OULUN YLIOPISTO

FACULTY OF TECHNOLOGY

SMR TEHCHNOLOGY’S POTENTIAL FOR MERCHANT MARINE PROPULSION

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ENVIRONMENTAL ENGINEERING
Bachelor’s thesis
April 2023

ABSTRACT

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University of Oulu, Degree Programme of Environmental Engineering

Bachelor’s thesis 2023, 35 pp.

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Shipping accounts for about 2,9 % of global greenhouse gas emissions. Although the main objective of the sector has been to reduce emissions for years, in 2050 shipping could cause up to 17 % of global CO_2 emissions if no further action is taken. In 2018, the United Nation’s International Maritime Organization decided that the sector’s emissions must decrease by half by 2050 comparing to the 2008 level. The growth in emissions is due to the growth of economies and trade in developing countries, which leads to an increase in travelled distances.

90 % of world trade is transported by sea, and although shipping is the most environmentally friendly mode of transportation, the sector requires new fossil-free fuels to achieve their emission reduction goals. The aim of this work is to explore the potential of SMR technology as a source of commercial maritime propulsion. The work examines the current state of nuclear power and development of SMR technology. The paper also studies operating and former nuclear-powered ships.

The first nuclear-powered vessel was launched in 1955 and technology has been developed ever since. Due to the development of small modular and fourth generation reactors, nuclear power is much safer than it was 70 years ago. The work states that strict standardization and regulation of nuclear-powered ships makes it possible to make operating safe. The work also concluded that the operation of nuclear commercial ships would be technologically feasible, but there are considerable legislative problems and social acceptance challenges.

Keywords: SMR, nuclear power, marine transport

TIIVISTELMÄ

SMR TEKNOLOGIAN POTENTIAALI KAUPALLISESSA LAIVALIIKENTEESSÄ

Joonas Porela

Oulun yliopisto, Ympäristötekniikan tutkinto-ohjelma

Kandidaatintyö 2023, 35 s.

Työn ohjaaja yliopistolla: Antonio Caló

Merenkulku aiheuttaa noin 2,9 % maailman kasvihuonekaasupäästöistä. Vaikka alan keskeisimpänä tavoitteena on jo vuosia ollut päästöjen vähentäminen, vuonna 2050 merenkulku saattaa aiheuttaa jopa 17 % maailman hiilidioksidi päästöistä, jollei lisätoimiin ryhdytä. YK:n alainen merenkulkujärjestö IMO päätti vuonna 2018, että alan päästöjen on vähennyttävä puoleen verrattuna vuoden 2008 tasoon. Päästöjen kasvun syynä on kehittyvien maiden talouksien ja kaupankäynnin kasvu, joka johtaa myös maantieteellisten etäisyyksien kasvuun.

Maailmankaupasta 90 % kuljetetaan meritse ja vaikka merikuljetus onkin varsinkin suuria kuormia kuljetettaessa ympäristöystävällisin kuljetusmuoto, vaativat laivat uusia fossiilivapaita polttoaineita päästötavoitteiden saavuttamiseksi. Tämän työn tavoitteena on tutkia SMR teknologian potentiaalia kaupallisen merenkulun työntövoiman lähteenä. Työssä tutkitaan ydinvoiman ja SMR teknologian kehityksen nykytilaa sekä tutustaan entisiin ja nykyisiin ydinkäyttöisiin laivoihin.

Ensimmäinen ydinkäyttöinen alus otettiin käyttöön vuonna 1955 ja teknologiaa on kehitetty siitä lähtien. Pienten modulaaristen- ja neljännen sukupolven reaktoreiden kehityksen takia ydinvoima on huomattavasti turvallisempaa kuin 70 vuotta sitten. Työssä todettiin, että tiukalla standardisoinnilla ja säännöstelyllä ydinkäyttöisten laivojen operoinnista on mahdollista tehdä erittäin turvallista. Työssä johtopäätöksenä todettiin, että ydinkäyttöisten kaupallisten laivojen operointi olisi teknologisesti täysin mahdollista, mutta siihen liittyy huomattavia lainsäädännöllisiä ongelmia sekä ennakkoluuloja.

Asiasanat: SMR, ydinvoima, merenkulku

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BWR	Boiling Water Reactor
GHG	Greenhouse Gases
HFO	Heavy Fuel Oil
IAEA	International Atomic Energy Agency
IMO	International Maritime Organization
LOA	Length Overall
LOCA	Loss-Of-Coolant Accident
LWR	Light Water Reactor
MWe	Mega Watts of electricity
MWt	Mega Watts of thermal
NS	Nuclear Ship
PWR	Pressurized Water Reactor
SMR	Small Modular Reactor

1. INTRODUCTION

90 % of world's trade is shipped by sea. The total amount of transported cargo is rising all the time while developing countries' economies grow. Geographically travelled distances are also growing with even more intercontinental shipping required which increases the amount of shipped kilometres even more. Although sea transportation is the most environmentally friendly way of transporting big loads of cargo, it causes 2,89 % of world's greenhouse gas (GHG) emissions in 2018 (IMO, 2020). Even tough shipping is seen as the environmentally best option for cargo transportation, European Environment Agency (EEA) estimates in 2018 article, that shipping might cause 17 % of worlds CO_2 in the world in 2050. The percent rise is caused by other sectors decarbonising efforts and the increase in shipping (EEA, 2018).

Shipping relies on heavy fuel oil (HFO) because of its energy density. For example, world's biggest container ship, the 397 m long Emma Maersk consumes 14 000 litres of HFO per hour. This is a clear case that exemplifies the importance of developing an alternative carbon free marine propulsion power source technology, which is necessary as the industry moves forward with its longer-term decarbonisation efforts.

The International Maritime Organization (IMO) decided in 2018 to reduce emissions from marine transport. According to the decision, the absolute amount of GHG emissions must be reduced at least by half compared to the 2008 figures in 2050. It is necessary to reduce emissions by half, despite the increase in the volume of traffic (IMO 2018). Consequently, it is highly unlikely that new ocean-going vessels will be dependent on fossil fuels in 2030s as it is today. This means that the marine sector has under ten years to develop new carbon-free propulsion power sources. This thesis studies if nuclear power could be one of the solutions.

This thesis is a literature review work, which studies marine sectors emissions and the future goals. The thesis also studies the current status of small modular reactor (SMR) development and examines the possibility of utilizing SMR technology as a power source for commercial maritime propulsion. The review will study former commercial nuclear ships and currently in-use icebreakers and military vessels. Conclusions will be based on gained experienced from the case studies and from the studied technologies.

2. MARITIME TRANSPORT EMISSIONS

2.1 Global CO_2 emissions

Carbon dioxide emissions are the primary driving force of global climate change. CO_2 emissions from combustion of fossil fuels have increased since 1850. The rise has been especially rapid since the 1950s. In 2020 worlds CO_2 emission decrease was caused by COVID-19 pandemic as can be seen in figure 1. During the pandemic, international trade was marked by some of the largest reductions in trade and output volumes since World War II (OECD, 2022). The reduction in trade effected the global CO_2 emissions. Aviation's CO_2 emissions decreased by 75 % and surface transport emissions by 50 %. Also, power generation emissions were reduced by 15 % and industry sector emissions are estimated by ~35 %. A small increase, about 5 %, occurred in residential buildings CO_2 emissions (Global carbon project, 2021).

According to the Global carbon project's 2021 study, the biggest CO_2 reductions happened in transportation sector. While acknowledging aviation's big environmental effect, reduction in shipping had a large effect in total CO_2 emission reduction. Carbon free ships have similar CO_2 emissions than docked shut down ship. Consequently, decarbonising shipping would have comparable or even bigger effect in global CO_2 emissions than the pandemic's consequences. After the pandemic in 2021, global CO_2 emissions increased by 5,3% compared to 2020, reaching almost pre-pandemic numbers, as seen in figure 1.

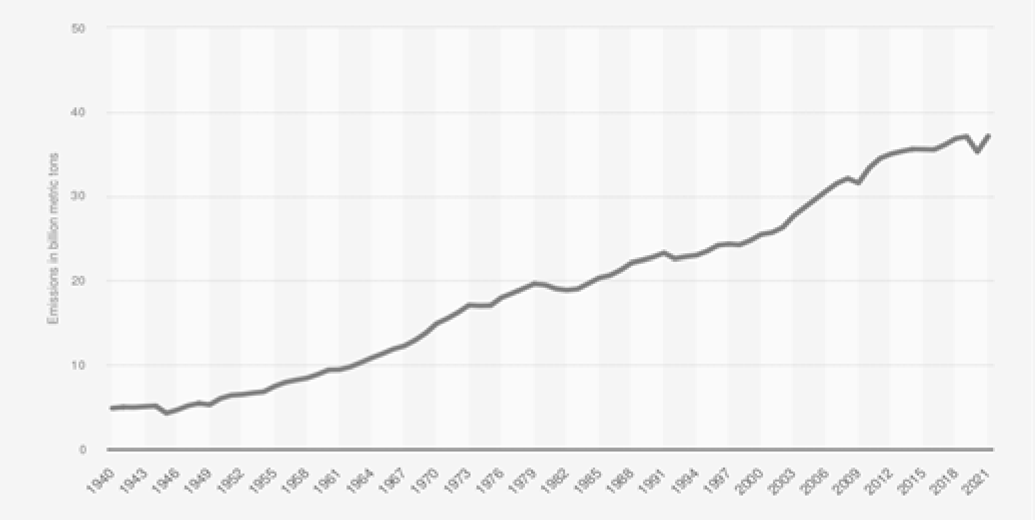


Figure 1. Annual global CO_2 emissions (statista.com).

Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 was lower than between 2000 and 2009 (IPCC 2022). That is the right direction, but more actions are needed to accomplish the 1,5 ºC global warming goal. Carbon-free fuels are expected to have a big role in achieving this goal, as the emission rise has occurred in all major sectors since 2010 globally.

According to the International Energy Agency (2022a), energy production causes the most energy-related CO_2 emissions with around 40 % of the total. As seen in the figure 2, combustion of coal is the biggest polluter. Transportation and industry sectors combined contribution represents 46 %, while the others fill up the rest 15% (IEA, 2022a). Most of transportation sector's emissions are from cars and trucks. Road transportation is used for both freight and passenger transportation. According to the International Energy Agency's (2022b) report, it caused about 75 % of transportation sector's CO_2 emissions in 2021. Aviation (~ 9 %) and shipping (~ 11 %) combined contribute for about one fifth of the total and the rest comes from rail and, for example, pipeline transportation Agency's (IEA, 2022b).

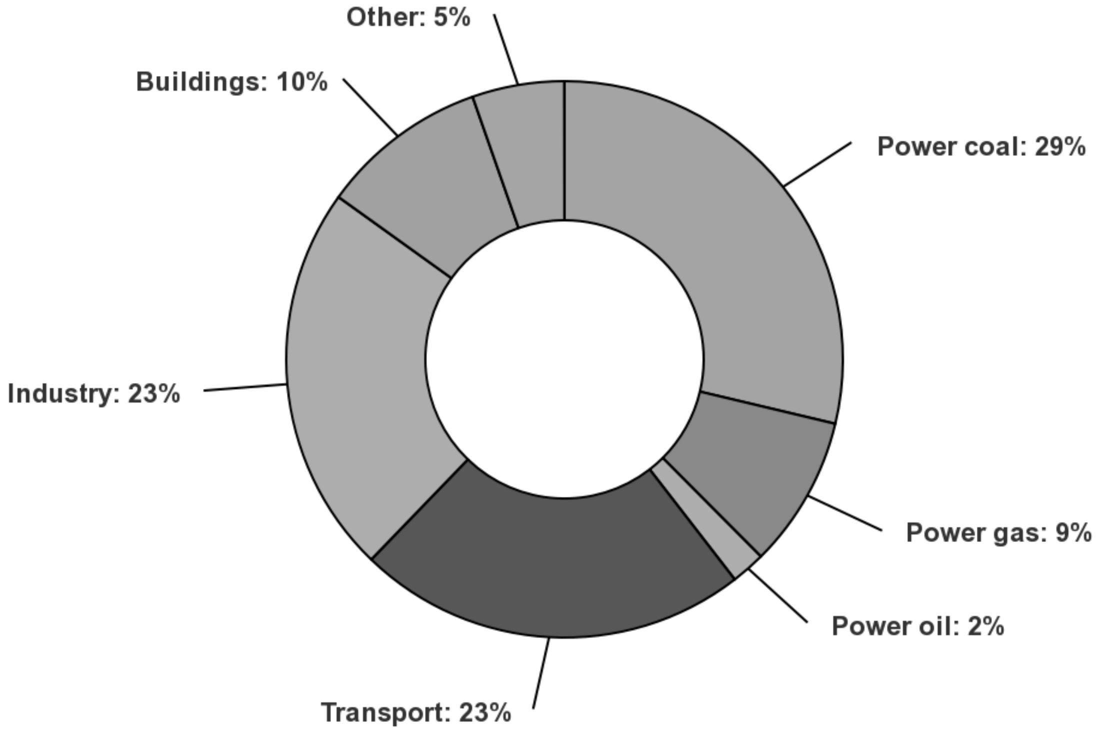


Figure 2. Global energy-related CO_2 emissions by sector (IEA, 2022a).

2.2 Marine emissions

Shipping is the environment friendliest mode of transportation especially when transporting cargo on large scale. According to IMO’s second greenhouse gas study (2009), big container ships produce about 3 g of CO_2 per tonne kilometre (gCO_2/tkm) of transferred cargo. In comparison, air freight ~ 435 gCO_2/tkm and truck ~ 80 gCO_2/tkm (IMO, 2009). Marine transportation’s advantage is that it can carry comparatively significantly larger cargos, which leads to smaller emissions per carried ton.

90 % of international trade is shipped through the seas and oceans, causing only about 2,9 % of all the world's CO_2 emissions in 2018 (IMO, 2020). In 2021 over 11 billion tons of both liquid and solid cargo was transported by sea (UNCTAD, 2022). Growing international trade means that the amount of shipping needed is going to get even bigger. According to the European Environment Agency (2018), by 2050, CO_2 from shipping could reach 17 % of global CO_2 emissions if no further action is taken.

Whole industry consumes 330 Mt of fuel in a year, with HFO, which is regarded to be a low-quality grade fuel, making up the majority of its energy supply with 77 % (Islam Rony et al., 2023). Despite of the relatively high efficiency of current propulsion systems, the use of HFO results in substantial high negative environmental consequences (Islam Rony et al., 2023). HFO is highly sulphurous and maritime transportation causes between 4 % and 9 % of world’s sulphur oxide emissions and between 14 % and 31 % of nitrogen oxide emissions (Gilbert et al., 2018).

2.3 Future goals

The IMO is the United Nation’s specialized agency which is responsible for regulating shipping. IMO decided in 2018 to cut emissions from marine transportation. According to the IMO’s 2018 climate agreement, GHG emissions from international maritime transport must be reduced by at least 50 % in 2050 comparing to 2008 levels (IMO, 2018). Reduction must happen despite the increase in traffic volumes. In the agreement, IMO also states that they have a strong emphasis on increasing the cut towards 100 % by 2050 if this can be shown to be possible. IMO will review the emission reduction strategy in 2023 in order to ensure that the agreed measures are on the way to a complete removal of GHG as soon as possible.

To be able to reach the IMO’s minimum goal (50 % GHG reduction by 2050), new propulsion technologies are needed. As stated before, modern propulsion systems have high efficiency, but zero-emission shipping requires new innovations and fuels. New power sources are already in use, such as liquefied natural gas (LNG), but it is not carbon-free. Some are under development, for example hydrogen, methane and even wind power might be making a comeback to shipping industry. However, this paper examines the low-carbon, high intensity fuel that has been used in shipping for a long time: nuclear power. For example, military ships and icebreakers have been using nuclear fuel for nearly 70 years. The first nuclear powered ship was the submarine USS Nautilus of The United States navy, which began operating in 1955.

3. FUNDAMENTALS OF NUCLEAR POWER AND SMR TECHNOLOGY

3.1 Nuclear Power

Nuclear power produces low-carbon energy for societies around the world. According to the International Atomic Energy Agency's (IAEA) database on nuclear reactors, there are currently 422 active nuclear power plants (IAEA a) in 32 different countries (IAEA b). Nuclear power provides about 10 % of world's electricity and the total amount of energy produced is expected to rise in the future. Also, social acceptance for nuclear is generally growing which is likely to lead to building of more power plants. Research on the safety of the reactors is further developing, improving reliability and helping to reassure that other large-scale disasters will not occur. This section reviews fundamentals of nuclear energy and research different SMR designs.

Nuclear power is a highly efficient mode of energy production, and it produces high amount of energy from small quantity of fuel. Nuclear power's energy comes from the nucleus of atoms. The release of energy is based on fission reaction, where the nucleus of the atom breaks down into two or more smaller nuclei. When the atom breaks down, a large amount of energy is released as heat. In addition to the release of thermal energy, neutrons are also released. The high-speed released neutrons collide with the new atom and breaks them, causing a fission chain reaction as seen in the figure 3.

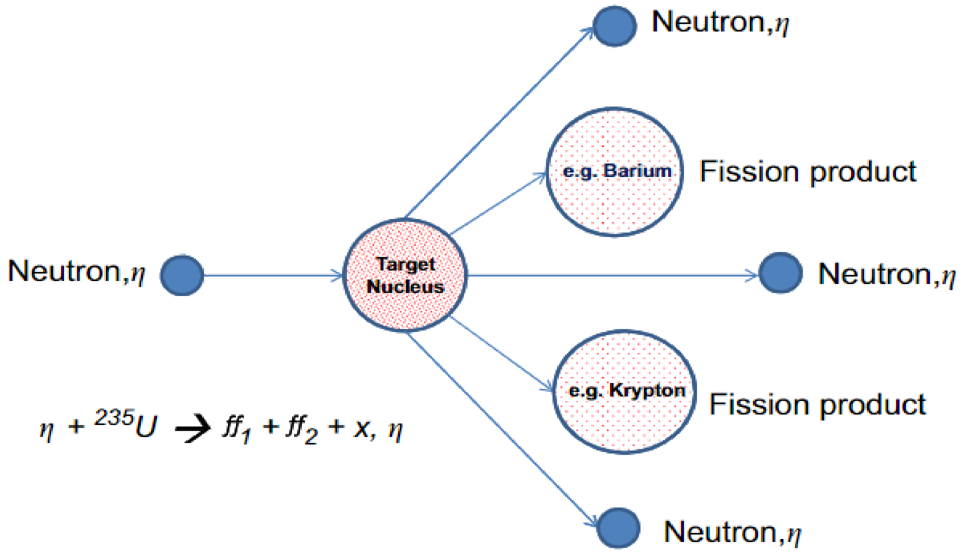


Figure 3. Basic nuclear fission reaction (Hirdaris et al., 2014).

Uranium is the most used fuel by nuclear reactors. Also, for example thorium can be used as nuclear fuel but this thesis studies only uranium fuelled nuclear reactors (World Nuclear Association, 2020). Uranium is a metal that can be found in rocks all over the world. In the nature, uranium exists in three isotopes: U-234, U-235 and U-238. Uranium-238 is the most common isotope and its relative abundance by weight is 99,28 %. Second is U-235 with abundance of 0,72 %, and U-234 with 0,0057 % (IAEA c).

Different isotopes have same chemical characterises, but they are physically different. U-235 is the only isotope to contribute to fission reaction (though U-238 does so indirectly but it is not part of this thesis). The fuel used in light water reactors (LWR), which is the most used reactor type, usually contain about 3-5 % of U-235 (World Nuclear Association, 2022). Because of this, mined uranium must be enriched to meet the required percentage. Enrichment process utilizes the mass difference which is caused by the difference of three neutrons between U-235 and U-238.

Enriched uranium is converted to uranium dioxide powder at fuel fabrication plant. The powder is pressed and heated to create a hard ceramic material called fuel pellet. Fuel rods are made of pellets which are inserted into tubes. Rods are then grouped together to from fuel assemblies which contains from around 90 to over 200 fuel rods depending on reactor type (World Nuclear Association a).

In conventional nuclear power plants, fuel assemblies are inserted in the reactor core where they produce carbon-free energy for a several years. In the core are also neutron-absorbing control rods which are often made of boron. Control rods have the task of controlling the fission chain reaction and preventing it from accelerating. A chain reaction would be free to accelerate if each U-235 fission reaction caused the breakdown of more than one U-235 core. Control rods allow the chain reaction to continue steadily, with the additional neutrons being absorbed by the boron, so that only one new fission reaction on average is caused by the decomposition of one uranium core (Breeze, 2019).

The reactor also has neutron moderator which usually is water. The moderator is designed to slow the neutrons down so that they have increased probability of hitting a uranium atom. Without moderator, nuclear chain reaction is not possible. The water used as moderator is recycled and therefore the reactor remains in a stable condition (Breeze, 2019).

This thesis does not study particle physics any deeper and instead examines pressurized water reactor's (PWR) fundamentals. PWR is a type of LWR, and it is the most common nuclear reactor type with 65,3 % of world's active nuclear reactors being this type at the end of 2017 (Breeze, 2019). In pressurized water reactor, the primary coolant water does not boil, unlike in boiling water reactors (BWR) which are the second most used reactor type (16,8 %). PWR's primary coolant, which goes through the reactor core (see figure 4), is used to transfers the created heat energy to the secondary cycle. Secondary cycle's water boils in the steam generator and turns into super-heated steam. The primary and secondary cycle's waters do not make direct contact with each other in the steam generator but are driven close in heat exchanger. According to U.S. Nuclear Regulatory Commission (U.S.NRC) (2020), a steam generator can contain anywhere between 3000 and 16000 tubes.

The produced steam is driven through the turbine and condensed back to liquid with the usage of coolant which is often pumped from nearby water. In Olkiluoto 3's case the coolant water comes from the Baltic Sea. Steam spins the turbine that converts the heat created in the reactor core to mechanical energy which is turned into electricity in the generator.

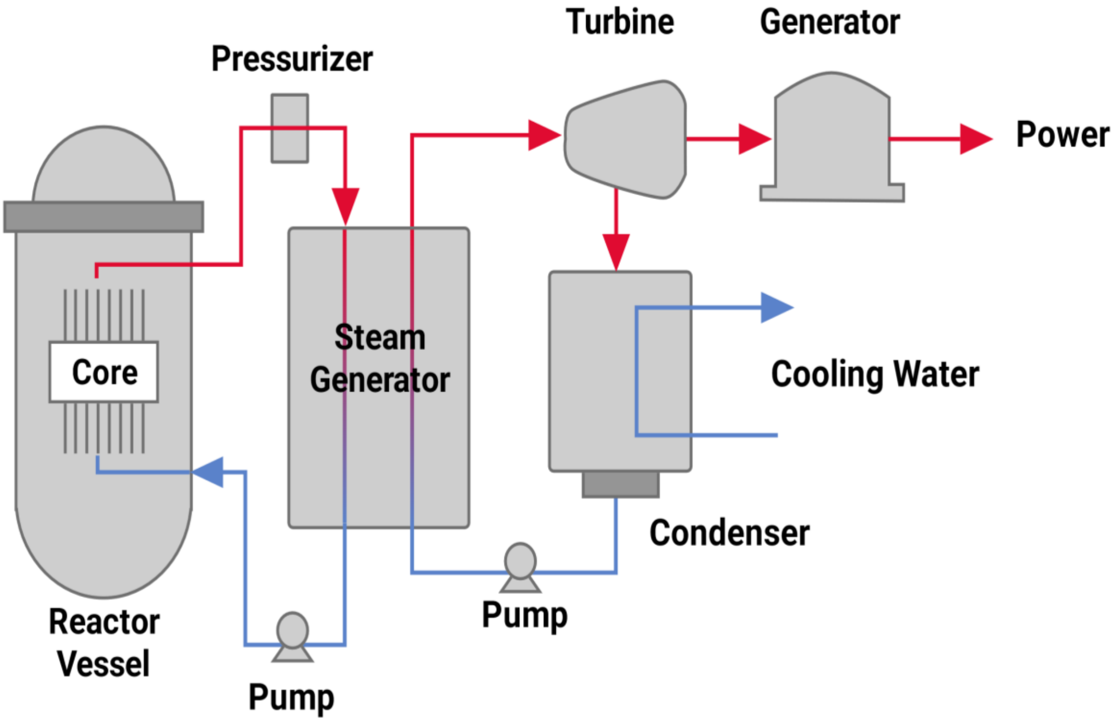


Figure 4. Pressurized-Water Reactor (Atomicarchive.com).

3.2 Small Modular Nuclear Reactors

3.2.1 Definition

Small modular nuclear reactors are defined by their size and modularity. Reactor's size can mean both reactors power rating and physical size because they usually grow at the same rate. SMR's have a power range from 10 to 300 MWe (Todreas, 2021) while big conventional nuclear reactors can reach as high as 1700 MWe but usually have power capacity of around 1000 MWe. SMR's power rating range have been selected so, that minimum value produces power suitable for the practical industrial application of interest. Maximum value puts the reactors to power rating to level where serial production has the most advantage. On these power ratings also electric grid opportunities can be realized (Todreas, 2021). SMRs small size could be beneficial in providing electric power to remote areas that are deficient in transmission and distribution infrastructures. Them could be also used to generate local power for larger population centres (Vujić et al., 2012).

Modularity refers to the unit which includes the reactor core and primary systems. The unit can be assembled from one or several submodules and the wanted plant can be created from one or many units depending what power rating is required (Todreas, 2021). The biggest advantage of modularity arises from the fact that the units are built at factories and then transported to the construction site. This will significantly quicken the construction of the power plant and reduce the likelihood of delays. Modularity also reduces the amount of the initial investments, and the risk decreases significantly. As well as the initial costs that are lower, also the operating and maintenance costs are low (Vujić et al., 2012).

3.2.2 SMR types

According to Vujic et al. (2012) there are three major categories of SMR designs which are actively being developed. The first group bases on proven LWR technology, which includes previously mentioned PWRs and BWRs. The second group consist of gas-cooled reactors and the third group includes SMRs that are cooled either by liquid salt or liquid metal. The gas used as coolant in group two reactors is chosen to be helium, but carbon dioxide is also used in advanced gas reactors in UK (Todreas, 2021). Liquid metal coolants are sodium, lead and lead-bismuth.

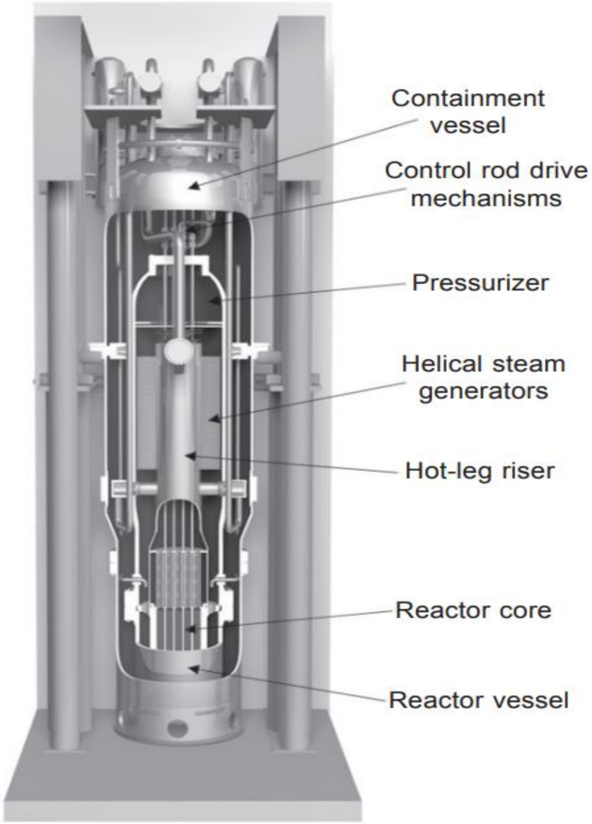
This paper will review SMRs that use LWR technology more in detail than the other two groups because the technology used in large conventional LWR plants can be quickly converted to SMRs. LWR's also have privilege in licensing processes because technology is better known (Rowinski et al., 2015). During the so-called atomic age in 1950 – 1970, three nuclear powered commercial vessels were built and one more in 1988 (Todreas, 2021). They all had LWRs which could have been classified as SMRs as power source. Also, military vessels, submarines and icebreakers were built in the 1960s especially in the USA and USSR. Most of these had LWR designs of different type as well and so does military ships which are built today. There will be more case studies included in chapter 4.

Light water cooled SMRs have similar concepts than LWR nuclear power plants. For example, PWR SMRs have two water cycles: primary and secondary. Primary cycle's coolant is pressurized water (up to 13 MPa) (Fakhrarei et al., 2021) so it does not boil. Primary cycle cools the reactor core and transfers the heat to secondary cycle which water boils. Secondary cycle's superheated steam spins the turbines and afterwards is cooled back to liquid. The process is similar than in conventional plants but in smaller scale. Many countries are developing their own SMR designs but right now most notable might be the U.S. based NuScale's SMR design.

3.2.3 NuScale SMR design

According to Ingersoll (2021) the NuScale reactor is being developed by NuScale Power LLC which was formed in 2007 whit a plan to commercialize the SMR design. NuScale's modules are designed to produce 50 MWe or 160 MWt (Ingersoll, 2021). Modules can be built together to form a plant which can accommodate up to 12 modules. According to NuScale's own web page, plant that consists of 12 reactors, could produce 924 MWe, which means each module generates 77 MWe. The NuScale's reactor became the first SMR to ever get certified by The U.S.NRC, with the agreement to build reactors in Idaho in 2029-2030. NuScale received their certification 21.2.2023 (Federal Register, 2023).

NuScale's SMR is a LWR, which uses naturally circulated water as a primary coolant. Natural circulation is a heat transfer process which is driven by the difference of the densities under the force of gravity (Ahmed et al., 2020). It does not require any pumps or outside force to work and because of that it is called a passive system.



Key parameters	
Electrical capacity:	50 MWe
Thermal capacity:	160 MWt
Configuration:	Integral
Primary coolant:	Light water
Primary circulation:	Natural
Outlet temperature:	300 °C
RV diameter/height:	2.9 m/17.4 m
Steam generator:	Helical (2)
Power conversion:	Indirect Rankine
Fuel (enrichment):	UO_2 (< 5%)
Reactivity control:	Rods, soluble boron
Refueling cycle:	24 months
Design life:	60 years
Status:	Preliminary/detailed design

Figure 5. NuScale SMR design (Ingersoll, 2021).

As seen in the figure 5, the reactor core is located at the bottom of 17.4 m high reactor vessel. Fission reaction in the core heats the primary cycle's water, which raises up in the hot-leg riser because hot water is less dense than cold. After delivering its energy to the secondary cycle in steam generator (Figure 5 and figure 6), primary water is turned back downwards. Colder water flows downwards naturally in downcomer (figure 6) until it's direction switches again at the bottom reactor vessel (Ingersoll et. al. 2014).

The secondary cycle is not passive, but the water is pumped into the steam generator. Water enters the vessel from feedwater (figure 6), and it is turned to super-heated steam in steam generator. Steam flows out of the vessel from main steam (figure 6) to turbine-generator or it is used to heat the district heating system. Low pressure steam exiting the turbine is condensed and recirculated to the feedwater system (Ingersoll et. al. 2014).

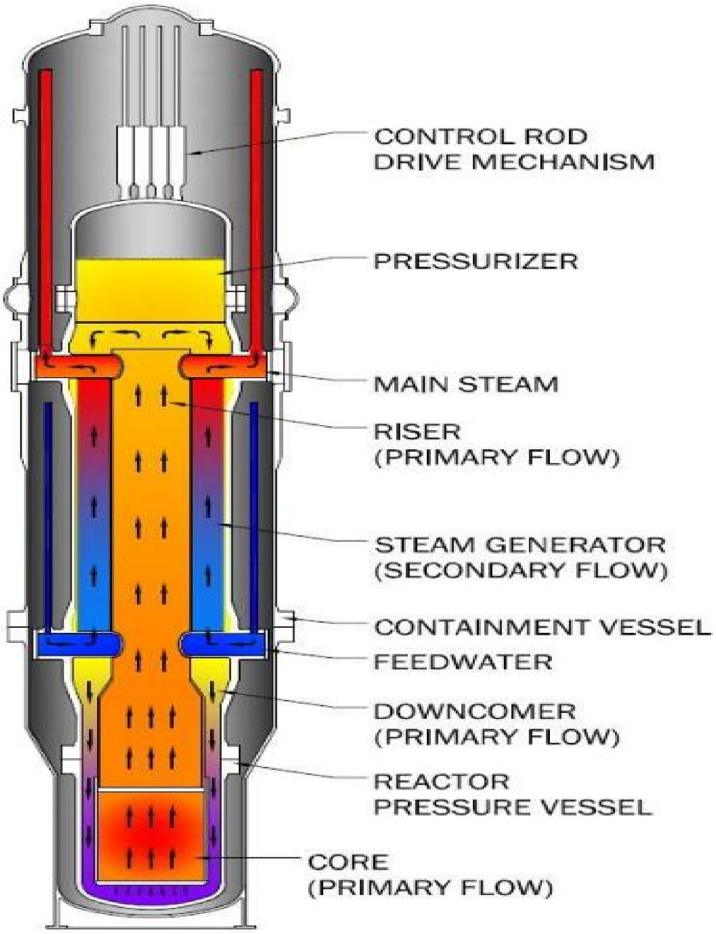


Figure 6. Schematic of the NuScale SMR (Ingersoll et. al. 2014).

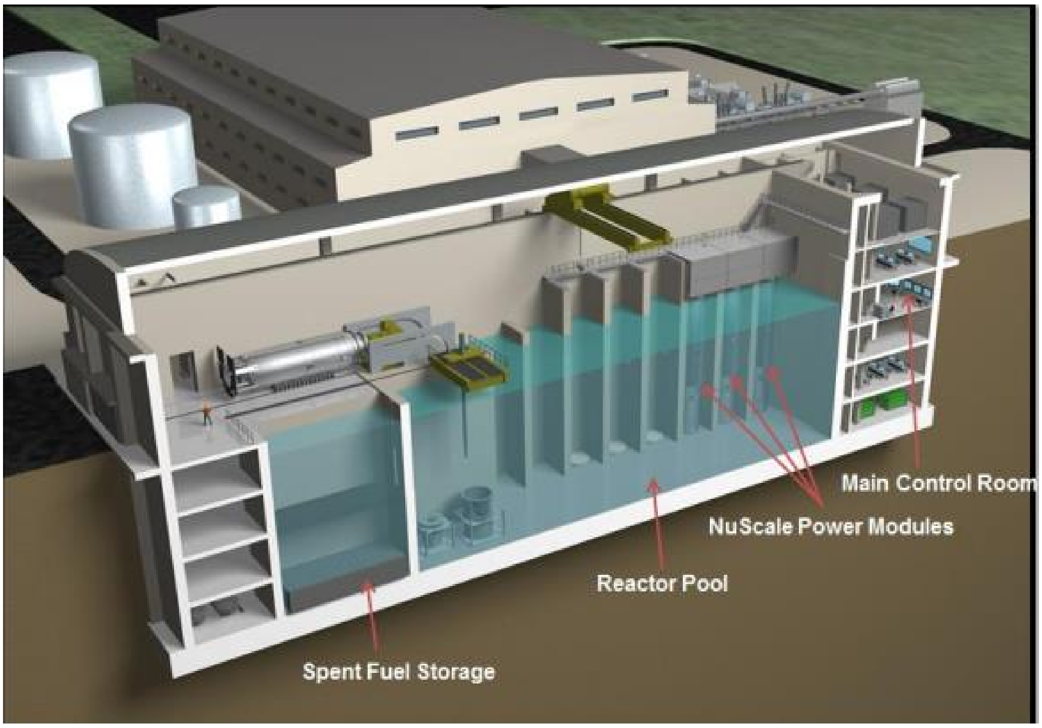


Figure 7. NuScale reactor building (Ingersoll et. al. 2014).

NuScale’s SMR power plant could consists of up to twelve modules which are placed inside reactor building capable of resisting an direct hit from aircraft (Ingersoll et. al. 2014). As seen in figure 7, each module is located below a ground level pool. The pool provides passive safety, containment cooling and decay heat removal. According to Ingersoll et. al. 2014, the pool provides an assured heat sink with a capacity to absorb all the decay heat produced by up to 12 fully mature cores for greater than 30 days, after which air cooling of the vessel is sufficient to avoid fuel damage.

As mentioned in 3.2.2 LWR type SMRs were used as power source in commercial vessels already in 1960s. According to Gravina et al. (2013), since the first nuclear submarine there have been about 700 (mainly military) nuclear powered vessels operating at sea and around 200 reactors were still in use in 2013. Now that SMR technology is advanced and more studied, it would be counterintuitive not to consider its possibilities in merchant marine again. Especially considering IMO’s goals to reduce emissions, where nuclear power could be potential answer. Next chapter studies cases where nuclear propulsion was/is used. This paper will not consider the laws and regulations which are required to fully commercialize SMR marine, but it acknowledges its necessity and importance.

4. CASE STUDY

4.1 Commercially used nuclear powered ships

This paragraph examines all four commercially used nuclear ships (NS) built and operated in history. The aim is to study the technology and gained experience. The four commercial nuclear ships are: NS Otto Hahn, NS Savannah, NS Sevmorput and NS Mutsu. First three will be studied more in detail, because they had longer operation periods. NS Mutsu will be studied as well but not in so detailed fashion.

4.1.1 Nuclear Ship Otto Hahn

NS Otto Hahn was built in 1968 in West Germany. She was designed to be an ore carrier cargo ship while also being used in research purposes at the same time. The primary research purpose was to gain experience for future nuclear ships. The reactor was decommissioned in 1979 after sailing 650 000 nautical miles on 126 voyages (Freire & Andrade, 2015; Hirdaris et al., 2014). In 1979 nuclear reactor was removed and replaced with a diesel engine after the research purpose was fulfilled and it became too expensive to operate (Hirdaris et al., 2021). The ship was finally scrapped in 2009. According to Schøyen and Steger-Jensen (2017), it experienced few technical difficulties, but not with the reactor. Bigger issue was that she did not receive sufficient clearances to enter ports and could not passage Suez Canal because of permission issues.

The ship had length overall (LOA) of 172 m and was 23,4 m wide (Schøyen & Steger-Jensen, 2017). Propulsion power for the ship was provided by a 38 MWt PWR which gave 8 MW to the propeller (Schøyen & Steger-Jensen, 2017). The reactor had similar principles than NuScale's SMR, but they were pretty far from each other as seen in figure 8. NS Otto Hahn reactor's primary cycle does not have natural circulation as NuScale's SMR does. Instead, the reactor had primary circulation pumps cycling the primary coolant water. Also, its secondary cycles coolant water runs differently inside the reactor vessel.

Sedondary cycle (figure 9) tranfers the energy to the propeller as a steam generated in the steam generator. The steam runs through turbine admission valve before entering the turbines which are connected to gearbox. After spinning the turbines and tranfering energy to proppeler, the steam is condensed back to liquid utilizing sea water. Liguid water is then pumped through heater and back to the reactor (Freire & Andrade, 2015).

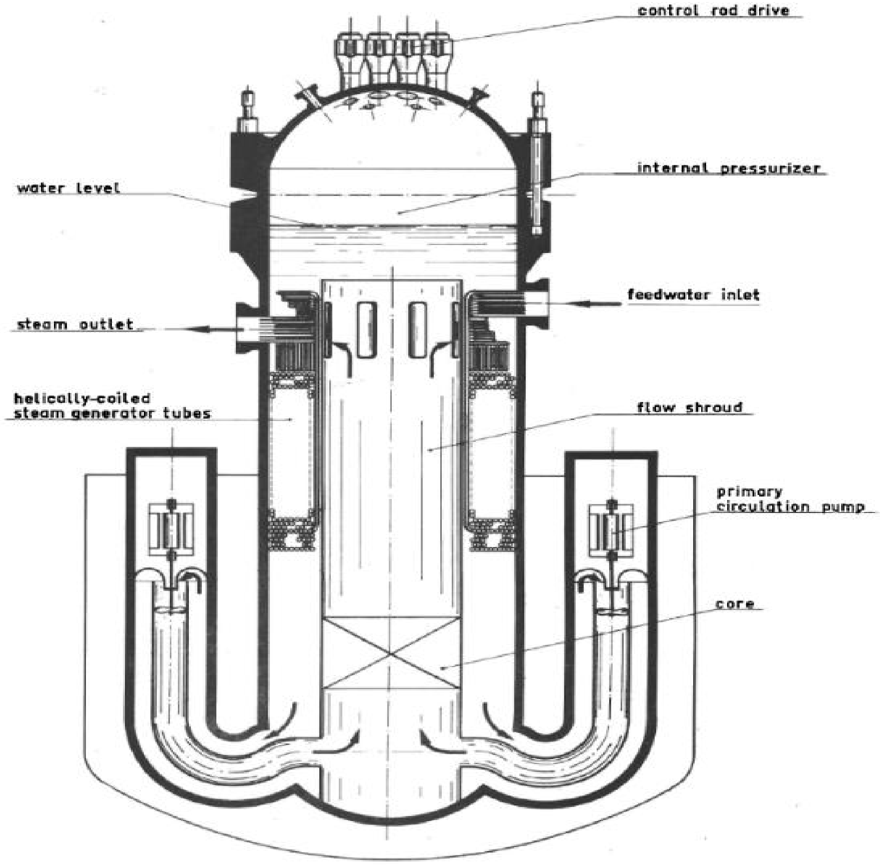


Figure 8. NS Otto Hahn’s primary loop (Freire & Andrade, 2015).

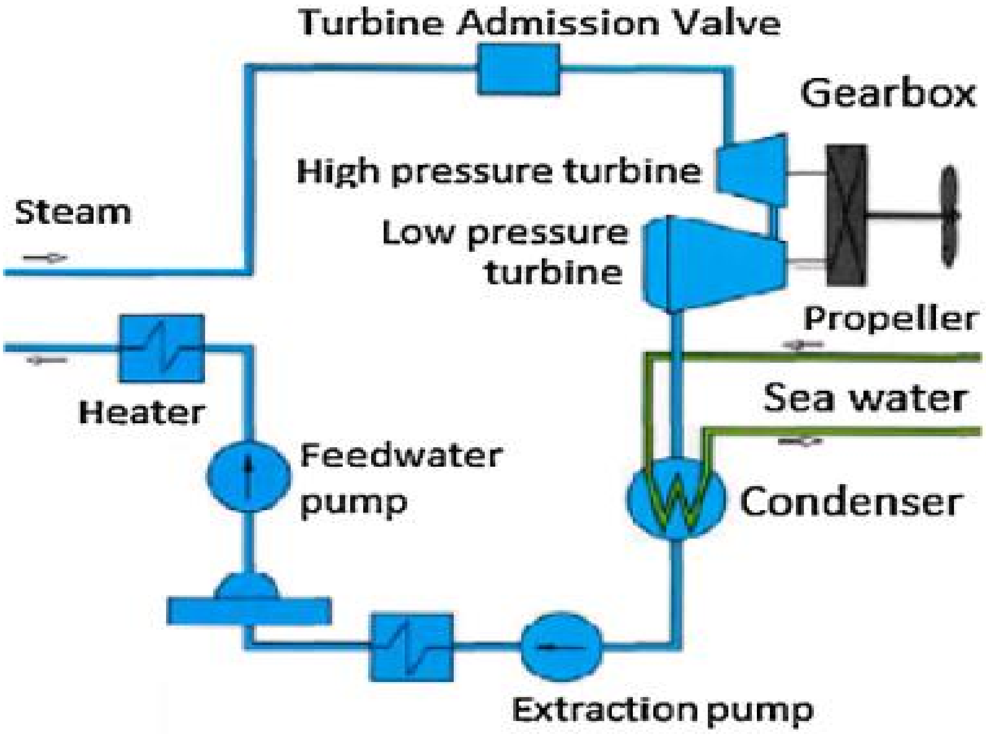


Figure 9. NS Otto Hahn’s secondary loop (Freire & Andrade, 2015).

4.1.2 Nuclear Ship Savannah

NS Savannah was the world's first commercially used nuclear powered ship. She was built in 1962 in U.S. and operated for ten years until 1972. NS Savannah was part of President Eisenhower's 'Atoms for peace' program which goal was to convince people of nuclear power's civilian possibilities. The ship was cargo and passenger combination with a capacity to carry 10 000 t of cargo and 60 passengers (Freire & Andrade, 2015). During the ten operating years NS Savannah travelled 450 000 nautical miles and was refuelled once. She visited ports in 29 countries but was denied access to Australia, New Zealand and Japan (Schøyen & Steger-Jensen, 2017). Technically NS Savannah was a success, but economically it was not: during a five-year period, she earned 12 million dollars and spent 90 million (Hirdaris et al., 2014; Freire & Andrade, 2015).

NS Savannah weighted 22 000 t, compared to NS Otto Hahn (15 000 t), she was clearly heavier. Savannah's LOA was 181,5 m and width 23,8 m. The used PWR had power capacity of 80 MWt and it gave 16 MW to the propeller (Hirdaris et al., 2014; Freire & Andrade, 2015). The nuclear containment system, which included the reactor, steam generators, primary and part of the secondary loop, was a cylinder with a 10,67 m diameter and 15,24 m height. It was made of 10 cm thick carbon steel. The reactor vessel itself was smaller and covered in more safety layers. When comparing this reactor to the NuScale SMR, the technological development that have happened in 60 years is clearly noticeable. Biggest differences are shown in table 1. As it is seen the size is many times smaller, but the power generated with same enrichment of uranium is double in NuScale's reactor.

Table 1. Differences between NuScale SMR and NS Savannah's reactor.

Parameter	**NuScale SMR**	**NS Savannah reactor**
Power Capacity	160 MWt	80 MWt
Reactor Vessel Height	17,4 m	15,24 m
Reactor Vessel Diameter	2,9 m	10,67 m
Uranium Enrichment	4,95 % of U-235	4-5 % of U-235

4.1.3 Nuclear Ship Sevmorput

NS Sevmorput is a still active Russian icebreaker and cargo ship which has operated since 1988 (Schøyen & Steger-Jensen, 2017). The ship operates in Russian arctic in Northern Sea route which is a lifeline for many Arctic settlements. The Northern Sea route have been in regular use since the second world war, and it connects Russia's Atlantic and Pacific ports as well as Arctic regions of Siberia to Murmansk. The route is open from ice between June and November but requires heavy fleet of icebreakers and ice class cargo ships rest of the year (Freire & Andrade, 2015). Icebreakers will be studied more in paragraph 4.2.

The most notable difference between NS Sevmorput and the two already mentioned ships is that NS Sevmorput uses 90 % enriched uranium as its fuel while in example NS Savannah had uranium enrichment percent between 4 and 5 depending on the fuel assembly (Freire & Andrade, 2015). The ship is 260 m long, and it is equipped with KLT-40 PWR which has a power level of 135 MWt (Reistad & Ølgaard, 2006) and it gives 29,4 MW propulsion power to the propeller (Schøyen & Steger-Jensen, 2017). The propulsion power is bigger when comparing to NS Otto Hahn (8 MW) and NS Savannah (16 MW). The reason for NS Sevmorput's great propulsion power is the icebreaking capability which needs a lot of force. She is also heavier as 33 900 t which helps with icebreaking (Hirdaris et al., 2014).

NS Sevmorput have not faced any major technical incidents during its operating years but have caused protests from the public. The ship's access was denied entering four major ports in far east Soviet Union in post-Chernobyl era. NS Sevmorput is today transferring cargo in remote Siberian icy waters (Schøyen & Steger-Jensen, 2017).

4.1.4 Nuclear Ship Mutsu

NS Mutsu was Japanese Atomic Energy Institute's prototype of nuclear commercial cargo ship (Schøyen & Steger-Jensen, 2017). She was built in 1972 but started her testing in 1974 after big protests from Japanese fishermen. During the testing period, while attaining 1,4 % of full power, fast neutron radiation was escaping the nuclear shielding (Freire & Andrade, 2015). The radiation leak was reported by the media as "Nuclear powered ship Mutsu leaked radioactivity". The already concerned fishing industry and local community denied the ships return to the port. NS Mutsu was removed from service in 1995 because of technical, commercial and most importantly political pressure (Hirdaris et al., 2014). The neutron leak was caused by lack of experience on shielding design (Freire & Andrade, 2015).

4.2 Icebreakers

According to Hidaris et. al. (2014), nuclear propulsion has been proven technically and economically essential to the Russian Arctic. There are two challenges of icebreaking on the North Sea route. First challenge is the thickness of ice which can be up to 3 metres. The second is refuelling difficulty which is caused by the lack of infrastructure in northern Russia. Icebreaking is an energy intensive process and icebreakers need a high propulsion power to be able to break the ice. Thus, nuclear power is utilized in Russian arctic which is heavily dependent of the sea transport. Nuclear ships don't have to be refuelled often and in example NS Sevmorput has an operating period of 10 000 effective hours (Freire & Andrade, 2015) which is around 416 days if operated 24 hours daily.

4.2.1 Icebreaker Lenin

The USSR icebreaker Lenin was the world's first nuclear-powered surface vessel which started operating 1959 and was in service for 30 years. The ship had LOA of 134 metres and weighted approximately 19000 t. When launched, Lenin had three OK-150 PWRs with power output of 90 MWt each. The three reactors were replaced in 1970 by two 159 MWt OK-900 PWRs following an accident. The accident suffered was a loss-of-coolant accident (LOCA) in one of its OK-150 reactor in 1966 during re-fuelling (Reistad & Ølgaard, 2006).

The United States Nuclear Regulatory Commission defines LOCAs as follows. An accident in which a breach in a reactor's pressure boundary causes the coolant water to rush out of the reactor faster than makeup water can be added back in. Without sufficient coolant, the reactor core could heat up and potentially melt the zirconium fuel cladding, causing a major release of radioactivity (U.S.NRC, 2023)

In icebreaker Lenin's case LOCA happened just after the reactor was shut down for re-fuelling. Primary loops coolant water drained from the core, and it was left without cooling. The heat generated in the core melted or deformed part of the fuel elements. The core consisted of 219 fuel channels and each of which contained 36 (189 channels) or 30 fuel rods (30 channels). That makes total of 7704 fuel rods in each of three reactors. Following the LOCA, only 94 of the 219 channels could be removed normally and the rest were removed by removing the "basket" with damaged fuel (Reistad & Ølgaard, 2006).

Lenin's OK-150 reactor's primary loop is presented in figure 10. It is notable that NuScale SMR have double power output capacity when comparing to OK-150 with around similar U-235 enrichment (Reistad & Ølgaard, 2006).

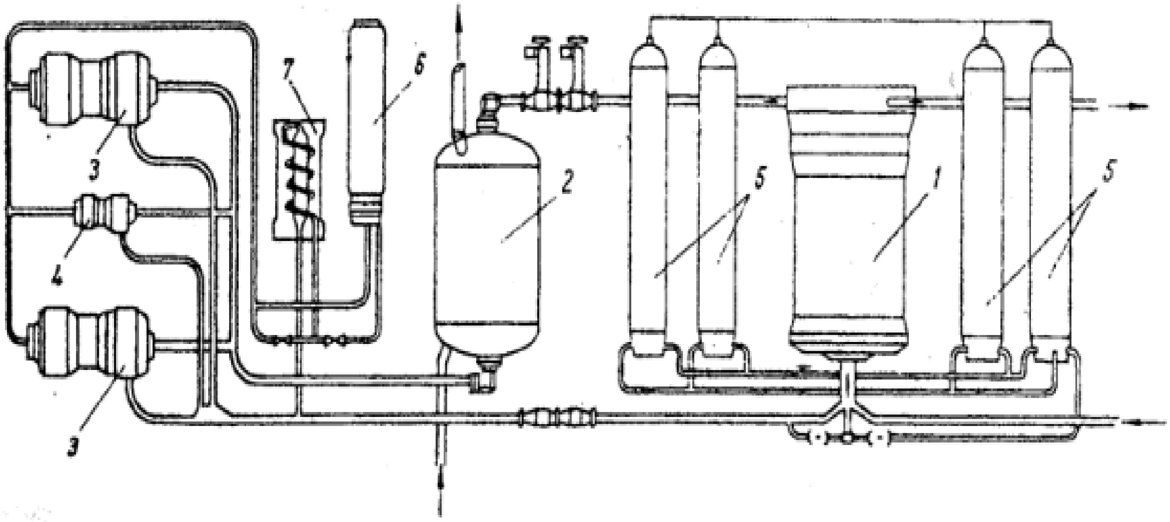


Figure 10. Primary loop of Lenin's OK-150 reactor (Reistad & Ølgaard, 2006).

1. *Reactor*
2. *Steam generator*
3. *Main circulation pumps*
4. *Emergency pump*
5. *Pressurizers*
6. *Filter*
7. *Filter cooler*

In the primary loop, pressurized waters enter the reactor from the bottom and that is where the loss-of-coolant happened (Reistad & Ølgaard, 2006). Pressurized hot water is then taken to the steam generator from the top of the reactor. Secondary loop's water enters the steam generator from the bottom as liquid and exits as steam from the top (presented with arrows).

Lenin's propulsion technology differed from the commercially used ships. As seen in figure 9, NS Otto Hahn's secondary loop's steam spins the turbines which are connected straight to the gearbox. Icebreaker Lenin used turbines to generate electricity in generators which delivered 34 MW propulsion power to the propellers (after reactor update) (Hirdaris et al., 2014). Lenin's four times stronger propulsion power when comparing to NS Otto Hahn is necessary for icebreaking capability. Despite having over four times more propulsion power, it had twice lower efficiency which are compared in table 2. Efficiencies are calculated by comparing only the reactor(s) output and propulsion power. As seen in the table, using electricity to generate propulsion lowers the efficiency but it might have other benefits, but it is not part of this thesis.

Table 2. Efficiencies comparison.

	Reactor Output	**Propulsion Power**	**Efficiency**
Icebreaker Lenin	2*159 = 318 MWt	34 MW	0,11
NS Otto Hahn	38 MWt	8 MW	0,21
NS Savannah	80 MWt	16 MW	0,2
NS Sevmorput	135 MWt	29,4 MW	0,2

4.2.2 Icebreaker Arctica

Russia have been developing its nuclear icebreaker fleet since the deployment of the icebreaker Lenin. The most recent class of icebreakers is project 22220 class which includes six ships of which three are launched (Naval news, 2022). The Arctica was the first and was commissioned in September 2020 after seven years of testing (Naval news, 2020). According to Ship Technology's (2015) article, the Arctica was the world's biggest and most powerful icebreaker when launched.

The ship has a LOA of 173 m, width of 34 m and weight of 33500t. The ship has two RITM-200 reactors with power capacity of 175 MWt in each. Reactors produce a total of 60 MW propulsion capacity for the icebreaker. Similar to icebreaker Lenin, Arctica generates electricity with turbo-generators and uses electric propulsion systems. Arctica's efficiency can be calculated to be 0,17. Therefore it is clear that there has been progress made regarding generators and propulsion systems.

RITM-200 is a PWR, and it is being used for the first time in icebreaker Arctica. It is a fourth reactor used by Russia in its civil fleet. The previous three, in order were OK-150, OK-900 and KLT-40, all of which have been discussed already. OK-150 in icebreaker Lenin, OK-900 in Lenin after the upgrade and KLT-40 in NS Sevmorput.

The reactor is very similar when comparing to NuScale's SMR as can be seen in figure 11. It has the primary cooling loop inside the reactor vessel just like in NuScale's design. The reactor uses 20% enriched U-235 and has 7-year refuelling cycle (Savitsky & Kuzmin, 2021). Russia have been planning a floating nuclear power plant which could be a solution to provide electricity to rural arias. The plant has been planned to have two modified RITM-200M reactors onboard which could produce 100 MWe in total (Balyeav et. al. 2019).

Figure 11. RITM-200 reactor (Savitsky & Kuzmin, 2021).

4.3 Military use

Nuclear power has been widely used by militaries around the world. According to world nuclear association's (2021) article, navies of 6 countries have nuclear powered vessels. The countries are US, UK, Russia, China, France and India. Russia and the US have had most with Russia having built 248 nuclear submarines and five surface vessels (plus nine icebreakers) between 1950 and 2003. The US have built 219 nuclear-powered vessels to mid-2010s. Today all of US's submarines and aircraft carriers are nuclear powered. As seen, most of nuclear-powered ships in the world are submarines because they have biggest advantages of being nuclear-powered. This paper will not discuss submarine technology because it is beyond of the considered topic. Anyway, researching about the technology used by militaries is difficult and therefore this paragraph focusses more about the gained experience and statistics.

4.3.1 Safety

United States navy have excellent safety record with its nuclear ships. According to World Nuclear Association (2021), they have accumulated over 6200 reactor-years without a single radiological incident. During the operating years, 526 nuclear reactors have sailed over 240 million km. The safety is a great example of what can be achieved with great research, standardisation, regulation and high quality of training. All which could be vital for commercializing nuclear power in marine sector. Russia, on the other hand, have logged over 6500 reactor-years by 2015. However, during Soviet Union's early endeavours, there were several accidents. Five cases where the reactor was irreparably damaged and more resulting in radiation leaks. From the third generation of Russian marine PWRs in 1970s onward, the safety and reliability became the priority.

All of US's nuclear-powered ships are equipped with PWRs. As previously noted, PWR technology is the most used and the most experienced with. Also, PWRs fit marine use because the coolant water is available all the time. The reactors are designed to survive wartime attack and to protect the crew against hazards. According to Japanese Ministry for Foreign Affairs (2006) report, US's nuclear ships have at least four barriers keeping radioactivity inside the ship even in highly unlike event of reactor incident. The defence in depths is studied because the same technologies could be utilized in commercial marine use. These barriers are the fuel itself, the all-welded reactor primary system, the reactor compartment, and the ship's hull.

The fuel used by US navy is solid metal and it is designed to withstand shock loads greater than 50 times the force of gravity without leaking fission products. The primary system, which includes the reactor core and the primary coolant loop, is located inside a thick metal barrier. The component is welded to match the high standards and constitutes a single structure which keeps pressurized high temperature water within the system. Reactor compartment is the third barrier used to keep radioactivity inside the ship in case of an accident. The reactor compartment would hold any release of primary systems coolant water or pressure leakage. The ship's hull is designed to withstand battle damage and the reactor compartments are located in the central and most protected section of the ship (Japanese Ministry of Foreign Affairs, 2006).

4.3.2 Gained Experience

During the 6200 reactor-years (World Nuclear Association 2021), the US navy have collected data, for example, about the personnel radiation exposure and reactor operation. The four barriers mentioned previously have shielded radioactivity so effectively that a typical crew member receives less radiation than a normal person would from background radiation in the US. This is due to the shielding within the ship and the fact that when deployed, the crew is absence from earth radiation which is most notably from radon. According to the United States Environmental Protection Agency (2023), the average annual radiation dose in the US is 6,2 millisieverts (mSv). In comparison, annual average since 1980 for ship crew is 0,44 mSv. The average has been in on a downward trend and since 2004 the average has been 0,38 mSv (Japanese Ministry of Foreign Affairs).

According to Japanese Ministry of Foreign Affairs, nuclear ship's reactors are shut down after docking into the port at least in Japan's case. That is due to the fact that reactors power level is primarily set by propulsion needs. Ship's other electricity needs are also powered by the reactors but only require a small amount of power compared to propulsion. When in port (Japanese ports) the electricity required for ship's services is provided from shore power supplies where power is available. This factor reduces accident risk even more and the article states that the amount of radioactivity potentially available for release from a US nuclear ship docked in a port is less than about one percent of that for a typical commercial reactor.

If shore power is not available, it is possible for ship to operate its reactor during its time in port. It is technically possible for a ship to produce electricity for port's and shore's need. This is not utilized because of for example the electricity and reactor owning difficulties. In the case of non-available shore power for the ship, its reactor would have to operate on almost minimal power. US aircraft carrier's reactors average power level during the life of the ship is less than 15 % of full power (Japanese Ministry of Foreign Affairs). That taken into consideration, if propulsion power is not needed, the power required would be a fraction of full power.

5. DISCUSSION AND CONCLUSIONS

The safety of the crew, environment and civilians must be the priority when designing a nuclear-powered commercial ship. Even though nuclear power is gaining atomic age-like popularity, with developments in SMRs and fourth generation technology, it still divides public's opinion. Nuclear accidents like Chernobyl, Three Mile Island and Fukushima are one of the main reasons for those opposed opinions (Pedraza, 2013). Despite the fact that nuclear technology is far more advanced and safer than in 1970-1980s many ports and canals would still deny access of nuclear-powered ship. It is also worth considering the fact, that for example nuclear accident in Suez Canal would prevent the usage of the canal for a long time. That would have enormous effect on whole shipping industry. There are also a lot of legislative problems with nuclear ships that need to be resolved before vessels can be launched. This paper does further elaborate on these problems as it deliberately focuses on technical aspects and possibilities.

The above-mentioned problems include, for example, the question of responsibility in case of an accident in a foreign port or in international waters. In view of these considerations, commercial nuclear ships would operate in a legally simpler framework if it would sail only between ports of the same country. A good example of this is the Russian icebreakers on the Arctic Sea route. For example, the United States could use nuclear cargo ships on its long coastlines from the Gulf of Mexico to the northeast coast or along the West Coast. Also transport between two countries and two specific ports alone, such as the Atlantic or the Pacific passing routes, could also be feasible. For example, from the US to Netherlands or to Japan. It can be found almost impossible to operate a randomly worldwide sailing nuclear cargo ship.

When taking IMO's 2018 climate decision into consideration, shipping needs new power sources. As discussed in section 2.3, the decision states that gCO_2/tkm emissions must be reduced by half in 2050 when comparing to 2008 levels. Nuclear power does not produce any CO_2 emissions and could be one of the answers. According to The Guardian's (2008) article, world's largest containership Emma Maersk burns 350 tonnes of HFO a day and emits around 300 000 tonnes of CO_2 in a year. Converting the biggest freighters to nuclear ships would benefit the IMO's goal the most. Biggest ships transfer most cargo and that's why it would lower the gCO_2/tkm the most.

According to Ship Technology (2021), the 397 m long and 56 m wide Emma Maersk's world's largest diesel motor produces maximum of 108 920 hp. That is equivalent to about 81 MWs which is used in the upcoming calculations. Theoretically NS Emma Maersk would need two and a half NuScale SMR units if the efficiency is set to be around the 0,2 range which it was (around) in the case studies when the turbines were connected straight to gearbox.

$$\text{Required NuScale SMR units} = \frac{81\ \text{MW}}{0{,}2 * 160\ \text{MW}} = 2{,}53 \qquad (1)$$

Assuming that technology have developed in 50 years so that efficiency has increased. Two NuScale SMR would be enough to produce 81 MW of propulsion power if efficiency could reach 0,25 as shown in the formula 2.

$$\text{Efficiency required} = \frac{81\ \text{MW}}{2 * 160\ \text{MW}} = 0{,}25 \qquad (2)$$

According to IAEA report (2013), NuScale's entire reactor system is closed in a steel containment that is 24,6 metres tall and 4,6 metres in diameter. It can be pictured as 4,6*4,6*24,6 m rectangular prism. Two SMRs next to each other would be around 9,2*4,6*24,6 m with a volume of around 1041 m^3. In comparison Emma Maersk's Wärtsilä-Sulzer RTA96-C engine is 26,5 m long and 13,5 m high. Therefor SMRs could be easily usable as propulsion source when comparing the sizes.

In conclusion the technology to build and operate a nuclear-powered cargo ship is available and has been for over 50 years. When considering fourth generation and SMR technology, statistics suggest it is a significantly safer technology than in the 60s and 70s when the few freighters were built. In example NuScale's passive safety feature is great showing of safety development. Also, SMRs are safer than conventional big nuclear power plants because of their smaller pressures and temperatures.

Biggest issues concerning nuclear ship development would still be the publics opinion and social acceptance, which leads down the road to companies' resistance to research and develop nuclear ships. This thesis studied technology which could be usable for nuclear shipping. Next topics that should be studied is the legislative side of nuclear-powered ships and how it could be modified to make nuclear shipping possible. Also ship and infrastructure designs and safety features should be studied.

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