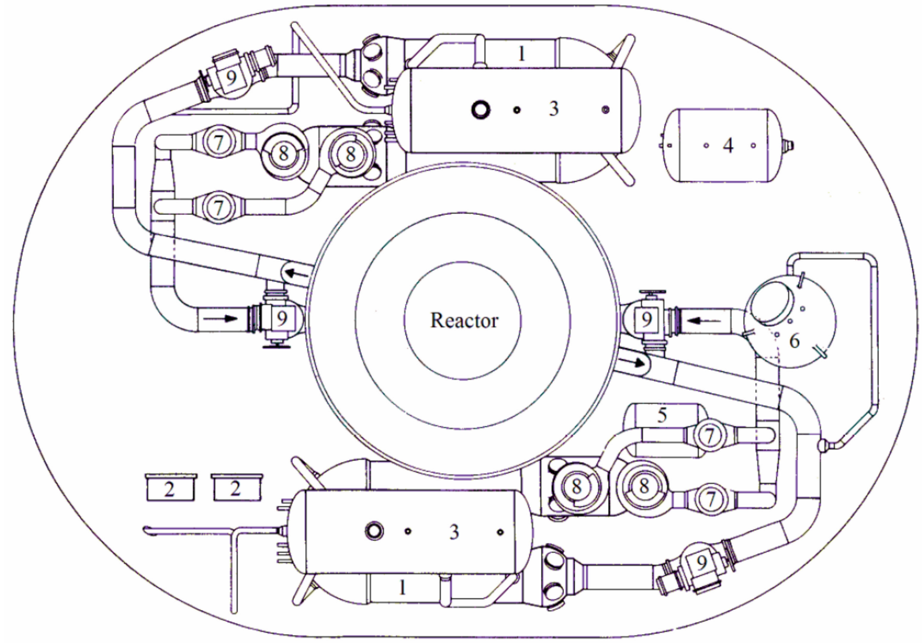

Figure 9. Top view of the *Savannah* nuclear steam supply system (NSSS), which was a two-loop PWR housed within a steel containment vessel [143,152]. Legend: 1. steam generator horizontal U-tube bundle, 2. letdown coolers, 3. steam drum, 4. effluent condensing tank, 5. containment drain tank, 6. pressurizer, 7. check valve, 8. primary coolant pump, and 9. gate valve.

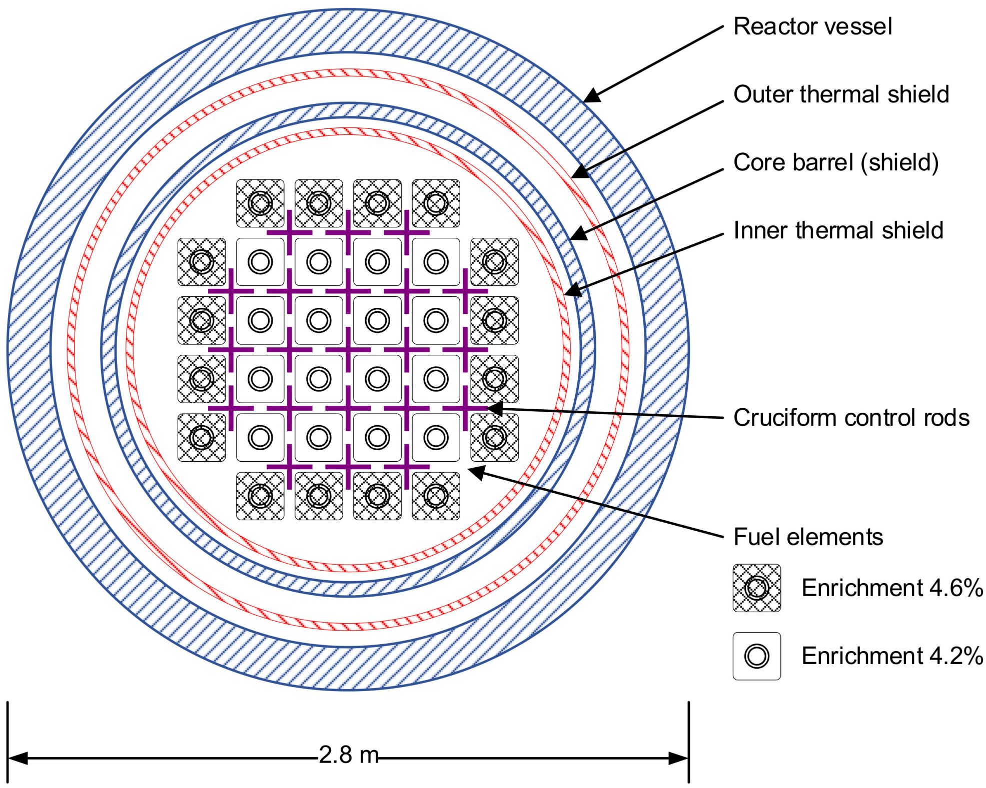

Figure 10. Top view of *Savannah* reactor core, including the three concentric thermal shields protecting the reactor pressure vessel [149] (pp. 165, 541), [153]. The middle thermal shield also serves as the core support shroud [149] (p. 153).

The 227-ton, 40,000 ft^3 (1130 m^3) reactor containment vessel shown in Figure 11 was designed and hydrostatically tested to a pressure of 173 psig (1190 kPa), which was the maximum credible accident (MCA) conditions based on an instantaneous release of the primary system fluid energy at full power [151]. The reactor compartment provided secondary containment and housed the containment vessel and secondary shielding. Other standard accident scenarios analyzed included reactivity accidents, loss of power, and fire [143]. The mobile nature of the *Savannah* was an impetus in 1962 for modifying the Atomic Energy Commission (AEC) Reactor Site Criteria that were originally developed for stationary reactors [154].

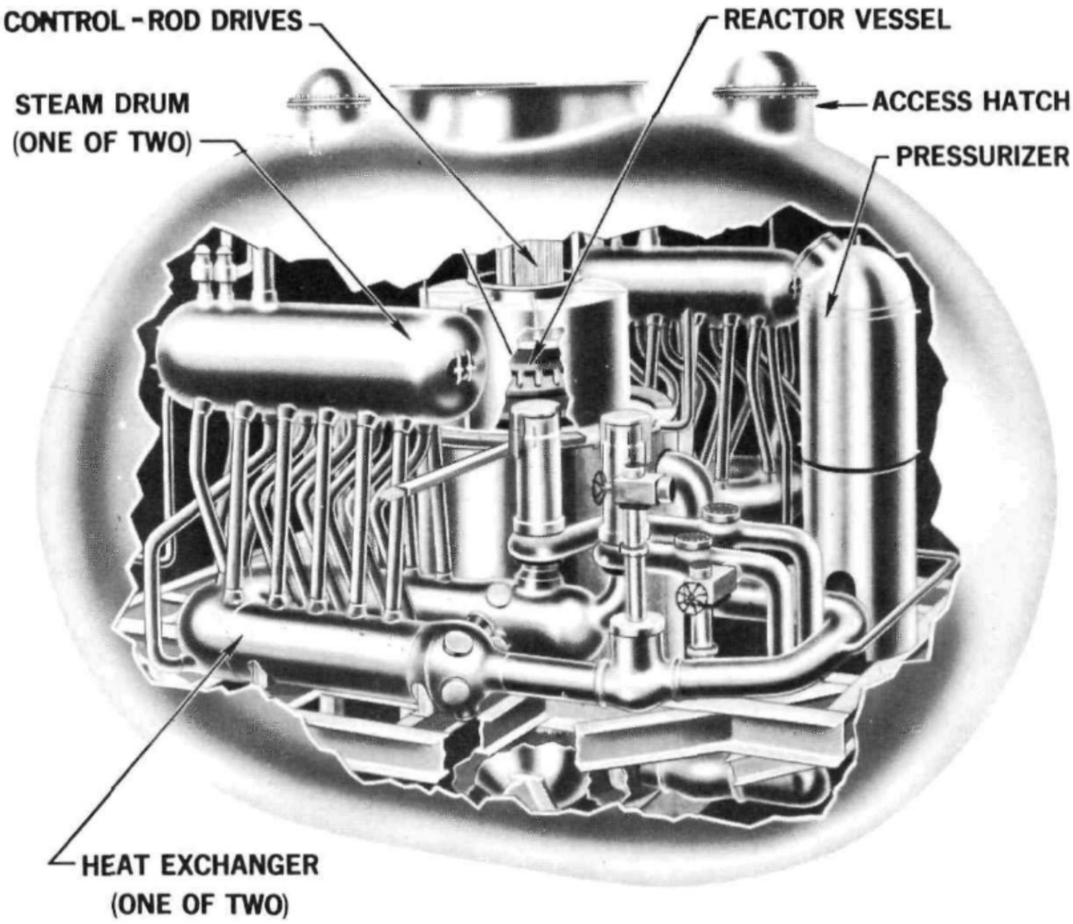

Figure 11. The entire NSSS of the *Savannah* was housed within a steel containment vessel. Source: [152].

The NS *Savannah* reactor was designed for a normal operating power of 63.5 MWt using an initial U-235 loading of 312.4 kg [153]. The first core provided 15,000 full power hours of energy, and the ship traveled about 330,000 miles [66]. In the latter half of 1968, the core was shuffled with interior and peripheral elements generally swapped and four new fuel assemblies installed in the center to form Core Ia [151]. Although a minor fuel failure was detected prior to the fuel shuffling, operations were not limited. A tender named *Atomic Servant* supported refueling and liquid waste operations [155]. Core II had been designed and its 36 new fuel elements obtained, but it was never used [151].

For primary shielding, the reactor vessel was surrounded laterally by a 33 inch (84 cm) thick annulus of water and 1 to 4 in. (2.5–10 cm) of lead [151]. The secondary radiation shield consisted of 1077 tons of concrete and 559 tons of lead and polyethylene surrounding the containment vessel [17,151]. The radiation dose during the initial year of commercial operation of the *Savannah* was an average of 88 mrem (0.88 mSv) and a maximum exposure of 1140 mrem (11.40 mSv) to a crew member, and no exposure to members of the public [156] (p. 6-2). In comparison, the average dose to crew of the Soviet icebreaker *Lenin* during the first three years of operation was much larger at 1.62 rem/y (0.162 mSv/y), and two individuals exceeded the 5 rem/y (0.5 mSv/y) average in the performance of maintenance work [157].

Backup electric and propulsion systems were installed in the event reactor power was unavailable. Twin 750 kW auxiliary diesel generators could start and supply power within 15 s [143]. In addition, a 300 kW emergency diesel generator was onboard to supply vital systems. An alternative (so-called take home) propulsion system was provided in the form of a 750 hp reversible electric motor that could yield about 6 knots.

Entering service in May 1962, the *Savannah* would visit 32 domestic and 45 international ports in 26 countries before retirement in July 1970 [46,66,151], but the ship was excluded from port visits to Australia, Japan, and New Zealand [5]. The U.S. government had indemnified the *Savannah* against nuclear accidents up to USD 500 million [9,158]. The *Savannah* had two operating phases over her lifetime: 1962–1965, passenger and cargo demonstration, and 1965–1971, cargo-only experimental commercial demonstration [151]. Operating and maintenance experiences are chronicled in the literature [9,159] including the fact that a 60 psig leak rate test of the containment vessel caused an air leak into the electrical terminal bushings of two canned main coolant pumps in June 1965, resulting in the replacement of all four primary coolant pumps [160]. Having a peace mission, the NS *Savannah* was never meant to be an economical endeavor since a tanker or bulk (e.g., ore) carrier would achieve a better return on investment than a passenger–dry-cargo ship [149] (pp. 47, 131), [161]. The ship was designated a national historic landmark in 1991. Somewhat interestingly, a labor dispute arose in 1962 because the deck officers objected to earning less pay than the engineers, who were being paid extra because of their special training and licensure as reactor operators [162,163]. Consequently, operations halted, and the ship sat idle for a year, resulting in a new company being contracted to operate the *Savannah* and an entirely new crew having to be trained [156].

5.2. Otto Hahn

Named after one of the co-discoverers of fission, West Germany's *Otto Hahn* was an experimental ore cargo carrier but predominantly a research ship, and, because of the large number of research personnel, she also served as a passenger vessel [22]. The original contract called for an organic cooled and moderator reactor [164] before choosing the first-of-a-kind integral PWR [22]. The normal mechanical power output was 10,000 German shp (1 English shaft horsepower = 1.104 German shp) [148], with a 11,000 shp maximum, and electrical power was supplied by two 450 kW turbogenerators [22]. In addition, 450 kW auxiliary and 240 kW emergency diesel generators were installed [22]. When the ship was in port, a reactor output of 10% full power was sufficient to supply the turbogenerators, which served the non-propulsion (i.e., "hotel") load [22].

Although the *Otto Hahn* predated the IMO Code (1982) requiring an emergency propulsion system (so-called "take-home" drive) be provided for nuclear ships equipped with a single reactor of undemonstrated reliability [18] (§5.7), two oil-fired auxiliary boilers could provide 2000 shp to propel the ship at 8.5 knots [22] back to homeport from a distance of about 2500 miles [164].

First achieving criticality on 26 August 1968, the *Otto Hahn* reactor core was unique in its initial use of 12 square and 4 triangular fuel elements [22], as seen in Figure 12. The core had an active height and equivalent diameter of 1.12 m and 1.15 m, respectively, and an average thermal neutron flux of 1.1×10^{13} n/(cm^2·s) [22]. The square elements utilized a 17 × 17 array of mostly stainless steel fuel rods composed of sintered UO_2 [22].

Using four radial enrichment zones of 2.80%, 3.23%, 3.90%, and 4.86% enrichment, with an average of 4.03%, the initial core design anticipated 500 full days and a burnup of 7260 MWD/MTU from its 298 ton of UO_2 [22,148]. The twelve T-shaped B_4C control blades (rods) also used a stainless steel shell [22]; the burnable poison rods contained pellets of ZrB_2 in ZrO_2 [148]. The reactor coolant inlet and exit temperatures were 266.8 °C and 278 °C [148]. Although physically smaller with greater neutron leakage and having a larger power density (53.1 kW/L vs. 33.8 kW/L for the first core), the second core design eliminated the triangular elements and utilized zircaloy cladding, with a target burnup of 25,000 MWD/MTU [148].

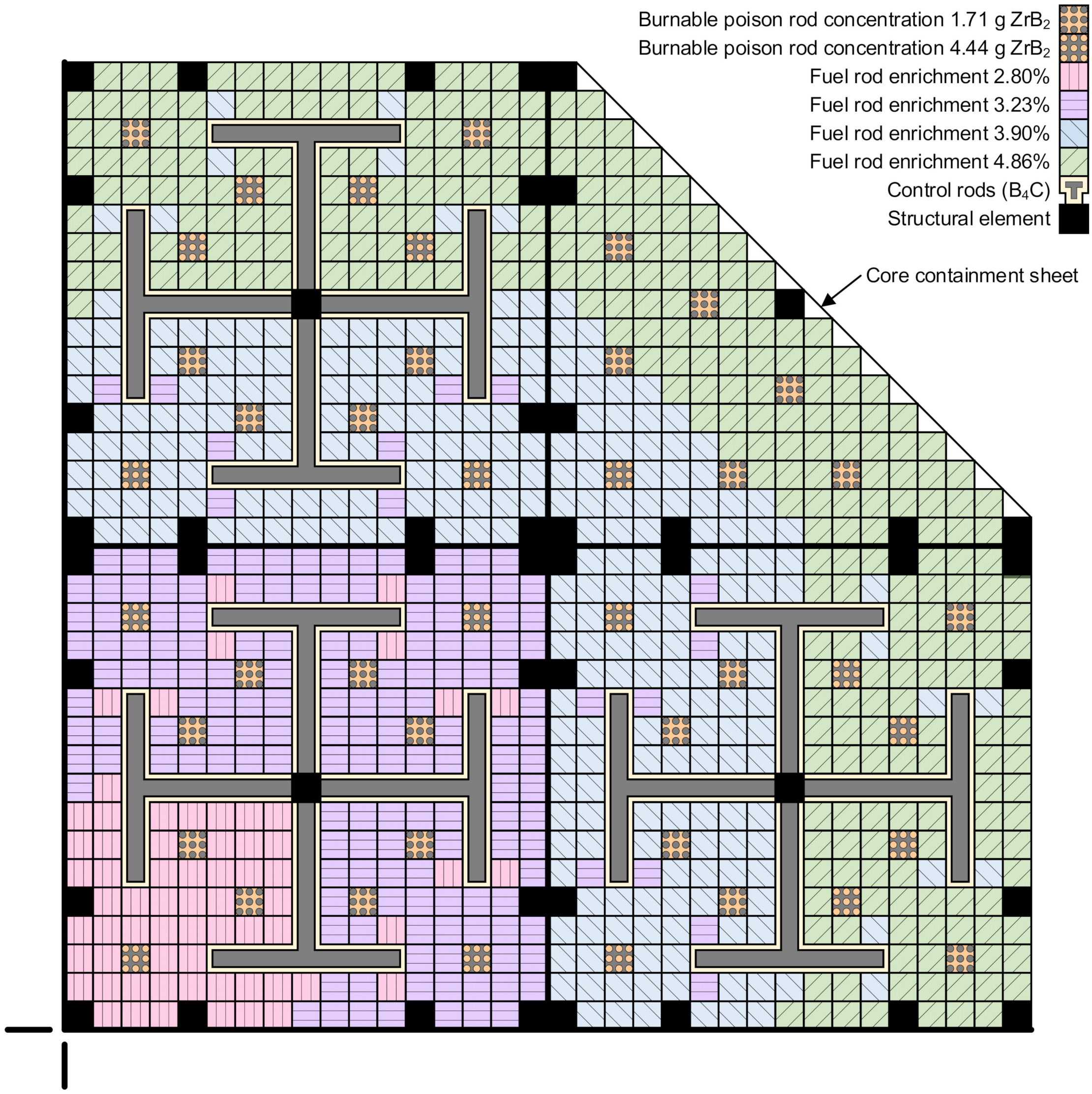

Figure 12. Top view of the first *Otto Hahn* reactor, which had quarter-core symmetry [148]. The radial enrichment zones were intended to flatten the power across the core and achieve uniform fuel consumption [20,148]. The second core design removed the triangular elements at the corners.

The *Otto Hahn* provides an instructive example of the uniqueness of marine reactor design. During a docking maneuver, reactor power demand would often vary from 10% to 70% over a few minutes [22]. Based on a maximum wave-induced acceleration of ±0.5 g and a void fraction of 5 vol.% due to nucleate boiling in hot channels at full power, the void effect amounted to a reactivity differential of 0.6% Δk, which could cause periodic (sinusoidal) power fluctuations of less than 10% in the reactor [148]. Moreover, reactor operations under such conditions should be scram-free [165].

Integrated PWRs (iPWRs) are not a new concept and have been used in both military and civilian vessels. An integral reactor has several advantages for marine applications, including the following:

- Reduction in weight and physical dimensions of the NSSS;
- Easier to enclose NSSS in a compact containment vessel;
- The absence of large primary pipes reduces the impact of a potential loss of coolant accident (LOCA);
- The possibility of achieving significant coolant circulation without pumps.

Germany's *Otto Hahn* ore carrier employed a modified version of the Consolidated Nuclear Steam Generator (CNSG) designed by B&W [10,66]. B&W is said to have estimated that the 2500-ton *Savannah* NSSS could have been replaced by an integrated unit weighing less than 800 tons [161], although there seems to be some inconsistency in the latter weight since the 38-MWt *Otto Hahn* containment vessel with its internal equipment weighed about 1000 tons [22]. The once-through helical-coil steam generators residing within the RPV produced 36 °C superheated steam [66,164]. The heat exchanger included 162 parallel helical tubes, each about 50 m long [148]. The upper head of the RPV constituted the iPWR pressurizer, and the three reactor coolant pumps were mounted to the RPV sides as what some describe as "horns". Harrington [20] says that about 25% full power could be produced by natural circulation. However, the compactness of an integral PWR can have unintended ramifications. For instance, without proper shielding, fast neutrons from the core could travel the short distance to the steam generators and activate the secondary coolant via the $^{16}O(n,p)^{16}N$ and $^{17}O(n,p)^{17}N$ reactions; any radioactive steam could then travel to the unshielded engine room [166]. Bünemann et al. report that 2.5 cm thick lead shielding in the hot well was sufficient to reduce the *Otto Hahn* dose to the required maximum of 0.06 mrem/h (0.6 μSv/h) in the engine room [148].

To achieve a maximum permissible dose rate of 60 mrem/h (0.6 mSv/h) within the containment vessel, the biological shielding around the RPV consisted of an annular water tank with two concentric layers of cast iron, but the three primary coolant pumps interrupted the arrangement [148]. The secondary shielding included 0.6 m of concrete outside the containment vessel [148]. Having a design pressure of 1.42 MPa at 200 °C, the 930-ton containment vessel was 13.4 m tall and 9.5 m in diameter [148,164]. In the event of sinking, flooding valves would have opened at an external overpressure of about 300 kPa, allowing seawater to enter the containment vessel to avoid its collapse [148]. During full load conditions, the primary shielding reduced dose rates to 15–20 mrem/h (0.15–0.2 mSv/h), thereby permitting short-term entry into the containment vessel [22].

The *Otto Hahn* visited 46 ports in 22 countries [46]. Pocock points out that environmentalists were organizing protests to nuclear power when the *Otto Hahn* was put to sea, thereby reducing the number of welcoming ports, unlike when the *Savannah* was commissioned [161]. Ulken et al. (1972) describe the initial operating experience during the life of the first core, including port-of-entry problems [167]. Justo and dos Santos (2000) reveal how a proposed German–Brazilian agreement concerning nuclear ships did not come to fruition [168]. After ten years of service, the nuclear propulsion system was replaced by a diesel engine [8]. A similar fate would befall the next nuclear ship—Japan's *Mutsu*.

5.3. Mutsu

The N.S. *Mutsu* was a single-propellor cargo ship equipped with a 10,000 shp geared saturated-steam turbine [169]. The propulsion steam turbine consisted of ahead and astern turbines [170]. The Mutsu was equipped with an auxiliary oil-fired boiler capable of driving the ship at 10 knots in the event nuclear propulsion was lost [171,172]. In addition to the two main 800 kWe ac generators, the ship had two auxiliary (720 kW each) diesel generators, a 240 kW emergency diesel generator, and separate batteries for instrumentation (1 kAh) and emergency (300 Ah) power [173].

Like the *Savannah*, the *Mutsu* reactor was a two-loop PWR using cruciform-shaped control rods [172]. In contrast, the *Mutsu* comprised only two reactor coolant pumps and employed two contemporary vertically oriented U-tube recirculation-type steam generators, as well as having the RPV inlet and outlet nozzles located above the top of the core [172,174]. The 36 MWt NSSS was housed in an almost spherical containment vessel with an inside diameter of about 10 m, free volume of 480 m^3 [174], and design pressure of 1.23 MPa [173].

The cylindrical core had an effective height and diameter of 1.04 m and 1.15 m, respectively [175]. The core consisted of 32 fuel assemblies, with each having 112 fuel rods and nine burnable poison—boron carbide (B_4C) dispersed in zircaloy—rods in an 11 × 11 square lattice [169,172,174]. The 12 interior assemblies were fueled with 3.2% enriched uranium dioxide pellets in stainless steel tubes while the outer 20 elements were 4.4% enrichment [171,172]. The 12 control blades employed an Ag-In-Cd alloy [169,171]. The reactor inlet and exit coolant temperatures at full load were 271 °C and 285 °C [172]. The initial core life was intended to deliver 9000 effective full power hours (~2 y) of operation, thus providing 13,500 MWD, which corresponds to a burnup of 5500 MWD/MTU for the 2.77-ton loading of UO_2 [169,172].

All ten articles in the June 1969 issue of *Nuclear Engineering and Design* were devoted to the *Mutsu*. Potential hazards were divided into two categories corresponding to those to the ship and those to the reactor [169]. In the former case, Ando judged that among the possible ship accidents of collision, grounding, heavy weather, fire, explosion, flooding, and sinking, collision appears to be the most serious because of the possibility of containment rupture and release of radioactive material [171]. Ando also tabulated an informative hazard analysis that compared the *Savannah* and *Mutsu* [171]. The reactor accident scenarios included reactivity accidents such as start-up, rod withdrawal and secondary system rupture, mechanical failures, loss of power to primary coolant and feedwater pumps, and power supply failure [169].

The importance of good radiation shield design can be illustrated using the Japanese merchant vessel *Mutsu*. Although shielding mockups had been carried out in the 1960s [176,177], during initial testing at sea in September 1974, the Japanese merchant ship experienced an unexpected increase in fast neutron leakage escaping the radiation shielding while at only 1.4% full power [8,178]. This event was reported in the media as "nuclear powered ship Mutsu leaked radioactivity" [178] (which is clearly an erroneous equating of the terms "radioactivity" and "radiation"). Consequently, the local fishermen were exceedingly concerned and protested, and the ship was not allowed back into the harbor for about 1.5 months after this maiden voyage [178]. Based on their design review, Westinghouse Electric Company had warned ahead of time that the planned shielding might permit radiation streaming, but the Japanese did not modify the original design [8]. The escaping neutrons leaked through an air gap of approximately 130 to 250 mm between the reactor pressure vessel and the primary shield [179]. After undergoing repairs in 1978–1982, *Mutsu* only operated in 1991–1992 [5,8]. The total shield mass was more than 70% of the reactor plant, with 2000 tons (88%) of the overall shield weight of 2260 tons being that of the secondary shield outside the containment vessel [166,173]. Like the *Mutsu*, the *Sturgis* had encountered a major flaw in the neutron shielding at full power [118] (p. 100).

5.4. *Sevmorput*

Named for the northern sea route upon which it operates, the N.S. *Sevmorput* is a nuclear-propelled, icebreaking freighter, as seen in Figure 13. The Russian ship is sometimes termed a LASH (lighters aboard ship) cargo carrier since the *Sevmorput* can transport

74 lighters, which are flat-bottomed barges (with each having a 300-ton cargo capacity). The lighters can be unloaded at sea where harbor depths are too shallow to permit ship entry. Alternatively, the *Sevmorput* can serve as a cargo container vessel. Thus, some refer to the *Sevmorput* as a lighter–container ship [121].

Figure 13. *Sevmorput* icebreaking lighter–container carrying freighter. Photo courtesy of Rosatom.

Commissioned in 1988 by the Soviet Union, the *Sevmorput* was the first nuclear-powered icebreaker cargo vessel constructed according to the IMO Code for nuclear cargo ships [121,180,181]. Considered a third-generation icebreaker, the *Sevmorput* employs a single 135 MWt KLT-40 reactor [121]. Compared to the other three nuclear merchant vessels, the *Sevmorput* is unique in that it was not a demonstration vessel and in its use of 90% enriched U-Zr alloy fuel [90,182,183]. The 1.00 m tall $\times$ 1.21 m diameter [184] core consists of 167 kg of high-enrichment uranium (150.7 kg of U-235) [8,182], which permitted its first core lifespan of 15 y [12]. In addition, the reactor comprises 241 fuel elements with 55 fuel pins each on a triangular lattice [91]. With respect to dynamic response, Ølgaard (1993) lists a power variation rate of 0.1 and 1 %/s but does not indicate which value is for load increase versus decrease [184]. Additional specifications of the KLT-40 reactors are given later in Table 5, as well as by Reistad and Ølgaard (2006) [182].

In terms of protective equipment, the biological shielding consists of steel plates, concrete, polyethylene, and lead [184]. The steel containment vessel can withstand a pressure of 360 kPa [184]. Normally, electric power is supplied by two of three 1700 kW turbogenerators; however, two 600 kW standby diesel generators are installed, as well as two 200 kW emergency diesel generators [184]. Like the other nuclear merchant vessels, an auxiliary boiler is available to take the ship home at 10.5 knots for 2000 miles if the nuclear propulsion system fails [184].

Surprisingly, the *Sevmorput* was denied entry into four major Soviet ports in 1988 because of post-Chernobyl fears and public protests [5]. With an initial design life of 100,000 h, which was attained in 2006, the reactor life was extended to 150,000 h [180,185]. Reportedly, the *Sevmorput* will be retired in 2024 [3], leaving the planet without any civilian nuclear-propelled merchant ships. Like the non-cargo-carrying icebreakers discussed in the next section, the *Sevmorput* is state-owned by the Russian Federation but operated by the company Atomflot.

Table 5. Soviet Russian nuclear icebreaker characteristics.

Class	Lenin	Arktika I	Taymyr	Arktika II
Ships	*Lenin*	*Arktika*, *Sibir*, *Rossiya*, *Sovetskiy Soyuz*, *Yamal*, [*50 Let Pobedy*]	*Taymyr*, *Vaygach*	*Arktika*, *Sibir*, *Ural*, *Yakutiya*
Class service period (circa)	1959–1967 1970–1989	1975–present [2007–present]	1989–present	2020–present
Reactor system (quantity)	OK-150 (3) OK-900 (2)	OK-900A (2)	KLT-40M	RITM-200 (2)
Enrichment (wt%)	5.0 36, 60	36, 60	90	46.7 (avg.)
Reactor power (MWt)	90×3 159×2	171×2	171	175×2
Propulsion power (shp)	44,000	75,000	50,000	80,000
Speed (knots)	18	20.6 [20.4]	16.5	22
Ice break thickness (m) at speed (knots)	2 2	2 2	1.77 2	2.8 2

Notes: The *50 Let Pobedy* is a larger ship, and when its specifications differ from those of the other Artika I class vessels, they are given in square brackets. Data sources: Makarov et al. (2000) [121]; Podvig (2011) [186]; Zverev et al. (2020) [185]; Bayraktar and Pamik (2023) [187].

6. Nuclear-Powered Icebreakers

The number (about a dozen) and operating time of nuclear-powered icebreakers significantly exceed that of the nuclear merchant ships. Although icebreakers are in the civilian sector, they are not necessarily categorized as merchant vessels because of structural features atypical of cargo ships [30,149] (pp. 7, 497). Kostin et al. (2007) noted that the icebreakers have operated 85–90% of the time in ice under conditions of elevated impacts and vibrational loads [101]. The Soviet Russian experience with nuclear-powered icebreakers is unchallenged; see Table 5. However, China is investigating nuclear icebreakers [188,189], and the U.S. has considered them in the past [17,190].

6.1. Soviet Russian Icebreakers

Launched on 5 December 1957, as the first non-U.S. nuclear-powered vessel, the Soviet Union's NS *Lenin* embarked on its maiden voyage on 15 September 1959, and entered service in December 1959 as the world's first nuclear-propelled surface ship [149] (p. 497). The *Lenin* icebreaker boasted three 90 MWt each, OK-150 PWRs, with one reactor kept in reserve for an emergency [61] (pp. 41–42), [149] (p. 48), [191]. The tri-reactor system supplied four main turbogenerators [181]. With a total engine power of 44,000 hp (33 MW), the three (aft) propellers were driven by electric motors with the center shaft being twice as powerful as the outboard units [192]. The three PWRs were located side by side in an isolated reactor compartment at the center of ship [193] (p. 18). Given the limited supply of HEU in the 1950s, it is understandable that the UO_2 fuel enrichment in the original *Lenin* OK-150 reactors was 5.0% [193] (p. 18), [186,194]. A water-filled steel shield tank surrounded the PWRs, and a biological shield comprising concrete and a heat-resistant composition of graphite and boron was located above the reactors [193] (p. 18). The original three 90 MWt OK-150 reactors in the Lenin would be replaced by two 159 MWt OK-900 reactors in 1970 [121,185], as discussed in the next subsection. The OK-900 cores employed HEU fuel with two zones enriched to 36% and 60% [186].

The first-generation icebreaker Lenin was followed by the second-generation *Arktika* class in 1975. The reactors in all the Russian icebreakers supply turbogenerators, which in turn power the propulsion motors. On 17 August 1977, the 75,000 shp Soviet nuclear-powered icebreaker *Arktika I* (Arctic I) would be the first surface vessel to reach the North Pole [195,196]. The second-generation icebreakers—*Arktika (I)*, *Sibir (I)*, *Rossiya*, *Sovetskii Soyuz*, *Yamal*, and *50 Let Pobedy*—employed two 171 MWt OK-900A reactors, which were improved versions of the OK-900 [121]. Like the KLT-40 type reactors, the OK-900(A) reactors use a block layout in which the steam generators and RCS pumps are in close proximity to the RPV.

Third-generation icebreakers utilized a single reactor, the KLT-40(M). Two shallow-draft icebreakers—the *Taymyr* and the *Vaygach*—for rivers were built jointly with Finland [181,197], with the propulsion system using the 171 MWt KLT-40M (modified) reactor whereas the *Sevmorput* container–icebreaker employed a 135 MWt KLT-40 reactor [121]. The KLT-40 reactor met the 1982 IMO code, which was required to enter foreign ports [121,180]. Among other modifications, the KLT-40M reduced the biological shielding mass and thus lowered the icebreaker draft through optimization [180,185].

The fourth-generation icebreakers, which include the *Arktika (II)*, *Sibir (II)*, and *Ural* with additional ships under construction (e.g., *Yakutiya*), utilize two 175 MWT RITM-200 evolutionary PWRs each. The RITM-200 NSSS boasts an integral reactor configuration with the core and steam generators within the RPV and the four coolant pumps as horns on the RPV [198]. Besides the characteristics presented in Table 6, Zverev et al. (2020) provide additional quantitative information about the RITM-200 such as the primary coolant flow rate of 3250 ton/h, the feedwater temperature of 105 °C, and the power rate of change of 0.1%/s [185]. Zverev et al. (2020) also state that the average U-235 enrichment of the fuel is 46.7% (HEU), which provides an estimated core life of 75,000 h and a service life of 10–12 y [185]; however, Beliavskii et al. (2022) list an enrichment of 19%, which is HALEU, that leads to a core life of 48,500 h [199]. Zverev et al. (2020) also present data on the future RITM-400 core, including its average enrichment of 53.8% [185].

Table 6. Specifications of the Soviet Russian icebreaker nuclear reactor systems.

Parameter	First Generation OK-150	Second Generation OK-900 (A)	Third Generation KLT-40 (M) [S]	Fourth Generation RITM-200 (400)
Nominal reactor power, MWt	90	159 (171)	135 (171) [150]	175 (315)
Power density, kW/t	89.5	130.6	82.6 (130) [80.2]	159.1 (?)
Core energy resource, TWh	0.4	2.1	2.1 (?) [2.1]	4.5 (6)
Reactor unit mass, t	3017	2432	1634 (1300) [3740]	2200 (?)
Core inlet temperature, °C	261	278 (273)	279 (273) [280]	277 (279)
Core exit temperature, °C	284	318 (316)	311 (316) [316]	313 (325)
Reactor coolant pressure, MPa	18	13	13 [12.7]	15.7
Steam flow, tons/h	120	220 (240)	215 (240) [240]	248 (450)
Steam temperature, °C	290	305 (290)	290 (300) [290]	295
Steam pressure, MPa	3.1	3.19 (3.34)	4 (3.4) [3.82]	3.82 (3.83)

For the second, third, and fourth generation columns, the values in the parentheses are for the OK-900A, KLT-400M, and RITM-400, respectively, if they differ from the OK-900, KLT-40, and RITM-200, and the values in the square brackets are for the KLT-40S. Data sources: Makarov et al. (2000) [121], Zverev et al. (2020) [185], Belyaev et al. (2020) [119], Petrunin (2021) [200], Zverev et al. (2019) [180]. In three instances, data were not found and as such are denoted with a question mark (?).

6.2. Lenin Accident(s)

The *Lenin* icebreaker suffered one, or perhaps two, nuclear-related accidents in the 1960s. During a period of openness after the dissolution of the Soviet Union, Russian Federation President Boris Yeltsin declassified information about dumping liquid and solid radioactive wastes in the northern and far eastern seas [194,201]. The resulting report, known in Russia as the White Book, was published in March 1993 [194,202–205], and its primary author, A.V. Yablokov, provides an extracted version in [201].

The following events have been pieced together, but to the author's knowledge, an official explanation of the incident(s) has not been published publicly. In February 1965, a loss-of-coolant accident (LOCA) occurred while the *Lenin* was at port undergoing scheduled (refueling) maintenance; in particular, due to human error, the center reactor became uncovered by water, resulting in some fuel melting from decay heat [61] (p. 44), [193] (p. 10), [194,202]. That center, number two (N2), PWR last operated on 13 November 1964 [193] (p.20), [194,203]. The three-month period between shutdown and the LOCA should have permitted decay heat to reduce to <0.4% of the normal power depending on the operating power history of the N2 reactor. For instance, in later studies to evaluate the radioactivity of the spent fuel, Rubtsov and Ruzhanskii (1996) assumed an average power of 54.4 MWt with a bimodal power histogram for the N2 reactor [203]. Like the NS *Savannah*, which had a tender named *Atomic Servant* [155], the *Lepse* was a tender for reloading fuel in the *Lenin* and other icebreakers [206] and storing spent fuel [207], but the exact role, if any, of the *Lepse* in the *Lenin* accident(s) is unstated.

On 18 September 1967, the screening assembly and 125 of the 219 fuel assemblies from the N2 reactor of the *Lenin* were dumped into the Kara Sea (Figure 14) in a reinforced concrete and stainless steel shell container because "the irradiated fuel assemblies could not be removed from the core plate of the OK-150 reactor unit" [193] (pp. 7, 38), [201,205]. Elaboration is useful with respect to the so-called "screening assembly", which Refs. [193] (p. 38), [205], term the core barrel, whereas Sivintsev's (1994) description of concentric stainless steel cylinders to minimize heat and radiation effects to the reactor pressure vessel [194] indicates that the screening assemblage encompasses the thermal shields. Timms et al. (1997) provide a more definitive explanation by stating that the N2 core barrel with five thermal shields and the 125 lodged fuel assemblies were included in the dumped screening assembly [205]. Prior to sea disposal, criticality calculations on the 125 fuel assemblies in distilled water showed deeply subcritical conditions [194].

On 19 September 1967, the reactor compartment (RC) with the three irradiated reactor pressure vessels emptied of spent fuel was dumped separately into the Tsivolka Fjord in an operation that involved detonating explosives to release the RC through the bottom hull of the *Lenin* [193] (p. 38). Note that some references use the terminology "reactor bay" instead of reactor compartment [202,208]. Amosov and Eryalov (2012) provide an enlightening and detailed description of this unique dismantlement process for the 3700-ton RC [209]. These sea disposals predated the London Convention of 1972, which banned dumping of high-level radioactive waste in the oceans [29,102,210]. The Tsivolka Fjord is located on the eastern coast of the archipelago Novaya Zemlya, where many atmospheric nuclear weapons tests were conducted in 1955–1962 [211], and is at the western edge of the Kara Sea, as shown in Figure 14.

Figure 14. Location where the *Lenin* reactor compartment and other radioactive wastes were dumped according to [208]. The underlying map is from https://en.wikipedia.org/wiki/File:Barents_Sea_map.png (accessed on 11 November 2024) (CC BY-SA 3.0).

Table 7 shows that the estimates of the radioactivity dumped at sea vary somewhat. Sivintsev and Kiknadze (1995) apparently combined the activation product activities from both the RC and the screen assembly [202]. Timms et al. (1997) provide tables that break the activities down to the particular radionuclides [205]. Sarkisov et al. (2007) estimated that the spent fuel screen assembly and reactor bay would have activities of 1579 TBq and 60 TBq, respectively, as of 1 January 2000 [208].

Table 7. Estimated radioactivity for the *Lenin* components disposed of in the Kara Sea.

Date for Which Estimate Applies and Reference	Estimated Radioactivity *			
	Reactor Compartment	Core Barrel and Stuck Spent Fuel Assemblies		
	Activation Products	Activation Products	Actinides	Fission Products
1967 1994 Sivintsev and Kiknadze (1995) [202]	1880 TBq (50.7 kCi) 230 TBq (6.3 kCi)		269 TBq (7.26 kCi) 85.1 TBq (2.3 kCi)	17,400 TBq (470.2 kCi) 1880 TBq (50.9 kCi)
1993, Timms et al. (1997) [205]	170 TBq (4.6 kCi)	63 TBq (1.7 kCi)	85 Bq (2.3 kCi)	1900 TBq (51 kCi)
1995, Rubtsov and Ruzhanski (1996) [203]	No estimate	No estimate	144 TBq (3.90 kCi)	1930 TBq (52.2 kCi)

* In all these references, the activities are presented in curies such that those values are explicitly given here.

In the essay entitled "Give the Nuclear Icebreaker Lenin a New Power Plant" in [209], Adrianov who was until 1971 the Deputy Head of the Instrumentation and Automation Service on the *Lenin* provides the greatest detail of the incident uncovered in this research.

In the interest of transparency, Ref. [209] is in Russian and was translated to English using Google. This is not to imply that a Google translation is substandard as during this research Russian papers translated by humans had readily identifiable errors (e.g., the IMO being termed as the Institute of International Relations [212]). Regardless, these first-person essays provide valuable insights into the events. Adrianov (2012) says, "The first-generation nuclear power plant OK-150, used on the nuclear icebreaker 'Lenin' until 1966, had many shortcomings that constantly appeared, due to which the icebreaker was under repair most of the time". He then provides a short list of some of those deficiencies including the following which may be relevant to the accident(s):

- "The reactor vessel had an inlet bottom pipe, which increased the likelihood of draining the core in the event of a leak. Repair of valves on pipelines located below the upper level of the core required freezing the pipeline to create an ice plug."
- "Horizontal circulation pumps with a water supply system for hydraulic bearings had low reliability, which led to pump failures. The use of a high-temperature fuel composition with poor mechanical properties (swelling, cracking) contributed to rapid depressurization of the fuel element shells and, as a consequence, high activity of the first circuit water."
- "However, the austenitic stainless steel steam generators installed for decades lost their tightness after 3000 h of operation in radiation fields due to chlorine intercrystalline corrosion. Their replacement required a large amount of work carried out in rooms with powerful radiation."

Later in the essay, Adrianov states that in 1965, "The use of 'home-grown' technology during the repair of the main circulation pumps with the opening of the first circuit led to the melting of the active zone of the second reactor with the destruction of the process channels. During the navigation of this year, the icebreaker worked up to 50% of its capacity, since at the third reactor, due to a leak in the steam generators, only one loop remained in operation (two-loop scheme of the coolant of the first circuit)". The bottom RPV inlet for the Lenin's OK-150 reactor is confirmed from diagrams within Russian journal articles [198,200] and drawings [105] (p. 11). Adrianov then describes two important events in 1966:

1. "At the beginning of the year, a violation of technology during welding work in the equipment room led to a major fire and the destruction of cable routes. At the cost of incredible efforts, the second reactor was restored to working order, the consequences of the fire were eliminated, and the steam generator in the third reactor was replaced".
2. "In the summer of 1966, the crew was preparing for navigation. But when the installation was put into operation, a leak was discovered in the first reactor: the stainless steel 'jacket' that protected the reactor's power vessel from corrosion on the first circuit side had lost its tightness".

Based on the first event of 1966, which is somewhat reminiscent of the cable tray fires in March 1975 at the Browns Ferry Nuclear Plant in the U.S. [213], the *Lenin* was ready to return to service. Steam generator replacement was described above as requiring "a large amount of work carried out in rooms with powerful radiation" such that this activity could be a supposed second radiation-related accident.

The second event of 1966 is also consistent with other eyewitness reports in [209]. Khlopkin and Pologikh in their essay, "Kurchatov Institute of Atomic Energy in the Modernization of the Nuclear Power Plant of the Icebreaker 'Lenin'", confirm that a leak occurred in reactor number one that required considerable repair time and concomitantly increased personnel dose [209]. More specifically, the essay entitled "Unloading the OK-150 Nuclear Power Plant from the Icebreaker Lenin" of Amosov and Erykalov records that fixing the leak in the No. 1 reactor vessel would have required its replacement [209].

An externally authored report provides a different version of the events surrounding the second accident. Ref. [214] reads:

> "*the pipe system of the third circuit sprung a leak following the loading of fresh nuclear fuel. In this instance it was necessary to open the biological shield of the reactor compartment in order to locate the leakage. This protection was made of concrete mixed with metal shavings and it required the use of sledgehammers to break through the shield. This led to further damage of the reactor installation. Upon later examination, it became clear that it would be impossible to repair the damage incurred to the reactor installation by the sledgehammers*".

The third circuit is apparently used to provide cooling water for equipment within the reactor compartment.

It is unfortunate that detailed information on these accidents is unavailable because everyone can benefit from lessons learned from such incidents. Subsequently in 1970, the three first-generation OK-150 reactors were replaced by two 159 MWt second-generation OK-900 reactors, which provided the same total shaft output of 44,000 hp as the original installation [121]. A goal of the replacement effort was to return Vladimir Lenin's namesake to service in 1970 on the 100th anniversary of his birth [209]. The *Lenin* was decommissioned in 1990 [61] (p. 41) and is now a museum [181].

7. Closing Remarks

The use of nuclear energy for marine propulsion and electricity/heat production has clear benefits in terms of reducing carbon dioxide emissions, which are contributing to climate change. However, as the example of the *Lenin* LOCA reveals, nuclear safety remains paramount. After the March 1979 accident at Three Mile Island Unit 2, the Institute of Nuclear Power Operations (INPO) was formed in the U.S. to share operating experiences at nuclear power plants in the U.S. in order to strengthen nuclear safety—although electric utilities are now stronger competitors in the deregulated power markets, that sharing of information continues. Similarly, after the April 1986 accident at Chernobyl Unit 4, the World Association of Nuclear Operators (WANO) was formed to share information internationally. Future marine nuclear operators would hopefully be encouraged likewise to share information that enables nuclear safety.

From November 2023 to January 2025, merchant shipping was targeted by Yemeni Houthis with at least two ships (the Belize-flagged *Rubymar* [215] and the Liberian-flagged *Tutor* [216]) sunk and more damaged by missiles in the Red Sea and Gulf of Aden; this adds a new dimension to the topic of nuclear maritime safety, specifically, the possibility that a nuclear-powered merchant ship may be sunk by missile attack. The risk of general sinking was already considered in the 1982 IMO safety code [18], but now ships have been severely damaged by anti-ship ballistic missiles. Although piracy has existed for hundreds of years, modern terrorists have taken the tactics to new levels. The Houthis also hijacked the *Galaxy Leader*, a Bahamas-flagged ship, and removed her 25 crew members who remained as hostages for 14 months [217,218]. Had this been a nuclear-powered vessel, would these non-state actors have known and allowed the crew to remain onboard to ensure that decay heat removal continued, or should passive residual heat removal now be a design requirement for the engineer? Furthermore, if terrorists can hijack airplanes, what is to prevent them from commandeering a nuclear ship with intent to utilize it as a radiological dispersal device (RDD)? This review is not the first to contemplate such scenarios for nuclear ships [13,219] or FNPPs [220,221]. Certainly, possibilities such as these are an impetus to design reactors that are inherently safe and capable of unattended shutdown and cooling.

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