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Nuclear fusion as unlimited power source for ships

E.S. van Rheenen^{1*}, J.P.K.W. Frankemölle^{2,3} and E.L. Scheffers¹

ABSTRACT

Every now and then, every marine engineer dreams of a compact, lightweight and inexhaustible energy source to power large ships across the seven seas. Nuclear fusion of deuterium and tritium promises to be a safe, compact, carbon-free, and inexhaustible energy source. Even though it will take decades before conventional power plants may be replaced with nuclear fusion, the concept of nuclear fusion for marine propulsion has already been put on the table by commercial parties. This research investigates the potential of nuclear fusion onboard ships. The design investigates putting the smallest imaginable magnetic confinement reactor, ARC, on a ship. The only commercial ship requiring significant amounts of power is the Queen Mary 2. The large power output of ARC (200 MWe) is one of the major issues of putting a fusion reactor on a ship. Other issues may include intact stability, structural design and influences of vibrations on the fusion reactor. All in all, we found that a fusion reactor onboard a ship is unlikely to be feasible in the near future.

KEY WORDS

Nuclear Fusion; Nuclear ships; Powerful ships; Conceptual Design; Retrofit Design

INTRODUCTION

Like many other domains, the maritime industry needs to dramatically decrease its harmful emissions by 2050 (International Maritime Organization, 2023). Sustainable powering of ships is the key to reducing emissions during the ship's operational life cycle. Therefore, research into alternative fuels is essential to reach the emission goals. Those fuels range from hydrogen, hydrogen-based fuels such as methanol and ammonia, to nuclear-driven ships (Houtkoop et al., 2022). However, none of these fuels are a perfect match for maritime applications, as all have their drawbacks. Hydrogen has a low volumetric energy density and is extremely flammable (Van Rheenen et al., 2023). Both methanol and ammonia are toxic. Additionally, methanol still generates carbon emissions, and ammonia is hard to combust (Van Rheenen et al., 2023). Nuclear-powered ships currently refer to ships powered by fission reactors. While nuclear fission reactors are a proven technology, their use in commercial ships remains limited. Not only are nuclear-powered ships expensive, but the risks of meltdowns and long-lived radioactive waste have also slowed their adoption for marine power generation (Wang et al., 2023).

Nuclear fusion represents an alternative to nuclear fission, which can potentially mitigate many of the risks associated with conventional nuclear technology. While atoms are split in the nuclear fission process, the principle of nuclear fusion is to glue two atoms together. The most conventional form of nuclear fusion uses the deuterium–tritium (D–T) reaction:



¹ Department of Maritime and Transport Technology, Delft University of Technology, Delft, the Netherlands

² SCK CEN, Belgian Nuclear Research Centre, Boeretang 200, BE-2400, Mol, Belgium;

³ KU Leuven, Dept. Mechanical Engineering, Celestijnenlaan 300, BE-3000, Leuven, Belgium;

* Corresponding Author: E.S.vanRheenen@tudelft.nl

From left to right, the fusion of a deuterium atom (a hydrogen atom with an extra neutron, also noted as hydrogen-2) with a tritium (a hydrogen atom with two extra neutrons, also noted as hydrogen-3) yields an alpha particle (a helium atom, also noted as helium-4), a neutron and 17.6 MeV of energy split amongst the reaction products (Freidberg, 2007). Deuterium (hydrogen-2) is stable, and can be found naturally. Conversely, tritium (hydrogen-3) has a half-life of 12.3 years and decays to helium-3 under beta minus emission (Bé et al., 2006). Tritium needs to be generated on-site through a second nuclear reaction: neutron capture of lithium-6 and lithium-7, the neutron being supplied by the D–T reaction (equation 1).

So the only fuel a fusion-powered ship would have to carry would be deuterium and lithium, two light-weight isotopes. A ship would require only little fuel to travel far because D–T fusion has an energy density of approximately 340E6 MJ/kg. Table 1 gives a comparison of the energy density of different fuels. Nuclear fusion fuels have the highest energy density. The difference in the energy densities of nuclear fusion and conventional marine diesel oil is extremely large. The amount of fuel that has to be bunkered for nuclear fusion is negligibly small compared to conventional fuels.

Table 1: Energy densities of different fuels (Freidberg, 2007; Aronietis et al., 2016)

Fuel	Energy density [MJ/kg]
Deuterium-tritium fusion	340 000 000
Fission (U-235)	88 000 000
Pure hydrogen	120
Heavy Fuel Oil	40

Nuclear fusion is an interesting ship fuel source, as it is safe, carbon-free and virtually inexhaustible. Ships powered by fusion would only need to be refuelled rarely and can thus have a higher up-time. Additionally, these ships would not only be carbon-free, but their only emissions would be helium, which is not considered a greenhouse gas or harmful. Moreover, fusion-driven ships would theoretically have a significantly larger range than fossil-fuel ships.

However, nuclear fusion is still under development. Currently, a reactor is being built in France, ITER, which aims to generate ten times more energy than is required to operate it. While ITER should hopefully be up and running by the late 2020s, it will be another fifteen years before it makes its first D–T fusion reactions (Lopes Cardozo, 2019). EUROfusion, the European fusion research consortium, aims to deploy the first European demonstration power plant (DEMO) by 2060 (Lopes Cardozo, 2019). An economy of scale will likely not be achievable before 2100 (Lopes Cardozo, 2019). These plans all focus on land-based fusion power plants. Nonetheless, looking at fusion reactors on ships is still interesting, especially since companies are already advocating for fusion power on ships (Lockheed Martin, n.d.; DNV, 2021). Lockheed Martin (n.d.) not only promotes fusion on ships, but they also deem it to be one of the first applications of so-called compact fusion. DNV (2021), on the other hand, have made a preliminary calculation of placing a fusion reactor on a ship, based on a reactor designed by General Fusion. It is likely, that the main motivation for placing nuclear fusion reactors on ships is the resulting large range, combined with low fuel costs and no carbon emissions.

This paper aims to get insight into the implications of putting a nuclear fusion reactor onboard a ship from a design perspective. For this study, we decided to place a selected nuclear power plant onboard an existing ship, which provides a certain base in dimensions, mission and requirements. The selection of this ship is based on its suitability and adaptability for a nuclear fusion power plant. To structure our thinking, we loosely performed one iteration of the design spiral (Evans, 1959). We did not assume this would yield an exhaustive overview of all the pros and cons of nuclear fusion on a ship. However, we did feel it would give sufficient scoping to our research.

This work is structured as follows. First, we describe the basics of nuclear fusion (Section "Basics of nuclear fusion"). This section describes the plant’s working process, basic design characteristics, and constraints. This theory is followed by an overview of design considerations and related challenges, loosely based on a first iteration of the design spiral (Section "Stepping Through Design Spiral"). The part "Mission and Owner Requirements" of this section contains the considerations regarding selecting a suitable vessel for our case study. The next section discusses scope boundary determination and overall design concept feasibility (Section "Discussion"). In conclusion, we provide an overview of the drawn conclusions and future research recommendations (Section "Conclusion and Outlook").

BASICS OF NUCLEAR FUSION

Nuclear fusion of deuterium and tritium atoms does not readily take place. Under normal situations, the Coulomb force between the two nuclei – which are both positively charged – keeps them far apart. The nuclear force becomes dominant only when they get very close together. Then fusion can occur. Very high temperatures, on the order of several million Kelvins, are required for nuclei to brave the Coulomb barrier and for fusion to occur at all. At these temperatures, deuterium and tritium form a plasma: free electrons, deuterium ions, and tritium ions coexist in a gaseous state. Besides the temperature of the plasma, the number density is also important: if more deuterium and tritium are present, more reactions will occur. Finally, if we want to use fusion for net power generation, the plasma should be well enough insulated that the fusion power production offsets the thermal losses. A figure of merit that is often quoted in this context is the triple product $n\tau_e T$, where n is the number density, τ_e is the energy confinement time – which is a measure of the insulation – and T is the temperature. Only when this triple product is larger than some value can a fusion reactor produce net power (Freidberg, 2007).

The main difficulty in achieving fusion on Earth is the energy confinement time τ_e . The materials of the wall limit the temperature at the wall of a fusion reactor, while the inside of the plasma has to be in the order of 150 million Kelvins. This large temperature difference results in extremely steep temperature gradients. Such gradients drive thermal transport, which turns the question of insulating the plasma into a huge problem. Several methods have been proposed to tackle this issue, but magnetic confinement fusion (MCF) is the most conventionally accepted method. MCF uses the Lorentz force to constrict charged particles within specially designed magnetic fields, limiting the heat transfer from the plasma to the reactor wall by several orders of magnitude. The large magnetic fields required for MCF can only be achieved using superconducting magnets, which operate at very low temperatures (Freidberg, 2007).

MCF-based designs are toroidally shaped. The best-known torus is a doughnut. The size of a doughnut is determined by its minor radius a , i.e. the radius of the uncurved cylinder, and its major radius R_0 , i.e. the distance from the doughnut's central hole to the middle of the curved cylinder. They come in two flavours, tokamaks and stellarators, but the details of what sets them apart do not factor into the present study. Most reactors, including ITER, are tokamaks. Figure 1 visually represents a tokamak. This part houses the plasma, the layer around it, and its main auxiliary components. It is called the vacuum vessel. A near vacuum inside the vessel exists because of the low density. The magnets are placed outside the vacuum vessel. Nowadays, tokamaks are closer to curved elliptic cylinders, meaning that a can be larger in the vertical direction than in the horizontal, which is referred to as elongation and denoted by κ . For more information on the basics of nuclear fusion, we refer to Freidberg (2007).

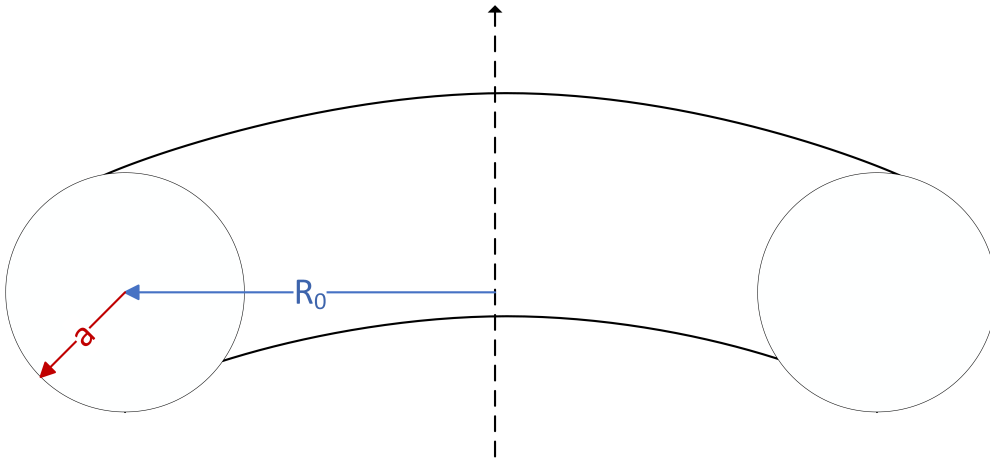


Figure 1: Representation of tokamak

Important for this study is that there exists a limit to how small toroidal reactors can become. This is caused by the choice of the D–T reaction on the one hand and the fact that MCF designs require superconducting magnets on the other. The D–T reaction produces a neutron with extremely high energy that, if it arrives at the superconducting magnet with sufficient en-

ergy, would quench the magnet, rendering the fusion reactor inoperable. These magnets are placed both on the inboard-side as well as on the outboard-side of the torus. To prevent quenching, the magnets are shielded by the blanket. The thickness of this shielding depends only on the shielding material and the energy of the neutron that it is meant to stop. The energy of the neutron is imposed by the D–T reaction (14.1 MeV, cf. equation 1) while other functions of the blanket impose constraints on the materials it can contain. As a result, the blanket will always have to be about a meter thick regardless of the reactor size (Freidberg, 2007), resulting in a minimal major radius and, thus, a minimal size of the torus.

More detailed 0D modelling based on plasma-physical considerations yields results that are largely in line with back-of-the-envelope reasoning. There is a strong coupling between the geometry of the reactor and the plasma performance, which means that not all parts of the design space are available. One cannot simply choose reactor size and power output. Using current-day superconducting magnet technologies (NbTi and Nb₃Sn) and available plasma physics regimes, economically viable reactors would need a major radius $R_0 = 8\text{--}9$ meters. Advanced superconducting magnet technologies like Rare-Earth Barium Copper Oxide (REBCO) might reduce R_0 to 5 meters. Such reactors generate power well over the level that can be utilised by a single ship. To make economically viable tokamaks that are smaller still, like the Affordable, Robust, Compact (ARC) reactor (Sorbom et al., 2015), one would need more optimistic assumptions on the physics performance (Zohm, 2019).

The concept of MCF could be disregarded completely, and alternative fusion concepts could be looked into. One that sometimes makes the news is inertial confinement fusion (ICF) using high-intensity lasers. While headway is being made (Betti & Hurricane, 2016) and ignition (a self-sustained fusion reaction) was even recently achieved (Osolin et al., 2023), it is unclear what an ICF-based power plant would look like. Then there is a host of more and less exotic designs that are championed by private industry. They often promise much shorter road maps to commercial reactors than presented in, e.g., the European road map (EUROfusion, 2018), but they usually rely on large technological breakthroughs. While such developments cannot be ruled out, they are far from certain. Although not much is known about the compact fusion concept for ship propulsion (Lockheed Martin, n.d.), we may assume that it will sit somewhere in this category. Alternatively, it might be a tokamak after all in which case all of considerations with regard to MCF apply to it.

In our opinion, ARC strikes a balance between being innovative enough to allow potential application on a ship – conventional fusion technology results in far too bulky machines – while being conservative enough – requiring limited technological development in some domains – to be deemed likely based on today’s available technology. It also aids the present work that a rather detailed design study is already available (Sorbom et al., 2015). The ARC reactor produces 525 MW of fusion power and has a total thermal power of 708 MWth. After considering thermal efficiency and recirculating power in the auxiliary systems, 190 MW net electric power is left. The vacuum vessel has a major radius $R_0 = 3.1$ m, minor radius $a = 1.1$ m and elongation $\kappa = 1.84$. The on-axis magnetic field, i.e. the field at $r = 0$ where r runs from 0 to a , is 9.2 T while the peak on-coil magnetic field is 23 T. The entire reactor, excluding the balance of plant equipment, fits in as little as 1320 m³, weighs 7190 tonnes and would cost 5.5 billion dollars. In this study, we will work with rounded numbers for convenience and install a reactor that has dimensions $10 \times 10 \times 10$ m³, a weight of 7000 metric tonnes and that produces 200 MWe net power.

STEPPING THROUGH DESIGN SPIRAL

This study aims to provide a preliminary overview of the adjustments required and the feasibility of installing a fusion reactor as part of the ship power train. Therefore, all relevant aspects within the ship design process need to be addressed, as if the refit will take place in the near future. Several approaches to the ship design process exist, such as concurrent design (Sohlenius, 1992), set-based design (Doerry et al., 2014) or design-space exploration (de Vos, 2018). Since this study is not focused on design methodologies, one of the more basic design approaches is followed: an iterative design process following the design spiral as defined by Evans (1959). Since this study is, to our knowledge, the first paper on installing nuclear fission onboard a ship, developing a complete detailed design is considered unfeasible and premature at this moment. Therefore, following the six design stages as defined by Lamb (2003): (1) Concept Design, (2) Preliminary Design, (3) Contract Design, (4) Functional Design, (5) Transition Design, (6) Workstation/Zone Information Preparation, this study remains in the domain of concept or early-stage design.

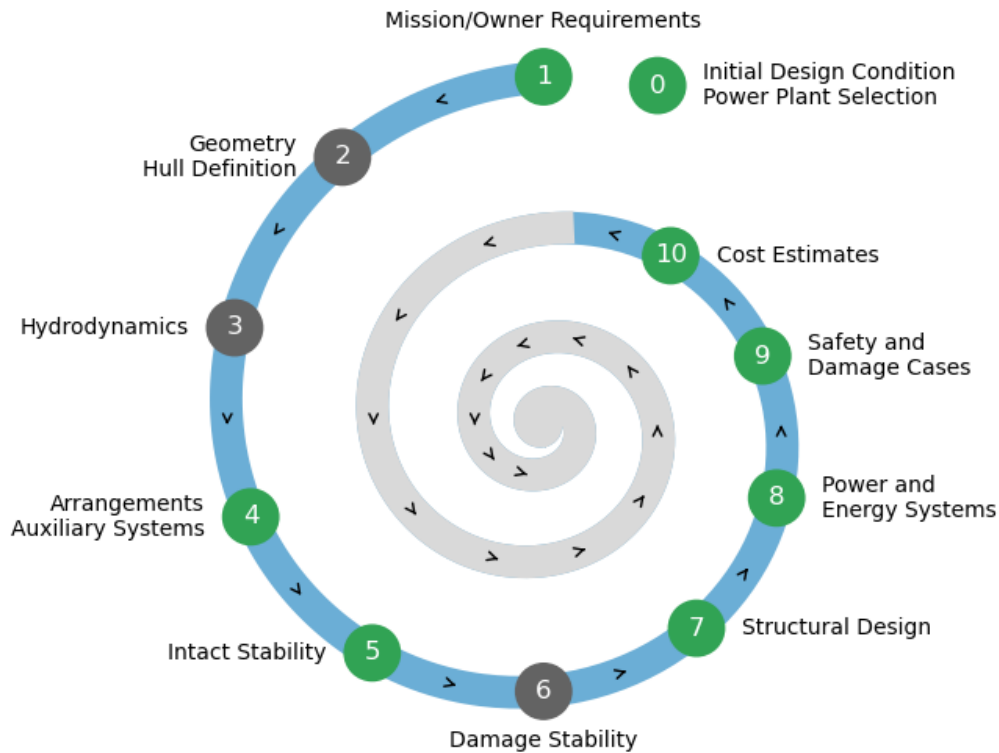


Figure 2: Ship Design Spiral (Evans, 1959) adjusted showing the first (blue) iteration of the ship design process: the concept design phase. The green design aspects are considered within the scope of this study, and the grey design aspects are either considered to be more fitting in later design stages or considered less relevant within a retrofit design process. All aspects are reconsidered in secondary and tertiary iterations.

Design spiral

In the design spiral representation of a design process (Figure 2), only a single iteration addressing the different design aspects is completed. Note that the power plant concept selection is considered "design aspect 0" for it is an initial requirement in the design process within this study.

Disregarded Ship Design Aspects

Several of the design aspects are considered less relevant within this specific study. Some of these should be considered for later design phases, whereas others are generally less relevant for a retrofit. The hull form and by extension the hydrodynamics, for example, is assumed to remain rather constant. Therefore, this study does not consider the design aspects concerning hull lines, body plan, and Bonjean curves. The floodable length and freeboard calculations are considered unchanged as well. Thus, steps 2 and 3 from Figure 2 are left out in this study.

Damage stability refers to the case in which one or more watertight compartments have been damaged or breached, often caused by grounding (Costa Concordia) or collision (RMS Titanic). Stability considerations in these cases are a vital concept in guaranteeing the ship's overall safety. However, current knowledge on the Queen Mary 2 with a nuclear fusion power plant retrofit does not permit a thorough damage stability analysis.

Mission and Owner Requirements

In this first step of the design spiral, the selection of a suitable case study is addressed. In the Theory Section, we described a lower limit to the power that can be generated by a fusion reactor of approximately 200 MWe. This is over the upper limit of the generators that drive the world’s biggest commercial ships and is only surpassed by the newest naval fission power plants (Sea Forces, n.d.). As a result, only very few use ships are potentially compatible with a fusion reactor based on power requirements. We decided to reverse-engineer the mission/owner requirements from existing vessels. To this end, we looked at various extremely large or powerful ships.

Table 2 gives an overview of very powerful ships. The most powerful ships are aircraft carriers. However, aircraft carriers are naval vessels that play a vital role in national defence. Information on these ships is thus minimal, which is why they are disregarded as reference ships for this study. Icebreakers demand high power and significant autonomy, making nuclear propulsion an interesting option. The most powerful icebreakers are propelled by nuclear power (Brigham, 2022.; Manaranche, 2021.). However, information about these Russian nuclear icebreakers is extremely limited. Thus, they are disregarded as reference ships for this study.

Current cruise ships are all optimized for high energy efficiency and comfortable travel. Their speed is less important, and they have a low power demand compared to their size (Thakkar, 2023). Ocean liners, however, are generally sailing faster. The fastest ocean liner, the SS United States, required 185MWe to set the record for the fastest crossing of the Atlantic Ocean in 1952. Due to the ship’s retirement, however, this ship is not considered. On the other hand, the second fastest ship was built more recently. The Queen Mary 2 is another ocean liner, with 117MWe installed power and top speeds of 30 knots. This ship was also featured in significant ships of 2003, the year she was delivered (Chanev, 2022.). Thus, the general arrangement and the power and propulsion layout of the Queen Mary 2 is known. Consequently, Queen Mary 2 was chosen as the reference ship for this study.

Table 2: Overview of powerful ships

Ship name	Ship type	Installed power	Power generation type	Source
Gerald R Ford	Aircraft carrier	600 MWe	Two nuclear reactors	(Sea Forces, n.d.)
Admiral Kuznetsov	Aircraft Carrier	150 MWe	Eight boilers, four steam turbines	(Naval Technology, 2021)
Charles de Gaulle	Aircraft Carrier	122 MWe	Two nuclear reactors	(Naval Technology, 2018)
Project 10510	Icebreaker	120 MWe	Nuclear reactor, planned	(Manaranche, 2021.)
Arktika	Icebreaker	60 MW shaft power	Nuclear reactor	(Brigham, 2022.)
Icon of the Seas (Largest cruise ship as of 2023)	Cruise ship	67.5MW	Six multi-fuel engines	(Thakkar, 2023)
SS United States	Ocean liner	185 MWe	Eight boilers, four steam turbines, ship retired	(Gibbs, 2021.)
Queen Mary 2	Ocean Liner	118 MWe	Diesel generators and gas turbines	(GE, 2017.; Chanev, 2022.)

The Queen Mary 2, visible in Figure 3, is the largest ocean liner ever built (Chanev, 2022.). It has a Combined Diesel Electric and Gas Turbine (CODEG) power plant layout, with four Wärtsilä diesel engines and two General Electric gas turbines (GE, 2017.; Chanev, 2022.). The diesel engines provide 16.8 MWe each, while the turbines provide 25 MWe each. The turbine sets, designed by GE, are about 35 tons lighter than similar turbines, resulting in more design freedom (GE, 2017.). The Queen Mary 2 has split engine rooms. The diesel engines are in one room, and the two gas turbines are in a different room (Cruise Industry News, 2004.). The power delivered by the power plant is used for propulsion, hotel, platform and auxiliary systems. The Queen Mary 2 has a small hospital with 11 beds. Its desalination plant can produce 2000 tons of fresh water daily. The garbage system requires heat of up to 1000 °C to burn trash (Chanev, 2022.). All these additional systems require energy, next to the energy needed for systems to keep the guests entertained. The ship currently takes up to 6 hours to fully bunker its fuel tanks (Chanev, 2022.). The Queen Mary 2 is 345m long, with a beam of 41m at the waterline (Chanev, 2022.). She is 72m high (including the funnel) and has a draft of 10m. The gross tonnage of the Queen Mary 2 is about 150000 GT. The block coefficient of the Queen Mary is 0.61 (Cruise Industry News, 2004.).



Figure 3: Queen Mary 2 in the port of Boston, from Oceanhistory46 (2013), Wikipedia, (https://commons.wikimedia.org/wiki/File:Qm2_portboston.jpg), CC BY-SA 4.0 Deed

Arrangements & Auxiliary Systems

The main consideration is adapting a standard diesel generator power plant with its related auxiliary systems into a fusion reactor power plant. Whereas the current systems of the selected vessel can be found in the ship's general arrangement (GA), such a list is less standardized for nuclear fusion plants. Therefore, land-based plants are assumed to provide sufficient information to estimate the required auxiliary systems' main dimensions on the concept design level.

The Queen Mary 2 has an integrated electric propulsion set-up featuring a CODEG plant layout, consisting of four diesel engines and two gas turbines (Chanev, 2022.). These engines, including their fuel, will not be required anymore when installing a fusion reactor. As a fusion reactor forms a single point of failure, an emergency generator set is advised that can generate sufficient power for emergency board systems such as fire fighting, communication and basic lighting. It is outside the scope of this paper to define the exact power required for these emergency systems. Next to removing three diesel engines and two gas turbines, the fuel tanks are not required anymore either. These fuel tanks can hold 3000 tonnes of fuel and are thus of significant size. As the ship is already operating on electric propulsion, this does not need to be changed; a fusion reactor produces electricity, too. The hotel systems are not expected nor required to change significantly. Therefore, the HVAC System, water desalination and distribution systems, and low-voltage electricity distribution systems remain intact.

Several additional auxiliary systems are required to keep a fusion reactor running. Some of these systems, such as the blanket and plasma diagnostics, are embedded inside the fusion reactor (Sorbom et al., 2015). Other fusion-specific auxiliary systems are not embedded into the system. Federici et al. (2017) estimates that the DEMO fusion power plant will need a tritium recovery plant, heating and current drive (H&CD) systems, control systems, a cryoplant and a vacuum system. Other auxiliary systems will be similar to those of fission power plants, such as the requirement of a secondary cooling system (Garcia et al., 2012; Lee et al., 2023). Table 3 gives an overview of the auxiliary systems and their estimated relative locations, while the estimated influence of removing the current engine room with ARC is visualised in figure 4 (Chanev, 2022.).

Auxiliary system	Location	Size
Cryoplant	Relatively close to power plant	Large
Tritium recovery plant	Relatively close to power plant	Small/medium
Heating and Current Drive	Next to reactor	Small
Control systems	Irrelevant	Medium
Vacuum system	Next to reactor	Small
Secondary cooling system	Close to reactor	Large
Turbines	Close to reactor	Medium

Table 3: Overview of auxiliary equipment and approximate locations of equipment

The cryoplant is significantly sized, as the cryoplant used in ITER will be approximately 6000m² with a maximum height of the buildings of 19m, excluding the storage required for storing the gaseous helium and liquid nitrogen (Fauve et al., 2017). In ITER, this cryoplant will require approximately 35 MW of electrical power to run. In contrast, the electrical power to run the cooling systems of ARC is estimated to be only 5.1 MW (Fauve et al., 2017; Sorbom et al., 2015). Despite this large difference, it is still assumed that the cryoplant will be the most significant auxiliary system. The cryopumps themselves will likely be small as the ITER exhaust pumping system will consist of 8 cryopumps (Day & Murdoch, 2008). A full-scale prototype torus cryopump has been developed by Day and Murdoch, which was 1.8m long and 1.6m in diameter. Next to the cryopumps, ITER also makes use of roughing pumps. These pumps themselves do not have to be located close to the reactor. In ITER, the vacuum systems are connected to a roughing pump in a vacuum pump room located 40m away from the torus (Day et al., 2004). Additionally, as there are only 8 pumps, the size they take up is considered to be relatively small. The tritium recovery plant is estimated to be small, especially if direct internal recycling is used (Day & Giegerich, 2013). The heating and current drive systems must be close to the main reactor. The size of these systems depends on their power and the choice of the system. For example, an ion cyclotron resonance heater capable of delivering 20 MW of power is approximately 14m³ and weighs between 45 and 50 tonnes (Brans, 2020). As the external heating power for ARC is estimated to be approximately 25 MW, the size of this auxiliary system will be moderate. The control system is not fusion-specific, as fission reactors also need control systems. These systems do not have to be close to the reactor and can be distributed throughout the ship. They are also not expected to be extremely large. Comparison with the control system space in ITER is not likely useful, as this building in ITER will also be used as a visitor space next to ITER being a testing facility. The main control room of ITER will be able to house 60 to 80 people (ITER, 2023). The turbines are not specific to fusion-driven ships and are expected to be of medium size, similar to current turbines (No, Kim, & KIM, 2007; Houtkoop et al., 2022).

Intact stability

In this subsection, we consider the static stability effects of putting a nuclear fusion power plant onboard a ship. We study the effect of adding the reactor on the ship's draft and analyse the freedom in placing the reactor in terms of trim. We use the ship's length $L_{OA} = 345\text{m}$, width $B = 41\text{m}$, height $H = 62\text{m}$ (including funnel $H_{total} = 72\text{m}$), draft $D = 10\text{m}$, displacement $\Delta = 79287\text{tonnes}$ and block coefficient $C_B = 0.61[-]$, combined with the sea water density $\rho_{sw} = 1025\text{kg/m}^3$ and gravitational constant $g = 9.81\text{m/s}^2$. Figure 4 gives an overview of the main dimensions of the Queen Mary 2. The length at the waterline L_{WL} is calculated based on the given displacement and block coefficient:

$$L_{WL} = \frac{\Delta}{B \cdot D \cdot C_B \cdot \rho_{sw}} = 309[\text{m}] \quad (2)$$

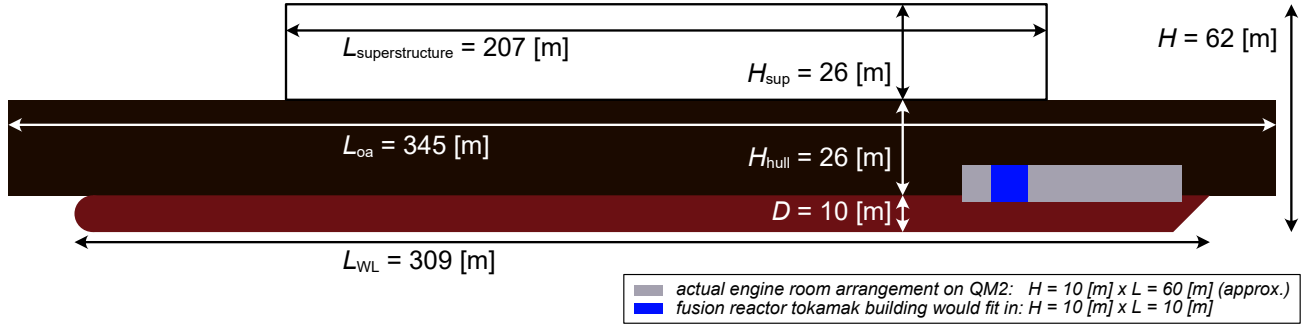


Figure 4: Schematic side view showing the main dimensions of Queen Mary 2 as well as the current location of the engine room approximately to scale. The tokamak building of the fusion reactor has been drawn, again to scale, inside this engine room to indicate that it would fit.

The fusion plant has a mass m of 7000 tonnes and is regarded as a point mass, due to its relatively small volume $V_m = 10 \times 10 \times 10 = 1000 \text{m}^3$. In our calculations, we use dimensions as shown in Figure 4 and use the following notation:

$$\begin{array}{lll}
 K_z & 0 & [\text{m}] \\
 K_{0,y} = B_{0,y} = G_{0,y} & 0 & [\text{m}] \\
 G_{0,z}, G_{1,z} & \frac{KG_0, KG_1}{G_{1,y} - G_{0,y}} & [\text{m}] \\
 y & \frac{KG_1 - KG_0}{\Delta_m} & [\text{m}] \\
 z & \Delta_m & [\text{kg}] \\
 M & &
 \end{array} \quad (3)$$

Draft

The change in draft is a relative simple calculation once the waterline area is known. We assume that the waterline area is

$$A_{WL} = L_{WL} \cdot B \cdot C_B^{2/3} [\text{m}^2]. \quad (4)$$

Where the block coefficient is adjusted to not take the draft into consideration. This gives us the difference in draft δD and the new draft D_m , which are

$$\begin{aligned}
 \nabla_m &= \frac{m}{\rho_{sw}} & [\text{m}^3], \\
 \delta D &= \frac{\nabla_m}{A_{WL}} & [\text{m}], \\
 D_m &= D + \delta D = 10.75 & [\text{m}].
 \end{aligned} \quad (5)$$

This draft does not take the reduced mass by removing the fuels of the ship into consideration. If we address this reduced mass, m_{fuel} of 3000 tonnes, the new draft D_1 becomes 10.43m. Based on visual inspection of the ship's hull shape, this change in draft is not expected to change the waterline area markedly. It has, therefore, limited effects on the ship's stability.

Center of Gravity Height

The ship's current centre of gravity (CoG) has not been explicitly mentioned in the studied literature. Therefore, we calculate its location based on the three assumptions. First, we assume that the spaces below the waterline are mainly technical spaces. Second, that technical spaces have double the density of the hotel spaces. Third, that the block coefficient and main dimensions determine the volume below the waterline, while the volume above the waterline consists of two blocks that

represent the part of the hull above water and the superstructure (see Figure 4). Therefore, we find

$$\begin{aligned}
M_{AWL} &= V_{AWL} \cdot \rho_{AWL} & [\text{tonnes}], \\
M_{BWL} &= V_{BWL} \cdot \rho_{BWL} = V_{BWL} \cdot 2\rho_{BWL} & [\text{tonnes}], \\
\overline{KG}_{tot} &= \frac{M_{AWL} \cdot \overline{KG}_{AWL} + M_{BWL} \cdot \overline{KG}_{BWL}}{M} = 21 & [\text{m}].
\end{aligned} \tag{6}$$

Here, subscript $_{AWL}$ refers to the volume V and mass M above waterline and $_{BWL}$ the submerged mass and volume. This gives the original CoG \overline{KG} as 21m. It is known amongst ship designers that adding mass above the CoG leads to less stability, whilst adding mass below CoG increases the ship's stability. If, however, \overline{KG} is too large, the ship's overall level of comfort reduces due to its movement. Therefore, placing the plant in the lower part of the hull but not in a fully submerged area is recommended.

Trim

The trim caused by placing the reactor at any other place than the CoG requires additional ballast (water) to be present at all times. Since this would lead to a certain increase in draft, it also causes an increased resistance. Therefore, this design aspect is chosen so that the maximum angle caused by the presence of the reactor is 5° degree. This degree can still be considered a "small angle" and is sometimes described as the angle of comfort: a larger angle would reduce comfort levels for the cruise passengers. All calculations regarding trim follow from (Moore, 2010), where GM is the difference between the center of gravity and the metacentric height. First, we calculate the maximum deviation in transverse direction (y -axis), which yields

$$\begin{aligned}
\overline{GM} &= \overline{KB} + \overline{BM} - \overline{KG} \simeq \frac{D}{2} + \frac{I_T}{\nabla} - \overline{KG} = 6.72 & [\text{m}], \\
\frac{y_{max} \cdot m}{M + m} &= \overline{GM} \sin(\phi_{max}) & [\text{m}], \\
|y_{max}| &= \overline{GM} \sin(\phi_{max}) \left(1 + \frac{M}{m}\right) = 7.22 & [\text{m}].
\end{aligned} \tag{7}$$

Next, we calculate the maximum deviation in the longitudinal direction (x -axis), which yields

$$\begin{aligned}
\overline{GM}_L &= \overline{KB} + \overline{BM}_L - \overline{KG} \simeq \frac{D}{2} + \frac{I_L}{\nabla} - \overline{KG} = 1291 & [\text{m}], \\
|x_{max}| &= \overline{GM}_L \sin(\phi_{max}) \left(1 + \frac{M}{m}\right) = 1386 & [\text{m}].
\end{aligned} \tag{8}$$

Both values do not instantly constrain the placement of a reactor onboard the Queen Mary 2. It is self-explanatory that the location is more limited than the location of fuels onboard, but we consider the available positions to be within acceptable limits. In line with Payne et al. (2005), having a maximum longitudinal location of $|x_{max}| = 1386\text{m}$ off-centre suggests that longitudinal stability, also in the case of head waves, is not a major issue for this ship.

Structural Design

Nuclear fusion reactors are known for their high density, with ARC weighing over 7000 tonnes with a volume of $V_{reactor} = 10 \times 10 \times 10\text{m}^3$. This gives the entire reactor a density $\rho_{reactor}$ of $7000 \frac{\text{kg}}{\text{m}^3}$ and is equivalent to adding a solid block of lead of over 600m^3 near the heart of the ship. Structurally, we do not consider this mass to be a critical point within the design considerations.

A second consideration are the mechanical vibrations. Power spectra on a ship might differ considerably from those observed on land. In a first-order approximation, let us only consider the one-way couplings: ship-to-reactor vibrations and reactor-to-ship vibrations. Ship-to-reactor vibrations may come either from the ship itself or the interaction between the ship and its environment. Regarding the former, Van Dokkum (2005) identifies the two most common onboard sources of vibrations as the propellers and the engine. In the QM2 case, only the propellers survive the retrofit. Regarding the latter, wave-induced resonance-based vibrations like springing and whipping must be accounted for, as well as the potentially exacerbating effects of heavy weather. A perusal of the literature did not, in fact, yield a starting point for assessing the consequences of such ship-to-reactor vibrations outside of one. Land-based reactor designs consider the effect of seismic activity (also discussed in the ITER Preliminary Safety Report (Taylor et al., 2009)) on the structure of and components in the tokamak building (Ushigusa et al., 2000; Sorin, Barabaschi, & Sannazzaro, 2003), and ways of mitigating these via seismic pads (Syed et al., 2014). However, these studies do not seem principally interested in the reactor operation under vibrations but rather whether the structure would survive. This indicates that external vibrations do not seem top-of-mind in the operation of a fusion reactor. For the plasma itself, this makes sense in that it needs to be actively controlled for a large range of frequencies anyway.

Moving to reactor-to-ship vibrations, the story is quite different. While there are no large moving parts in a fusion reactor (hence no large vibrations during routine operation) and the thermal content of the plasma is negligible, there are large currents and magnetic forces at play. Failure modes that tap into these represent a serious risk. Plasma disruptions, Edge-Localised Modes (ELMs) and Vertical Displacement Events (VDEs) are to be avoided for various reasons (Hassanein, Sizyuk, & Ulrickson, 2008), but the mechanical stresses that they cause are certainly among them. In terms of mechanical stresses, the worst-case scenario is a VDE. For ITER, symmetric VDEs are expected to result in vertical forces on the reactor structure up to around 100 MN, while asymmetric VDEs result in horizontal forces up to 50 MN. While the vibrations that these cause in the ship will depend on the power spectra of these events – which are beyond the scope of this work – such vibrations are perhaps subordinate to the instantaneous mechanical stresses that VDEs cause in the ship's structure. Making a back-of-the-envelope estimation, a vertical force of 100 MN is equal to a weight of 10,000 tonnes. As a reactor weighs about 7000 tonnes, this amounts to a weight increase of +150%. While it is not clear how VDE forces in ITER translate to ARC (although they are similar in terms of fusion power) and the ship's structural material response to transient forces is not necessarily the same as to constant forces, this does indicate that the structural requirements need to take such failure modes into account.

Assuming that we design the ship to withstand these transient loads, it would seem that one-way coupled effects, both ship-to-reactor and from reactor-to-ship, are not showstoppers per se. It remains the case, however, that both fusion reactors and ships have eigenmodes that are best avoided. For example, the coil system of ITER has an eigenfrequency at around 1.5 Hz (Ushigusa et al., 2000). Designing ships such that they do not resonate at certain frequencies is already a complex issue (Kianejad et al., 2020) and adding a tokamak on board introduces a host of extra eigen frequencies that need to be taken into consideration. Two-way-coupled effects will start playing a role here: we want to prevent characteristic frequencies of the ship from exciting those of the tokamak and vice versa. Tackling such resonances would seem to be a challenge in the ship design. Further research in this area would be recommended.

Finally, damage stability is already considered outside the scope of this study. However, preventing the case where damage stability is required can be considered. Queen Mary 2 currently has a double hull for strength and collision protection, having a second function as storage space for fluids like ballast water and fuel. If the retrofit permits changing this structure, the "Y-Scheldehuid" could be considered as an alternative (Roller, 2012). This hull type, based on Y-shaped stiffeners, reduces the chance of crack formation in case of a collision. This hull type cannot prevent damage to the reactor resulting from the impact but might improve ecological preservation.

Powering and Energy Systems

The Queen Mary 2 has an installed power of 118 MWe, but it does not often use its full power. Payne et al. (2005) investigated several scenarios, ranging from constant power and accepting delays to using more power to recover delays. In all of these scenarios, the engines were mostly run at 60% or less. Engine usage of 60 to 80% was used in three of the four sce-

narios, and engine usages above 80% were very limited (Payne et al., 2005).

ARC, on the other hand, produces approximately 200 MW of electrical power available for the ship (Sorborn et al., 2015). Fusion and fission reactors are similar because they provide a large amount of high-quality heat. On fission-powered ships, a direct drive from the gas turbine to the shaft can be used to minimize conversion power losses (Houtkoop et al., 2022). Thus, a fusion reactor could also be coupled with a direct drive. It is estimated that this results in a system which is approximately 5% more efficient than using electrical power only. However, direct drive is disregarded here for several reasons. First of all, the Queen Mary 2 currently operates a full electric system and four azimuth thrusters for propulsion (Chanev, 2022.). Installing direct drive would result in significant changes in the propulsion system.

Secondly, a direct drive from the fusion reactor to the shaft results in more unnecessary power sources on board. When looking at the general arrangements, two turbines are required to transfer energy from the fusion reactor to electricity or the shaft. One or two backup engines are also required depending on the arrangement (Houtkoop et al., 2022). If an all-electric backup is chosen, only one backup engine is needed; otherwise, an additional one is necessary. Without direct drive, only one turbine is needed, and with an all-electric system, only one backup engine is required, resulting in two power sources instead of three or four. So the system becomes more complicated when using direct drive.

Finally, the Queen Mary 2 only requires 118 MWe at peak moments but usually requires around 75 MWe. It is not straightforward to reduce the power output of a fusion reactor, because of complex interplay of plasma parameters, which was also discussed in the context of reactor size (cf. Section "Basics of nuclear fusion") ("The resilience of an operating point for a fusion power plant", 2015)¹. A system optimized for energy efficiency is thus not necessary. However, in port lower power requirements are often in place. A useful approach to overcome this challenge would be ship-to-shore-power, which is feasible in case of an ocean liner only visiting a limited number of ports. On the other hand, a reliable electrical system is needed regardless for the hotel load. If the power surplus is to be used to charge batteries, create conventional fuels using the Fischer–Tropsch process or create hydrogen, an electrical system is needed. Thus, an electrical system results in more desirable flexibility of the system.

Safety and Damage Cases

Novel damage cases occurring on ships are hard to qualify or quantify exactly. Consequently, we will explore a non-exhaustive list of situations unique to ships that may influence fusion reactors and assess their potential impact on a fusion reactor. While crucial in the design of a ship, a traditional damaged stability analysis is far beyond the scope of this conference paper. However, a crude conceptual analysis is possible assuming the fusion reactor does not affect the rest of the ship in terms of safety and damage cases. Under that assumption, the only novel damage cases are those inherent to the fusion reactor design and those arising from putting that reactor on board a ship.

To understand the specific risks associated with a fusion reactor, we looked at a summary of the Preliminary Safety Analysis Report for ITER (Taylor et al., 2009). In this summary, it is described that the two main fusion-specific safety functions of ITER relate to the confinement of radioactive material and the limitation of exposure to ionising radiation. While ITER is an experiment and will not be used to generate electricity, at 500 MW of fusion power, it is in the same ballpark as ARC. Two risks that are not present in fusion reactors, as opposed to fission reactors, are runaway thermal reactions (meltdown) and proliferation. Other safety concerns exist, of course, but those are of the conventional types associated with large industrial facilities.

Worst-case: Confinement of Radioactive Waste in Case of Sinking

The current design phase does not consider the detailed effects of a ship sinking due to the complexity of predicting the outcome. Several factors significantly influence the consequences, including the specific design of watertight compartments

¹This would clearly pose a challenge for vessel types with times of low or even no propulsion whilst at sea.

and bulkheads, the fusion reactor's location, and its compartment's size and contents. Additionally, the specific location of the sinking event itself can further impact the situation. It's important to note that while fission is considered a viable option for some ships, the potential consequences of a sinking event involving a fusion reactor are not necessarily deemed significantly worse. However, further research is necessary to fully understand the impact due to the numerous and unpredictable factors involved.

In this research, we only look at what could happen to the radioactive materials in case of a sinking. The confinement of radioactive material is probably the most pressing question in this case. Perfect safety cannot be guaranteed, and it stands to reason that incidents will happen. In 2001, IAEA released a tech doc listing the release rates due to wrecks that resulted from past marine accidents (*Inventory of Accidents and Losses at Sea Involving Radioactive Material*, 2001). Fusion reactors do not produce much long-lived radioactive waste compared to fission reactors, and much of that waste is locked into the structure – the vacuum vessel and components behind it are neutron-activated – so that the radioactivity cannot escape all at once. Besides activated structures, there is operational waste, the coolant may be activated and part of the fuel (tritium) is radioactive.

The operational waste for ITER is estimated at, at some 200 tonnes/year (Taylor et al., 2009). Only 5% of this is expected to be non-short-lived waste. It stands to reason that this waste can be stored such that it will not be released all at once in the case of an accident. For ARC, there is the additional consideration of FLiBe, which is used as coolant (as opposed to ITER, which uses water). However, FLiBe solidifies below 732 K (Sorbom et al., 2015), so we assume that it will be solid on the sea bed. Moreover, activity in FLiBe dies out rather quickly (Bocci et al., 2020). If it can be contained for a year, it does not pose a radiological risk afterwards (but it might still pose a chemical risk).

Finally, there is the question of the fuel. While deuterium is stable and naturally present in the sea, tritium is radioactive. The total amount of tritium in the plasma is negligible. For a fusion reactor of the size of ARC (with a plasma density of $n_e = 1.3 \times 10^{20} \text{ m}^{-3}$ and a plasma volume of 141 m^3), the weight of the plasma is approximately 0.07 grams as can be seen from the simple calculation

$$m = n_e V m_a = 1.3E20[\text{m}^{-3}] \cdot 141[\text{m}^3] \cdot \frac{2+3}{2} \cdot 1.66E-24\text{g} = 0.07[\text{g}] \quad (9)$$

with m in kg, n_e in m^{-3} , V in m^3 , m_a in u. However, there are orders of magnitude more tritium in the rest of the fusion system, mainly in the tritium recovery. The exact amount depends on, amongst others, the burn-up fraction and the throughput time. Our previous research showed for a burn-up fraction of 5%, a total tritium inventory of approximately 1 to 2kg per GW of fusion power, including an emergency inventory (Van Rheen, 2021). The overall inventory can be as low as 500 grams per GW of fusion power without the emergency inventory. As ARC has a fusion power of 500 MW, the expected total tritium inventory is approximately 1 kg. At a specific activity of 358 TBq g^{-1} , this means that a total source term of 358 PBq radioactivity is present. This is on the order of the total amount of tritium that has been released by the Le Hague reprocessing plant over the last thirty years (Bailly du Bois et al., 2020).

Whether this tritium source term is problematic depends strongly on how it is released, but that it is significant can be seen using a back-of-the-envelope approach. Regulatory recommendations for tritium in drinking water range from 30 kBq/L to 100 Bq/L (Dingwall et al., 2011). Taking these recommendations, we can calculate the equivalent bodies of water in which 358 PBq needs to be homogeneously dissolved to be compliant. For 30 kBq/L that would be 12 km^3 , and for 100 Bq/L 3580 km^3 . Of course, much depends on the mixing properties of the ocean. A surface release will disperse very differently than a release at depth. When the ship would sink in shallow water, and assuming a mixing depth of 100 m (D'Asaro, 2014), the tritium would have to spread over 2000 km by 2000 km to stay under 100 Bq/L or 10 km by 10 km to stay under 30 kBq/L. A very crude estimate of how far the effects range can be made using an analogy from atmospheric dispersion physics (Stockie, 2011). Assuming a Gaussian puff (a conservative approach, which assumes that the entire inventory is released as a single puff) and a horizontal eddy diffusivity on the order of $5\text{--}20 \text{ m}^2\text{s}^{-1}$ (Döös & Engqvist, 2007), the distance that the puff needs to travel from the release point ranges between 500 km to 2000 km to go under the 30 kBq/L limit, and much further to go under 100 Bq/L. This tritium inventory thus poses a potential hazard to the environment, and suitable measures must be taken to ensure that it is not released to the environment in case the worst happens.

What the sinking of a fusion-driven ship would ultimately do to local and regional marine life and to human activities in

the area is too complex to answer in this conference paper. Taking a broader perspective, we feel that recommendations would need to be put into place, preferably at an international level by the IAEA, regarding the licensing of fusion reactors on ships. However, such policies at the moment appear insufficient even for conventional nuclear reactors on board ships (Wang et al., 2023).

Reactor Safety Risks caused by Motions of Vessels in Waves

A major difference between a fusion reactor based on a ship, contrary to on land, is the movements of a ship. As a ship moves in waves, the fusion reactor will also experience these movements. As the plasma has a very low density and is contained by magnets, we believe that the influence of the movement on the plasma itself may be negligible. These magnets, however, are suspended in concrete and may be influenced by ship motions. All auxiliary components, too, must be designed to withstand ship motions and movements. Placing the reactor at a height such that \overline{GM} is positive but relatively small diminishes the ship's accelerations, possibly reducing the motions' influence on the reactor.

Cost Estimate

Capital expenditure (CAPEX) and operational expenditure (OPEX) costs of a fusion reactor are expected to change over time. The first fusion reactors will likely be significantly more expensive than later generations, the difference is estimated to be over a factor of 2 for small reactors (Lopes Cardozo, 2019; Lindley et al., 2023). Additionally, small, ARC-like reactors are estimated to be approximately 2.11 to 2.31 times relatively more expensive than larger, conventional fusion reactors (Lindley et al., 2023). Sorbom et al. have made an estimate for the CAPEX costs of ARC, which would lie at 428M USD for the materials, and a total fabrication cost of 5.56B USD. A nuclear fission reactor of a similar size would cost approximately 1.2B USD. The costs of building the Queen Mary 2 were approximately 780 million USD, in 2002 (Keck, 2003.). Thus, a fusion reactor of the size of ARC is approximately 7 times more expensive than the Queen Mary 2, while a fission reactor is only 1.5 times more expensive.

The operational costs are more difficult to estimate. Fuel costs are only a small part of the operational costs, estimated for a demonstration fusion reactor (DEMO2) to be 0.44 USD/MWh, only 1% of the total electricity cost (Entler et al., 2018). The total cost of electricity is estimated to be around 60 USD/MWh. The main part of the cost of electricity consists of the depreciation costs (57%), replaceable components (23%) and operation and maintenance (17%). The first of these costs, the depreciation costs, are likely to become much lower over time, as these are related to the CAPEX costs (Entler et al., 2018). To compare this with fission costs, the energy cost for a fission reactor is approximately 136 USD/MWh and is estimated to be around 99 USD/MWh in the future (Lindley et al., 2023). Thus, no overall cost estimate can be made due to the uncertainty of the operational costs. However, a nuclear fusion reactor's investment costs will be extremely high, both compared to fission reactors and to the overall cost of the ship in general.

DISCUSSION

Table 4 summarizes various aspects, data availability, and impacts of using fusion for ship propulsion from this research's design spiral. Drawing definitive conclusions based on the table is hindered by insufficient data for several aspects. Nevertheless, the available information highlights potential challenges with utilizing fusion as a ship's power source.

Two of the aspects were estimated to have a problematic influence on adding a fusion reactor as a power source on a ship. These aspects are matching the power supply and demand for the mission and owner requirements and the cost estimates. A fusion reactor will likely be too powerful and expensive for commercial ships. The influence on the arrangements and auxiliary systems, structural design and safety and damage cases all require additional data to estimate the influence of these aspects. Our first results show that the arrangements and auxiliary systems may not be problematic. Nothing can be said about the structural design and safety and damage cases with any certainty, as these aspects are too complex to estimate

Aspect	Availability Data	Estimated influence
Mission/Owner requirements	Sufficient	Problematic due to mismatch output power fusion reactor and required power ship
Arrangements/ Auxiliary systems	Insufficient	Not enough data, but does not seem to be problematic
Intact stability	Sufficient	Not a problem
Structural design	Insufficient	Adding a fusion reactor is likely to influence this Exact influence unclear
Powering	Sufficient	Additional power problematic, rest of system not a problem
Safety and damage cases	Insufficient	General safety too complex, more information required
Cost estimate	Sufficient	Likely too expensive for commercial application
Nuclear fusion power plant	Sufficient	Technology Readiness Level still too low for commercial application

Table 4: Summarizing table

their influence. The powering itself will, except for the large surplus of power, probably not form any large problems. Additionally, the fusion reactor can be placed in the ship without compromising the intact stability.

While this single iteration of the adjusted design spiral provided valuable insights, its scope is limited, and additional considerations are crucial. We highlight two such issues, acknowledging there are likely others to explore.

Constructing a vessel to meet specific power needs does not resolve the surplus power problem. An additional problem with fusion reactors is their constant power output, whereas conventional engines and fission reactors can adjust based on demand. Complex control systems with batteries or storage solutions are necessary to bridge this gap.

Additionally, current fusion reactor designs anticipate the need for regular significant maintenance activities. A component called the diverter, amongst others, has to be replaced every 2 years. As the diverter is in the centre of the reactor, this replacement process is believed to take 3 months. Maintenance will thus significantly influence the ship's operational time. This poses a major challenge for sectors that prioritize high availability, such as cruise ships and ocean liners.

CONCLUSION AND OUTLOOK

While nuclear fusion holds the potential to offer ships a virtually limitless energy source, its practical application remains distant. Despite this, this paper aims to identify specific challenges of implementing fusion technology on ships by exploring the influence of placing the fusion reactor ARC on the most powerful, commercial, available ship, the Queen Mary 2. Several factors have the potential to become critical roadblocks.

The minimum power output of an MCF fusion reactor, around 200 MWe, poses a challenge for its application in commercial shipping. While naval vessels may require such high power levels, current commercial ships operate at most with a maximum required power of about 120 MWe. This mismatch necessitates a significant increase in commercial shipping's power demands or the exploration of alternative applications for the surplus energy such as green fuel production. Additionally, a fusion reactor will likely require significant maintenance every two years, which poses a major challenge for

commercial ships focusing on high availabilities. Next to the power mismatch, deploying a fusion reactor on a ship introduces additional complexities. The influence of the ship's motions and vibrations on a fusion reactor is not trivial and could significantly influence the design and the working mechanisms of the fusion reactor. Researching these influences is crucial to determine potential mitigation strategies and the feasibility of a fusion reactor on a ship. Besides, placing a fusion reactor onboard a ship, a floating platform in the middle of the ocean, will result in safety and damage cases that have never been considered before. Because of the risks associated with nuclear materials, these safety and damage cases must be thoroughly addressed. The financial feasibility of a fusion reactor on a ship is a significant concern. A fusion reactor will be significantly more expensive than a fission reactor and additionally more expensive than the ship itself, as the estimated costs are 7 times more expensive than the Queen Mary 2.

Therefore, addressing these factors is crucial for fusion deployment onboard ships. Each of these factors may prove to be prohibitive to the use of fusion power on ships. While the idea of fusion on ships is captivating, its realization in the near (before 2100) future or with current technologies, appears unlikely. At least, these conclusions are true for 'conventional' fusion technology, i.e., those concepts based on magnetic confinement fusion (MCF). While more exotic, future fusion technologies might turn out to be the holy grail of ship propulsion, we believe it for the best that the nuclear fusion community should first vet such concepts.

With the current status of the technology behind nuclear fusion, using it as a power source on ships seems far-fetched. However, this research failed to present a single point of failure regarding the application of nuclear fusion onboard ships. Thus, only time will tell whether fusion will in the far future be used on ships.

CONTRIBUTION STATEMENT

E.S. van Rheenen: Conceptualization; methodology; investigation; writing – original draft; writing – review and editing; project administration. **J.P.K.W. Frankemölle:** Conceptualization; methodology; investigation; writing – original draft. **E.L. Scheffers:** Conceptualization; methodology; visualization; formal analysis; writing – original draft.

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