Molten Salt Reactors: Current technology status and the challenges for maritime applications

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Synopsis

The 2015 Paris Agreement mandates a 40% domestic reduction in GHG emissions by 2030 compared to 1990 levels. Amidst rising interest in alternative fuels to power commercial shipping, hydrogen and biofuels emerge as leading contenders. However, for military vessels, multiple fuel sources pose logistical challenges. Nuclear technology, historically developed for energy and weaponry, offers a consistent energy supply, especially for naval fleets.

Nuclear technology, rooted in 20th-century research, has seen significant advancements, particularly in Pressurised Water Reactors (PWRs) dominating commercial energy production. Molten Salt Reactors (MSRs), initially researched in the 1950s, experienced a resurgence in the early 2000s, offering potential advantages over PWRs. MSRs operate with molten salts, presenting diverse configurations and fuel options.

Advantages of MSRs include enhanced safety, economic efficiency, and environmental benefits, such as reduced nuclear waste. However, challenges like material corrosion, limited operational experience, and regulatory complexities hinder widespread adoption. Despite these hurdles, ongoing research and collaboration worldwide signal a growing interest in MSR technology, with various projects at various stages of development.

In maritime applications, integrating MSRs for propulsion and power generation presents both technical and regulatory challenges. While MSRs offer compact designs, higher thermodynamic efficiency, and reduced nuclear waste, concerns over safety, infrastructure, and regulatory frameworks persist. Addressing these challenges requires interdisciplinary collaboration and innovative solutions.

Assessing MSR technology readiness levels (TRLs) reveals progress in reactor technology but underscores the need for further development, particularly in marine applications. Despite the lower TRLs for maritime-based MSRs, exploring integration possibilities and addressing regulatory gaps are crucial steps toward realising their potential.

In conclusion, MSR technology holds promise for reducing emissions and ensuring energy security in maritime operations. However, overcoming technical, regulatory, and workforce challenges is essential for successful integration into naval and commercial fleets. Collaborative efforts across industries and regulatory bodies are imperative to advance MSR technology and navigate its complexities effectively.

Keywords: Molten salt reactor; technology readiness levels; alternative fuels; Nuclear powered ships; Occam Group.

Biography

Matthew Dunn is a Chartered mechanical engineer who works as a Senior Consultant at Occam Group Ltd. He has an MSc from Cranfield University in Advanced Materials and extensive experience working for Defence Equipment and Support prior to his employment at Occam Group. Matthew specialises in safety management, design assurance and engineering change linked to the integration of explosives onto naval ships.

1. Introduction

The 2015 Paris Agreement (The United Nations, 2015) is a legally binding international treaty on climate change and has 195 members who are party to the agreement. In response to this, the International Maritime Organisation (IMO) and Member States have adopted the Strategy on Reduction of Greenhouse Gas (GHG) Emissions from Ships (International Maritime Organisation, 2023), requiring member states to work towards its target of increasing zero or near-zero GHG emission technologies, and reduce CO_2 emissions by at least 40% by 2030, compared to 2008 levels. This legislative drive to reduce emissions means the debate surrounding alternative fuel sources for shipping has been at the forefront to enable nations and ship owners to achieve the goals of the legislation.

The global trends for alternative fuel choices in the commercial sector are trending towards one of two categories, hydrogen-based fuels, and biofuels (Raucci, McKinlay and Karan, 2023) with no clear single alternative fuel across the sector being clearly identified. This may suit the commercial sector’s needs, but for military applications, using multiple fuel sources is impractical and severely restricts the global reach of a nation. Nuclear technology for ships is used by several Navies across the world (World Nuclear Association, 2023) and the ability to have a never-ending supply of energy for a ship can present significant benefits to owners and operators.

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Nuclear technology development traces its roots back to the early 20th century with most development focused during the second world war for use in the atomic bomb. Following the war, the focus changed to harnessing the energy of a nuclear reaction to generate electricity with the main driver in this field occurring in the 1950s (U.S. Department of Energy, 1995). The current reactors in nuclear power plants are dominated by Pressurised Water Reactors (PWRs) encompassing 66% of all plants across the world (Ho et al., 2019). The United States Navy drove this development to power its ships, and like most technology research, when funded sufficiently, a suitable solution develops that is employed for use across the world.

Molten Salt Reactors (MSRs) were researched in the 1950s through to the 1970s at the Oak Ridge National Laboratory (ORNL). Between 1980 and the early 2000s very little research was undertaken (LeBlanc, 2010). However, since 2002 there has been renewed interest in this field of nuclear technology.

2. Molten Salt Reactor Technology

2.1. Classification

MSRs are a nuclear reactor where molten salts (typically fluoride or chloride salts) form a significant part of the nuclear reaction. MSRs can be grouped across a broad range of technologies where the molten salt is used as a fuel, a fuel carrier, a coolant, or used to moderate the nuclear reaction. There have been several attempts classifying MSRs (Smith et al., 1974; Taube, 1978), the most comprehensive of which has been developed by the International Atomic Energy Authority (IAEA), grouping MSRs with three layers of taxonomy. Figure 1 shows the various types of MSR technology grouped under the differing classifications.

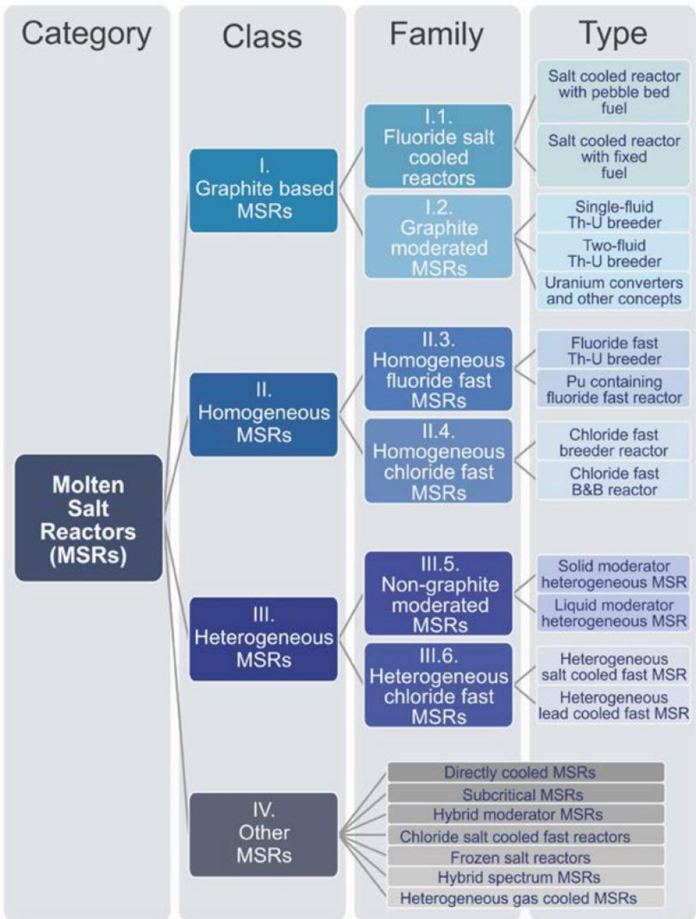

Figure 1 –Three layers of MSR taxonomy as a block diagram (Martinez-Guridi, Peguero and Reitsma, 2023)

2.2. Generic Architecture of a typical MSR

The main architecture of MSR reactors consists of a reactor vessel, reactor core and a fuel. There are coolant pumps to push the coolant through the system to maintain temperature, and a heat exchanger system that leads to the power generator. Figure *2* shows a typical MSR configuration where the salt is used as a fuel.

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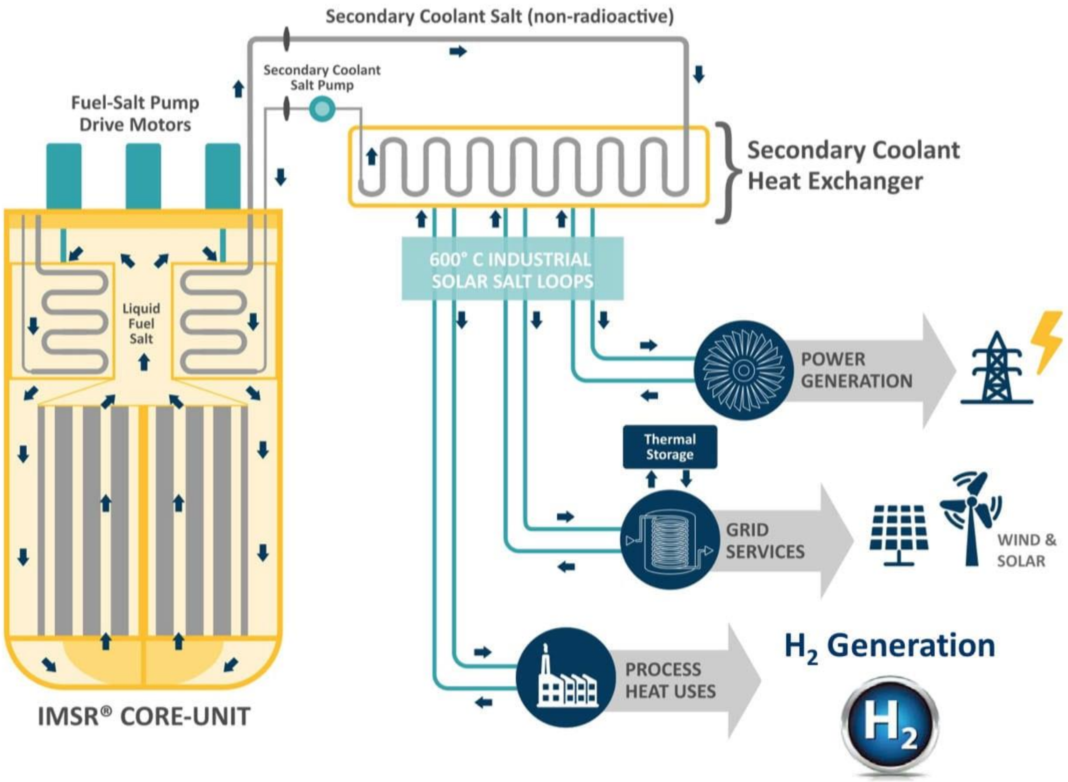

Figure 2 – MSR architecture using salt as a fuel (Terrestrial Energy, 2017)

Table 1 summarises the three major classes of MSRs and respective reactor types, however, this does not cover the other MSRs from Figure 1.

As can be seen, there is a wide variety of reactor types, configurations, reaction methods, and types of salts used in MSR technology. This diversity poses challenges for MSR developers because the range of technologies requires research and development efforts to be distributed across multiple areas rather than focused on a single technology.

2.3. *Advantages and Disadvantages*

MSRs have several advantages over traditional PWRs, as stated by Elsheikh, 2013; Furukawa et al., 2002; Gat and Engel, 2000:

2.3.1. Safety

- Operation at near atmospheric pressure (lower than 5 bar), reducing the risk of salt leakage or potential core breach caused by steam or hydrogen explosion.
- Molten salts are chemically inert and not flammable.
- The ability to remove fission products avoids potential pressure build up.
- As a fuel source, molten salts are in liquid form so cannot be damaged mechanically.
- Molten salts have a high boiling point, close to double the current operating temperatures in PWR's.
- Liquid fuel allows for flexibility in the fuel cycle and the fuel composition can be chemically adjusted.
- The reaction is self-regulating, as the reaction overheats, reactivity of the core automatically slows down.
- As the fuel is in liquid form, it can easily be removed from the reactor into a passively cooled dump tank.
- Less high-level waste generation than PWRs.
- The reactor fuel cycle has excellent non-proliferation credentials.

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Table 1 – Comparison of the six major MSR families (Martinez-Guridi, Peguero and Reitsma, 2023)

Class	**I. Graphite Based MSRs**		**II. Homogenous MSRs**		**III. Heterogenous MSRs**	
Family	I.1. Fluoride Salt Cooled Reactors	I.2. Graphite Moderated MSRs	II.3. Homogeneous fluoride fast	II.4. Homogeneous chloride fast	III.5. Non-graphite moderated	III.6. Heterogenous chloride fast
Fuel State	Solid	Liquid	Liquid	Liquid	Liquid	Liquid
Spectrum	Thermal	Thermal	Fast	Fast	Thermal	Fast
Salt Type	Fluorides	Fluorides	Fluorides	Chlorides	Fluorides	Chlorides
Neutronics Performance	Burner, converter	Burner, converter, breeder	Burner, converter, breeder	Burner, converter, breeder, breed-and-burn	Burner, converter, breeder	Burner, converter, breeder, breed-and-burn
Actinides	Enriched U, TRU, Th as a semi-inert matrix	Enriched U, TRU, closed Th-U cycle	Enriched U, TRU, closed Th-U and U-Pu	Enriched U, TRU, closed Th-U and U-Pu	Enriched U, TRU, closed Th-U cycle	Enriched U, TRU, closed Th-U and U-Pu
Irradiation induced issues	Limited burnup of fuel in graphite matrix	Limited graphite moderator lifespan	Limited vessel lifespan	Limited vessel lifespan	Limited vessel and structural material lifespan	Limited vessel and structural material lifespan
Fuel extensive pumping	No	Yes	Yes	Yes	Yes (No if cooled by a moderator)	No
Heat Transport medium	Fluoride coolant salt	Fluoride fuel salt	Fluoride fuel salt	Chloride fuel salt	Fluoride fuel salt (or moderator)	Molten salt or lead coolant
Primary heat exchange	In-core	Ex-core	Ex-core	Ex-core	Ex-core (in-core)	In-core

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2.3.2. Economic

- High boiling point of molten salts allows for operation to be conducted at higher temperatures which gives high thermodynamic efficiency.
- Low wastage from the reaction, using more of the fuel.
- Liquid fuel allows for a more compact reactor design when compared to a solid fuel PWR system.
- If Thorium is used it is about 3 times more abundant on earth than uranium.

2.3.3. Other Factors

- Reputationally, MSRs can provide a good roadmap towards de-carbonising both the land-based power generation as well as in the maritime industry.
- Certain MSRs can be used as nuclear fuel waste burners, thus providing a route to recycle spent nuclear fuel.
- There is a cadre of engineers currently supporting the build of the United Kingdom's (UK) third generation nuclear power plants, this knowledge and experience could be used to support the use of MSR technology.

MSRs have several disadvantages/challenges that currently hamper further development, as detailed by (Nuclear Innovation and Research Office, 2021; Pedersen, 2019; Roper et al., 2022; Science Innovation and Technology Committee, 2023; Wright and Sham, 2018)

2.3.4. Safety

- There is no single suitable material for the reactor core. Molten salts are highly corrosive, the reactor operates at very high temperatures introducing significant creep challenges, and high radiation dosage mean new alloys need developing as well as novel ways to manage material challenges.
- Minimal modelling and simulation data is available to understand core physics.
- The reaction produces tritium, which provides corrosion risks, containment risks, and is a significant hazard to humans. Significant progress has been made by companies such as Copenhagen Atomics who have developed several strategies to address the corrosion issues associated with MSRs.
- Reactor monitoring is a challenge due to the liquid fuel and high temperatures.
- There is no current precedent for manufacture and qualification of fuels.
- Operational experience of MSRs is severely limited across the globe.

2.3.5. Economic

- There is limited supply chain in the UK that could produce components needed to build an MSR, current estimates put about 5% of the components could be UK sourced.
- Implementation costs are not fully quantified, there is still an extremely high initial outlay required in terms of R&D to overcome the challenges.

2.3.6. Other factors

- As there is a spread of research and projects looking at differing types of MSR reactor technology, there is a significant licensing/regulatory challenge. The capacity and ability of national regulatory bodies to evaluate and approve such a broad spectrum of technologies is limited.
- As there has not been any MSRs licensed, there is a lack of testing facilities that can be used to verify new designs and new technology, coupled with the lack of expertise of MSR technology in the UK to undertake this type of testing.
- There is a significant gap of engineering capability in the UK currently. Current estimates are that the UK must recruit an average of 7,234 personnel each year until 2028 to combat the lack of personnel and the current ageing nuclear expertise in the UK.

2.4. Current MSR Research and Projects

There is a wide range of activity undertaken in MSRs, with the Nuclear Energy Agency identifying ten projects at varying stages of development in its Small Modular Reactor Dashboard. Of these ten projects, none have progressed further than design approval, and three of these designs were for marine-based applications (Cameron and Mir, 2024). Since 2000, there has been a steady trend of research linked to MSR technology.

Analysis of Google Scholar articles and Dimension articles using the search terms 'MSR', and 'Molten Salt Reactor' shows an upwards trend in academic and research articles linked to the technology. Figure 3 shows this trend, but it should be noted that this research was severely limited and to gain a more in-depth analysis of the actual published articles would require extensive modelling and research.

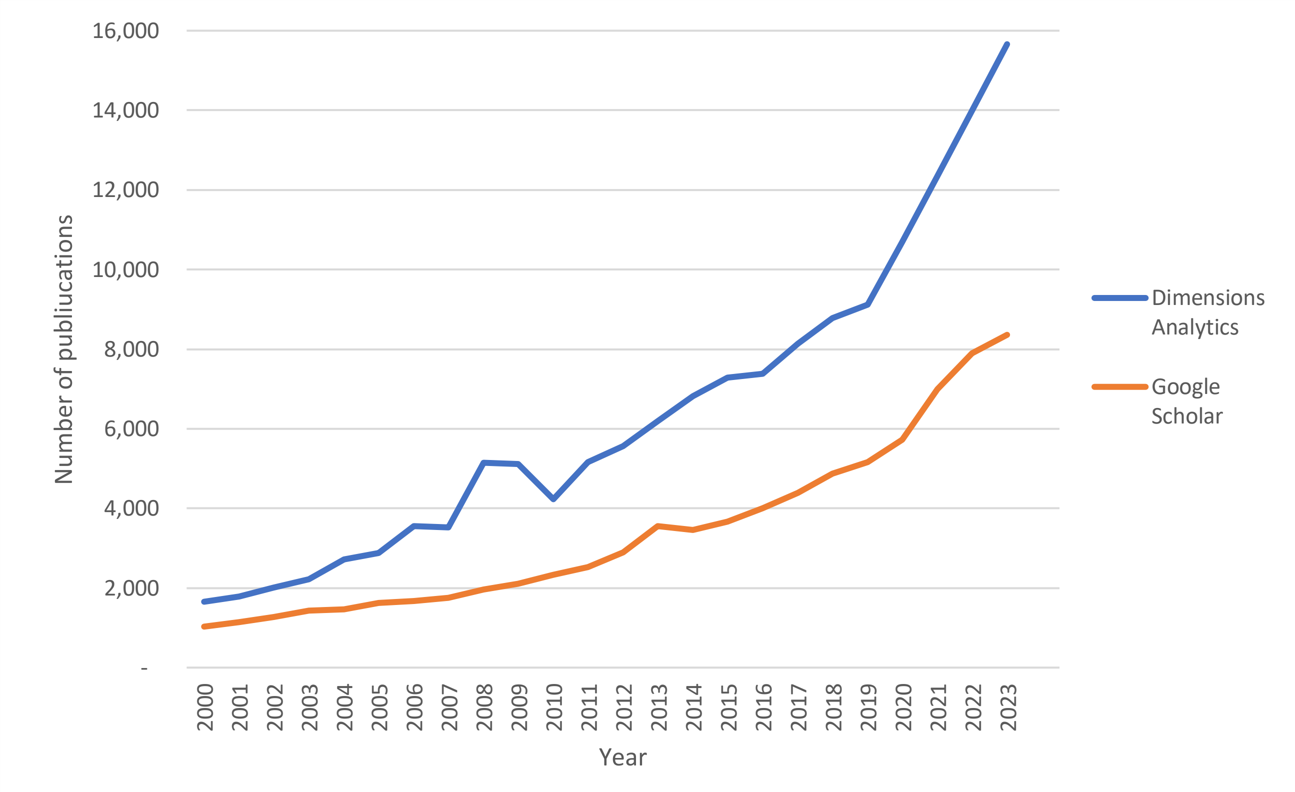

Figure 3 – Analysis of publications using key words 'Molten Salt Reactor and MSR' from the year 2000.

Table 2 details 15 active projects across the world with several of these projects working in collaboration to accelerate the technology to commission their MSRs. There is a strong link into the UK with Terrestrial Energy, Moltex and UK Atomics, which is a subsidiary of Copenhagen Atomics with offices in the UK that are working towards MSR technology. Alongside this, the UK Department for Energy Security and Net Zero has joined Net Zero Nuclear, a collaboration between industry and government that aims to build understanding of the value of nuclear energy, deliver the political and financial enablers to propel nuclear energy's growth and remove the roadblocks that prevent nuclear from fully realising its contribution to global clean energy security. Several companies in this partnership are actively developing MSR technology, with some such as Terrapower and UK Atomics actively targeting the UK for deployment of their systems. There are four projects that are targeting MSR use in the marine environment.

Of these four, two projects are being undertaken by ship designers and builders, rather than organisations focusing on the reactor technology. The project through the China State Shipbuilding Corporation has only recently been announced, very little detail is available. Ulstein have significant background in ship design, ship building, and systems integration, but are not a company that has a history of work in the nuclear industry.

There is an upwards trend in interest for MSRs both in land-based applications and as prime movers or floating power stations. The use in the marine environment is beginning to gain momentum due in part to research and development of small modular reactors.

2.5. Integration of MSRs for power generation in ships

Power generation in ships is undertaken by a range of systems such as diesel, diesel-electric and gas-turbines. The latter common in naval ships where the higher power output allows for greater acceleration and manoeuvrability, as required by naval vessels. Gas turbine systems are generally only utilised when ships are above an average displacement of 3,500T, with smaller naval ships utilising conventional diesel engines (GE Marine Solutions, 2018).

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Table 2 - Current active MSR research and projects

Country	Organisation	MSR Taxonomy	Description	Fuel	Thermal Power MW(t)	Electrical Power MWI	Target Application	References
Canada / UK	Terrestrial Energy	I. Graphite based I.1 Fluoride salt cooled Salt cooled reactor with fixed fuel	Small Modular Reactor	Low-enriched uranium	400	190	Power generation	(Cameron and Mir, 2024; Hussain et al., 2018)
Canada / UK	Moltex Energy	I. Graphite based I.2 Graphite moderated Uranium convertor/other concepts	Stable Salt Reactor-Wasteburner (SSR-W) that uses recycled nuclear waste as fuel.	Recycled spent fuel	750	300	Wasteburner for countries with high levels of spent nuclear fuel.	(Cameron and Mir, 2024; Canadian Nuclear Safety Commission, 2021)
Canada / UK	MoltexFlex	I. Graphite based I.2 Graphite moderated Uranium convertor/other concepts	MoltexFlex Stable Salt thermal spectrum fast reactor with a Thorium breeding blanket	Low-enriched uranium	750	300	Power generation where there is access to low-enriched uranium fuel	Cameron and Mir, 2024; Canadian Nuclear Safety Commission, 2021)
China	China State Shipbuilding Corporation	No current reactor data	Ship based MSR	Potentially thorium	No data available	No data available	Large containership	(Riviera News, 2023)
China	Chinese Academy of Sciences	No current reactor data	Thorium-based molten salt experimental reactor	Thorium	2	No data available	Power generation	(National Nuclear Safety Administration, 2023; World Nuclear News, 2023a; Zhang et al., 2018)

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Country	Organisation	MSR Taxonomy	Description	Fuel	Thermal Power MW(t)	Electrical Power MWI	Target Application	References
Denmark / UK	Copenhagen Atomics/UK Atomics	III. Heterogenous III.5 Non-graphite moderated Liquid moderator heterogenous	Small, modularised fluoride salt based molten salt reactor encased in a 40-foot shipping container	Thorium	100	No data available	Ship or barge-based power systems. Biofuel production and desalination plants	(Cameron and Mir, 2024; Hussain et al., 2018)
Denmark	Samsung Heavy Industries / Seaborg Technologies / Korea Hydro & Nuclear Power	III. Heterogenous III.5 Non-graphite moderated Liquid moderator heterogenous	Single salt, ultracompact molten salt reactor	Low-enriched uranium	750	200	Power generation using a Power Barge to supplement other renewable energies.	(Seaborg Technologies, 2024; World Nuclear News, 2023b)
France	Naarea (in collaboration with Thorizon)		Micro-reactor using spent nuclear fuel from conventional nuclear fission reactions	Recycled spent fuel	80	40	Power generation	(Cameron and Mir, 2024; NAAREA, 2023; Thorizon, 2022)
Indonesia	ThorCon	I. Graphite based I.1 Graphite moderated Uranium convertor/other concepts	Fluoride Molten Salt Fuel Reactor	Low-enriched uranium	557	250	Reactor encapsulated in a ship's hull to provide power generation in developing nations with fragile grids, used on shoreside locations.	(World Nuclear News, 2023c)
Netherlands	Thorizon (in collaboration with Naarea)	III. Heterogenous III.5 Non-graphite moderated Liquid moderator heterogenous	Modular designed thorium reactor fuel cartridges with fuel dissolved in a molten salt	Spent nuclear fuel and thorium	250	100	Power generation	(Cameron and Mir, 2024; NAAREA, 2023; Thorizon, 2022)

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Country	Organisation	MSR Taxonomy	Description	Fuel	Thermal Power MW(t)	Electrical Power MWI	Target Application	References
Norway	Ulstein	No current reactor data	Ship based MSR	Thorium	No data available	No data available	Floating, multi-purpose power station to support electric ships	(Ulstein, 2022)
Russia	Rosatom State Atomic Energy Corporation	No current reactor data	Molten Salt cooled reactor	Recycled spent fuel	10	No data available	Burning of the products of nuclear reactions	(Nuclear Engineering International, 2024)
USA	Kairos Power	I. Graphite based I.2 Graphite moderated Salt cooled reactor with pebble bed fuel	Reactor fuel combined with a low-pressure fluoride salt coolant	TRISO fuel in pebble form	320	140	Power generation	(Blandford et al., 2020; McGrath, 2023; Pérès, 2020)
USA	Southern Company and TerraPower	II. Homogenous II.4 Homogenous Chloride Chloride fast breed-and-burn	Molten Chloride Fast Reactor	High-assay low-enriched uranium	840	No data available	Power generation	(Cameron and Mir, 2024; TerraPower, 2022)
USA	Flibe Energy	I. Graphite based I.1 Graphite moderated Two-fluid Th-U breeder	Scalable Lithium Fluoride Thorium Reactor	LiF-BeF2-UF4 (FLiBeU)	600	250	Various applications, small modular reactors for use in transport/space up to power plants for power generation.	(Cameron and Mir, 2024; Flibe Energy Inc, 2024)

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A concept design for a Thorium MSR using gas turbine generator was proposed in 2012 which had the reactor located centrally between four closed cycle gas turbines, as shown in Figure 4 and Figure *5* (Hill, Hodge and Gibbs, 2012).

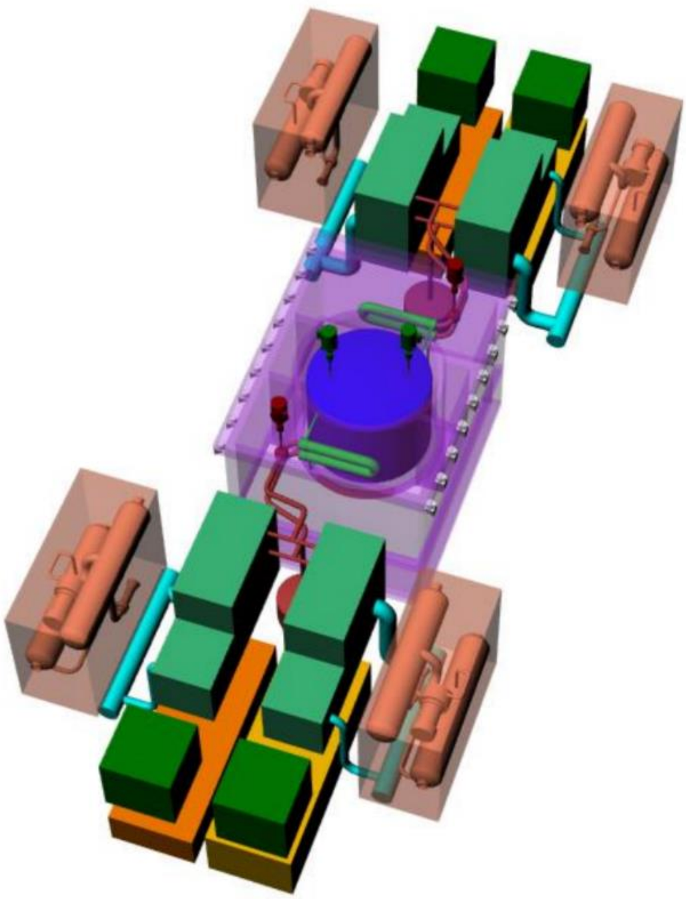

Figure 4 – Proposed Machinery and Reactor Arrangement

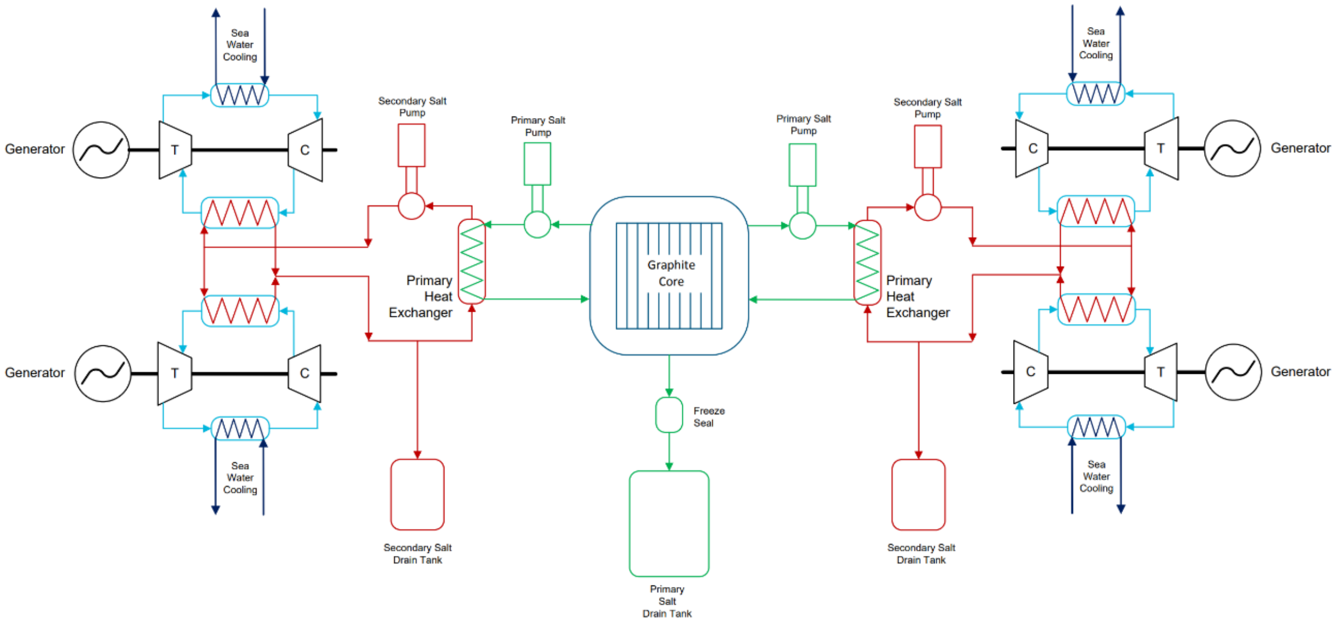

Figure 5 – Proposed diagrammatic plant layout.

The use of turbines has been identified as being the most favourable option for converting thermal power to mechanical power by other studies (Houtkoop et al., 2022) and this arrangement has several advantages, which include the prime movers being directly adjacent to the reactor compartment, reducing the piping length needed for the molten salt to travel; the prime movers being located forward and aft of the centralised reactor; and all machinery linked to the reactor is outside of the reactor compartment, allowing for maintenance activities. This design is a very good conceptual baseline that could be used to drive forward the concept of an MSR on a ship. The author noted one major disadvantage; they based the reactor design on the original ORNL designs that are outdated and sub-optimal. With some of the designs and projects identified in Table 2 reaching maturity soon, a more modern and more recently tested MSR would prove beneficial in updating this conceptual design.

There are significant advantages in employing MSRs in ships over and above those listed in paragraph 2.3, these are:

2.5.1. Technical

- With the acceleration in small modular MSR development, they potentially require less volume than current traditional power generation systems.
- With the correct selection of reactor and output, MSRs negate the energy density reduction of alternative fuels such as Hydrogen.
- There would be a significant volume reduction, as there is no need to have fuel tanks distributed around the ship, this also reduces the pipe runs and associated equipment to move the fuel, thus saving weight.
- Similar fire risk in comparison to diesel engines; Swapping diesel fuel for molten salts will require different mitigation measures, but the causal factors are not increased.
- It is envisaged that the vessel's deadweight would decrease even when considering the shielding required to protect the ships/crew form the reactor compartment (Scott and Beard, 2022).
- The Royal Navy (RN) currently manage the safety of nuclear reactors for its submarines, if the safety case for these can be justified, then the safety case for MSRs in ships is achievable and can be brought to a level that is as low as reasonably practicable (ALARP). It should be noted however, that submarines do not generally visit as many populated port areas as ships do.
- Replenishment at sea would be minimised to solids only.
- MSRs produce less nuclear waste than conventional PWRs, with one study identifying an LFTR would produces 35 times less waste than a traditional PWR on an annual basis, where 873% of that waste would reach stable natural uranium levels after just 10 years (Pool, 2014).

2.5.2. Economic

- The need for ships to supply fuel, or for ships to go to port to bunker fuel would be removed, thus saving money in capital costs as well as through life.
- The decommissioning of an MSR reactor is likely to be cheaper as the half-life of the fissile products is significantly less than conventional plutonium.
- With the development of MSRs that use spent nuclear fuel, spent fuel can be re-purposed, providing a potential route for waste management.

2.5.3. Other advantages

- There is an established nuclear cadre and training programme in the RN in support of its submarines. Adapting this and expanding it would provide a wider pool of nuclear expertise across the navy.
- With the current construction of Hinkley Point C, and the planned construction of Sizewell C, there is a growing cadre of nuclear expertise in the civilian sector that can provide the wider support required outside of ship operations.
- There is already built infrastructure to support both in-service nuclear submarines and those in the disposal chain. However, this will need to be increased to meet future requirements.

There are a range of challenges related to MSRs being installed onto ships, such as:

2.5.4. Technical

- There is no current MSR system in use on a ship or any detailed designs that integrate an MSR as a prime mover.

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- Hill, Hodge and Gibbs (Hill, Hodge and Gibbs, 2012) determined that their concept design could increase the solid vertical centre of gravity (KG) by as much as 5%. This could be offset by a reduction in the centre of gravity on other equipment associated with traditional prime movers, such as the complete removal/need for uptakes/down takes as well as other equipment reductions.
- To maintain the safety of the system the MSR needs to have dump tanks as part of the system. This brings two potential challenges:
  - The reactor would need to sit higher than current prime movers in use, as the dump tanks must be situated directly below the reactor in a vertical configuration.
  - When the molten salt is 'dumped' into these tanks in an emergency scenario, the ship would lose its prime mover. If this happened at sea it could cause a catastrophic loss of the ship. Redundancy systems in this event would need to be designed and built in.
- Survivability/vulnerability characteristics of MSR reactors is not understood and will require significant modelling and trialling to provide evidence of how they can remain safe to threats such as underwater shock or blast/fragmentation from conventional weapons.
- MSRs would not be suitable for all naval vessels due to their size.
- Retrofitting any MSR technology to current in-service ships will be a significant challenge and may not provide value for money.
- Maintenance will require new remote methods not widely exploited in UK naval ships.

2.5.5. Economic

- Shore facilities would need to be significantly upgraded, and the naval bases are in highly populated areas. Nuclear unarmed submarines regularly go into Devonport (Scottish Affairs Committee, 2012) so the safety case challenges are already being managed.
- The UK supply chain would need developing to support MSR ships.

2.5.6. Regulatory challenges

There are a specific set of challenges linked to the regulation of nuclear ships.

- Port state control and access is a significant blocker. There are at least ten memoranda of understanding across the globe operating under a cooperative agreement with IMO (Scott and Beard, 2022). New Zealand has banned nuclear powered or armed ships from entering its waters (Ministry of Foreign Affairs and Trade, 1987). The USA operate the Nimtz-class nuclear powered aircraft carriers and evidenced to congress that they can go to over 150 ports, in over 50 countries globally without issue (O'Rourke, 2009).
- The IMO adopted the Code of Safety for Nuclear Merchant Ships in 1981; however, its provisions in the UK were not a priority until the Maritime and Coastguard Agency (MCA) brought into law The Merchant Shipping (Nuclear Ships) Regulations 2022, implementing Chapter VIII in the Annex to the International Convention for the Safety of Life at Sea, 1974 (SOLAS), relating to commercial nuclear-powered ships.
- Whilst there are statutes in place, both flag states and classification societies have not had to actively manage the additional standards/regulation and assurance requirements for nuclear ships.
- Commissioning MSRs on UK ships would be subject to regulatory scrutiny from the MCA, Classification Societies, the Office of the Nuclear Regulator, and the Health and Safety Executive, introducing complexity into the licensing and approval system.

2.5.7. Other Challenges

- There are significant challenges related to Suitably Qualified and Experienced Personnel (SQEP):
  - There is a significant struggle to recruit nuclear submariners (Church, 2023), increasing this cadre against current engineering shortfalls (Ruane, 2023) would pose a significant challenge.
  - The need to have skilled engineers to provide shore-based support, maintenance and design activities is potentially a greater issue than many of the technical challenges listed.
  - UK shipyards do not have the SQEP; the only current SQEP linked to integrating nuclear technology for prime movers resides in the construction of the RN submarines.

- o There is no current cadre of suitably qualified and experienced nuclear engineers for surface ships, the lack of generational experienced personnel will be significant in safely implementing this concept.
- Nuclear technology has a negative reputation across several organisations and campaign groups in the UK. MSRs will be included under the large umbrella of nuclear technology.

2.6. Technology Readiness Levels (TRLs)

To define the TRL, this paper uses the Ministry of Defence (MOD) definitions which are shown in Table 3. The assessment looks at the TRL of the reactor concepts, and then of any potential TRL of these concepts in ships. This paper aims to examine the overall TRL of MSRs, but the supporting technology and systems are vital to its success.

Table 3 - MOD TRL Definitions

TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Technology basic validation in a laboratory environment
5	Technology basic validation in a relevant environment
6	Technology model or prototype demonstration in a relevant environment
7	Technology prototype demonstration in an operational environment
8	Actual technology completed and qualified through test and demonstration
9	Actual technology qualified through successful mission operations

MSR technology has moved on considerably, there are several regulators across the world actively issuing licences for reactor builds and development of novel and new MSR technologies. There is a trend in academia and industrial research that has continued to grow year on year, this is enabling the progress towards proven MSR designs that will be commissioned and in use for power generation in the very near future. The assessment undertaken in Table *4* shows reactor technology is advancing. Previous studies have shown MSR reactors to be at lower TRL. There are several state-backed companies advancing MSR technology at considerable pace for land-based systems, driving not only MSR reactors, but supporting technology levels and supply chains. There are several prototype demonstrator reactors planned to be commissioned before the end of this decade, with at least three companies expecting to have commissioned reactors by 2028.

2.7. The Next Steps for Shipping

To integrate MSRs into future ships, it is crucial to address the challenges. An evaluation of these challenges against the Defence Lines of Development (DLOD) has been undertaken and detailed in Table 5. This analysis has been extended to encompass a DLOD+ approach, specifically aimed at tackling regulatory issues that go beyond the conventional DLOD framework. The DLOD+ analysis includes a projected timeline for achieving Initial Operating Capability (IOC) for naval ships powered by MSRs. It is important to note that this assessment focuses solely on new ship construction and does not encompass retrofitting existing ships, it also does not focus on the economic aspects of implementing MSR's onto ships, this is a topic worthy of several academic papers on its own.

Table 4 - Current TRL Status of Reactor and ship concepts

Country	Organisation	Current Status	Planned Development	Reactor TRL	Ship Based Application TRL
Canada	Terrestrial Energy	Design has passed the first 2 stages of the Canadian licensing process (Pre-licensing vendor design review)	early 2030's - Planned Commissioning of the first power plant	4	NA
Canada/UK	Moltex Energy	Design has passed the first stage of the Canadian licensing process	early 2030's - Planned Commissioning of the first operational reactor	4	NA
Canada/UK	Moltex Energy	Design has passed the first stage of the Canadian licensing process	early 2030's - Planned Commissioning of the first operational reactor	4	NA
China	China State Shipbuilding Corporation	Concept Stage	No project data available, concept announced in Dec 23	No reactor data available	2
China	Chinese Academy of Sciences	Operating license issued	373 MWt reactor built by 2030	5	NA
Denmark	Copenhagen Atomics	Non-fission prototype proven	2025 - Criticality test on demonstrator reactor 2027 - Final design review 2028 - First waster burner commissioned	4	NA
Denmark	Samsung Heavy Industries / Seaborg Technologies / Korea Hydro & Nuclear Power	Concept Design	2026 - Commercial Prototype built 2028 - Production of power barges	4	2
France	Naarea (in collaboration with Thorizon)	Concept Design	2023 - Finalization of a digital twin 2028 - Submitting the safety options dossier (DOS) for commissioning of a prototype 2030 - Launching mass production	4	NA
Indonesia	ThorCon	Concept design in preparation for licensing	2029 - Demonstration plant fully commissioned	4	2
Netherlands	Thorizon (in collaboration with Naarea)	Concept Design	2035 Commissioning of a pilot reactor	2	NA

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Country	Organisation	Current Status	Planned Development	Reactor TRL	Ship Based Application TRL
Norway	Ulstein	Concept Stage	10-15 years for launch of Thor	No reactor data available	2
Russia	Rosatom State Atomic Energy Corporation	Preliminary design completed	2031 - Plant in operation	4	NA
USA	Kairos Power	Construction permit issued by US Nuclear Regulatory Commission	2027 - Initial deployment of a demonstration plant 2028 - The first plant produces domestic power	4	NA
USA	Southern Company and TerraPower	Design testing using an Integrated Effects Test (non-nuclear)	2025 - Molten Chloride Reactor Experiment completed early 2030's - Demonstrator commissioned 2035 - Full commercial operations planned.	3	NA
USA	Flibe Energy	Pre-licensing activity / concept design	2030-2035 - Power generation plants in operation	4	NA
USA	Transatomic Power	Concept design completed, currently undertaking lab-scale experimentation.	No timescale available, plan is to: Create the detailed blueprint specs. Refine reactor design Complete a demonstration reactor	3	NA

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Table 5 - DLOD+ to IOC Analysis

DLOD	**Challenge**	**Potential Solutions to support DLOD maturity**	**Indicative timescales to achieve potential Initial Operating Capability (Years)**	**References**
Training	Naval nuclear training delivery needs expanding	Utilise civilian personnel with MSR knowledge to supplement training, noting there is currently limited MSR SQEP globally Expand all naval engineering training to include nuclear/MSR technology at the earliest opportunity Develop bespoke training for MSR maintenance and support	3 - 6	(Butler, 1990; Department of the Navy, 2016)
	Limited SQEP across maritime domain in Nuclear Technology	Sponsor naval personnel to undertake apprenticeships and degrees into MSR and nuclear technology Arrange for naval engineers to go on secondment to in-build or in-service MSR plants to increase SQEP and enable them to support the development of personnel	5 - 10	(McGee, 2021)

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Equipment	The TRL of any ship based systems is very low, meaning there is significant technical risk in deciding to implement MSR technology early	Implementing a programme to specifically drive the MSR technology to a suitable TRL in ships will allow for a focused approach to the risks to be managed effectively and for the technology to be developed to a high TRL Early engagement with MSR manufacturers to be undertaken through DASA/DSTL Work to set the outline requirements for all MSR based systems needs to be undertaken to enable concept system designs to be developed and increasing the TRL for ship systems	15 - 25	(Riviera News, 2023; World Nuclear News, 2023d)
	Maintenance will require new remote methods	Employ methods used in current nuclear submarines Work with MSR manufacturers to modify current technology for use in ships	5 - 15	
	Survivability/vulnerability characteristics of MSR reactors is not understood and will require significant modelling and trialling to provide evidence of how they can remain safe to threats such as underwater shock or blast/fragmentation from conventional weapons	Implement a specific project to model and assess the reaction of MSR's to threats such and UNDEX, fragment etc to assess the safety of MSR's in the Naval Environment	5 - 15	(Harinath et al., 2022)
	Impact of pitch and roll on MSR's in not understood	Implement a specific project to model and assess the reaction of MSR's to a variety of pitching and rolling motions and understand the safety and performance aspects Instigate trials non a non-fissile system to prove modelling outputs	3 - 5	

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	Impact of dumping all Molten Salts into the drain tanks, stopping the fissile reaction in an emergency could have significant safety implications at sea as the prime mover potentially loses all power	Undertake a study to identify potential scenarios when this would need to occur, undertake hazard analysis and identify suitable controls and mitigations that need to be in place	3 - 5
	Shielding requirements are unknown	Implement a specific project to model and assess the amount of shielding required and how it would be maintained	3 - 5
Personnel	There is a significant challenge in recruiting nuclear submariners, introducing MSR's onto ships could impact the in-flow of engineers into the submarine service	Review naval career structures to allow for an expanded movement of personnel between surface and submarine service	3 - 5
	There are limited shore-based SQEP nuclear engineers available to handle the increased workload needed to support the fleet	Implement a national training programme for nuclear engineers from apprenticeships through to degrees to support MSR's Through life-support contracts will require suppliers to have sufficient SQEP	10 - 15
	The lack of generational experience in nuclear technology in the RN will have a significant impact on safely implementing MSR's onto ships	Setup a programme to retain submariner nuclear SQEP at the end of their careers so they can support the initial implementation and next generation	3 - 6
	UK Flag state (MCA) and classification societies have not had to actively manage the additional standards/regulation and assurance requirements for nuclear ships	Arrange for personnel to upskill and work with other nuclear operators to generate expertise	5 - 10
Information	Information from systems to manage and monitor reactor health and status need defining	Work with MSR manufacturers to modify current systems for use in ships Monitoring of MSR fuel status is vital to understand the fissile status of the reactor to enable re-fuelling to be undertaken	2 - 5
Concepts & Doctrine	Impact on current doctrine is not defined	Undertake an analysis on all CONUSE, CONEMP and CONOPS in-service to identify impacts	5 - 10

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	New CONUSE, CONEMP and CONOPS are required for ships	Develop as part of the initial requirements setting and implementation	2 - 5	
	Current CONUSE, CONEMP and CONOPS and other doctrine for interfacing systems will require updating	Update these as the MSR implementation progresses using the Capability Planning Group system	5 - 10	
	Impact of MSR on operational doctrine is not defined	Undertake a study to identify area in naval doctrine and to understand where this will require changing	2 - 4	
	Port state control and access could be an issue	Understand global limitations and determine the impact on global deployments. USA and France both operate nuclear powered ships so global deployment doctrine through NATO collaboration and LFE could provide suitable solutions	5 - 10	
Organisation	Additional units/expansion of existing organisation to support the assurance of Nuclear ships is required, e.g. Operational Sea Training, Defence Regulators, Naval Base safety teams	A full study to understand the changes and impacts to the organisation is required to take a holistic view of the impact on the defence operating model and how to implement the change	5 - 10	
Infrastructure	Extended shore based facilities will be required to support training and such as operator training simulators, shore based prototypes and other classroom based systems	Undertake a full study on the requirements to understand what shore based systems are needed	5 - 10	
	Dockside facilities need expanding to support nuclear ships, this could come at a significant cost	Undertake a study to identify exactly what facilities will be required, the costs of these and the wider impacts	3 - 6	(Navy Lookout, 2020)
	Commercial dockyards and the supply chain are not setup to support ships with nuclear reactors	Development of commercial dockyards to support MSR's in ships needs to be supported from UK Government Strategy. National shipbuilding strategy needs to be updated to support MSR technology and support the drive for a UK wide approach National funding needs identifying to support a significant increase in infrastructure to support MSR through life	5 - 15	

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	Thorium salt reprocessing plant could be required to manage the supply chain	Build a reprocessing plant to support both naval and commercial thorium re-processing, this could provide a good commercial market for the UK in re-processing thorium form across the world Identify a short term solution for Thorium reprocessing until sovereign capability can be achieved	5 - 25
Logistics	The required supply chain to support MSR's is not understood	Undertake a supply chain analysis to identify high level requirements to inform the strategy for implementing	2 - 5
	Supply chain in the UK is not established to support MSR implementation	National shipbuilding strategy needs to be updated to support MSR technology and support the drive for a UK wide approach Funding and grants should be made available to encourage supply chains to diversify and develop the knowledge and expertise necessary to support MSRs as part of the UK Plc initiative Current supply chain supporting PWR's could expand to support MSR's	5 - 15
	Support facilities for maintenance globally need to be identified and agreements in place to berth nuclear ships with flag states	Work with NATO partners to mirror current global support arrangements and best practice	5 - 10
Regulatory	Commissioning MSRs on UK ships would be subject to regulatory scrutiny from the MCA, Classification Societies, the Office of the Nuclear Regulator, Defence Nuclear Safety Regulator and the Health and Safety Executive, introducing complexity into the licensing and approval system	Agree the approach for licensing and regulations of ships between all regulators, with agreed primacy as appropriate in line with current nuclear submarine approach	2 - 5
	Current commercial regulations need a significant re-write as they focus on PWR	Update regulations to apply to non-conventional reactor types	4 - 10

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Interoperability	Exact implications of nuclear powered ships and their interoperability is not understood	Undertake analysis to identify all the areas of interoperability that could be impacted both positively and negatively to implement MSR technology	5 - 10

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2.8. Conclusions

MSR technology is advancing rapidly, prompting ship designers and various countries to explore its potential benefits for ship-based applications. While most are considering MSR systems primarily as marine power generation facilities, China stands out with its ambitious concept for a 24,000 TEU container ship aimed at maximizing MSR advantages. Marine-based MSR concepts are currently at a lower TRL, largely due to the predominant focus on reactor technology development. Despite this, stakeholders such as sponsors, ship owners, and designers should not overlook MSRs. Now is an opportune moment to delve into the technical integration aspects of MSRs in ships and to evaluate their broader implications in maritime environments. The technical challenges for integrating MSR's onto ships are significant, but if work to assess the challenges were to be undertaken at risk ahead of mature MSR reactors being available, solutions could be easily identified allowing for designs to be matured ahead of the wider systemic issues being addressed.

Although previous MSR-based power generation system concepts exist, specific design work remains unexplored. Advancing the TRL of marine-based MSRs hinges on undertaking interdisciplinary design work across Naval Architecture, Marine Engineering, and System Engineering disciplines. This approach would also facilitate the detailed development of regulations, standards, and certification processes by flag states and classification societies.

Deploying MSRs on ships, whether commercial vessels or naval ships, poses significant systemic challenges, particularly in non-technical areas. Regulatory environments, for instance, are intricate and necessitate comprehensive definition and resource allocation. Currently, only three nuclear-powered commercial vessels have ever been commissioned globally, with the Russian cargo vessel Sevmorput, commissioned in 1988, being the sole operational example today. UK regulators and assurance bodies, lacking prior experience in consulting on nuclear-powered ship commissioning, face a steep learning curve traditionally handled by the MOD and RN.

Another critical systemic issue is the shortage of SQEP in nuclear engineering within the UK. This scarcity could potentially hinder the deployment of nuclear power on ships, whether on board or in supporting shore-based roles. Increased demand for SQEP engineers not only risks impacting projects such as next-generation nuclear power plants and the RN Submarine Service but also underscores the need for substantial investment in expanding infrastructure across military and commercial yards to support nuclear ships.

In summary, while MSR technology holds promise for ship-based applications, addressing regulatory complexities, enhancing technical readiness, and bolstering nuclear engineering capabilities are essential steps towards realizing its full potential in maritime operations.

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