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Review

Fundamental Understanding of Marine Applications of Molten Salt Reactors: Progress, Case Studies, and Safety

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Abstract: Marine sources contribute approximately 2% of global energy-related CO_2 emissions, with the shipping industry accounting for 87% of this total, making it the fifth-largest emitter globally. Environmental regulations by the International Maritime Organization (IMO), such as the MARPOL (International Convention for the Prevention of Pollution from Ships) treaty, have driven the exploration of alternative green energy solutions, including nuclear-powered ships. These ships offer advantages like long operational periods without refueling and increased cargo space, with around 200 reactors already in use on naval vessels worldwide. Among advanced reactor concepts, the molten salt reactor (MSR) is particularly suited for marine applications due to its inherent safety features, compact design, high energy density, and potential to mitigate nuclear waste and proliferation concerns. However, MSR systems face significant challenges, including tritium production, corrosion issues, and complex behavior of volatile fission products. Understanding the impact of marine-induced motion on the thermal–hydraulic behavior of MSRs is crucial, as it can lead to transient design basis accident scenarios. Furthermore, the adoption of MSR technology in the shipping industry requires overcoming regulatory hurdles and achieving global consensus on safety and environmental standards. This review assesses the current progress, challenges, and technological readiness of MSRs for marine applications, highlighting future research directions. The overall technology readiness level (TRL) of MSRs is currently at 3. Achieving TRL 6 is essential for progress, with individual components needing TRLs of 4–8 for a demonstration reactor. Community Readiness Levels (CRLs) must also be addressed, focusing on public acceptance, safety, sustainability, and alignment with decarbonization goals.

Keywords: molten salt reactor; small modular reactor; nuclear-powered ship; nuclear fuel; thorium fuel; maritime propulsion; ship-board reactors; non-proliferation; nuclear safety protocol; waste management

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1. Introduction

CO_2 emissions pose a significant threat to global climate change, contributing to ocean acidification, ecosystem disruption, adverse health effects, and substantial economic costs. Currently, global CO_2 emissions have reached approximately 35 billion tons annually, exacerbating these environmental and societal challenges. CO_2 emissions from marine sources constitute approximately 2% of total global energy-related CO_2 emissions, with 87% of these emissions generated by the shipping industry (including bulk carriers, oil tankers, and container vessels) [1]. When considered as a single entity, the shipping industry would rank as the fifth-largest emitter of CO_2 globally, releasing 1076 million metric tons of CO_2 annually [2]. This places it behind China (11,680 million metric tons), the United States (5000 million metric tons), India (2710 million metric tons), and Russia

(1580 million metric tons), but ahead of Japan (1150 million metric tons), accounting for 2.9% of global emissions [3–7]. Environmental regulations established by the International Maritime Organization (IMO), particularly the Marine Pollution (MARPOL) treaty, are strictly enforced to reduce pollution from ships. These stringent regulations have prompted the shipbuilding industry to explore alternative green energy solutions, with a growing focus on nuclear-powered ships [8]. Nuclear-powered ships offer the significant advantage of operating for years without the need for refueling, eliminating the requirement for large fuel tanks (Figure 1) [6]. This provides more space for passengers and cargo, enhancing economic efficiency. Currently, approximately 200 nuclear reactors are in operation across 160 naval vessels and submarines worldwide [9–12].

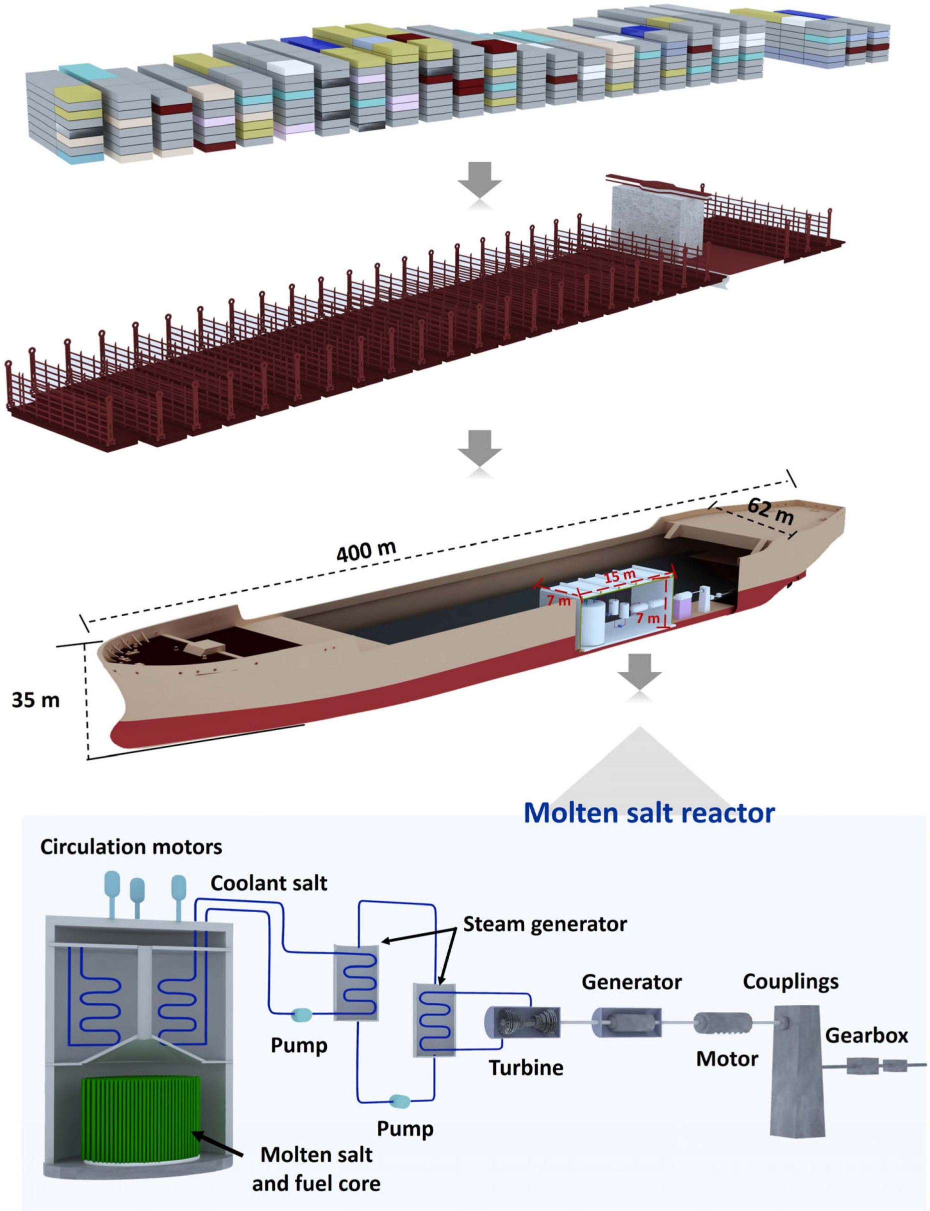

Figure 1. Schematic illustration of a cargo ship powered by a molten salt reactor [9].

The MSR is an advanced reactor concept well-suited for marine and ocean-based applications due to its inherent safety features, compact design, high energy density, and potential to address concerns related to nuclear waste and proliferation [13]. Molten salt-cooled reactors are considered an advanced energy technology, where molten salt serves either as a coolant for solid fuel or as a fuel salt. In its liquid phase, molten salt exhibits a significantly higher heat capacity per cubic meter than gases. The system operates at low pressure due to the liquid phase and allows for a compact design. Over its lifetime, a nuclear-powered ship could save approximately USD 70 million compared to a similar vessel powered by heavy fuel oil [9].

The molten salt system presents radiological and chemical challenges, particularly related to tritium production and corrosion. Tritium production must be carefully controlled or minimized, as it is hazardous to human operators and difficult to contain. Corrosion is another critical issue in molten salt systems. The absence of a passive oxide film on structural materials in the thin molten salt configuration necessitates regular purification or processing of the salt to control the redox potential or the use of redox buffers [14]. Additionally, volatile fission products such as cesium, iodine, and strontium exhibit complex behavior in fluoride and chloride salt systems. Understanding their solubility, volatility, precipitation, and impact on corrosivity is essential, especially when considering recycling processes [15,16].

It is essential to thoroughly understand the characteristics of molten salt nuclear reactors under marine conditions, where they are exposed to various types of motion induced by waves, wind, and currents. Ocean-induced motion exerts external forces that significantly impact the reactivity feedback and thermal–hydraulic behavior of these reactors. Inclination can cause asymmetric behavior due to the reactor operating on a slope or due to the displacement between the center of gravity and center of mass, which can lead to transient design basis accident scenarios and pose a potential threat to the safety systems [17–21]. Beyond technical feasibility, regulatory frameworks pose significant challenges to the viability of the nuclear-powered shipping industry. Achieving unanimous global agreement among port state controls (PSCs), the IMO, MARPOL, and SOLAS (International Convention for the Safety of Life at Sea) is essential for accommodating MSR technology by thoroughly understanding and evaluating its safety potential in practical use [22,23]. This review focuses on the current progress of MSR-based technology, addressing its challenges, ongoing research efforts, and the conditions under which it could be feasible for the shipping industry. It also examines safety protocols, and the technological readiness of MSRs, and outlines future research directions. This review discusses the potential of MSRs, highlighting their higher efficiency, superior coolant properties, real-time fission product removal, enhanced safety features, self-regulating systems, and high-temperature operation within a broad safety margin. It also sees deep into several challenges, particularly concerning molten salt purity and corrosion control, as well as the toxicity of residual water, isotope generation, tellurium-induced corrosion, salt refining issues, and increased shielding requirements. In maritime applications, factors such as rolling motions, dynamic marine environments, and multi-physics phenomena are examined in relation to system regulation and performance. Safety protocols are evaluated concerning fission product transport, helium bubbles, noble metal deposition, off-gas management, iodine behavior, corrosion resistance, sloshing dynamics, and the control of tritium and other corrosive gases. TRLs assess the maturity of MSR technologies, while CRLs gauge public acceptance. Key technological challenges have been evaluated across materials and components, liquid salt chemistry, fuel cycles, system design, operations, and safety protocols, necessitating comprehensive integration assessments.

2. Molten Salt Reactors

MSRs differ fundamentally from traditional nuclear reactors, such as those based on Pressurized Water Reactor (PWR) technology (Figure 2) (Table 1). Traditional nuclear reactors typically employ solid fuel rods composed of uranium oxide, encased in zirconium alloy cladding. In these systems, pressurized water serves as the coolant, transferring heat from the reactor core to the steam generator. In contrast, MSRs offer a distinct design approach, where molten salt is utilized either as a coolant (eutectic LiF/BeF_2—66/33 mol.% at 600 °C, LiF/CaF_2—860 °C, NaCl/KCl—700 °C, LiCl/KCl—450–500 °C, etc.) in systems that still use solid-state fuel or in a dual role, functioning simultaneously as both fuel and coolant (LiF/BeF_2 carrier salt with fertile ThF_4 and fissile elements UF_4). In circulation liquid fuel systems, salts, such as halide, dissolve with uranium or plutonium [24,25].

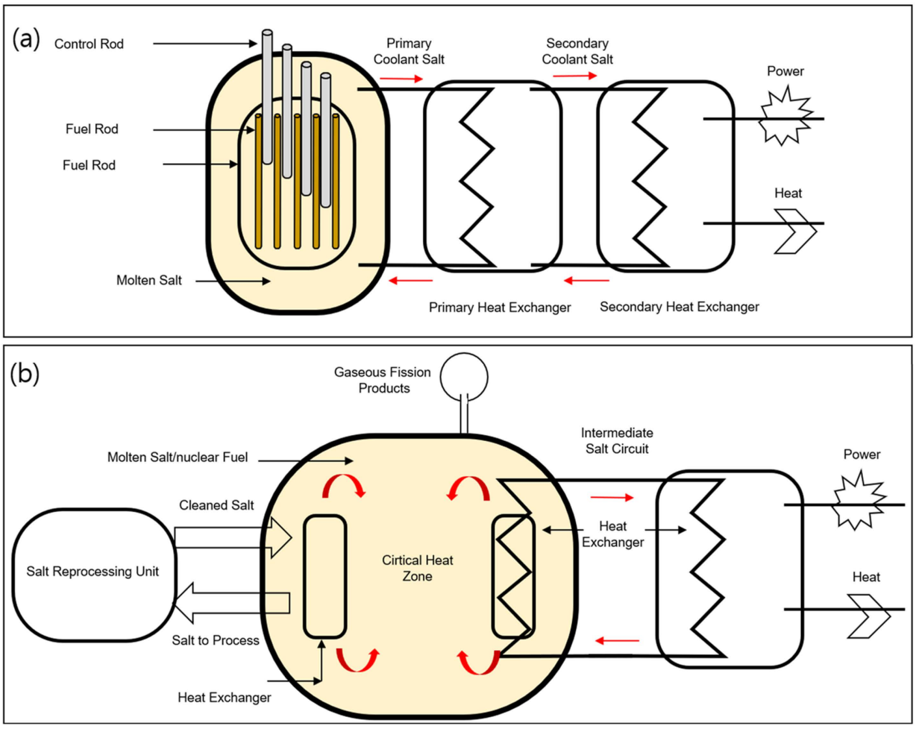

Figure 2. Operation principal of molten salt reactor. (**a**) Molten salt coolant with solid-fueled reactor; (**b**) nuclear fuel mixed with molten salt as liquid-fueled reactor.

Table 1. Advantages and impacts of molten salt reactor technology from safety, economic, non-proliferation, and environmental perspectives.

Factors	Advantages	Impacts	Disadvantages
Safety	(i) low pressure (1 atm), (ii) liquid state stability	(i) avoidance of fuel or clad leaking fission products, (ii) avoids rapid steam expansions/explosions	(i) corrosions of reactor materials due to high temperature molten salts, (ii) radiation damage of structural components becomes radioactive
Economic	(i) design simplification, (ii) compact design (L:15 m, W: 7 m, H: 7 m), (iii) used [1] LWR fissile material	(i) cost (20–30% reduction compared to traditional nuclear reactor), (ii) shipped to reactor sites to reduce construction cost, (iii) reducing waste materials	(i) technical maturity in experimental stage and competitive with established technologies, (ii) viability in theoretical stage to lower operation cost and waste
Non-proliferation/ Environmental	(i) breed abundant thorium than plutonium, ii) recycle or burn actinide, plutonium recycled	(i) expand global fuel supply, (ii) reduce waste inventory (80–90% volume)	(i) proliferation-prone due to extracting of weapons-grade materials, (ii) handling of radioactive molten salts is challenging

[1] light water reactor.

MSRs utilize a fuel salt mixture, typically composed of fluoride salts (e.g., LiF/BeF_2, LiF/NaF/KF) with dissolved fissile materials such as uranium-235 or thorium-232 (e.g., LiF/UF_4, LiF/ThF_4) or chloride-based salts (e.g., $NaCl/UCl_3$, $MgCl_2/UCl_3$, $CaCl/UCl_3$). The reactor core contains channels made from corrosion-resistant alloys like Hastelloy–N or Inconel, both nickel-based alloys, which ensure efficient heat transfer while minimizing corrosion as the molten salt fuel flows through. The containment vessel, often constructed from stainless steel or Hastelloy–N, contains chromium, molybdenum, and iron to maintain structural integrity at high temperatures and radiation levels, preventing the release of radioactive materials. Graphite is typically used as the core moderator to slow down fast neutrons, increasing the likelihood of further fission reactions and improving overall reactor efficiency [26,27]. The fission process occurs when fissile materials, such as uranium-235, undergo fission upon neutron absorption, releasing energy, neutrons, and fission products (U–235 + n $\rightarrow$ Fission Fragments + 2.5 n + Energy). This continuous neutron release sustains the fission chain reaction. In MSRs, thorium-232 breeding reactions occur, where thorium absorbs a neutron to form thorium-233, which undergoes beta decay to form protactinium-233 and then uranium-233 (Th–232 + n $\rightarrow$ Th–233 $\rightarrow$ Pa–233 + β^- $\rightarrow$ U–233 + β^-). This breeding process generates more fissile material from fertile thorium, enhancing fuel efficiency. Heat generated from fission is absorbed by the molten salt, which is circulated through a heat exchanger—typically made of graphite or ceramic materials—to transfer heat to a secondary coolant loop. The secondary loop contains another molten salt that helps generate steam, which drives turbines to produce electricity. High-temperature sensors and radiation-hardened electronics are employed to monitor reactor conditions and ensure safety [26–29].

2.1. Potential of MSR Technology

MSRs offer significantly higher thermodynamic efficiency, ranging from 45% to 50%, compared to traditional light water reactors (LWRs), which typically achieve efficiencies of 33% to 35%. This increase is primarily due to the higher operating temperatures of MSRs (500–700 °C) compared to LWRs (300 °C). Additionally, the utilization of molten salts as coolant provides superior heat transfer properties and higher thermal conductivity than water, enhancing the overall efficiency of the heat exchange process. MSRs also offer the potential for real-time removal of fission products, including neutron poisons, which can help reduce the generation of high-level radioactive waste. These reactors operate at low pressures with primary circuit fluids that exhibit low volatility. The fluid–fuel system in MSRs provides a high thermal expansion coefficient, contributing to a large negative temperature coefficient of reactivity; as the liquid expands with heat, the nuclear reaction rate slows, thereby enhancing the self-regulating capability of the reactor. Fission products and actinides can be removed online or in batch mode through helium sparging or physiochemical processes and reintroduced into the fuel circuit. This approach allows for higher fuel burnup compared to conventional nuclear reactors, eliminating the costs associated with the transport and fabrication of new fuel elements (Figure 3) [13,30,31]. The architecture of MSRs offers enhanced safety performance due to the low pressure of both primary and secondary systems, typically operating below 5 bar [32]. This significantly reduces the risk of accidents related to salt leakage or high-pressure system failures. Unlike the Fukushima accident, MSRs present no risk of fire or explosions involving air or water, as both the fuel and coolant are chemically inert. The reactor operates at a temperature of approximately 700 °C, with the boiling point of the molten salt being around 1400 °C, ensuring that the pressure within the primary system remains within safe limits [32,33].

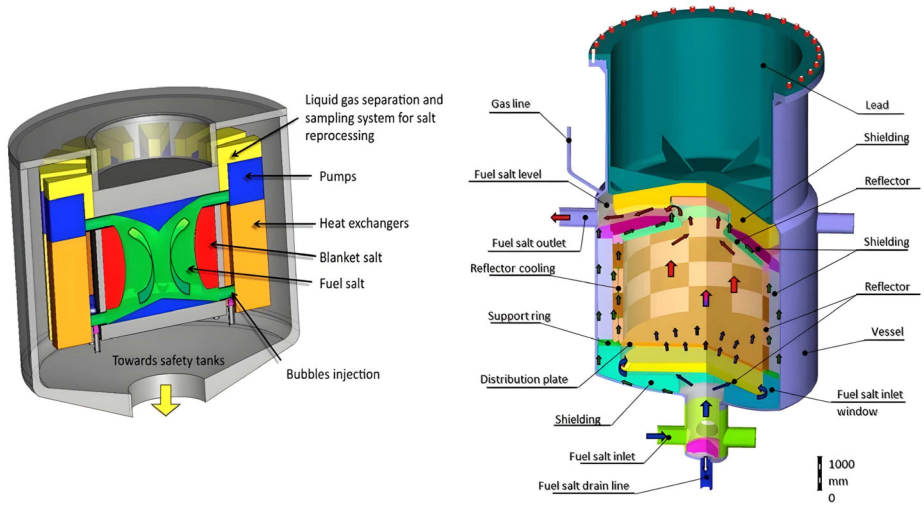

Figure 3. MSFR (molten salt fast reactor) and MOSART (molten salt actinide recycler and transformer) concept. Reproduced with permission: Copyright 2014, Elsevier Ltd. [13].

2.2. MSR Challenges

Maintaining an MSR environment with impurity levels below 10 ppm is essential for ensuring corrosion resistance in the core design. Residual water from pyro-hydrolysis of raw materials can lead to oxide formation, resulting in solid particle or scale deposits that significantly impede heat transfer efficiency. Achieving such high purity levels requires consistent and meticulous control throughout the entire process, from raw material selection and handling to salt processing. This involves using pre-treated high-purity materials, vacuum distillation to remove volatile impurities, and maintaining an inert atmosphere to prevent environmental contamination. Additionally, continuous removal of solid particles during operation is crucial. While maintaining this level of purity may increase operational costs, failure to do so could lead to corrosion, component failure, safety hazards, and reduced operational efficiency [34–37]. In MSR systems, certain isotopes are generated not only by fission but also through interactions with the salt itself. For example, the use of natural chlorine in the salt can lead to the production of sulfur and the isotope ^{35}Cl. Sulfur can accelerate structural deterioration through corrosion, while ^{35}Cl is a long-lived radiological hazard. Similarly, bromine in the salt generates selenium, which significantly enhances steel corrosion. The use of iodine in the salt does not significantly increase the production of radioactive iodine but does double the generation of tellurium. Tellurium causes intergranular corrosion by migrating along the grain boundaries of nickel-based alloys, leading to cracking and material failure. The diffusion of tellurium into these alloys results in the formation of nickel telluride (Ni_3Te_2) and chromium telluride (CrTe), which embrittles the material structure, further compromising the integrity of the reactor components. Barrier-based methods incorporate materials with very low diffusivity (e.g., carbides, ceramics) into the heat exchanger [38]. Salt polishing and refining in MSR systems are complex due to the high activity of the salt, and it is practically impossible to chemically separate radioactive materials from the salt. Gamma spectra of fluoride, chloride, iodide, and bromide salts reveal the presence of fission products, indicating the need for shielding in MSR systems (Figure 4). Bromide salts, in particular, exhibit two auxiliary peaks on either side of the 1 MeV peak, identified as gamma decay from ^{82}Br, which has a half-life of 35 h. Among the salt options, bromide systems require increased shielding due to the potential rise in selenium production and gamma emissions [39].

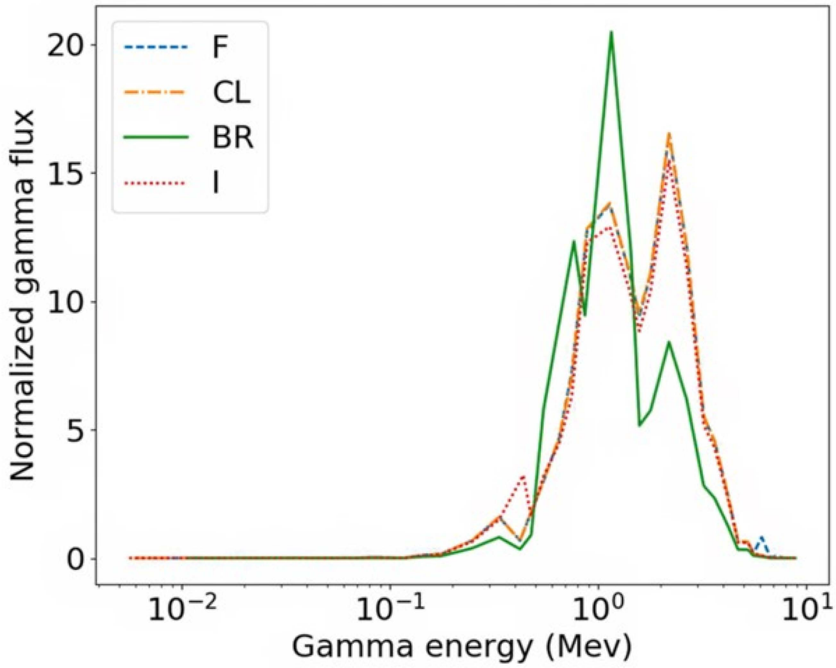

Figure 4. Gamma spectrum of the irradiated salt. Reproduced with permission: Copyright 2021, Elsevier Ltd. [39].

2.3. Molten Salt Chemistry

Molten salts (ionic liquids) are considered advanced materials for heat transfer and thermal management in high-temperature energy production systems. In their solid state, salts exhibit ionic characteristics. When in the molten state, these salts demonstrate a complex interplay of ionic and covalent interactions, influenced by the addition of components, the formation of fission products, and off-gassing [25]. The chemical behavior of molten salts can be challenging to control due to fundamental fluctuations. Ionic salts undergo dissociation through thermal energy when dissolved in solution. For example, LiF dissociates at its melting point into Li^+ and F^- ions. Conversely, BeF_2 forms a chain network of Be and F atoms at its melting point, resulting in high viscosity. The decomposition of nitrate-based salts depends on their composition, temperature, and specific experimental conditions. The selection of molten salts for reactor applications requires that the salts possess chemical and radiolytic stability at high temperatures, along with low melting points and high boiling points. Additionally, the salts must exhibit optimal thermodynamic properties, including a large specific heat capacity, high thermal conductivity, and a lower vapor pressure than water (e.g., <1 mm Hg at 900 °C). A low vapor pressure is crucial to minimize the formation of a vapor phase within the reactor system when operating at high temperatures [40,41].

2.3.1. Fluoride-Based Salts

Fluoride-based salts such as LiF, NaF, and BeF_2 are considered for reactor applications due to their appropriate melting ranges (Figure 5). Among these, BeF_2 has the lowest thermal neutron cross-section of the fluoride salts (σ ~ 0.010 b). A salt mixture of LiF/BeF_2 (66/34 mol.%), known as Flibe, is considered the most compatible for reactor use. However, BeF_2 is hazardous, and LiF can produce tritium in a neutron flux environment. To mitigate tritium generation, lithium must be purified to 99.99%, a process that is both complex and costly. An alternative mixture, LiF/NaF/KF (46.5/11.5/42 mol.%), known as Flinak, offers similar benefits to Flibe without the toxic characteristics. However, NaF/ZrF_4 and KF/ZrF_4 salt mixtures eliminate the tritium generation issues associated with lithium fluoride but present challenges due to the high vapor pressure of KF/ZrF_4 and the high melting point of NaF/ZrF_4 [41,42].

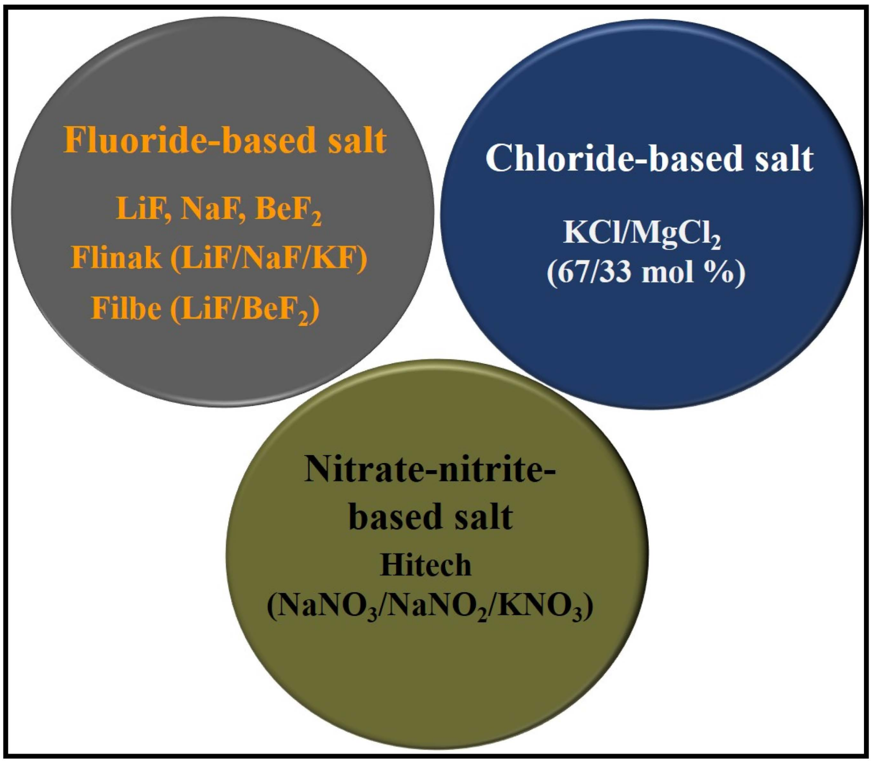

Figure 5. Schematic of the different molten salts used in nuclear reactors.

2.3.2. Chloride-Based Salts

Chloride-based salts, such as KCl/$MgCl_2$ (67/33 mol.%), could be utilized as coolants, exhibiting behavior similar to fluoride salts, including similar corrosion effects. However, Li-containing chloride salts require isotopic purification to limit tritium generation in a neutron flux, and chloride must be managed to prevent the formation of Cl-36 by transmutation [43,44].

2.3.3. Nitrate–Nitrite Based Salts

Nitrate–nitrite-based salts, such as $NaNO_3$/$NaNO_2$/KNO_3 (Hitec), have also been considered as molten salts, though their radioactive behavior has not yet been fully evaluated. At high temperatures (500–600 °C), nitrate–nitrite salts lose stability and decompose into nitrites and oxides (at 600 °C in air). Above 800 °C, the reaction rate increases, leading to gas formation and boiling. Oxide impurities actively contribute to corrosion, and reactions between nitrate–nitrite salts and fuel can generate actinide oxides, which then react with the graphite moderator [43].

3. MSR Technology Progress in Ship Industry

MSR technology differs from conventional nuclear power generation, enabling ship decarbonization and enhancing fuel efficiency, with a lifespan of 25–30 years. Molten chloride fast reactors operate at ambient pressure, showing excellent fuel efficiency and maintaining the minimum waste emission of 1 g per MW per day. In the application of MSR technology for ships and floating structures, comprehensive evaluations of propulsion systems, reactor systems, and steam systems are essential. These evaluations consider multiphysics phenomena and external environmental impacts, which are the focus of various research studies.

3.1. Factors Need to Be Considerd for the Ship Industry

Nuclear reactors typically operate in vertically stable conditions, allowing for precise control of reactor power in a closed-loop system by adjusting coolant temperature, thereby accommodating load variations to maintain continuous and stable power output. However, under marine conditions, the heeling and rolling motions affect the reactivity feedback due to thermal and hydraulic characteristics of reactor systems. Variations in heeling angles alter the operational characteristics of reactors, emphasizing the need for advanced control systems that can handle the nonlinear and time-varying properties of the core model. These advanced controllers must offer robust and adaptive capabilities suited for marine environments [45,46].

Automatic control of reactor power often relies on managing the average coolant temperature through various control theories. Proportional–integral (PI) controllers are used to regulate the coolant inlet temperature, optimizing the coolant's average temperature to maintain power stability. The optimization of PID parameters using genetic algorithms has been employed to control the required power output of nuclear plants [47,48]. A fuzzy–PID composite control method has been introduced for molten salt reactors, providing simplicity and stability in power regulation; however, this method lacks adaptive capabilities for time-varying systems [49]. While other models, such as PI control based on internal model control (IMC), and H–infinity robust controllers for heat pipe-cooled reactors, are effective for power tracking under stable conditions with lower model accuracy requirements, they also lack the adaptive capabilities and responsiveness needed in nonlinear and time-varying marine environments [50,51].

The Han group proposed a model-free adaptive control (MFAC) method designed to address the challenges of dynamic marine environments [52]. The MFAC method identifies initial model parameters tailored to marine conditions and adjusts the control law based on real-time input and output data. Simulations demonstrated that the MFAC controller exhibits superior adaptive capabilities, including enhanced disturbance rejection and robustness, allowing it to maintain the average coolant temperature and accurately track setpoints under fluctuating conditions, characterized by time-varying and nonlinear behaviors, in lead–bismuth reactors. When disturbances occur in the system, the actual average output coolant temperature deviates from the setpoint value. The Model-Free Adaptive Control (MFAC) controller demonstrates a significantly shorter disturbance rejection time compared to the Proportional–Integral–Derivative (PID) controller (Figure 6). Analysis of heeling state characteristics indicates that reactivity leads to maximum variations in coolant temperature, and an increase in heeling angle during rolling motion further reduces the core's heat transfer capacity. A comparison of the performance of PID and MFAC controllers under various heeling angles reveals differences in their adaptive capabilities (Figure 7). Under conditions of heeling and rolling motion, the PID controller maintains a stable average coolant temperature without overshoot but requires a longer time to correct small steady-state errors. In contrast, the MFAC controller quickly achieves the setpoint for the average coolant temperature without overshoot or steady-state error. This highlights the superior responsiveness and adaptability of the MFAC controller in dynamic marine environments [52].

Microreactor design concepts emphasize the role of heat pipes (HPs) in passive heat removal and core heat transport. Integrating heat pipes with MSRs eliminates in-core thermal stress and the need for pumps, which are common in traditional MSRs. This passive operation of heat pipes in MSRs makes them particularly suitable for maritime applications due to their compact design and high energy density [53,54]. However, heat pipe-cooled MSRs in ocean environments face unique challenges not encountered in terrestrial applications, which typically rely on static conditions and natural convection of molten salt.

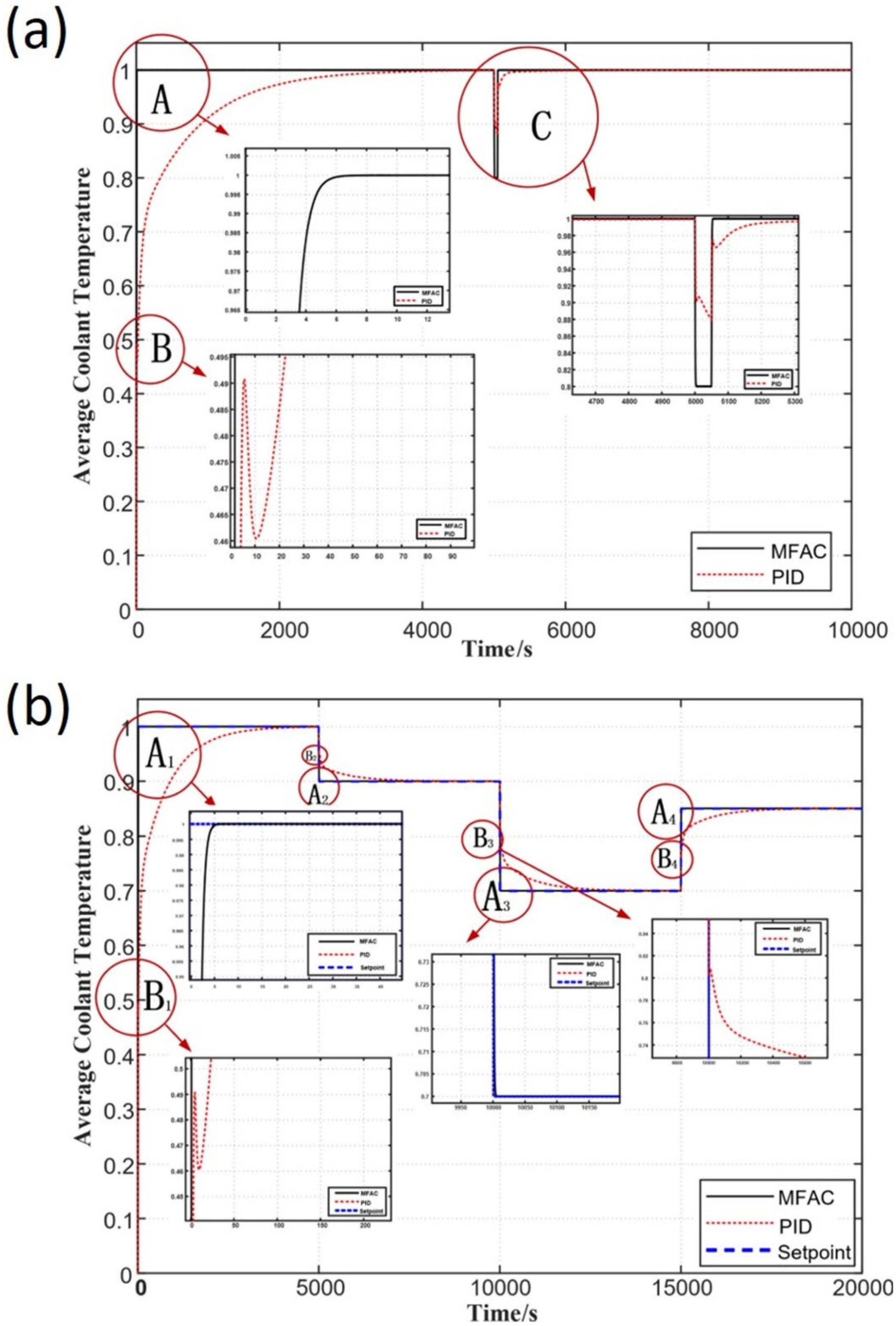

Figure 6. (**a**) Disturbance rejection capability test (comparisons point between MFAC and PID at A: MFAC (0–12 s), B: PID (0–30 s), C: MFAC/PID (4,900–5,100 s)); (**b**) setpoint tracking ability test (comparisons point between MFAC and PID at A_1: MFAC (0–40 s), B_1: PID (0–50 s), A_2: MFAC (5,000–6,000 s), B_2: PID (5,000–6,000 s), A_3: MFAC (10,000–10,150 s), B_3: MFAC/PID (10,000–10,600 s), A_4: MFAC (15,000–15,200 s), B_4: MFAC/PID (15,000–17,000 s)). Reproduced with permission: Copyright 2023, Elsevier Ltd. [52].

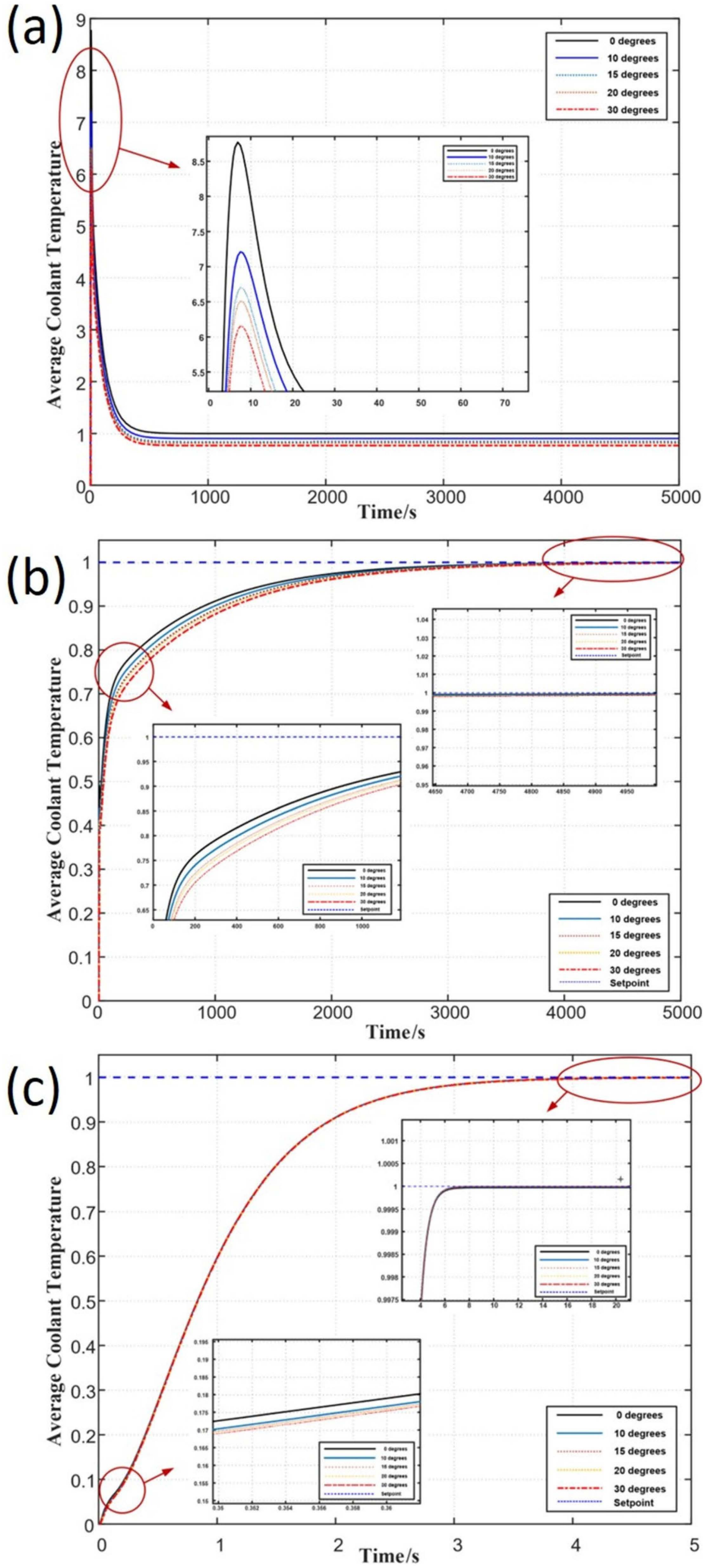

Figure 7. (**a**) Characteristics of the reactor core under heeling motion conditions; (**b**) performance of PID controller at various heeling angles; (**c**) performance of MFAC controller at various heeling angles. Reproduced with permission: Copyright 2023, Elsevier Ltd. [52].

The six degrees of freedom in oceanic motion—rolling, pitching, yawing, heaving, surging, and swaying—introduce complex inertial forces that can significantly affect the flow and heat transfer characteristics of the molten salt fuel. Ocean-induced motion perturbations in the fuel flow can alter core heat transfer, posing potential impacts on the safety and performance of HP–MSRs [5,55,56]. To tackle these challenges, the Gu group applied computational fluid dynamics (CFD) using ANSYS numerical simulations to the core of HP-cooled MSRs. They integrated a universal force model into the momentum equations within the FLUENT code to study the thermal hydraulics under oceanic motion conditions [57]. The findings reveal that rolling motion promotes a more uniform temperature distribution in the reactor core by improving fuel salt mixing and increasing flow velocity (Figure 8).

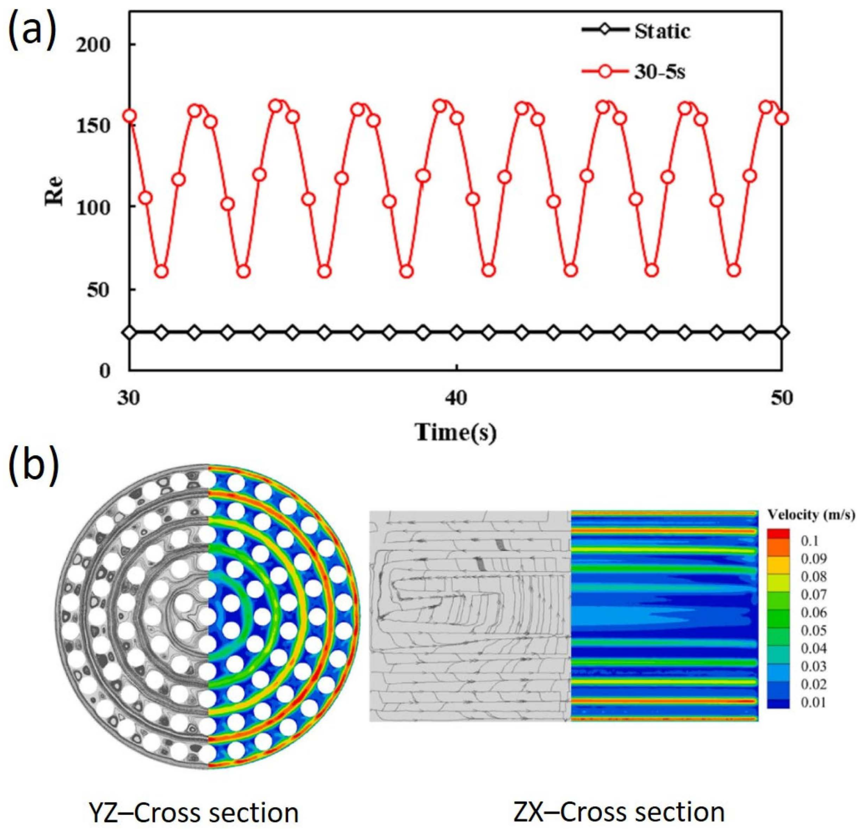

Figure 8. (**a**) The average Reynolds number variation curve from the static and rolling condition of 30°–5 s; (**b**) streamline combined velocity contour of the motion condition (30°–5 s). Reproduced with permission: Copyright 2024, Elsevier B.V. [57].

The maximum temperature difference is reduced from 57 K to 14 K, which helps lower thermal stress on the equipment and balance the power output across each heat pipe. Even under maximum angular acceleration, the average core temperature drop remains under 10 K, thanks to the molten salt's enhanced heat transfer properties. The flow field primarily consists of tangential fluid motion around the rotational axis, with increased velocity during rolling conditions. Vortex pairs develop in the circumferential gaps between neighboring heat pipes, and the interaction between the tangential flow and vortex structures boosts heat transfer performance (Figure 9). The heat flux on the heat pipe surface fluctuates by 10–25%, suggesting a potential impact on overall heat pipe performance [57].

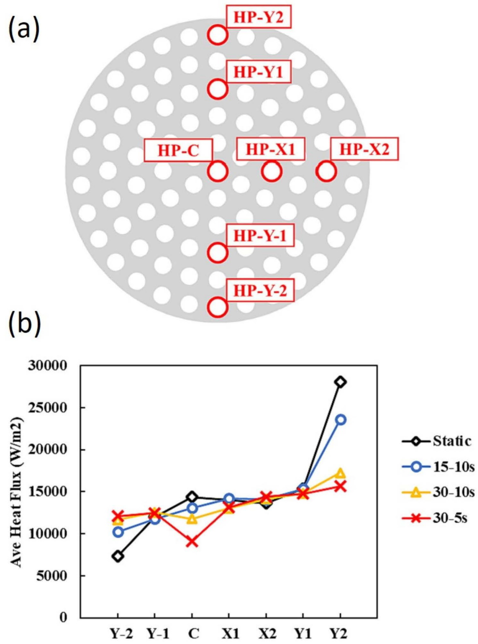

Figure 9. (**a**) Locations of heat pipes of the analysis object in the HP–cooled MSR core; (**b**) the average surface heat flux of each heat pipe under different rolling motion conditions. Reproduced with permission: Copyright 2024, Elsevier B.V. [57].

3.2. Case Study of MSRs in Shipping Industry

Ulstein, a leading name in the various marine-related industries, has developed a conceptual design for a floating multi-purpose power station named Thor, envisioned as a zero-emission solution for maritime and ocean industry applications (Figure 10). This concept is further extended with the development of the Ulstein SIF, a 100 m long, zero-emission expedition cruise ship with a capacity of 160 persons on board (POB). The SIF is classified as an ice-class 1C vessel and utilizes next-generation batteries powered by Thor, which can recharge up to four vessels within a 24 h period while at sea [58,59].

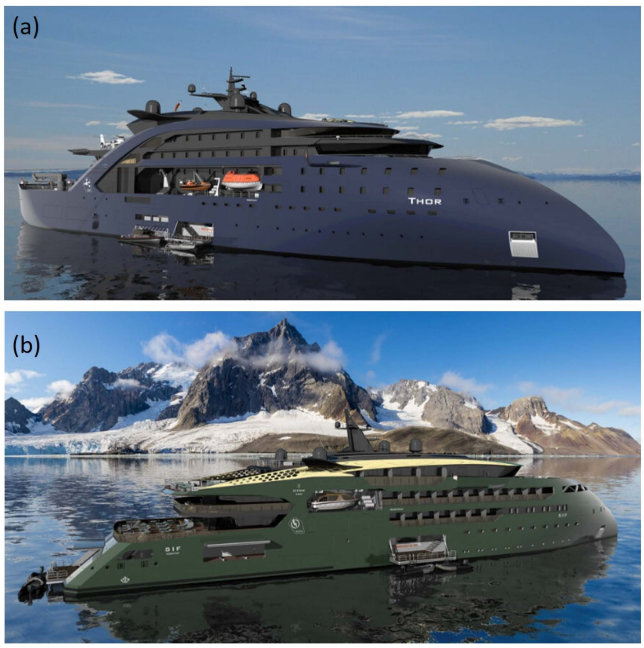

Figure 10. Ulstein X–BOW design concept. (**a**) Thor concept (molten salt reactor); (**b**) SIF cruise ship concept [58,59].

Thor employs thorium as an alternative fuel, dissolved in molten salts to sustain a chain reaction that heats the salt (fluoride or chloride salts), generating steam to drive turbines and produce electricity. Remarkably, Thor does not require refueling, embodying a vision of self-sufficient vessels for the future. From a cost-efficiency perspective, thorium MSR power generation offers an abundant energy source, presenting a promising approach for clean, efficient, and cost-effective energy with a smaller environmental footprint.

Both Thor and SIF feature Ulstein's innovative X–BOW design, which enhances onboard comfort, operational functionality, and fuel efficiency. The Thor platform is equipped with a range of self-sufficient energy features, including helipads, firefighting equipment, rescue booms, workboats, drones, cranes, laboratories, and autonomous surface vehicles. The SIF can accommodate 80 passengers and 80 crew members, making it well suited for expeditions in Arctic and Antarctic waters [58].

The Chinese state-run shipyard group Jiangnan, under the China State Shipbuilding Corporation (CSSC), recently announced plans to develop a molten salt reactor utilizing thorium as fuel for a 24,000 TEU container ship [60]. It is estimated that 1 ton of thorium can provide an equivalent amount of energy to 3.5 million tons of coal, making thorium a cost-effective and zero-emission alternative to uranium-based reactors. China, with its large reserves of thorium, views this technology as a strategic advantage. The reactor design prioritizes safety by operating at high temperatures and low pressure, significantly reducing the risk of core meltdown. Unlike traditional reactors, thorium reactors do not require high-pressure vessels, extensive piping, or large water-cooling systems. In the event of an accident, the core solidifies at ambient temperature, allowing for a normal shutdown. The design also emphasizes that molten salt fuel can be rapidly drained from the reactor to prevent the spread of radioactive materials [60,61].

UK-based Core Power has announced plans to equip nuclear-powered ships by 2030. The proposal emphasizes zero emissions and highlights that nuclear energy will enable ships to travel faster while also providing power to land-based grids when docked. Core Power is focused on developing an MSR system utilizing chloride salt as a heat transfer medium. The company plans to develop and build a micro-reactor test design in collaboration with Idaho National Laboratory (INL) in the United States. Additionally, Core Power is collaborating with US-based TerraPower, Washington and power utility Southern Co. Georgia to develop the Molten Chloride Reactor Experiment (MCRE). One of the key benefits of the MSR is that the reactor core cannot melt down, as the fuel is in liquid form and is locked into the coolant, preventing radioactive isotopes from escaping in the event of an accident. The modular design also emphasizes safety; even if a ship were lost at a depth of 800 m on the ocean floor, the liquid fuel would cool and solidify, forming solid rock that remains entombed within the vessel [62–64].

Samsung Heavy Industries, in partnership with Denmark-based startup Seaborg Technologies and Korea Hydro and Nuclear Power (KHNP), has planned the development of a Compact Molten Salt Reactor (CMSR) with a modular design capacity ranging from 200 to 800 MWe. This reactor can be installed on barges, providing a flexible and scalable power solution. The project has progressed with the conceptual design of the CMSR power barge and has secured Approval in Principle (AIP) from the US-based American Bureau of Shipping (ABS) classification society. CMSR technology is a progressive approach to power generation, capable of providing both thermal energy and electricity to land and sea installations using small molten salt reactors. The technology offers significant advantages, including a shorter construction period of approximately two years and lower costs compared to traditional nuclear technologies, making it particularly suitable for floating facilities. Additionally, it simplifies the process of obtaining permits and construction sites. Depending on power demand, the CMSR power barge can be equipped with two to eight 100 MW-class units. Each CMSR is coupled with a steam turbine generator and equipped with transmission and distribution systems. Further development will focus on integrating marine system interfaces, propulsion technology, and hydrogen production using molten salt reactors. The initiative involves collaboration among several organizations, including the Korea Atomic Energy Research Institute (KAERI), the Korea Research Institute of Ships and Ocean Engineering (KRISO), Wooyang Shipping Co., Sinokor, H–Line Shipping, and HMM. These entities are working together to develop nuclear-powered ships and are considering the strategic deployment of small modular nuclear reactors (SMRs) for ship propulsion [65,66].

Seaborg claims that mixing fuel with molten fluoride salt, which serves as the coolant, provides significant safety advantages. If exposed to the atmosphere, the molten salt would solidify into rock, encapsulating all radioactive materials. Additionally, the reactor operates at near-atmospheric pressure, further enhancing safety by reducing the risk of accidents. The operational principle involves a 12-year fuel cycle, after which the fuel is processed to remove short-lived fission products. These byproducts, which are radiologically comparable to hospital waste, can be handled using conventional methods. The remaining salt can then be recycled and mixed with new CMSR fuel at a supply facility, contributing to the reactor's sustainability [67,68].

Denmark-based Seaborg Technologies is advancing the CMSR, a thermal neutron spectrum reactor with an electric output of 100 MWe and a thermal output of 250 MWth, utilizing uranium-based fluoride fuel (Figure 11). The system employs sodium hydroxide (NaOH) as a moderator, which helps prevent radiation damage and combines advanced materials for corrosion control, enabling a service life of up to 12 years. Extensive studies have been conducted to control the corrosion potential of NaOH. A modular CMSR design is targeted for barge power applications, providing electricity outputs of 200–800 MWe, with an operational lifetime of 24 years per power module, each consisting of two CMSRs [69].

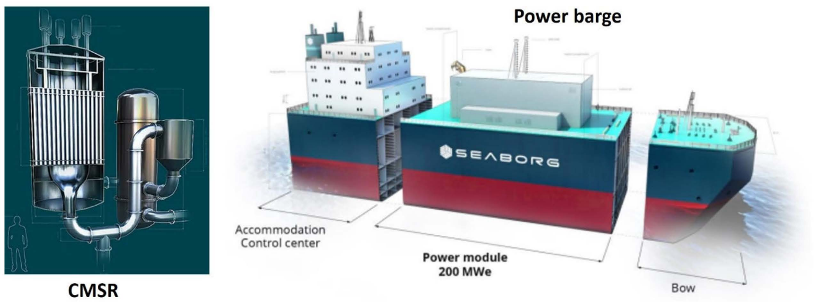

Figure 11. CMSR based power barge. Reproduced with permission: Copyright 2024, Springer Nature [69].

The conversion chain of ^{232}Th is complex, leading to the production of ^{232}U and ^{232}Pa, which have relatively longer half-lives (27 days) compared to isotopes in uranium fuel cycles, such as ^{239}Np (half-life of 2.4 days). This requires a 12-month cooling period to allow the complete decay of ^{233}Pa to ^{233}U before reprocessing, preventing the loss of valuable ^{233}U fissile material. Some protactinium can pass into the thorium fission product waste, producing long-lived radiological isotopes like ^{231}Pa (half-life of 3×10^4 times years), an alpha-emitting isotope in the thorium burnup chain. Approximately 98% of protactinium can be separated using selective adsorption by Vycor glass, followed by elution in an extractive separation process [70].

^{232}U is formed alongside ^{233}U during the irradiation of ^{232}Th, or in mixed ^{232}Th–^{233}U and ^{232}Th–^{239}Pu fuels. Its formation occurs through reactions involving ^{233}Pa and ^{233}U at a 6.37 MeV threshold (n, 2n) reaction. The presence of ^{232}U leads to gamma radiation hazards due to the formation of short-lived isotopes such as ^{228}Th, ^{212}Pb, ^{212}Bi, and ^{208}Tl, which emit high-energy 2.6 MeV gamma radiation. Chemically, the recovered thorium cannot separate ^{228}Th, resulting in high-energy gamma radiation fields from reprocessed ^{228}Th and ^{233}U, necessitating remote handling during refabrication or reprocessing. In irradiated thorium assemblies, the expected content of ^{232}U is 500–1000 ppm. This can be further minimized to 2–11 ppm by positioning thorium blankets 15–20 cm away from the core boundary, reducing ^{232}U production in 1.3 g ^{233}U per kg of thorium [70].

4. MSR Safety Protocol and Understanding

4.1. Fission Product Species Transport and Deposition in Molten Salts

In MSR technology, fission products generated in liquid fuel salt are free to migrate and mix within the reactor. The composition of the fuel salt and its cycling through the reactor core are crucial for maintaining the spatial distribution of fuel composition. The spatial distribution of fuel–salt composition is influenced by the generation of insoluble fission products, such as noble metals and noble gases, which are insoluble and lyophobic (solvent-repelling) in the fuel salt. These insoluble fission products tend to form solid particulates or gaseous bubbles during reactor operation. In an MSR system, most fission products form ionic pairs with the ionic base of the carrier salt. However, due to their lyophobic nature, insoluble fission products leave the fuel–salt system through mass transfer processes and accumulate in the primary loop. This mass transport and accumulation of insoluble fission products can lead to safety and efficiency challenges in the reactor. The extensive deposition of noble metals (e.g., Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te) and reduced corrosion products can cause clogging in narrow tubes and fouling in heat exchangers, thereby altering the heat transfer coefficient. Insoluble corrosion products can also interact with liquid–gas contactors, potentially leading to unexpected reactor behaviors [71,72]. Additionally, the cumulative localized decay heat from insoluble fission products can cause structural damage and inefficient cooling, promoting multiphysics effects and altering the reactor's thermal–hydraulic behavior. Furthermore, volatile fission products may result in radiation release in the event of an accident, posing significant safety concerns [72,73].

Regarding MSR licensing evaluation and operational safety, the Ji group focused on the transport and deposition of noble metal fission products within the loop system where a circulating swarm of helium bubbles is present [74]. Circulating helium bubbles are utilized in MSRs to extract noble metals. The group developed a Noble Metal–Helium (NM–He) deposition model to better understand the multiphysics effects occurring during the operation of Molten Salt Reactor Experiment (MSRE) runs with ^{235}U and ^{233}U fuels. The helium bubble model and noble metal mass transport analysis provide insights into reactor behavior influenced by noble metal deposition and helium bubble swarm dynamics. The analysis of the ^{235}U and ^{233}U runs revealed that the number of entrained helium bubbles increases while their average size decreases. This change in bubble entrainment behavior indicates that noble metals and insoluble corrosion products at the liquid–gas interface surface act as surfactants in the pump bowl. The evolving characteristics of the bubble swarm enhance the extraction and deposition of noble metals and insoluble corrosion products into the off-gas system and pump bowl [74].

4.2. Off-Gas Management

A comprehensive understanding of MSR technology, particularly the chemistry of the salts and fuel behaviors, including the properties of produced gases, is still not fully established. Gaseous fission products with low solubility in fuel salts tend to migrate to the gas phase. MSRs are designed with drain tanks containing headspaces to facilitate the removal of off-gases (Figure 12). Some fission products, such as lanthanides, which act as neutron poisons, are soluble in the salt, while others, such as xenon (Xe) and krypton (Kr), are gaseous and escape from the salt, accumulating in the headspace. The off-gas stream composition will vary depending on the specific MSR design (Table 2). Off-gases affect the solubility and volatility of fission products in the salts. Approximately half of the fission products in off-gases are noble gases, such as radioactive isotopes of Xe and Kr, which have a range of half-lives, most of which are short. These noble gases are swept from the salt and passed through decay tanks, where they reside for 1–2 h to remove decay heat. Overall off-gas confinement is maintained for approximately 90 days to minimize radioactive release to the environment. Long-lived gases are either contained for further decay or recirculated through the cover gas [75–78].

Various materials, such as activated carbon, zeolites, metal–organic frameworks, and chalcogels, are used to capture noble gases, allowing short-lived radionuclides to decay while enabling effective capture and separation. The performance and efficiency of these materials vary based on their properties, making them a subject of significant interest for the development of efficient noble gas capture technologies in research. To remove particulates, mists, and aerosols and prevent clogging of the cover gas, filters are installed after the decay tank. A pressurized headspace (5 psig) is maintained to sparge the salt and push fission gases through a series of metal filters and charcoal beds before releasing them into the environment [79,80]. The capture of halogen and interhalogen compounds is achieved using solid adsorbents (such as silica-based aerogels, porous metal-exchanged impregnated zeolites, sulfide-based aerogels, graphene powders, and granular activated carbon) or liquid scrubbing methods (such as Mercurex, Iodox, gravitational scrubbers, packed bed scrubbers, and caustic scrubbing) [76,81].

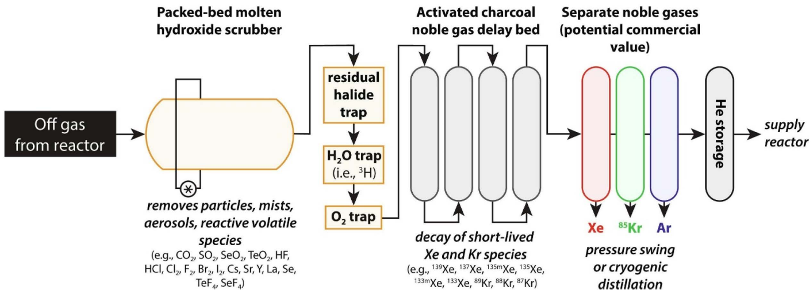

Figure 12. Schematic of an overall off-gas system for a commercial MSR. Reproduced with permission: Copyright 2019, Elsevier B.V. [76].

Table 2. Potential gases and species of the MSR technology.

Types	Species
Volatile species	Cl_2, Br_2, I_2, HF, ^{3}HF, ICl, IF_5, IF_7, Cs, Ba, Rb, Sr, La,
Aerosols/mist	Graphite debris, corrosion, salt residues
Tritium	$^3H_2$, ^{3}HH, ^{3}HF, ^{3}HF, ^{3}HHO, or ^3H_2O
Short-lived fissions gases	^{139}Xe $t½$ = 39.5 s, ^{137}Xe $t½$ = 3.83 min, ^{135}Xe $t½$ = 15.3 min, ^{135}Xe $t½$ = 9.1 s, ^{133}Xe $t½$ = 2.19 d, ^{133}Xe $t½$ = 5.25 d, ^{90}Kr $t½$ = 32.3 s, ^{89}Kr $t½$ = 3.18 min, ^{88}Kr $t½$ = 2.84 h,
Long-lived radionuclides	^{129}I $t½$ = 1.57 × 107 y, ^{79}Se $t½$ = 6.5 × 104y, ^{85}Kr $t½$ = 10.7 y, ^{36}Cl $t½$ = 3 × 105 y

half-life ($t½$).

Tritium release and prevention are considered using absorption, stripping, or barrier methods. Absorption involves introducing activated carbon, chemically bound tritium (^{3}H) in the tertiary and secondary coolants into the fuel salt. Fission product tellurium in molten salts is undesirable because it accelerates the degradation of reactor materials, reducing the reactor's lifespan and increasing maintenance costs. Care must be taken to match the thermal expansion properties of these barrier layers to prevent tellurium and chipping, as no barrier materials have yet achieved high Technology Readiness Levels (TRLs) [76,82].

4.3. Impacts of Iodine in MSR System

A fundamental understanding of the radiation-induced behavior of iodine as a fission product, particularly within molten salt environments and its associated redox chemistry, is crucial. In a designed MSR system, fluoride and chloride salts are employed as coolants, and iodine, as a fission product, is present as a solute within the salt system [83–85]. These fission products dissolve directly into the molten salt, where the iodide ion (I^-) acts as a chemical scavenger, contributing to the formation of interhalogen and polyhalide species (e.g., $XI^{\bullet-}$, $XI_2{}^-$, X_2I^-, and XI) as shown in Equations (1)–(3) [86,87]. Equation (1) represents the reaction where an unpaired electron species (halogen) reacts with iodide to form a complex, $XI^{\bullet-}$, which carries both an unpaired electron and a negative charge. As the reaction progresses, two complexes combine to form a dimer, (XI_2^-), or react to form X_2I^- with the release of an ion, X^- (as described in Equation (2)). The dissociation of the dimer is a reversible process, where larger complexes break down into simpler species, returning to their constituent parts (Equation (3)).

The radiolysis products have the capacity to modify the corrosion potential, leading to the formation of hazardous halide gases and metal clusters [88]. The Horne group has evaluated the performance and stability of these interhalogen species in the MSR environment [89]. Picosecond electron pulse irradiation shows that impacts on the iodide ions generate radiation-induced transient radicals in the molten salt mixture (e_s^-, $Cl_2^{\bullet-}$) at 400–700 °C. The transient spectrum detected three species: e_s^-, $Cl_2^{\bullet-}$, and $ICl^{\bullet-}$ radical anions. Here, the lifetime of e_s^- is not affected by the addition of I^- ions. The interhalogen radical anion ($ICl^{\bullet-}$) shows a lifetime on the order of microseconds, and its decay occurs through a reaction with the $Cl_2^{\bullet-}$ radical anion. $ICl_2{}^-$, a fission product of iodine, is assumed to impact MSR technology significantly [89].

In liquid-fueled MSRs, both fuel and fission products are soluble in the molten salt. A chemical processing unit is required to continuously remove fission products from the reactor without shutting down the system, returning the processed salt to the reactor chamber in situ. However, insoluble fission products can deposit on the structural surfaces of the heat exchanger, reducing the system's heat transfer efficiency. The accumulation of these deposits, which concentrate radionuclides, necessitates reactor shutdown for their removal [24,87].

$$X^{\bullet} + I^- \leftrightarrow XI^{\bullet-}, \quad (1)$$

$$XI^{\bullet-} + XI^{\bullet-}/X_2^{\bullet-} \leftrightarrow XI_2^-/X_2I^- + X^-, \quad (2)$$

$$XI_2^-/X_2I^- \leftrightarrow XI + I^-/X^-, \quad (3)$$

Molten salt serves as an effective barrier against the release of radioactive materials in the event of an accident. Gelbard's group employed the Generalized Radionuclide Transport and Retention (GRTR) submodel within MELCOR to simulate molten salt behavior over time in a control volume [90]. The model tracks radionuclide release into the salt and calculates the mass distribution of each radionuclide in five forms: dissolved in the salt, suspended as insoluble salt particles, insoluble particles at the gas–liquid interface, particles adhering to structural surfaces, and gases released into the atmosphere above the salt pool (Figure 13). Insoluble fission products often form very small colloidal particles (Form 2), which can be transported to the gas–liquid interface (Form 3) and subsequently deposited on heat–exchange surfaces (Form 4). Additionally, aerosol particles (Form 3) may be released into cooler atmospheric regions, a process that generally occurs naturally [90].

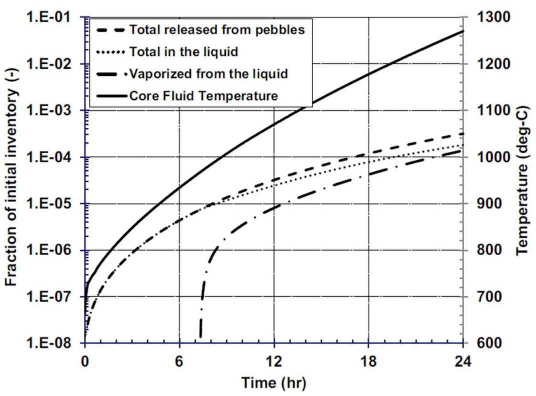

Figure 13. Simulated cesium releases from a loss-of-coolant accident LOCA (10% pipe break of the salt drain line) in the Mark–1 PB–FHR power plant. Only the solid curve uses the right y-axis for the temperature, and the three other curves use the left y-axis. Reproduced with permission: Copyright 2024, Taylor & Francis [90].

4.4. Sloshing Dynamics of Molten Salt

Drain tanks, a critical component for holding molten salts in Molten Salt Reactors (MSRs), must be designed with consideration of accident scenarios, particularly for handling decay heat and containing radioactive materials. The reactor's high efficiency makes the design of drain tanks complex, with factors such as size, shape, and aspect ratio significantly influencing fluid dynamics under various ocean conditions that induce salt sloshing due to ship motion. For safety considerations, understanding fluid dynamics and sloshing effects, as well as the loading impact on tank walls, is essential [91,92].

The Lee group employed CFD simulations using OpenFOAM to study the sloshing dynamics of molten salt within drain tanks of different configurations (aspect ratios) with identical volume (e.g., cylindrical tank with a diameter of 1.27 m, height of 2.18 m, and volume of 2.26 m^3) [93]. The density of molten salt is approximately twice that of water, which results in higher sloshing pressures when compared to water. Tanks with a low aspect ratio (aspect ratio 0.855; diameter 1.5 m, height 1.28 m) experience more free surface breaking and a higher splashing amplitude than those with a higher aspect ratio (aspect ratio 2.88; diameter 1 m, height 2.88 m; and aspect ratio 1.40; diameter 1.27 m, height 1.78 m). The rise time of impact pressure in molten salt is longer due to the damping effects caused by its viscosity.

When comparing low-amplitude (0.01) lateral excitation in water and molten salt, the pressure distribution across all aspect ratios is slightly higher for molten salt due to its higher density. However, under high-amplitude (1.0) lateral excitation, this difference becomes more pronounced. Free surface resonance can be mitigated by the use of baffles, and the presence of internal bayonet tube heat exchangers can function as damping buffers, effectively reducing impact pressure and side pressure distribution [91].

4.5. Corrosion Resistance Approach

In MSR systems, there is a research opportunity to control the redox potential of the salt using redox buffers to prevent or limit the corrosion of structural materials. To mitigate core material corrosion, it is suggested that the U (IV)/U (III) concentration ratio (buffer couple) should be maintained between 10 and 100. In the presence of carbon within the core, carbon reacts with uranium to form carbides (UCx). In the absence of carbon, tritium generation occurs from fission reactions as TF, which is then reduced to tritium (T_2) and can diffuse through structural materials. If the salt's redox potential is too oxidizing, core materials may corrode, resulting in the dissolution of metals [94,95].

To avoid such issues, carbon-free structures, such as Hastelloy–N, are selected as core materials. Hastelloy–N consists of Ni (68%), Mo (17%), Cr (7%), Fe (5%), and Mn (1%). In uranium fuel systems, Cr is the most reactive element, and its oxidation in structural materials can be controlled by maintaining a U (IV)/U (III) concentration ratio between 10 and 100. The lower limit of 10 corresponds to the solubility limit of U (III), while the upper limit relates to an acceptable Cr corrosion rate. However, even with precise control of temperature and redox potential, preventing Cr oxidation remains challenging. At a U (IV)/U (III) ratio of 100, the mole fraction of dissolved Cr (II) in the salt becomes reasonable (Figure 14) [95,96].

The Chamelot group explored the use of reducing metals in the salt to spontaneously decrease the redox potential by consuming U(IV) [96]. Their research demonstrated that a reducing agent, such as Gd or U, introduced into the salt (eutectic LiF–CaF_2 at 850 °C) significantly affects solute concentrations, as identified by electrochemical measurements. The study showed that Eu (III) could be fully converted to Eu (II) using a metallic Gd plate, as outlined in Equations (5) and (6).

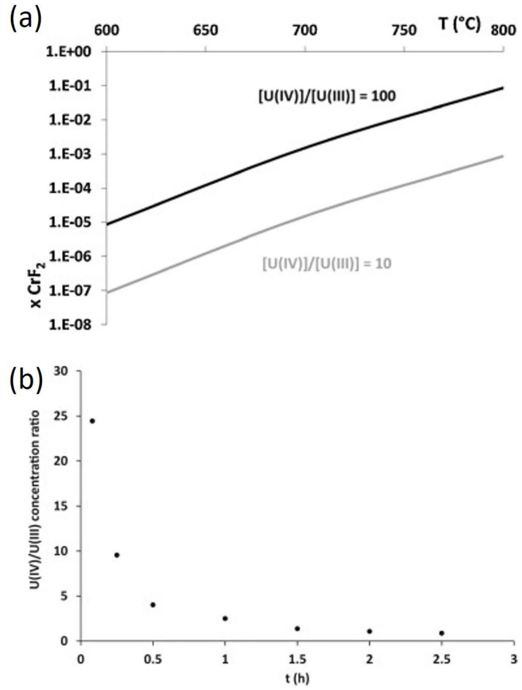

Figure 14. (**a**) Mole fraction of dissolved CrF_2 as a function of temperature for two different uranium concentration ratios; (**b**) U(IV)/U(II) concentration ratio versus the U immersion time at 850 °C. Reproduced with permission: Copyright 2015, Elsevier Ltd. [96].

Further, in an electrochemical experimental setup involving U (IV)/U (III) with a metallic U plate, the kinetics of U (IV) reduction were found to be rapid, reaching equilibrium between U (IV)/U (III) and U (IV)/U (2.5 h for S/V = 16.10^{-3} cm^2/cm^3). The results suggest that while the initial concentration approaches infinity (only U (IV)), it is possible to decrease it to 1 [96].

$$\text{Cr} + 2\text{U (IV)} = 2\text{U (III)} + \text{Cr (II)}, \quad (4)$$

$$3\text{Eu (III)} + \text{Gd} = 3\text{Eu (II)} + \text{Gd (III)}, \quad (5)$$

$$3\text{U (IV)} + \text{U} = 4\text{U (III)}, \quad (6)$$

4.6. Waste Management

Material properties must be validated at temperatures up to 900 °C, considering the effects of thermal expansion and heat gradients, which significantly impact material longevity. Steel alloys are prone to corrosion in molten fluoride salts, rendering them unsuitable for MSR components. Chemically passive materials such as gold (Au), nickel (Ni), and tin (Sn) are more suitable for MSR components in contact with corrosive salts; however, their high cost and difficulty in scaling for large structures present challenges. Alternatively, noble metal plating can create an inert protective layer to shield other metals from salt-induced corrosion. Corrosion rates accelerate at elevated temperatures due to the thermal gradient in molten salts containing fission products, and most alloys are limited to tolerating up to 750 °C. This narrows the selection of suitable materials, necessitating effective redox monitoring and management [70,97,98].

In addition to off-gas management through the confinement of fission gases and trapping of particulates during on-line maintenance, assessing off-gas performance during reactor operation remains a significant challenge. Gamma spectroscopy is commonly used in conventional reactor designs, but the effectiveness of this technique is reduced in MSRs due to their unique off-gas characteristics. MSR waste streams include metal waste, carbon waste, separated salt, operational waste, and decommissioning (D&D) waste. Electrochemical dehalogenation processes are utilized to stabilize chloride salts within an iron phosphate glass matrix, while UCl_3 is reincorporated into fresh fuel salt. Reactor containment materials, such as nickel and nickel-based alloys, may become activated or surface-contaminated with actinides, classifying them as waste and requiring appropriate disposal. Currently, no comprehensive strategy for MSR waste management has been established, although it is often assumed that MSR waste and light water reactor waste will be handled similarly. The recycling of waste materials is also under consideration. It is evident that a fully validated technical roadmap for waste stream management, aimed at minimizing risk, remains incomplete. The most viable approach for advancing MSR development and licensing involves focusing on waste stream treatment and used fuel processing. This includes the indefinite reuse of actinides and the stable packaging of remaining solid fuel salts for safe, long-term surface storage until decay [70,76,97–99].

5. Technology Readiness Levels (TRLs)

The TRL framework evaluates the maturity of advanced reactor technologies for potential test or demonstration reactor missions. A dedicated working group assesses the readiness of major systems and subsystems for each component to provide a comprehensive overall readiness assessment (Figure 15) [100–102]. This group collaborates closely with subject matter experts and technology proponents to ensure thorough evaluations. The study focuses on three main areas: (a) the current technology readiness status and identification of key technological hurdles that must be addressed, determining whether these challenges require only testing or a full demonstration reactor; (b) achieving a TRL of at least 6 is necessary for the base technology to proceed to a test reactor phase; and (c) each technology component must reach TRLs of 4–8 for demonstration reactor setup, with all feasibility issues resolved before proceeding to demonstrations [97,103].

System operation	TRL 9	Actual full range system operation
System commissioning	TRL 8	Actual system completed and qualified
	TRL 7	Full–scale, pilot–scale demonstration
Technology demonstration	TRL 6	Validation in pilot–scale (prototypical)
Technology development	TRL 5	Validation in small-scale
	TRL 4	Validation in laboratory
Research to prove feasibility	TRL 3	Experimental and critical function proof
	TRL 2	Technology concept application formulated
Basic technology research	TRL 1	Basic principles observed and reported

Figure 15. Schematic representation of the scale of Technology Readiness Levels (TRLs).

Beyond TRLs, it is crucial to evaluate and map Community Readiness Levels (CRLs), particularly concerning public acceptance of commercial shipping operations on the seabed. This evaluation should encompass safety and environmental regulations, community engagement, education initiatives, evidence of safety and environmentally sustainable design, and alignment with global energy demands and decarbonization targets [104]. Furthermore, addressing technological challenges related to materials and components, liquid salt chemistry and properties, fuel and fuel cycles, system design and operation, safety systems design, and comprehensive system integration assessments is essential for the successful deployment and acceptance of these advanced technologies. The TRLs of molten salt reactors were evaluated based on the various factors illustrated in Figure 16 [97,103].

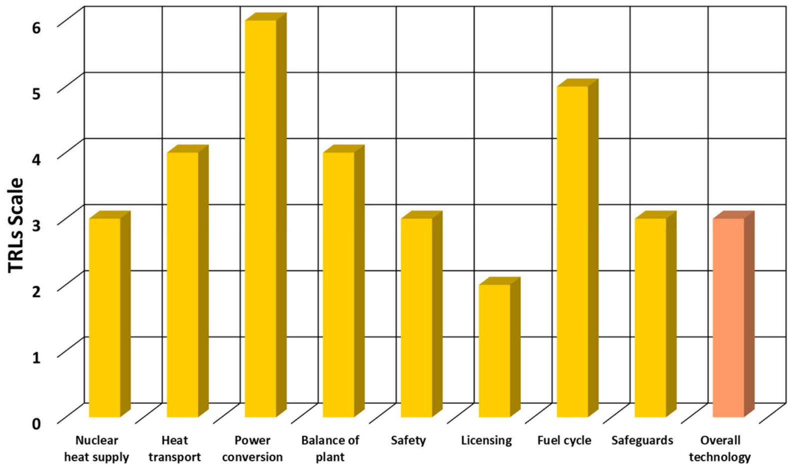

Figure 16. Comparison of Technology Readiness Levels (TRLs) of subsystem of MSR technology.

6. Conclusions and Future Research Perspective

Molten Salt Reactors offer high thermodynamic efficiency, real-time removal of fission products, and enhanced safety due to low operating pressure and chemically inert coolant. MSRs' fluid–fuel system provides a large negative temperature coefficient of reactivity (-4 to -6 pcm/°C, percent mile per degree Celsius), enhancing self-regulation. They allow higher fuel burnup, reducing the need for new fuel. However, MSRs face challenges with impurities, corrosion from isotopes generated within the salt, and complex salt management due to high radioactivity. Selection of suitable salts requires chemical and radiolytic stability, high thermal conductivity, low vapor pressure, and specific heat capacity, with specific salts demanding increased shielding due to gamma emissions.

The dynamic conditions at sea, such as heeling and rolling motions, impact the reactivity feed by thermal and hydraulic performance of MSRs. Advanced control systems, like Model-Free Adaptive Control (MFAC), provide robust, adaptive regulation of coolant temperatures under these conditions, outperforming traditional PID controllers. Integrating heat pipes into MSRs further enhances their suitability for maritime use by eliminating in-core thermal stress and pumps. However, oceanic motions introduce complex forces affecting fuel flow and heat transfer, necessitating advanced modeling techniques to ensure safe and efficient operation. Computational simulations reveal that rolling motion improves fuel mixing and heat transfer, reducing temperature variations and thermal stress, making MSRs viable for maritime applications with the appropriate control and design considerations.

For off-gas management, MSRs use systems like decay tanks and various materials to capture and contain volatile fission products, including noble gases like xenon and krypton. Effective management of off-gases and tritium is achieved through materials like activated carbon, zeolites, and various solid adsorbents or scrubbing methods. Structural integrity and safety are further maintained by using absorption and barrier methods to control tritium release. Overall, advancing the understanding and control of redox conditions, material interactions, and gas capture technologies is essential for enhancing MSR safety and efficiency.

MSR technology presents challenges related to controlling redox potential and managing corrosion, fission products, and off-gas management. Controlling the U (IV)/U (III) ratio between 10 and 100 is crucial for limiting core material corrosion, particularly chromium oxidation in Hastelloy–N. Despite maintaining these ratios, chromium oxidation remains challenging due to its reactivity, and adding reducing metals like Gd can effectively lower redox potential, potentially reducing the corrosion rates of structural materials. In MSRs, the transport and deposition of insoluble fission products, like noble metals, pose safety and efficiency challenges due to their accumulation in the primary loop, leading to potential clogging and heat transfer issues.

In the future, it is crucial to evaluate the risk factors associated with molten salt reactors in the context of military operations and potential military use. There is a significant possibility that military aggression, such as shelling by artillery, could damage reactor systems, leading to the dispersion of molten salt into the environment. Comprehensive assessments are needed to evaluate the threats and establish protocols for managing damage to reactor vessels, considering factors such as dispersal distances and varying intensities of attacks.

The direct use of MSRs for recharging electric vehicles poses challenges related to power storage and distribution. For efficient utilization, alternative power transfer methods, such as direct electricity generation or the production of alternative fuels (e.g., hydrogen or synthetic fuels), should be considered. When MSRs are used for alternative fuel production, it is essential to establish clear visions and comprehensive guidelines to ensure the safe, efficient, and sustainable integration of these technologies into the energy system.

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