New potential for integration of nuclear power in marine propulsion systems

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Synopsis

Nuclear power has seen widescale shore-based power application, as well as at sea for some of the larger navies of the world. Nuclear power offers some distinct benefits: very long range, long refuelling intervals, and, currently topical: no emissions. Currently, three large developments could impact new potential for both naval and commercial shipping: generation IV technology, small modular reactors, and the use of thorium instead of uranium. This paper starts with the relevant background of nuclear technology. Then the current developments and their relevance for the marine context are discussed, followed by a more detailed description of the reactor types presently in development. Two types are identified for both near-term (estimated 10-20 years) the Very High Temperature reactor, and for long-term deployment (20+ years) the Molten Salt Reactor. Then a selection is made for suitable energy conversion for ship propulsion. A variety of options are considered ranging from hydrogen generation to more conventional turbines, with open Brayton turbines as a suitable choice for the implementation, based on a variety of criteria such as efficiency and complexity. The implementation specifics of nuclear power are discussed, with important considerations such as the shielding, size, and weight. The nuclear power potential is benchmarked with a conventional fuel-based system, showing the distinct benefits of nuclear energy: no direct emissions, long range, strategic and operation autonomy, and reduction of signatures, as well as the trade-offs: nuclear waste production and higher up-front cost. Each of the topics is discussed giving an overview of the technical challenges but most importantly potential of implementing nuclear power in marine propulsion and power generation systems.

Keywords: Nuclear energy, Marine propulsion, Generation-IV, Small Modular Reactors, Thorium

1. Introduction: Potential of nuclear power

Nuclear power has seen widescale adoption in shore-based power application and in some established naval applications. In shore-based power plants the nuclear power plant has become a reliable option that emits no direct greenhouse gasses, with only limited emissions stemming from the production of the reactor and fuel (Schlömer, et al., 2014). Nuclear power is often used to supply steady power, with high uptimes and relatively stable loads.

In the naval application the nuclear-powered option is seen primarily on submarines and aircraft carriers, offering the advantages of a long range without intermediate bunkering and air independence (relevant for the submarine application) (Ragheb, 2011).

The commercial marine application has seen only a handful of ships built, with only a single nuclear powered cargo ship remaining in service, together with a small group of nuclear-powered icebreakers. The application however is currently very relevant, considering the industries emission reduction goals.

Nuclear power has been in development since the 1940's, with developments classified in "generations" with a timeline and types shown in Figure 1 of which the 2nd generation is currently still the most used.

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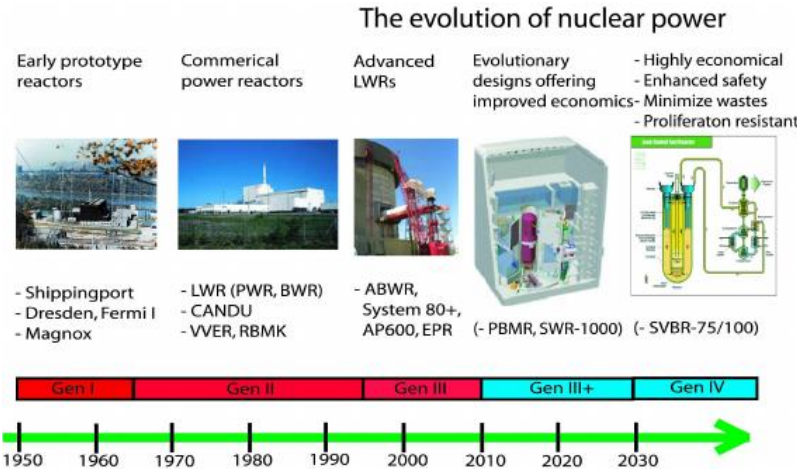

Figure 1 Generations of nuclear energy, image from (Carlsson, 2003)

In this paper a brief introduction will be given on the principle of nuclear fission power, before detailing some of the developments and their place, implementation, and benefits for both naval and marine application.

2. Basic properties of nuclear power

Nuclear power, specifically power from nuclear fission, is the principle where upon neutron absorption a nucleus splits into fission components and neutrons while releasing energy. The released neutrons subsequently absorbed by other nuclei allowing the sequence to continue. This principle is shown in Figure 2.

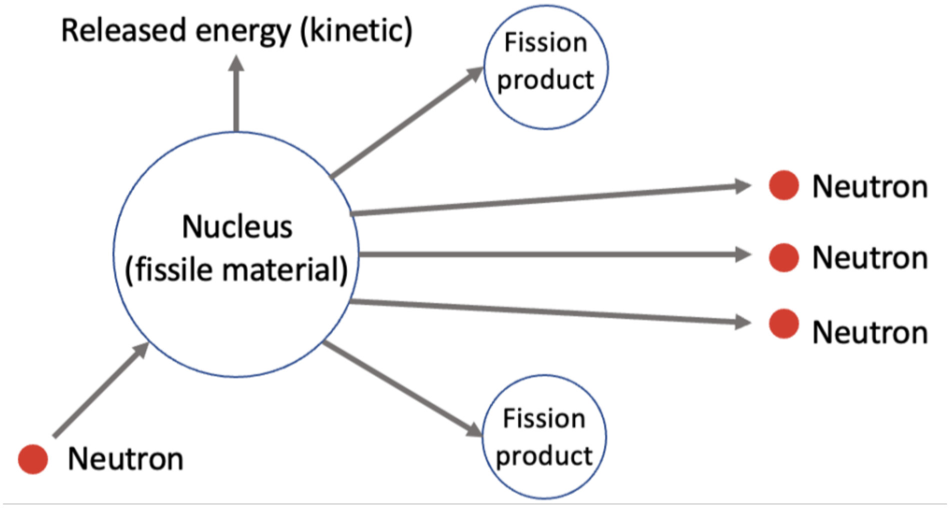

Figure 2 Fission reaction, simplified

This principle is only possible with so-called “fissile material” of which only uranium235 (U235) is naturally occurring. Other fissile materials are man-made, which is only possible from materials that are “fertile”. Notable fertile isotopes are uranium238 (U238, main component of natural uranium, decays to plutonium239) and thorium232 (Th232, decays to uranium233), which both can become fissile materials upon neutron absorption and subsequent decay periods (shown in Figure 3). Reactors that produce fissile material from fertile material (net gain) are called “breeder” reactors. If a reactor converts fissile material to power, it is referred to as “converter reactor” (De Sanctis, et al., 2016).

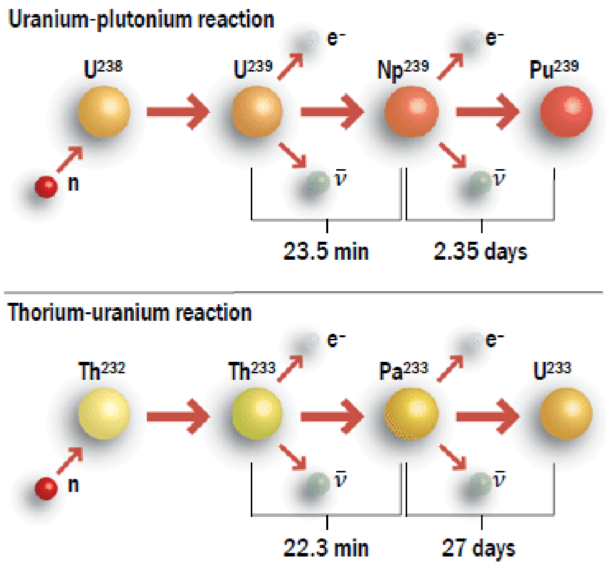

Figure 3 Common breeding reactions in nuclear power plants, with half-life times indicated (Gilleland & Ahlfeld, 2008)

The fission process must be tightly controlled, first to take place at all, second to deliver a steady amount of power. As each fission event could lead to two or three subsequent individual fissions events, releasing energy (Figure 2). This control is done in the reactor core, where the fuel is located, and a coolant pumped through to remove the generated heat. The coolant is used to transfer heat for power generation. Control rods are inserted in the core to control the reaction rate by capturing neutrons.   A simplified diagram of a core is shown in Figure 4.

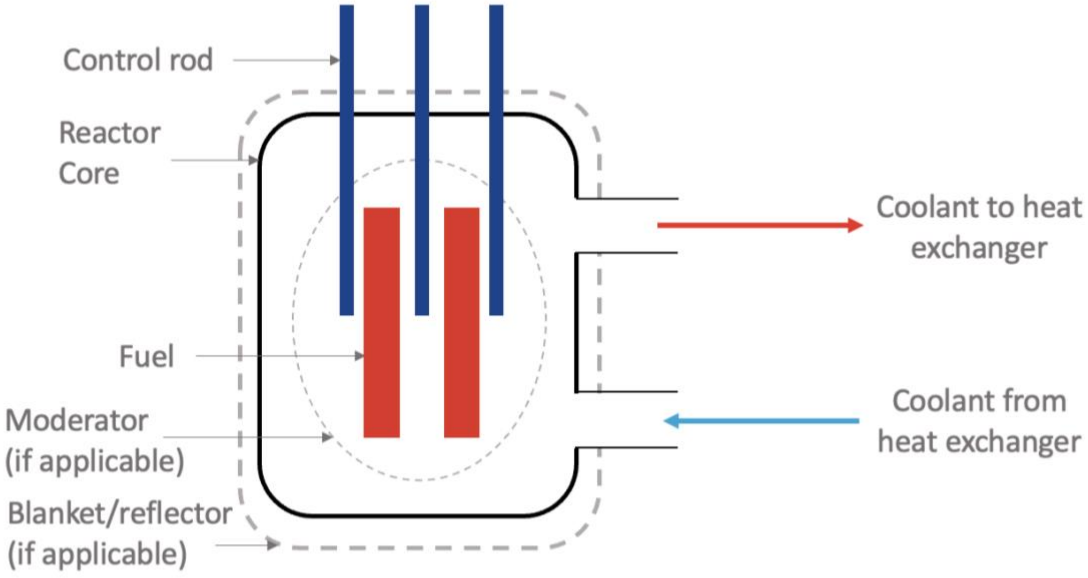

Figure 4 Simplified reactor core diagram, based on (Lamarsh & Baratta, 2014)

The fuel loaded in reactors is currently mostly “enriched” uranium, processed and encapsulated in fuel rods. The term “enriched” refers to the percentage of fissile uranium (U235) compared to fertile uranium (U238) in the fuel. Natural uranium contains less than 1% U235, with most reactors currently in use requiring 3-5% U235 in their fuel. The practically applied enriched uranium is often referred to as low enriched uranium (LEU) which is uranium enriched up to 20% U235. Uranium enriched beyond 20% is referred to as highly enriched uranium (HEU) (De Sanctis, et al., 2016). HEU is not in use for commercial power, as HEU has an increased proliferation risk.

Control of the fission process is done by controlling the density of free neutrons, commonly by active measures such as lowering or raising neutron-absorbing control rods (Lamarsh & Baratta, 2014). Passive measures also exist stemming from the physics governing the reaction in the reactor (often referred to as feedback coefficients) (De Sanctis, et al., 2016).

Besides this an important consideration is if the reactor contains a moderator, this moderator is a material that allows neutrons to share some of their energy upon interaction, effectively slowing them down and thus increasing their probability to cause fission when contacting fissile material. Reactors with moderators operate in the so called "thermal" neutron spectrum, reactors without moderation operate in the "fast" neutron spectrum. Most reactors in use today are thermal spectrum reactors, with fast reactors being a development that is of interest for higher fuel efficiency and breeding.

Finally, a blanket or reflector can be placed in the outer section of the core, with the intention of capturing or reflecting neutrons that move out of the reactor. This gives the neutrons greater chances of engaging in fission or being absorbed by a fertile material (Lamarsh & Baratta, 2014).

These basic principles are seen in all currently used reactors and reactor developments, with the type and reactor being of strong influence on its output temperatures (relevant for conversion efficiency, where higher temperature is favourable), and the efficiency measure "burnup" of the reactor, which indicates how much thermal energy can be extracted from a quantity of fuel: generally given in gigawatt days per ton of heavy metal (GWd/tHM) (Lamarsh & Baratta, 2014).

At the end of the fuel lifetime the depleted fuel is removed from the reactor. Part of the fuel still is fissile allowing it to be reprocessed and reused in new fuel batches. Reusing fuel is referred to as the closed cycle, reducing waste, and the amount of spent fuel that has to be stored. If the fuel is discarded after removal from the reactor it is referred to as the once-through-cycle. The spent fuel is referred to as high level waste and has to be stored securely due to its radioactivity and proliferation risk. This storage has to be done until it has sufficiently decayed, which for the commonly used uranium-based fuels is in the order of thousands of years (Hargraves & Moir, 2010). Besides this, nuclear reactors produce a relatively constant stream of low and intermediate level waste, which has to be stored for hundreds to a thousand years (Canadian Nuclear Safety Commission, 2021). The decommissioning at the end of the reactor's lifetime adds to this final waste stream (European Commision, 1999).

3. Topical developments in nuclear power

Three major developments in nuclear power are of relevance for the marine application. These three major developments are however not mutually exclusive as illustrated by the diagram in Figure 5.

- Generation IV technology: offering reduced waste production, increased safety and reducing the need for offsite emergency response, improved economics, and increased proliferation resistance (Generation IV international forum (GIF), 2014).
- Small Modular Reactors (SMR). the term SMR refers to reactors below 300 MWe (electrical power delivered). The goal of this smaller scale is to increase production rate and volume, increasing applicability as well as reducing cost (IAEA, 2020). These smaller modular reactors are favourable for ship design integration.
- Thorium: thorium is an alternative to the currently used enriched uranium; thorium however is not a fissile material but a fertile material (requiring breeding). The benefits of the thorium cycle are reduced waste longevity (less than 300 years of storage required), increased proliferation resistance (Hargraves & Moir, 2010), and high abundance on earth (compared to uranium) (IAEA, Nuclear fuel cycle and materials section, 2005).

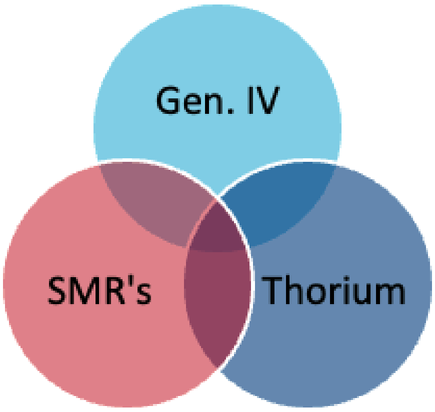

Figure 5 Venn diagram, developments in nuclear energy

For marine purposes it makes sense to establish a power limit for the applicability of the reactor, as the SMR definition of 300 MWe is quite large for a marine application. The limit is set at 100 MWe, which is considered to be suitable for the largest conventional and naval vessels. Using this initial filter, relevant reactors currently in development for the marine application are established. based on the publication by the IAEA[1] (IAEA, 2020), who maintain a database of SMR's that are currently in development, their details, and current stage of developments.

- The PWR (Pressurized Water Reactor), currently the most used reactor in the world seeing also significant development efforts for SMR format reactors. These small reactors are a scaled-down version of many currently used power reactors (IAEA, 2020). With the PWR also being the type used in naval applications, although they are used with HEU as fuel instead of LEU (Ragheb, 2011).
- The (V)HTR (Very[2] High Temperature Reactor), a Generation-IV development. These reactors offer significantly higher output temperatures allowing for a significant increase in conversion efficiency. Multiple types of VHTR's are being developed. The pebble type, where the fuel is encapsulated in a spherical pebble, allows for online refuelling (refuelling without stopping the reactor), with the prismatic type only allowing offline refuelling. The VHTR is relatively well developed with multiple small-scale and test reactors already built and operated over the past decades (IAEA, 2020).
- The GFR, LFR, SFR (Gas cooled, Liquid metal cooled, Sodium cooled Fast Reactors), Generation-IV developments. The three varieties of coolant all operate on the same principles and are different from other reactors as they are designed as fast reactors only (no shedding of neutron energy to a moderator) making these reactors very suitable for breeding of fertile materials and increasing their efficiency. The reactors are currently not in operation, they are still in ongoing development (IAEA, 2020).
- The MSR (Molten Salt Reactor), a Generation-IV development that has seen test designs dating as far back as the 1960's. The MSR has some very interesting characteristics: as the fuel and the coolant are mixed together as a liquid fuel salt. This enables it to be refuelled online as well as allow for potential (complete) operation on the thorium cycle (IAEA, 2020). Fuel salt that is not in fuel rods also negates some issues that are inherent to closed fuel rods, primarily the deterioration of the fuel rods (Hargraves & Moir, 2010) and the poisoning of the reactor by strongly neutron-absorbing fission products remaining in the fuel rod. The poisoning condition is a serious concern for mobile applications, as it can stall and stop the reactor, only allowing it to restart after sufficient fission products have sufficiently decayed (taking hours up to days) (Ragheb, 2011).

The different types of reactors and their respective properties are summarised in Table 1, detailing the considerations as described earlier. Baseload and load-following capabilities are added, since this is very relevant for a marine application and have only in recent decades become a bigger consideration for commercial nuclear power. The load-following capabilities of a conventional power grid are significantly less extreme in both magnitude and speed (IAEA, 2018) than those of a vessel. Similarly, going below a certain loading (50% load for many current reactors (IAEA, 2018)) is not an important issue for a power grid while a vessel does require this flexibility.

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[1] International Atomic Energy Agency, autonomous United Nations agency

[2] Prefix "Very" is added for HTR's that exceed 700 ℃ output temperature

Table 1 Relevant properties of reactor types with possible applicability for the marine application

Reactor type	**PWR**	**(V)HTR*, Pebble bed**	**(V)HTR*, Prismatic**	**SFR**	**LFR**	**GFR**	**MSR**
Neutron spectrum	Thermal	Thermal	Thermal	Fast	Fast	Fast	Thermal/ fast
Fuel cycle	Open/ closed	Open	Open	Open/ closed	Open/ closed	Open/ closed	Open/ closed
Burnup (GWd/tHM)	45-75	90-200+	90-200+	130+	130+	130+	90+
Fuel type	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th
Uranium enrichment	LEU <5% HEU in special applications	LEU (3-20%)	LEU (3-20%)	LEU (5-20%)	LEU (5-20%)	LEU (5-20%)	LEU (5-20%)
Type	Converter	Converter	Converter	Converter/ Breeder†	Converter/ Breeder†	Converter/ Breeder†	Converter/ Breeder†
Thorium capable	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding/ continuous cycle
Refuelling	Offline	Online	Offline	Offline	Offline	Offline	Online/ offline
Refuelling cycle (low end)	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y
Refuelling cycle (high end)	7 – 8 y	Continuous	1.5 – 2 y	Lifetime (20+ y)	Lifetime (20+ y)	Lifetime (20+ y)	Lifetime / Continuous
Passive safety	-	+	+	+	+	O	+
Active safety	+	+	+	+	+	+	+
Baseload	+	+	+	+	+	+	+
Load following	-	O	O	O	O	O	+
Operating temperature	< 330 °C	< 700 °C (V)* 700-1000+	< 700 °C (V)* 700-1000+	500-550 °C	<600 °C	<850 °C	< 800 °C
TRL (European Commission, 2014)	8-9	7-8 (V)* 6-7	7-8 (V)* 6-7	6-7	6-7	4-5	4-6

Based on Table 1 the most suitable reactors can be identified, For the near term (10-20 years) the (V)HTR is seen as more suitable than the more developed PWR. The (V)HTR is more attractive in terms of improved burnup, continuous refuelling options and higher temperatures. Additionally, it offers distinct advantages as it is a Generation-IV reactor, following this development in terms of safety and non-proliferation. For the long-term (more than 20 years) the MSR is an attractive option that shows more potential than the various fast reactors. The MSR offers many of the benefits of the (V)HTR, while also making it possible to operate fully on thorium in the future and having (theoretically) better load following capabilities.

4. Power conversion and layout

Nuclear power produces thermal energy from fission, this energy is distributed as hot coolant. In order to use this energy, it has to be converted to either mechanical or electrical energy. A simplified overview is shown in Figure 6.

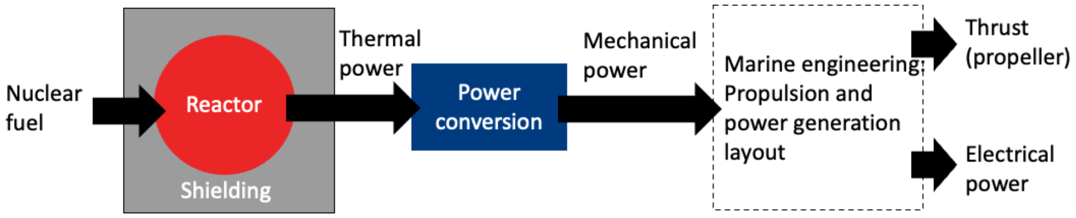

Figure 6 Nuclear based marine power and propulsion system, simplified overview

The shielding of the nuclear reactor is required to reduce the exposure to high-energy radiation for occupants and equipment to acceptable levels. Shielding is constructed to shield for the most penetrating of radiation which is gamma rays and neutrons. Historic applications used the common shielding materials of concrete, water, and lead for their shield. For many applications the shielding weighed in excess of 2000 tons (Sayres and associates corporation, 2017) & (Ol & Tanigaki, 1969). This makes it the dominant weight for a marine implementation.

For power conversion a variety of options is possible, these are shown in Figure 7.

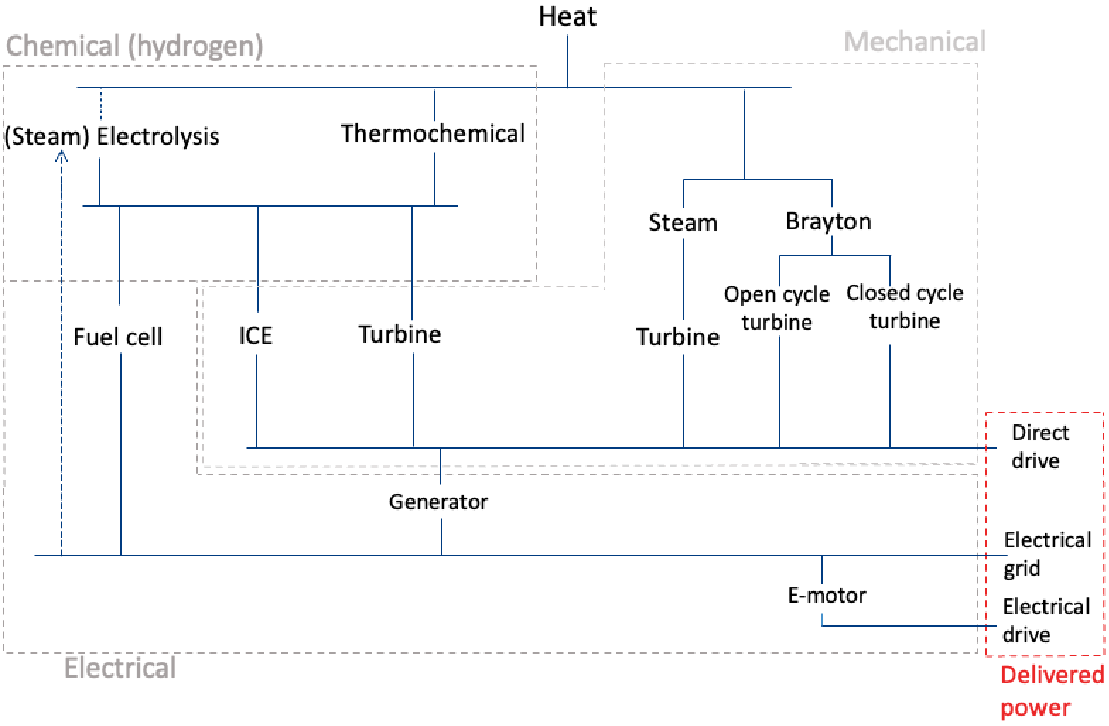

Figure 7 Energy conversion options for the marine application, based on (Tanuma, 2017), (McBirnie, 1980), (Yan & Lidsky, 1993), (Zohuri, 2021) & (Revankar, 2019)

The somewhat unconventional option of hydrogen generation using thermochemical, electrolysis and steam electrolysis methods was evaluated. Although technically possible, these methods are deemed impractical for direct use in a marine application. The production of hydrogen and subsequent conversion to mechanical and/or electrical power requires significant additional equipment which increases complexity. In addition, segregation of hydrogen production and the nuclear plant that is needed, as seen in shore-based concepts (more than 100 m of segregation for safety between the two plants) (Revankar, 2019).

The option of converting thermal power to mechanical power by means of a turbine is seen as a more favourable option, where different turbine options are considered: Rankine cycle, closed Brayton cycle, and open Brayton cycle. Each of these options require transfer of the thermal power from the reactor's coolant via heat exchangers to their operating medium.

- Rankine cycle (steam), currently the most used energy conversion method in both shore-based power plants as well as naval applications. The steam cycle is well developed, offering good efficiency although at high system complexities.
- Closed Brayton cycle (either helium, or supercritical CO_2 as medium), in development as a compact and efficient option. No commercial units are available at present, although projected efficiency is good.
- Open Brayton cycle (air as medium), closely related to the currently used aeroderivative turbines, for commercial power referred to as unfired turbine (as there is no combustion due to the use of a heat exchanger). The system offers a slightly reduced efficiency compared to the others, but at a reduced system complexity.

Different configurations of each cycle are considered, with each of the layouts having an efficiency between 30 and 40%. Load following is a consideration with each of the three turbine types, as the turbine must handle the load change of the reactor and the demand. Adequate load following for current reactors is 5% per min, with a lower limit of 50% minimum power (IAEA, 2018). However, further research has to be performed to investigate the low load capabilities of maritime SMR's. Achieving greater load-response and operating range is possible when considering heat rejection options for the turbines, research has been done into options for this on both steam plants (Connor, 2019) as well as closed Brayton plants (Gad-Briggs, et al., 2017). The option of load rejection is however considered to be most easily integrated in the open Brayton cycle, as this is open cycle and does not require the re-use of the operating medium (allowing for rejection). A schematic diagram is shown in Figure 8 for such a system, allowing for operations below 50% power, albeit less efficient.

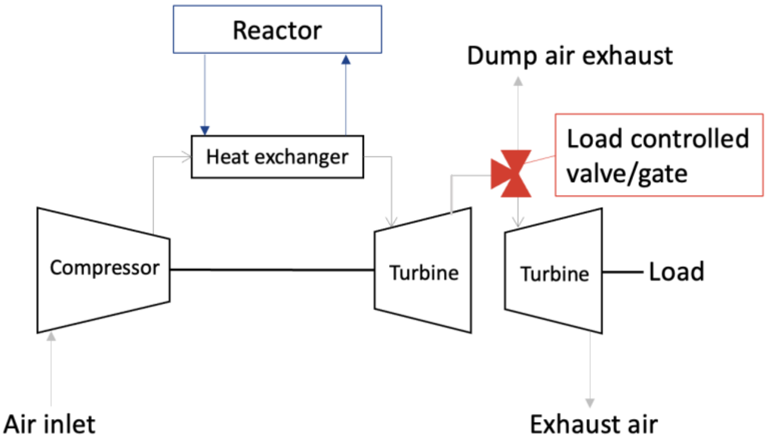

Figure 8 Schematic diagram for heat rejection in Open Brayton

The turbine has to be integrated in the marine propulsion and power generation system, which is similar in consideration to a conventional system. The main difference in the layouts is the considerations for system efficiency as well as complexity. Historic nuclear applications for marine use integrated emergency propulsion arrangements, for the purpose of maintaining power when the reactor must be stopped. The option of two separate reactors can also be considered, but this will add significant weight, size, and cost. Four options and their respective shaft-to-shaft efficiencies are shown in Figure 9.

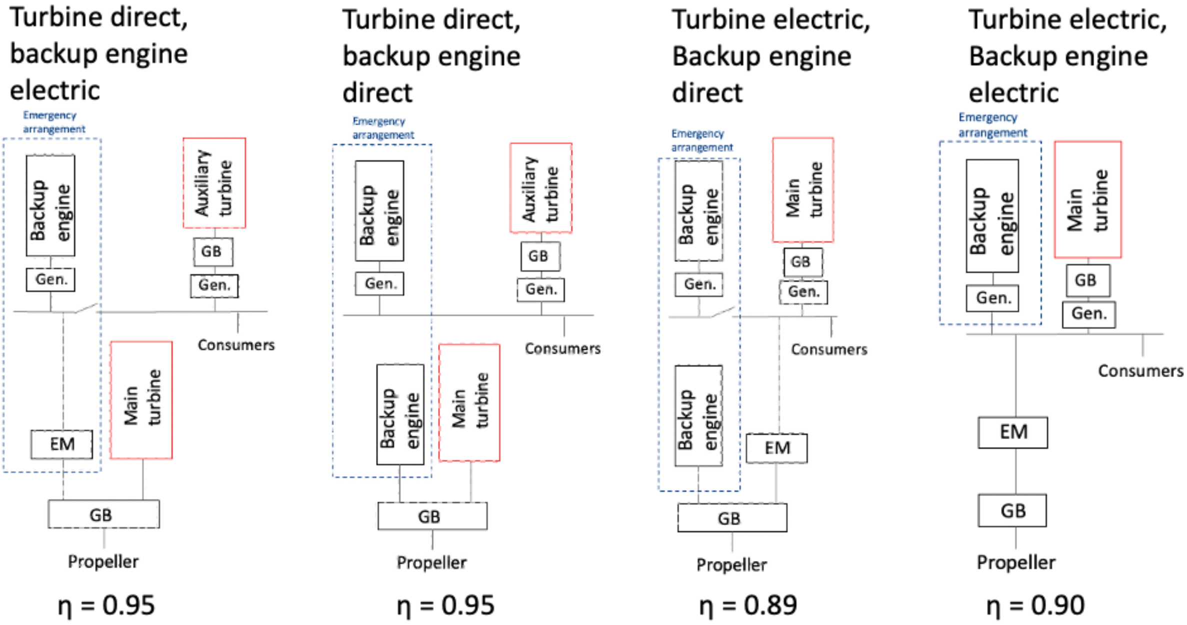

Figure 9 Different layouts for implementation of nuclear power in marine propulsion system. Red indicates that the component is connected to reactor, η is the efficiency

From Figure 9 it can be seen that some options are better suited than others from an efficiency perspective, but when considering system complexity and the possibility of adding battery systems (for enhanced load response and peak shaving purposes) only options with an electromotor remain. From these, the completely electric layout is seen as the most suitable, as it requires the least machinery and offers the greatest flexibility. This layout can be doubled for additional redundancy, where two shafts are fitted, which prevents any single-point failure from stopping the vessel.

5. Benchmark of nuclear power with conventional marine propulsion systems

Nuclear power has some distinct benefits over currently conventional (fossil fuelled) propulsion and power generation plants. The main differences stem from the different fuel properties.

Nuclear power offers greatly increased range, as the fuels are very energy dense. This allows for long refuelling periods and associated long range. Refuelling periods for the considered reactors range from 18 months up to a single fuelling for the reactors lifetime (more than 25 years), implemented systems could allow for significant autonomy. From a naval perspective in the new strategic realities after February 2022, a (modular) nuclear power plant offers a naval combatant an unsurpassed range and operational autonomy. The energy autonomy could allow for higher speeds and even facilitate (local) shipboard hydrogen production for naval drone propulsion. The elimination of fuel combustion is expected to reduce the thermal signature of the combatant.

The specific fuel usage is shown in g/kWh in Figure 10.

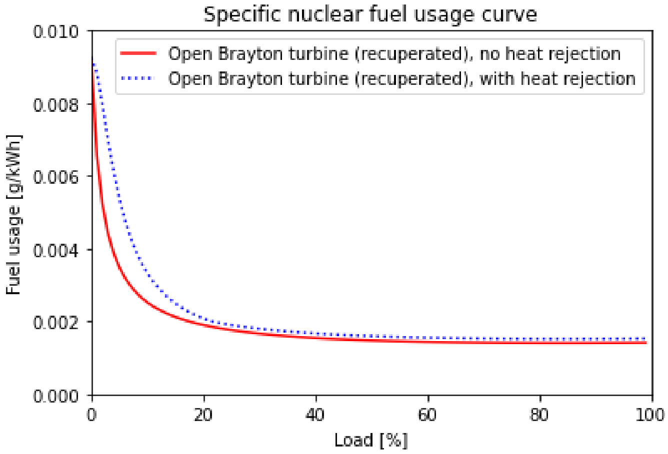

Figure 10 Specific nuclear fuel usage curve (for 90GWd/tHM burnup and 33% conversion efficiency)

Nuclear power offers greatly reduced greenhouse gas emissions, with the only emissions coming from the production processes. When comparing the $CO_{2\ \text{equivalent}}$ emissions per kWh the difference between nuclear and fossil-fuelled is over 98%. This comes at the trade-off of nuclear power producing nuclear waste of both the high-level and intermediate and low-level waste. Besides reduced greenhouse gas emissions also the air pollution is completely removed. The differences are shown in Table 2, where it should be considered that there is no generally accepted way of comparing nuclear waste and emissions. The use of thorium can be a large benefit, reducing waste longevity as well as tails.

Table 2 Comparison of environmental impact for conventional and nuclear power

	Conventionally fuelled[3]		**Nuclear reactor based**	
$CO_{2\ equivalent}$	Well-to-tank	95 g CO_{2eq}/kWh (Lindstad, et al., 2021)	Production process	12 g CO_{2eq}/kWh (Schlömer, et al., 2014)
	Tank-to-wake	568 g CO_{2eq}/kWh (Lindstad, et al., 2021)		
Air pollution	SO_x, NO_x, Particulate matter		None	
Solid waste	None		High level waste (spent fuel)	Equal to fuel usage in once-through or as low as 1/3 the fuel usage in closed cycle
			Low & intermediate level waste	0.05-0.1 m^3 per MWe installed per year
			Tails (fuel mining by-product, factor of fuel)	Between 8 to 38 times the fuel usage (in weight)[4]
			Decommissioning waste	Reactor size dependent

Economically nuclear power and conventional marine propulsion systems are distinctly different, the conventional systems come at relatively moderate CAPEX cost with the bulk of the OPEX cost being the fuel that is consumed during the lifetime. Nuclear power is a large departure in this regard, as it has high upfront (CAPEX) cost, with many estimates ranging from US$ 3800 to 6900$ per kW installed (Energy Options Network, 2017) & (U.S. Energy Information Administration, 2021), which would put it an increase of roughly 10 times the cost of conventional marine power plants. Besides this, decommissioning costs need to be considered, which can be estimated in the order of US$ 2000 per kW installed (United States general accounting office, 1992).

The OPEX of nuclear power is lower than that of conventional power; although the fixed maintenance and operational costs are higher, the fuel cost is significantly lower. Following similar assumptions as in Figure 10 and a fuel price estimate between US$ 2500 and US$ 10000 per kg (World Nuclear Association, 2021), (Tsoulfanidis, 2013) would result in a price between US$ 0.005 and US$ 0.02 per kWh, with conventional fuel costing US$ 0.07 to US$ 0.28 per kWh[5]. For the fixed operational costs (besides fuel) the cost of nuclear power generation is estimated to be three times higher than those of combustion engine-based power generation (based on figures for land use) (U.S. Energy Information Administration, 2021). A lifetime cost comparison is shown in Figure 11.

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[3] Operating on Very Low Sulphur Fuel Oil (VLSFO), with values for MGO almost identical

[4] Based on the feed factor calculations for low enriched uranium of 5% and 20% U235

[5] Based on a fuel consumption of 175 g/kWh and fuel costs between 400$ and 1600$ per ton

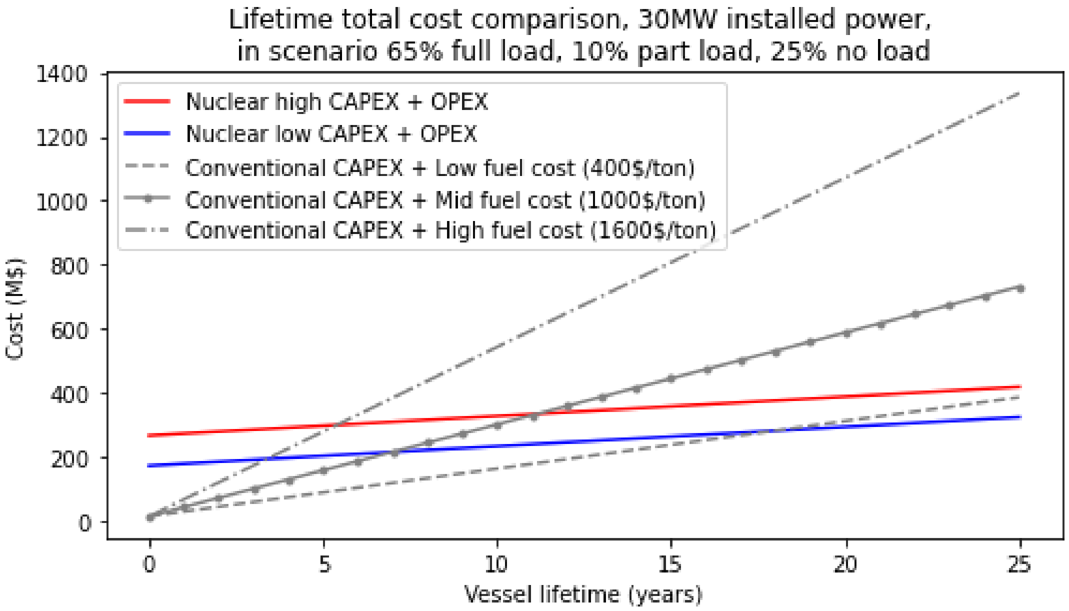

Figure 11 Lifetime cost comparison conventional and nuclear

The volume and weight of a nuclear power plant can be compared to conventional vessels. In this comparison it is important to consider that the nuclear based system will completely replace the vessels current fuel weight and volume as well. Vessels of moderate to large installed powers are best suited for an application without significant detrimental effect on usable space and weight on board. Similarly, vessels with large endurance (and thus fuel weight and size) are of interest, this is best shown when comparing the dominant weights in the layouts of shielding weight and fuel weight shown in Figure 12.

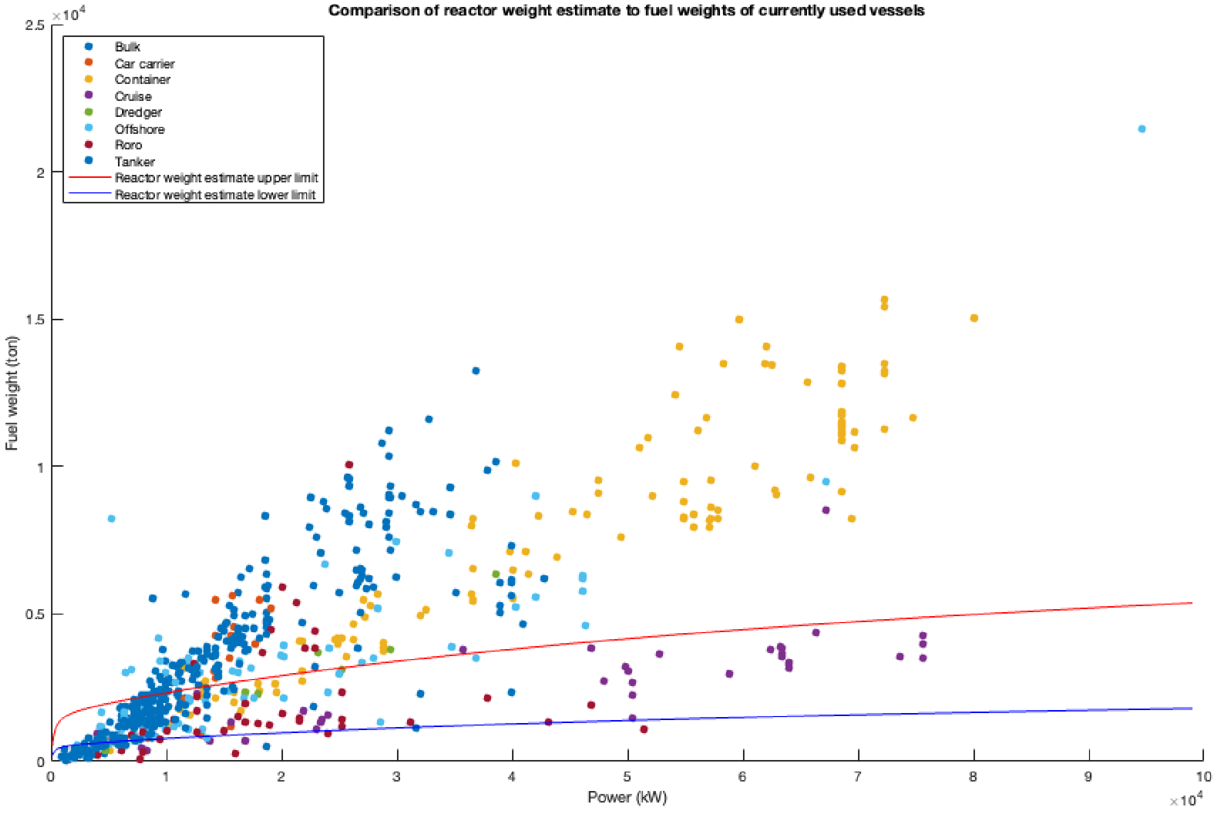

Figure 12 Comparison of conventional ship fuel weight (dots) and reactor shielding weight (lines based on analytical estimate) (Houtkoop, 2022)

A final consideration for the implementation of nuclear power is the societal and legislative aspect. The legislation for nuclear power in marine application is outdated and requires significant work for an application to be successful, especially for the commercial application.

From a societal aspect nuclear power requires work in public acceptance, as this is not something that is self-evident.

6. Conclusion

Nuclear power technology has seen many developments in the last decades, the implementation of state-of-the-art nuclear technology in terms of small modular reactors, Generation IV technology (VHTR and MSR) and thorium as fuel could facilitate a new potential for application in both commercial and naval ships. For naval operations it could add strategic autonomy, lower thermal emissions, flexibility for higher speeds and reduction of (thermal) signatures for a broader scope of surface ships than the presently used aircraft carriers. For all applications it reduces the uncertainty of availability and cost of future fuel, alongside reducing the emissions. The new developments relieve some of the issues that come with nuclear power: safety (increased resistance to accidents), increased proliferation resistance, and cost reductions.

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