# DESIGN AND SAFETY ANALYSIS OF A NAVAL REACTOR FOR NUCLEAR POWERED SHIP

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I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis. The thesis (fully or partially) has not been submitted for any degree or diploma in any university or institute previously.”

Muhaamad Monirul Hoaque Juwel
April 17, 2022

# ABSTRACT

The development of alternate sources of propulsion power is necessary because of the increasing demand for electricity, environmental concerns, the strain on fossil fuels, as well as pollution prevention and carbon emission control. Hence, in order to optimize propulsion power, it is decided in this study aims to present a nuclear naval small modular reactor in an existing merchant ship. The main idea is to reconsider whether nuclear propulsion is appropriate for merchant ships. Finally, the operational economics of nuclear ships have been compared to those of diesel ships. After a comparison of the available nuclear reactors, the KLT-40S small modular reactor is chosen due to its smaller size, lower power, and higher safety standards. Criticality analysis of the MONK simulation findings indicates that the KLT-40S reactor core is capable of operating for a 10-year period without refueling. The crews' necessary safety needs have been the subject of safety analysis, and additional safety measures for the marine nuclear environment have been recommended. Based on Rad Pro simulations, a plausible shield's safety design is proposed. In this study, it is found that a reactor shield made of 100 cm of polyethylene and 30 cm of lead worked better than steel at limiting radiation rates to 1 mSv/h. A performance evaluation tools model, which permits comparison of the nuclear commercial ship to a ship fueled by diesel, is used to examine the economic viability of the vessel. Finally, it can be concluded that, even with conservative assumptions about a high fuel price and capital cost, a nuclear-powered ship is a workable substitute for a diesel ship throughout the course of the ship's lifetime.

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# List of Acronyms

| **Abbreviation** | **Elaboration** |
|---|---|
| AGR | Advanced Gas Cooled Reactor |
| ALARA | As Low As Reasonably Achievable |
| BAR | Burnable Absorber Rod |
| BWR | Boiling-water Reactors |
| CAD | Computer Aided Design |
| CANDU | CANadian DeUterium PWR |
| CF | Container Feeder |
| DWT or dwt | Dead Weight Ton |
| ECCS | Emergency Core Cooling System |
| EES | Engineering Equation Solver |
| EHRS | Emergency Heat Removal System |
| EI&C | Electrical Instrumentation and Control |
| EM | Emma Maersk |
| EOL | End of Life |
| eV | Electron Volts |
| FG | Fractal Geometry |
| GA | General Atomics |
| GHG | Greenhouse Gases |
| GNEP | Global Nuclear Energy Partnership |
| GT | Gross Tonnage |
| HFO | Heavy Fuel Oil |
| HPC | High-pressure compressor |
| HSE | Health and Safety Executive |
| HTGR | High Temperature Gas-cooled Reactor |
| HTTR | High Temperature Thermal Reactor |
| HVAC | Heating, Ventilation and Air-conditioning |
| HVL | Half-Value Layer |
| IAEA | International Atomic Energy Agency |

| | |
|---|---|
| IMO | International Maritime Organization |
| IPWR | Integral Pressurized Water Reactor |
| LASH | Lighter Aboard Ship |
| LEU | Low Enriched Uranium |
| LMR | Liquid Metal Reactor/ Liquid Metal-Cooled Reactor |
| LOCA | Loss of Coolant Accident |
| LPC | Low-pressure Compressor |
| LWR | Light Water Reactor |
| MeV | Mega Electron Volts |
| MHTGR | Modular High-Temperature Gas-Cooled Reactor |
| MSR | Molten Salt Reactor |
| MWe | Mega Watts electrical |
| MWt | Mega Watts thermal |
| NDA | Nuclear Decommissioning Authority |
| NEA | Nuclear Energy Agency |
| NEI | Nuclear Energy Institute |
| NPP | Nuclear Power Plant |
| NS | Nuclear Ship |
| OTTO | Once Through Then Out |
| PBMR | Pebble Bead Modular Reactor |
| PBR | Pebblebed Gas Cooled Reactor |
| PCI | Pellet Cladding Interaction |
| PKA | Primary Knock-On |
| PR | Proliferation Resistance |
| PV | Present Value |
| PWR | Pressurised Water Reactor |
| SMR | Small Modular Reactors |

# List of Main Notation

| **Symbol** | **Definition** |
|---|---|
| °C | Degree Celsius |
| A | Area $[m^2]$ or Atomic Mass number |
| b | Reflector thickness |
| CF | Resistance coefficient |
| D | Diameter [m] |
| Dk | Hydraulic diameter |

# CHAPTER 1: INTRODUCTION

## 1.1 Background of the Thesis

This thesis investigated the operability of employing nuclear energy propulsion in merchant ships as an alternative to diesel fuel engines. Shipping is a key part of global trade with a highly competitive market that is constantly looking for flexibility and efficiency improvements in order to increase profits. In the commercial sector, there is currently no comparative alternative to diesel fuel and costs are likely to rise as demand for crude oil increases (Webster, 2007). Also, $CO_2$ emissions have increased 90% since 1960 and are predicted to continue in this manner unless alternative energy sources are developed and implemented. Although shipping only contributed to a small amount of these emissions, approximately 6%, an increase in the size of the world fleet was also predicted. By 2060, emissions from the world fleet are predicted to increase by 300% (IMO, 2020) and since the Kyoto protocol in 1997, industrialised countries have implemented taxes and financial constraints on these emissions in all sectors in order to encourage 'greener' energy. Therefore, the shipping sector faces losses in profits unless alternative propulsion technology can be implemented safely economically (Verfondern, 2001).

Nuclear powered ships were not a new concept; many naval forces currently employ nuclear powered submarines, aircraft carriers and icebreakers. However, the concept of nuclear powered ships being used as a profitable industry in the application of a ship is relatively unexplored. There have been a small number of nuclear powered ships in the past which were reasonably unsuccessful. To assess the achievability of a nuclear powered ship the analysis was broken down into smaller design and analysis segments.

A suitable naval reactor was selected using a systematic approach after an assessment of all the available designs. This will then allow the reactor physics calculations to be carried out as well as providing the framework for shielding calculations to be made in the future. The reactor environment can be harsh on the materials in use which means an assessment on the types of material used is crucial. Due to the public sensitivity of nuclear technology, other safety issues for different aspects of the ship life will be assessed specific to marine-use such as proximity to crew in order to provide good defense of the proposal in the future (Munton, 1966). There must also be a discussion of the global acceptance of nuclear shipping since the proposal must be accepted by ports and also the general public. Eventually the feasibility of a nuclear powered ship will depend on its industry potential and profitability compared to conventional fuels therefore a detailed analysis of the possible economic constraints on this thesis will occur. Due to the secretive nature of both the nuclear industry and military development, there are limitations on the amount of specific information that can be found on several topics. This means that this feasibility analysis was merely an initial step in defending the use of nuclear naval reactor in shipping applications and for this technology to be implemented in the future, more detailed work will be done in the future by interested parties.

## 1.2 Significance of the Thesis

The environment around nuclear merchant ship had changed significantly over the last few years. In present society, merchant shipping is essential to the global economy. The interaction between the major world economies has developed a complex system of international import and export, which has made regional economies and specialties dependent on the global oil, gas or coal extraction and overseas electronic goods production and so on. As a result of international market development and sea transport expediency, 95% of the goods of worlds are transported by maritime (Carlton, 2019). Figure 1.1 represented the continuous growth of world container shipping with small perturbations due to political and economic issues. These tendencies were predicted to continue in the future. This extreme growth in the shipping industry leads to the question of whether the current technology (oil, diesel tankers) was suitable for future global fleets. (Thamm, 1970). The main causes of the difficulties in future maritime development were the increasing fuel costs, regulations of environmental announced to alleviate the effects of climate change and the possible address of carbon taxes.

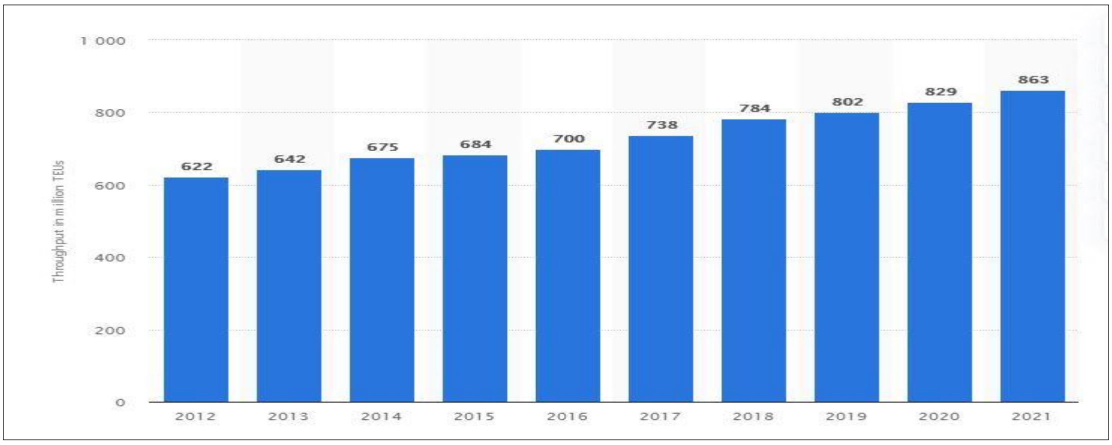


**Figure 1. 1: Container throughput worldwide from 2012 to 2021 (in million TEUs) (https://www.statista.com/statistics/913398/container-throughput-worldwide/)**

## 1.3 Objectives of the Thesis

A conceptual design and safety analysis is to show through simplified engineering analysis that a nuclear naval reactor can be commissioned to propel a merchant ship. To achieve this specific aim, this research embarks on the following objectives:

(1) To modify the design of a nuclear small modular reactor to suit a merchant ship.

(2) To analyze the safety of the selected reactor for use in a nuclear powered ship.

(3) To evaluate the operational cost of the nuclear powered ship compared to the diesel powered ship through the Performance Evaluation Tools (PET) model.

## 1.4 Problem Statement

The altering factors in the technological, environmental and economic areas seem to signpost a need to reconsider nuclear propulsion for maritime shipping. Nuclear reactors have many prospective benefits over diesel engines, such as:

a. low cost fuel over the life

b. zero or less carbon emissions

c. high energy density fuel and

d. long periods without refuelling.

## 1.5 Motivation of the Thesis

The Generation III initiative is a worldwide attempt to establish a paradigm of nuclear technology. If the goals of this initiative can be accomplished, it is anticipated that many new nuclear applications will become feasible. Most of these goals are achievable with technology that is available today. Light Water Reactor (LWR) designs, such as the marine based small modular reactors (PWR) that is currently under development, incorporate these technologies. Generation III/ III+ reactors enhance the following advantages: Passive safety features, Resistance against proliferation of hazardous nuclear substantial and Simplified operation and maintenance.

## 1.5 Structure of the Thesis

Chapter 1: Introduction- In this chapter, some basic information of nuclear powered ship discussed and also listed down objectives of this thesis.

Chapter 2: Literature Review- In this chapter, some literatures related to the research were mentioned and written as a summary.

Chapter 3: Methodology (Methods & Materials)- Explained the methodology in details and the key issues in implementation for design and safety analysis of a nuclear naval reactor for nuclear powered merchant ship. Discussed the specific ship that was identified for the research, as well as stating the basic assumptions and preliminary design considerations of the various types of nuclear reactors that were made during the research.

Chapter 4: Reactor Design Analysis: Reactor was selected as well as justification of the selected design and technical details of the reactor ware assessed in this chapter.

Chapter 5: Simulations Results and Observations- This chapter is the heart of the thesis. Based on the simulations results, addressed tabulated outcomes of the significance of the research. Besides, brief observations on the design and safely analysis of the nuclear powered ship ware detected.

Chapter 6: Discussion on Results and Relevance (Performance Evaluation)- In this section, the results were briefly explained and nuclear ship compares with diesel ship through Performance Evaluation Tools (PET).

Chapter 7: Conclusions and Recommendations- Finally, drawn conclusions from the research. Also identified the few areas for future works.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Synopsis

About 160 ships worldwide are powered by more than 200 small nuclear reactors, and more than 12000 reactor years of marine operation have been collected, according to the United States General Accounting Office 2021. This looks to be a low-risk, well-understood topic that should apply to marine shipping. The practice of nuclear marine propulsion is integrated into naval ships. Nuclear propulsion, which uses the nuclear fission process, is a highly complex system made up of water reactors and other tools for supplying fuel to the ship. The ship's naval reactor was also utilized to generate electricity.

Four merchant nuclear ships were built, such as the American Savannah; the German Otto Hahn; the Russian Sevmorput and the Japanese Mutsu. Table 2.1 contains relevant details of these ships (WNA, 2021), and (Wikipedia, 2021).

**Table 2. 1: Characteristics of Merchant Nuclear Ship**

| | NS Savannah (J. G. Wirt 1979) | Otto Hahn (Neumann, H. and Deutschen S. 2009) | Sevmorput (Lange, R. S. 1990) | Japanese Mutsu (Wikipedia 2021) |
|---|---|---|---|---|
| Comment | The ship was decommissioned after only eight years. It was a technical success, but not economically viable. This was to some extent due to low oil cost, a large specialized crew and expensive one-of-a-kind maintenance requirements. | 126 trips totaling 1200 000 km were made in ten years without any mechanical issues. But it turned out to be too expensive to run, so diesel Engine was added. | Ice-breaker and cargo carrier. World's first nuclear-powered oil-drilling vessel. Still in operation. Reactor pressure vessel is 4.6m high and 1.8m in diameter, enclosing a core 1m high and 1.2m in diameter. | Several technical and political problems resulted in an embarrassing failure. Never carried any commercial cargo. |

| | **NS Savannah (J. G. Wirt 1979)** | **Otto Hahn (Neumann, H. and Deutschen S. 2009)** | **Sevmorput (Lange, R. S. 1990)** | **Japanese Mutsu (Wikipedia 2021)** |
|---|---|---|---|---|
| Purpose | Bulk carrier | Ore carrier | Containership | Test ship |
| Start build | 1959 | 1963 | 1982 | +/-1968 |
| Start Date | 1961 | 1968 | 1988 | 1991 |
| End Date | 1971 | 1979 | Present | 1996 |
| Displacement | 21800 | 25790 | 33980 | 8242 |
| Length [m] | 182 | 164 | 260 | 130 |
| Beam[m] | 23.8 | 23.4 | 32.2 | 19 |
| Draught[m] | 8.8 | 5.3 | 11.8 | 6.9 |
| Fuel | Low Enriched Uranium (4.2-4.6%) | Low Enriched Uranium (3.5-6.6%) | High enriched Uranium (90%) | Low Enriched Uranium (3.7-4.4%) |
| Reactor Power [MWt] | 74 | 36 | 135 | 36 |
| Propulsion Power[MW] | 16.4 | 8 | 32.5 | 8 |
| Design Speed [knots] | 21 | 15.75 | 20 | 17 |
| Top speed | 24 | 17 | 20.8 | 18.3 |

Nuclear propulsion had been shown to be both technically and economically feasible for nuclear-powered icebreakers, according to Moskvitch (2012). Ships powered by nuclear energy can operate for years without refilling, and they have strong engines that are perfect for breaking through ice. In spite of two nuclear incidents, the Russian icebreaker Lenin served as the first nuclear-powered surface vessel for 30 years. Due to improved power and refueling advantages, nuclear ships have increased navigation in this area from 2 to 10 months each year. These vessels appear to fall between between military and commercial vessels. (Sarkisov2003)

## 2.2 Nuclear Reactor

Goldberg and Rosner (2011) has defined numerous designs of nuclear reactors as shown in Table 2.2. Based on generations, the reactor designs are categorized dived into 4 generations as follows:

Generation 1 designs were the prototypes,

Generation 2 designs were consequent from the prototypes and were produced for commercial purpose.

Generation 3 designs are the better-quality commercial designs created on Generation 2 designs.

Generation 4 designs are the newest upgraded innovative designs followed on Generation 3 designs. Intrinsically there is no experience with Generation 4 reactors. As a consequence of the above mentioned generations, these types of reactor will not be measured for maritime applications in this thesis.

Glasstone, S. and Sesonske, A. 2013 analyzed above 68% of the world's nuclear reactors are Pressurised Water Reactors. These form the fuel rods in a PWR and are sandwiched between carbon control rods inside a fuel container made of zirconium alloy. High pressure water is used to cool and moderate the reactor, which is housed in a steel pressure vessel to prevent boiling. To boil water at lower pressure and create steam, high pressure water is forced through a heat exchanger. A concrete radiation screen encloses the steam production and pressure vessel. The thermal efficiency of PWR is 33%.

Trianti, 2014 was examined A light water reactor known as the BWR has been produced since the 1950s. The fuel assembly consists of rods made of the fissionable substance. Regular water serves as the moderator and is directly connected to the fuel assembly. The steam generated is used to power a turbine that generates energy. In a condenser, the water is cooled before being re-fed into the reactor. The Canadian Nuclear power generation technology produced the pressurized heavy water reactor (PHWR) that was recommended by Chatterjee in 2017. It actually functions similarly to a PWR, but instead of utilizing regular water as a moderator, it uses deuterium (heavy water), allowing it to run on uranium that is naturally occurring without enriching it.

Advanced Gas-Cooled Reactors, according to Forsberg, 2019, are an advance over the Magnox design. To maximize thermal efficiency and power density, AGRs operate at higher temperatures than Magnox reactors (gas temperatures of up to 650 °C). To do this, it was necessary to raise the cooling gas pressure, switch the cladding material to stainless steel, and use pellets of uranium dioxide (UO2) instead of natural uranium metal as fuel. Similar to Magnox reactors, AGRs use concrete pressure vessels, radiation shields, and graphite moderators. According to Thompson (1977), AGRs have a thermal efficiency of roughly 42% and modern reactors in the United Kingdom produce between 1110 MW and 1250 MW.

According to Ade, 2021, the Magnox design is exclusive to the United Kingdom and is among the earliest commercial reactors. In order to cool the fuel pins and transfer the heat to the steam generator, a graphite moderator is used. The natural uranium metal used to make the fuel components is stored in Magnox cans. The reactor is named Magnox, a magnesium alloy created with corrosion resistance in mind. In a core made of graphite blocks and other vertical channels filled with drawable carbon rods that can absorb neutrons and so control the reaction, the fuel elements are loaded vertically. A concrete radiation shield and steel pressure vessel were utilized in earlier designs, while a concrete pressure vessel and shield were employed in subsequent versions. Magnox reactors have a thermal efficiency of 31% and run at a temperature of around 400 °C. The peak electrical output of power plants based on this architecture ranged from 200 MW to 950 MW.

RBMK 2019 analyzed the main Light water graphite reactor (LWGR) design is the RBMK, a Soviet design, developed from plutonium production reactors. The principle is nearly similar to in a BWR, moderator as a graphite and steam is created at 291°C. The main dissimilarity in LWGR is that the water is moving through graphite channels instead of open fuel assembly.

Kumar, 2022 and Chetal, 2006 mark outed the fast Breeder reactor strains fissile isotopes and was mostly used to produce fresh fissile products like as Plutonium. Energy is moreover created as in heat. The reactor employed fast neutrons to create new fissile material.

**Table 2. 2: Summery of different types of nuclear reactors**

| **Reactor type** | **Main countries** | **Number** | **GWe** | **Fuel** | **Coolant** | **Moderator** |
|---|---|---|---|---|---|---|
| Pressurised water reactor (PWR) | US, France, Japan, Russia, China | 302 | 287 | enriched $UO_2$ | water | water |
| Boiling water reactor (BWR) | US, Japan, Sweden | 63 | 64.1 | enriched $UO_2$ | water | water |
| Pressurised heavy water reactor (PHWR) | Canada, India | 49 | 24.5 | natural $UO_2$ | heavy water | heavy water |
| Gas-cooled reactor (AGR & Magnox) | UK | 14 | 7.7 | natural U (metal), | $CO_2$ | graphite |

| Reactor type | Main countries | Number | GWe | Fuel | Coolant | Moderator |
|---|---|---|---|---|---|---|
| | | | | enriched $UO_2$ | | |
| Light water graphite reactor (RBMK & EGP) | Russia | 12 | 8.4 | enriched $UO_2$ | water | graphite |
| Fast neutron reactor (FBR) | Russia | 2 | 1.4 | $PuO_2$ and $UO_2$ | liquid sodium | none |
| | TOTAL | 442 | 393 | | | |

Sources: WNA data, 2021.

## 2.3 Small Modular Reactor (SMR)

The The International Atomic Energy Agency (IAEA) defines an SMR as a reactor with an equivalent electrical power of less than 300MWe (WNA, May, 2021). Advances in Small Modular Reactor Technology Developments, an update to the IAEA's SMR book, was released in 2020 and features developer contributions for more than 70 different designs. In Appendix B, the basic design elements and current state of SMRs are summarized. In 2015, D. Kramer reexamined concepts for tiny nuclear reactor development that could one day be used for ship propulsion. Both Russia and the USA constructed nuclear naval reactors, the majority of which are PWRs. The PWR was specifically created for use at sea, although its design was later applied on land. Table 2.3 lists the naval reactors that are acknowledged on a global scale, and Table 2.4 lists the corresponding literature reviews.

**Table 2. 3: List of Naval Reactors**

| Name | Capacity | Type | Developer/ Country |
|---|---|---|---|
| VK-300 | 300 MWe | PWR | Atomenergoproekt. Russia |
| CAREM | 27 MWe | PWR | CNEA & INVAP, Argentina |
| KLT-40 | 135 MWe | PWR | OKBM, Russia |
| MRX | 30-100 MWe | PWR | JAERI, Japan |
| IRIS-I00 | 100 MWe | PWR | Westinghouse-led, international |

| Name | Capacity | Type | Developer/ Country |
|---|---|---|---|
| SMART | 100 MWe | PWR | KAERI, S. Korea |
| NP-300 | 100-300 MWe | PWR | Technicatome (Areva), France |
| PBMR | 165 MWe | HTGR | Eskom, South Africa, et ai |
| GT-MHR | 285 MWe | HTGR | General Atomics (USA), Mlnatom (Russia) |
| BREST | 300 MWe | LMR | RDIPE (Russia) |
| IFUJI | 100 MWe | MSR | ITHMSO, Japan-Russia-USA |
| KN-3 | 300 MWth | PWR | Russia |
| OK-150 | 90 MW | PWR | Russia |
| OK-900 | 171 MW | PWR | Russia |
| OK-550 | 155 MWth | LMR | Russia |
| OK-650 | 190 MWth | PWR | Russia |
| VM-4 | 70-90 MWth | PWR | Russia |
| VM-5 | 177 MWth | PWR | Russia |
| VM-A | 90 MWth | PWR | Russia |

**Table 2. 4 List of Literature**

| Sl # | Author (Year) | Title | Software/ Method used | Findings from the literatures |
|---|---|---|---|---|
| 01 | Alam, S. B. et al., 2016 | Burnable poison designs for a soluble-boron-free civil nuclear marine PWR core | PANTHER | The intended core can live for the desired 15 years. |
| 02 | Hass, B.S., 2014 | Strategies for the success of nuclear powered commercial shipping. | qualitative terms methods for the cost-effective | The creation of a reactor with broad market use and intrinsic safety that can meet these financial and safety objectives. |
| 03 | Dedes, E. et al. 2011 | Possible power train concepts for nuclear powered merchant ships. | Ship simulator | Given that nuclear fission produces no CO2, NOx, SOx, or PM emissions. |
| 04 | Schøyen, H., Steger-Jensen, K., 2017 | Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications. | Theoretical framework | The nuclear fuel is very inexpensive, high-speed operations' economic implications for traditional oil-fired ships do not apply, nuclear propulsion has a number of possible environmental benefits. |
| 05 | Bünemann, D. et al., 1972 | The core design of the reactor for the nuclear ship “Otto Hahn,” | PET | It is necessary to demonstrate a financial advantage over conventional vessels for the second generation of nuclear commerce ships. |

| | | | | |
|---|---|---|---|---|
| 06 | Namikawa, S. et al., 2011 | Nuclear powered ships–findings from a feasibility study. | PET | A number of nuclear transportation concepts, including but not limited to Ultra Large Ore Carriers, Ultra Large Container Carriers, and Ice Breakers, appear physically possible. |
| 07 | Vergara and McKesson, 2002 | Nuclear propulsion in high-performance cargo vessels. | PET | Because nuclear fuel is relatively inexpensive and reasonably constant, nuclear power produces an operation that is more stable. |
| 08 | Gravina, J. et al., 2012 | Concepts for a modular nuclear powered containership. | Probabilistic models. | Fossil fuel substitutes are being aggressively sought for as a result of dwindling fossil fuel supplies and owners' perceptions of their environmental impact. |
| 09 | Hirdaris, S. E. et al., 2021 | Concept design for a Suezmax tanker powered by a 70MW Small Modular Reactor. | Theoretical framework | An early concept design study for a Suezmax tanker that uses a traditional hull form and different configurations to fit a 70MW Small Modular Reactor (SMR) propulsion unit. |
| 10 | Carlton and Jenkins, 2011 | The nuclear propulsion of merchant ships: Aspects of engineering, science and technology. | Engineering Approach | The alternatives for using nuclear technology are discussed, along with some of the engineering ramifications of doing so. |
| 11 | Bahauddin Alam, S. et al., 2019 | Small modular reactor core design for civil marine propulsion using micro-heterogeneous duplex fuel. | PANTHER | To "open the option" of creating functioning cores with both the duplex and UO 2 fuel cores by observing the neutronic performance of the proposed duplex fuel in comparison to the UO 2 fuel. |
| 12 | Freire and Andrade, 2015 | Historic survey on nuclear merchant ships. | PET | Despite numerous efforts, nuclear power of the pressurized water reactor type is the only emissions-free energy that has been demonstrated at sea. |
| 13 | Hirdaris, S. E. et al., 2014 | Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for | Engineering Approach | The deployment of contemporary small and medium scale reactor technology on board ocean going boats has gone unnoticed in the commercial sector, notwithstanding how effective |

| | | | | |
|---|---|---|---|---|
| | | merchant marine propulsion. | | conventional nuclear propulsion has been in the naval and icebreaker ship segments. |
| 14 | Ondir and de Andrade, 2018 | Economically Feasible Mobile Nuclear Power Plant for Merchant Ships and Remote Clients. | System engineering and analysis | Nuclear power should only be used in remote islands and container ships because of their high energy needs. There is a good chance that nuclear power will be economically viable for large container ships. |
| 15 | Szewczuk-Krypa et al., 2018 | Comparative Analysis of Thermodynamic Cycles of Selected Nuclear Ship Power Plants With High-Temperature Helium-Cooled Nuclear Reactor. | System engineering and analysis | Advantages of nuclear power plants compared with the classical power systems dominating currently in sea transport advantages of nuclear power plants over the traditional power systems now used for maritime transportation |
| 16 | Ragheb, 2012 | Nuclear Naval Propulsion, in: Nuclear Power - Deployment, Operation and Sustainability. | Engineering Approach | In the majority of naval reactors, steam directly propels a turbine. |
| 17 | Crawford and Krahn, 1998 | The Naval Nuclear Propulsion Program: A Brief Case Study in Institutional Constancy. | Engineering Approach | The characteristics of the Naval Nuclear Propulsion Program are commensurate with those attributed to institutions that display institutional stability. The program exhibits both reliability and the ability to carry out programs. |
| 18 | Webster, 2007 | Alternative propulsion methods for surface combatants and amphibious warfare ships. | NAVSEA evaluation | An examination of practical near-term alternative power and propulsion system technologies and architectures, the break-even oil price (at which the life cycle costs of nuclear and fossil-fueled ship concepts are equal), and a comparison of the operational advantages of alternate architectures. |
| 19 | Thamm, 1970 | Nuclear power and the merchant marine crisis. | Engineering Approach | Accepting standardization of design to achieve economies of volume and proving that there is a demand for ships that meet the requirements for economic |

|  |  |  |  |  |
|---|---|---|---|---|
|  |  |  |  | parity are the fundamental prerequisites for receiving government financing. |
| 20 | Khlopkin, and Zotov, 1997 | Merchant marine nuclear-powered vessels. | Engineering Approach | It is emphasized that in order to ensure the safe operation of nuclear-powered commerce vessels, there must be internationally accepted norms, rules, and protocols. |
| 21 | Fitriyani, D. et al., 2008 | Design and safety optimization of ship-based small nuclear power reactors. | Quasi-static approach | The ability for natural circulation is beneficial for safety. |
| 22 | Kusunoki, T. et al., 2000 | Design of advanced integral-type marine reactor, MRX. | Engineering Approach | By contrasting the overall operating costs of a nuclear container ship with a ship with diesel engines, a feasibility analysis on economics is undertaken. The nuclear ship has the edge due to its faster speed and increased cargo carrying capacity. |
| 23 | Donnelly, 1965 | The Path Ahead for Nuclear Merchant Ships. | Engineering Approach | To demonstrate the capacity of fast ships to bring in a cargo mix with a greater average freight rate and more yearly tons than slower fleets. |
| 24 | Kalmanson, 1975 | Nuclear-Powered Merchant Ships: Some Legal and Regulatory Considerations | Engineering Approach | Requirements for Nuclear Regulatory Commission licensing, the need for coordination and agreement among the relevant federal regulatory bodies, and issues with foreign port access. |
| 25 | Peakman et al., 2019 | The core design of a Small Modular Pressurised Water Reactor for commercial marine propulsion. | MONK-9A and CASMO-4 | The here constructed core makes the idea of employing nuclear reactors for shipping feasible as it is the first practical design of a commercial marine reactor using conventional fuel. |

## 2.4 Economic Feasibility and Sustainability of Nuclear Ship

Some of the factors responsible for the change were delivered:

### 2.4.1 Increase in oil prices

Historically, there have been multiple factors that affect oil prices. In addition to the basic market factors (supply and demand), there are numerous other factors that affect the energy economy, including the capacity of the so-called downstream sector, speculation in the crude oil markets, less predictable factors (political instability, hurricanes, tsunamis, etc.), and the US Dollar exchange rate. Additionally, the cost of its substitution affects the price of crude oil as a commodity (s). Since the price of oil is frequently highly volatile and influences not only the prices of other commodities that are necessary for the food, chemical, and other industries, but also the macroeconomic indicators of both oil-exporting and -importing countries, it is in fact a topic of extensive research, expert debate, and analysis. Bunker prices have been increasing on average during the past 60 years, but there have also been significant swings in price. Figure 2.1 displays the average yearly OPEC crude oil price in US dollars per barrel from 1960 through 2020.

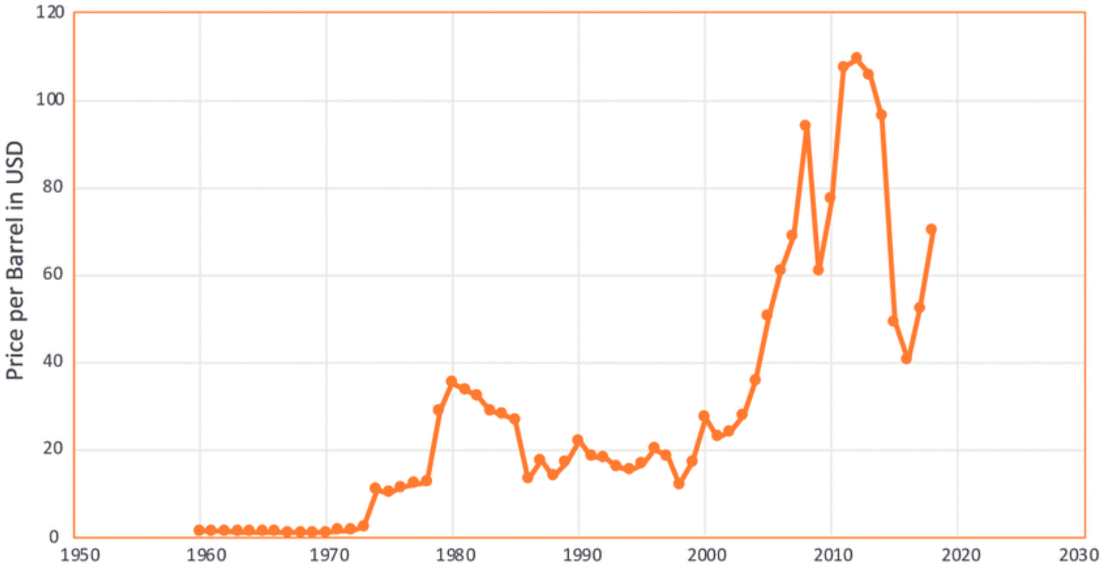


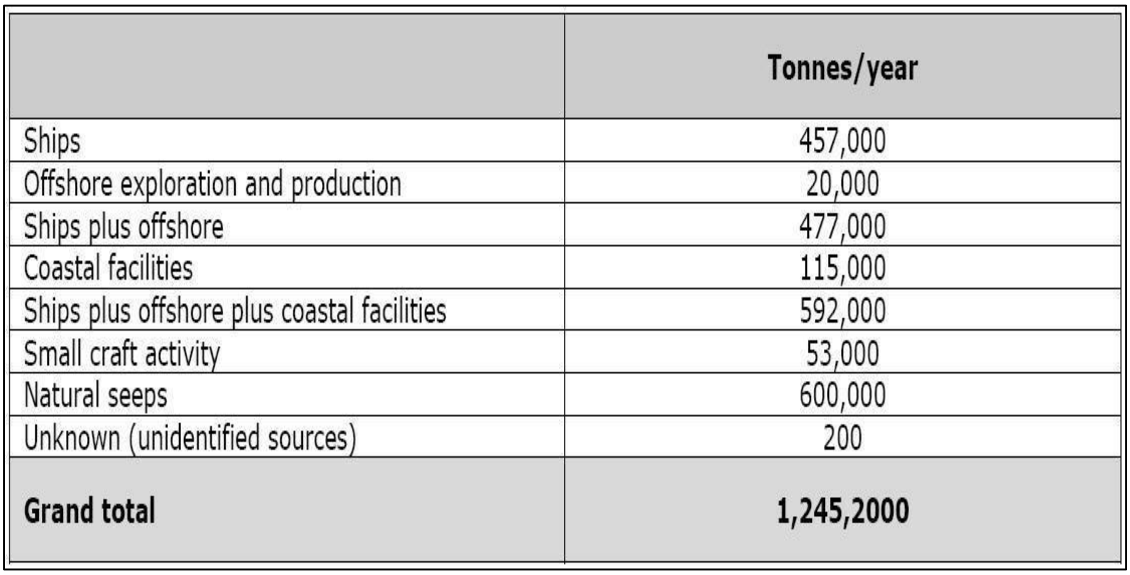
**Figure 2. 1: Average annual OPEC crude oil price from 1960 to 2020 in US$ per barrel Source: (Statista, 2020)**

### 2.4.2 Environmental pollution

Air pollution, water pollution, sound pollution, and oil pollution are only a few of the environmental repercussions of shipping. More than 18% of some air pollutants are caused by ships. In terms of greenhouse gas emissions, the International Maritime Organization (IMO) calculates that in 2012, carbon dioxide emissions from shipping accounted for 2.2% of all emissions that were caused by human activity globally. If nothing is done, IMO expects these emissions to increase by 50 to 250 percent by 2050.

Ships are the most energy-efficient way to move a given amount of cargo a given distance, yet due to their sheer size, the marine transport industry has a huge impact on the environment. Efficiency benefits from slow-steaming or other methods are outweighed by the yearly growth in shipping. Since the 1990s, the increase in tonne-kilometers of sea cargo has increased by an average of 4% annually; since the 1970s, it has increased by a factor of 5. Over 100,000 transport vessels, including about 6,000 huge container ships, are currently at sea. An increase in the world shipping industry was inevitably lead to a rise in the carbon footprint. According to the specialists' forecasts, taking into account the current trends, the amount of $CO_2$ emissions from the global fleet by 2060 will increase by 300% (IMO, 2020). The main pollutants from the shipping industry are $CO_2$ emissions and oil pollution. The information about the amounts of pollution from marine activities was given in Table 2.5. As it is clearly seen from the table, the main pollution was caused by natural seeps and ships.

Table 2. 5: Distribution of pollution from seabed activities (IMO, 2020)



| | Tonnes/year |
|---|---|
| Ships | 457,000 |
| Offshore exploration and production | 20,000 |
| Ships plus offshore | 477,000 |
| Coastal facilities | 115,000 |
| Ships plus offshore plus coastal facilities | 592,000 |
| Small craft activity | 53,000 |
| Natural seeps | 600,000 |
| Unknown (unidentified sources) | 200 |
| **Grand total** | **1,245,2000** |

### 2.4.3 Climate change (Greenhouse gas emissions)

Consistent with the European Commission, emissions from the worldwide shipping industry quantity to about 1 billion tons a year, accounting for 3% of the total greenhouse gas (GHG) of world emissions and 4% of the total emissions of European Union. Details of GHG emissions from shipping were provided in Figure 2.2. This is incompatible with the internationally agreed-upon target of limiting global warming to 2°C, which called for at least a halving of global emissions from 1990 levels by 2050. (Farkas, 2021). Taking into account increasing oil prices, oil pollution and high GHG

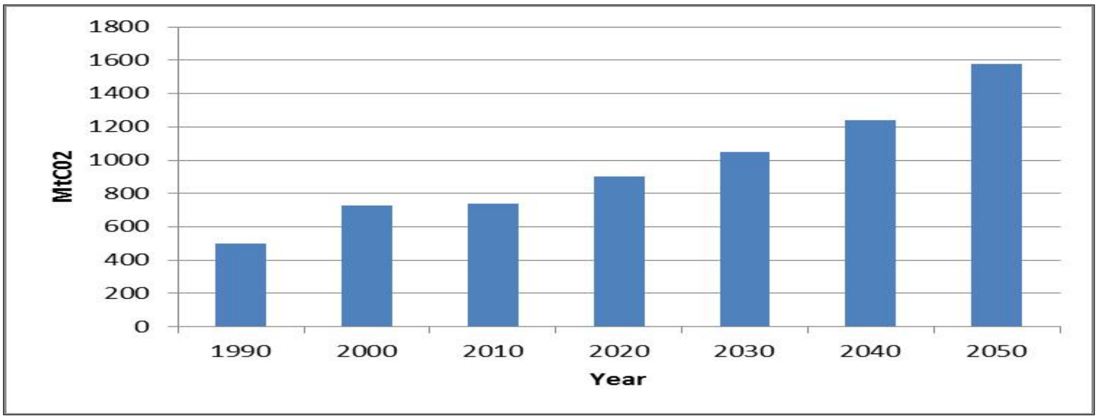


Figure 2. 2: Projected CO2 emissions from marine transport (Farkas, 2021)

emissions, it is evident that the current shipping technology will not allow for the growth of the world fleet without significant increases in cost and $CO_2$ emissions.

### 2.4.4 Public perceptions of nuclear energy

Many countries round the world were experiencing a growing realization that nuclear energy was a suitable alternative energy source. According to a very recent published by Bisconti Research, Inc. survey of U.S. public opinion June 2020, 60% of people agreed with renewing the license of nuclear power plants that continue to meet federal safety standards, 16% disagreed. 67% agreed it should prepare now in case new nuclear power plants were needed, 20% disagreed (Bisconti 2020). Figure 2.3 showed this changing public perception was based on improved knowledge and understanding, rather than emotional responses to events such as the Fukushima Daiichi nuclear disaster (2011), the Chernobyl disaster (1986), the Three Mile Island accident (1979) and Hiroshima and Nagasaki bombings (1945).

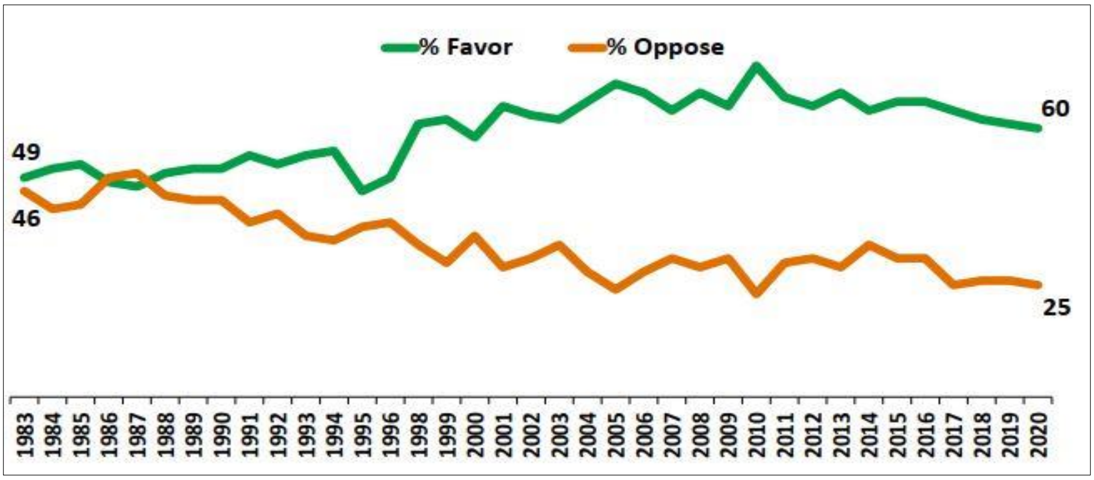


**Figure 2. 3: Public Perceptions of Nuclear Energy**

### 2.4.5 Energy density

Mass transport systems typically require very high energy density (power per unit of mass or size). This implied that the typical "Green Energy" options such as solar cells or wind turbines do not seem applicable. Nuclear energy potentially offers the highest energy density currently available. In fact, 1 kilogram (kg) of natural uranium can provide 20 000 times as much power as 1 kg of coal. This has a huge impact on the logistics of fuel transport. These factors would suggest that nuclear engines should be well suited to propulsion systems, especially where extended periods of operation are required, with limited fuel storage.

### 2.4.6 Sustainable solution

Currently, the shipping industry's top priority is to cut CO2 emissions by offering a sustainable solution that would enable the ongoing expansion of the global fleet (Andersson, 2020). An alternative to the conventional diesel engine driven propulsion unit might be one that is powered by nuclear energy, taking into consideration commonly utilized technologies, novel technical solutions, and experience in other industries such as military, transport, and energy propulsion. This type of ship could potentially be $CO_2$ emissions free, would involve only a negligible amount of gas release, and the amount of fuel used will be much less than for a standard oil-fueled ship (Dąbrowska, 2021). However, the use of a nuclear reactor on a ship causes a range of issues connected to safety, shielding, crew, etc. Moreover, nuclear power was not welcomed in several countries. On the whole, the Nuclear power phase-out program was supported by Belgium, Austria, New Zealand, Australia and many other countries. So, there were a lot of queries to be solved before nuclear shipping could be widely developed.

## 2.5 Summary of the literature Review:

In previous works, they determined the nuclear powered ships which were not economically feasible due to employed first generation prototype reactor as propulsion power. In this study, third generation small modular reactor was employed in the large container ship Emma Maesk as well as modified the shielding material in the surrounding of reactor containment building that reduced risk of radioactivity concentrations in ship surface. Besides, the economic evaluation presented for a mature nuclear propulsion system would be competitive with a diesel alternative if the life-cycle cost was considered.

# CHAPTER 3: METHODOLOGY

## 3.1 Target Sector Investigation

With the intention of establish a set of technical requirements that will drive the design analysis of a nuclear reactor, it is essential to first select a specific target market. The optimal target market should represent a good match between the type of ship and nuclear engines in general. The target market should also be sufficiently large, growing and profitable, to enable the establishment of a viable performance case. In selecting a target sector, a few assumptions were made about nuclear engines in general:

a. Nuclear engines are typically very large and heavy (the power plant of the Savannah weighed 2500 ton). This is mostly due to radiation shielding (that does not scale linearly with reactor power) and large metallic pressure vessels. This implied that a larger ship requiring a more powerful reactor will be more appropriate for nuclear propulsion.

b. Nuclear systems do not require frequent refuelling, but do require a specialized home port for handling radioactive waste, spent fuel and fresh fuel.

c. Nuclear ships do not require fuel space for long voyages, liberating space for cargo.

d. Nuclear engines are capital-intensive. Such engines would therefore make sense only for a ship that can earn sufficiently high revenues.

e. Nuclear engines would require relatively sophisticated maintenance and operational support.

f. All nuclear systems are tightly regulated by authorities, and the latter would thus impose a regulatory burden on the ships that are powered by such reactors. The type of shipping industry that is selected should be compatible with such a regulatory framework.

In an article by (Adams,R.M. 1995), criteria were set out for deciding on appropriate shipping applications for nuclear propulsion. These include:

a. Long trade route

b. Quick port turnaround

c. Large deadweight capacity

d. Emission limitations

e. Speed.

The article also proposed that the following types of ships would be well suited to nuclear propulsion:

a. Large container ships

b. Automobile carriers

c. Refrigerated cargo carriers

d. Long-distance passenger ships

e. Bulk cargo carriers

f. Any ship that spends most of its time in operation.

Refer to Figure 3.1 for a diagrammatic comparison of five examples of the largest ship types.

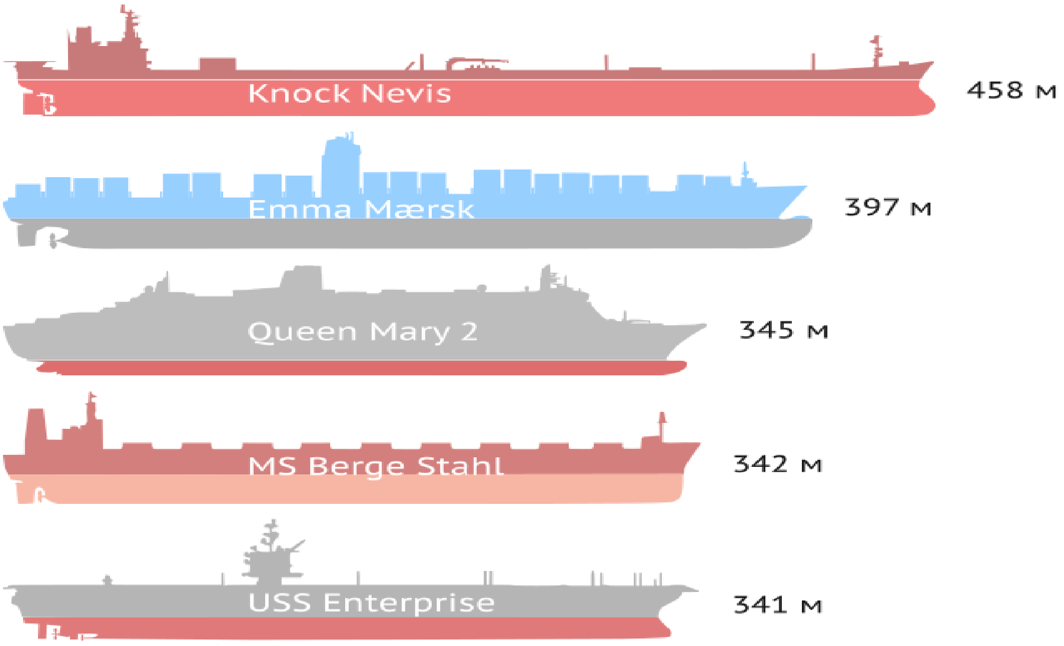


**Figure 3. 1: Size Comparison of Five of the Largest Ships (Wikipedia, 2020)**

Based on the factors listed above, the broad group of ships that seems best suited for nuclear propulsion is large oil tankers.

## 3.2 Vessel

For most aspects of the mission it would be convenient for an existing ship to be used as a case study to provide specific quantities and figures and also to provide an economic comparison of existing ships against the proposed nuclear powered vessel. The mission will provide a design for the nuclear ship using the statistics of a current and successful commercial vessel, since military vessels already have the expertise and budget to use nuclear reactors. The majority of non-military ships are either passenger ships, general service ships or commercial cargo vessels, a comparison of these can be seen in Table 3.1.

**Table 3. 1: A Comparison of Civilian Vessels**

| Type of Ship | Type of Cargo Transported | How Cargo Is Kept | Fixed "Trade "Routes | Max Length of Voyage |
|---|---|---|---|---|
| Container Ships | Any | In Containers | Yes | Long |
| Ro-Ro Cargo Ships | Vehicles (Mostly Cars) | Vehicles just packed together | Yes | Long (But typically short) |
| Bulk Carriers | Materials in bulk (eg Rice, Steel) | Different compartments | Yes | Long |
| Oil and Chemical Tankers | Oil and Chemicals | A Number of Tanks | No | Long |
| Gas Tankers | Gas | A Number of Tanks | No | Long |
| Passenger Ships | People | Cabins | Yes | Long |
| Offshore Vessels | No Cargo | N/A | No | Short |
| Service Ships | No Cargo | N/A | Yes | Short |

Passenger ships can be eliminated since it is assumed that passengers would be less willing to travel on nuclear powered ships as the general public feels uncomfortable with nuclear power. (Gutiérrez, 2014).

Due to the power density of nuclear reactors even with a small reactor, the power available to the proposed ship will be relatively large therefore larger times at sea will be more profitable. Also, the minimum size of nuclear reactor and the auxiliary plant are likely to be larger than could realistically be implemented on a small ship. Thus a certain size of vessel is required, preferably large ships with a large enough capacity to contain the nuclear reactor, auxiliary plant and cargo. Large ships are also preferable as with increasing room for cargo, profitability also increases. For any success with this work, due to the difficulties associated with it, there will inevitably have to be very large benefits also associated, i.e. large profits. (Zhang, Z. and Sun, Y., 2007)

Merchant ships are divided into 5 different size classes, depending on their gross tonnage, GT. These groups are:

- Very Small ships: 100 GT to 499 GT
- Small Ships: 500 GT to 2999 GT
- Medium ships: 3000 GT to 25000 GT
- Large ships: 25000 GT to 60000 GT
- Very Large ships: $\geq$60000 GT

Therefore, container ships appear to be the most feasible choice of case study. They can be extremely large, have regular and fixed shipping routes and can transport a variety of cargo. Also container ships spend a long time at sea which is ideal for a nuclear powered ship as refuelling will not be needed for long periods of time. There is also the possibility of using excess reactor power to provide extra commercial services associated with cargo shipping such as refrigeration/temperature control to increase the profitability of the nuclear powered proposal.

The largest container ships are the Maersk Triple-E fleet and the CMA CGM Explorer class, however these have only been in service since 2012, therefore there is little information available about them. The next largest currently available and operational for over 7 years is the Emma Maersk (EM). EM is 397 metres long with a beam of 56 metres, draft of 15.5m and a depth of 30 metres. The ship has a gross tonnage of 170974 and a net tonnage of 55396. (Orymowska, 2017). The ship has a capacity of 15000 TEU, with a TEU equivalent to one 20ft container. The ship has accommodation provisions for 30 people but the average crew is 13. The crew for the EM powered by the reactor will likely have to include several extra members, qualified in the maintenance of the chosen nuclear reactor and the auxiliary plant. There may also need to be an additional crew of security personal contracted to protect the highly sensitive fuel and technology from potential criminal activities. As an estimate it has been assumed that the crew will include 10 security personnel, 7 nuclear engineers and the conventional crew of 13 present on the EM, the full capacity of the ship.

The design of this nuclear proposal will therefore be a modified version of the Emma Maersk with the diesel engine replaced by a reactor to be chapter 4 of this thesis and Layout of the Reactor Plant. However, it must also be noted that it is possible that some nations' authorities will not allow nuclear power to be used within a certain proximity to their waters or shores. To allow for this, the ship must also carry some form of back-up power to use in these situations thus it will be assumed that the ship will continue to use approximately 3% of the same bunker fuel as the EM and carry the same back-up generators. This also indicated that a reactor with a flexible power output will be advantageous in the efficiency of the ship, or the excess power could be used to provide other services, such as potentially faster ship speeds, with the chance for a cost premium to be placed on such a service, further increasing profits.

## 3.3 Sample Ship

The Emma Mærsk was proposed used for this thesis, which can be seen below in Figure 3.2.

**Figure 3. 2: The Emma Maersk**

Principle dimensions of naval architectural of the ship are listed below:

- Name of the Vessel: Emma Mærsk
- Owner: A.P. Emma Mærsk A/S
- Port of Registry: Hellerup, Denmark
- Ship Type: Container ship
- Length Overall: 397 meters

- Beam: 56 m
- Depth: 30 m
- Displacement: 120,000+TEU
- Cargo Capacity: 11,000+ TEU
- Crew: 13
- Cruising Speed: 25 knots
- Maximum Speed: 31 knots
- Propulsion: Twin MAN engines, 32,000 kilowatts (43,000 hp) each
- Propulsion Power: 110,000 SHP Maximum
- Construction cost: US$145,000,000
- Shipbuilder Odense Steel Shipyard Ltd.

One of the largest container ships ever constructed is the Emma Maersk. The ship was constructed by Maersk Shipping Company at the Odense Steel Shipyard in Odense, Denmark. The obvious candidate for this investigation was the enormous art container ship, the Emma Maersk. A single 14-cylinder Wärtsilä diesel engine with 110,000 BHP or 80,080 kW at 102 revolutions per minute powered the Emma Maersk. (1982 Holtrop). Figure 3.3, below, shows this engine.

**Figure 3. 3: Emma Mærsk 's Propulsion Diesel Engine**

## 3.4 Design analysis process of a nuclear naval reactor

An initial core study might be performed when the reactor type was decided. The following limitations, which were supported by the earlier analysis, were applied to the reactor core design:

- The pressurized water reactor was the one that was chosen for the ship (PWR). The core was to be restricted to a maximum enrichment level of 20%, and the PWR was chosen because it is a tried-and-true reactor design that has been extensively employed in naval applications.
- The overall working lifetime of the reactor core was to be either four or ten years, based on the fact that 20% is the greatest enrichment level available to non-government enterprises.
- This choice was taken to ensure that a reactor refueling could be completed concurrently with the necessary ABS dry-docking checks, hence reducing the ship's downtime.
- The level of discharge burn-up was restricted to 60,000 MW-day per kilogram as the ultimate restriction. In contemporary nuclear reactors, this is the highest fuel burn-up that has ever been recorded.

## 3.5 Radiation Protection: Safety Aspects

Radiation is a serious safety concern in nuclear power industry specially in maritime domain. Preventing radiation from causing any harm to seaman and ocean environment. Radiation protection may be completed in three ways on board the ship:

- Decreasing the exposure time that a linear proportional effect on the dose absorbed.
- Growing the distance to the source of radiation which reduce radiation as per the inverse square law.

- Building shielding between the source and the receiver that will also reduce the absorbed dose.

Natural shielding is obviously very important for a nuclear reactor. Neutron radiation and gamma radiation are known as harmful radiations. Charged alpha and beta particles cannot travel very far inside a material due to the nuclei's electromagnetic repelling effects. Neutrons are known as neutral particles that can interact with other particles through collisions; they can move through several centimeters of material before doing so. Gamma radiation and photons are both neutral and have a very long range which are shown in Figure 3.4 (Sanctis, 2016).

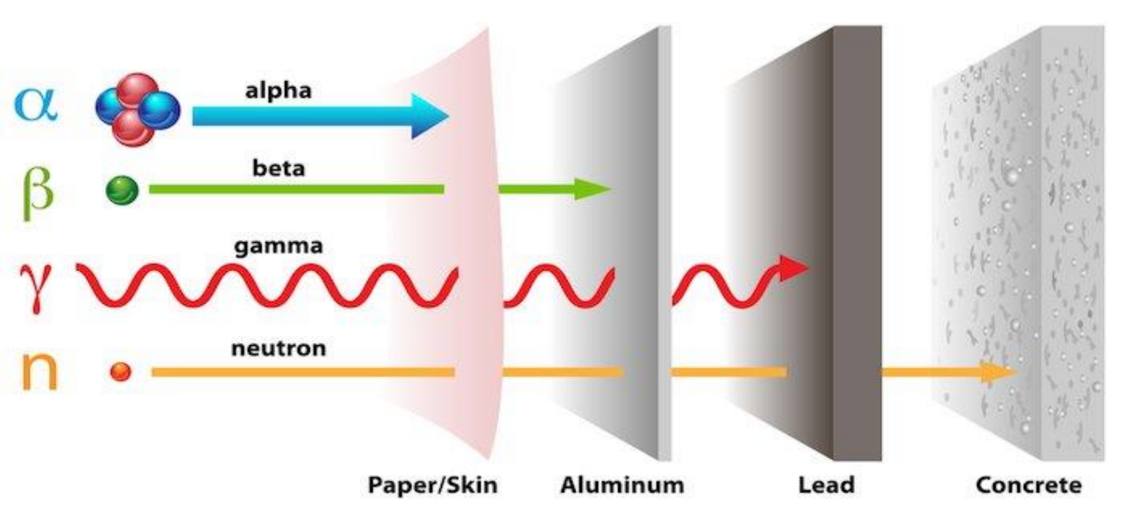


**Figure 3. 4: Radiation Penetration Courtesy of Sanctis, 2016**

## 3.6 Value System for A Nuclear Powered Ship

Safety in a merchant ship context is equivalent a hygiene factor, as described by Herzberg, F., 2005, which would not motivate a potential client to select nuclear ship above other modes, but if not treated properly will lead to a negative bias against nuclear ship. Factors that were considered to be important in determining the value of a nuclear ship were:

a. Economical cost (over the life cycle)

b. Reliability (Reactor selection)

c. Lightweight (SMR)

d. Compact (engine as well as nuclear fuel)

e. Easy to operate (long periods without refueling)

f. Environmental friendly

# CHAPTER 4: REACTOR DESIGN ANALYSIS

## 4.1 Reactor Selection and Justification of the Selected Design

### 4.1.1 Initial thoughts

As discussed above, the researcher chosen an available large merchant vessel for this research, namely the Emma Maersk (EM). The next stage in the system development was to select the reactor technology to power the propulsion system. Small Modular Reactors (SMR) are currently being developed by many countries including the USA, Japan, China, Korea, Russia and France as well as others (Vujic, 2012). The definition of an SMR, designated by the International Atomic Energy Agency (IAEA), is a reactor with an equivalent electrical power of less than 300MWe (IAEA, 2020). As the rough power requirement target for the ship is 100-200MWe, the reactor of choice therefore was well suited to an SMR.

SMR technology implementation has passed a significant milestone. The two-module KLT40S Akademik Lomonosov floating power unit in the Russian Federation was linked to the grid and began conducting business in May 2020. There are more than seventy (70) SMR designs in various stages of development. A motivation for the recent surge of interest in this field is due to the flexibility the technology offers. Several of the advanced SMR designs can offer a combination of process heat production, desalination and hydrogen generation, as well as electricity generation (IAEA, 2020). For this thesis, the reactor was required solely to generate power to transmit to the propulsion system, therefore several of the designs that were aimed at multiple gains, may be unsuitable.

The benefits of these new advanced SMR technologies however, are vast and very beneficial to the shipping application. The reactors and containment are physically smaller, and modular, and often weigh less than a typical Emma Maersk ‘Wartsila 14RT-Flex96C’ engine (2300 tons). The reactors have a very long life cycle, reducing the refuelling frequency, costs and space needed for fuel storage associated with large diesel engines. Other improvements to the advanced SMRs in comparison to standard conventional reactors which should also help in terms of the ever present issue of public perception, is the passive safety that they offer and the high level of proliferation resistance (Vujic, 2012). There are six major classes of advanced SMRs currently under commercial development and these are discussed next to present a brief review of the options available for selection. Detailed are the most appropriate candidates, with general information, advantages and disadvantages.

### 4.1.2 Pressurised water reactors (PWRs)

These designs are the most likely to be deployed in the near future as they are based on proven technologies of the large scale PWRs that account for over 60% of the 450 Nuclear Power Plants (NPPs) currently in operation worldwide. There is also some past experience and therefore a degree of confidence of the use of PWRs on ships, such as the use of an Integral PWR; which powered the German cargo ship, the Otto Hahn, as well as on nuclear naval submarines. Almost all of the PWR designs are integral reactors, meaning components such as the pressuriser and steam generators are inside of the Reactor Pressure Vessel (RPV). This eradicates large piping connected to the RPV and eliminates the potential for large Loss of Coolant Accidents (LOCA) (Ricotti, M.E., 2013). Selection of an integral design is likely to be necessary due to the major safety advantages the reactor delivers. The amount of proposed PWR designs is extensive, with many only in the design/development stage at present, the forerunners were considered in this process (The Ux Consulting Company, 2013).

The first reactor considered was the mPower design by Babcock and Wilcox (B & W). Babcock and Wilcox are a leading name in the field of nuclear propulsion, having developed reactors and propulsion systems for the US Navy for over 50 years (WNA, 2019). The mPower is a light water cooled, PWR and has a power output of 180MWe. B & W also estimated a refuelling period of four years and a typical 60 year service life. Major advantages of this reactor design include passive residual heat removal, passive emergency safety systems and its rather small physical dimensions of 4.5m diameter x 23m high (IAEA, 2020).

The second choice was the KLT-40S reactor from OKBM Afrikantov in Russia, which was adapted from the KLT-40 reactor that had been successfully used in icebreakers and was now being offered for wider usage in desalination and, on barges, for remote region power delivery. Here, a 150 MWt unit generates up to 35 MW of heat for district heating or desalination in addition to 35 MWe (gross) of electricity (or 38.5 MWe gross if power only). 45 GW/t is the burn-up. With the ability to refuel on board and the storage of wasted fuel, units are intended to operate for three to four years without refueling. Each such refueling involves replacing all fuel assemblies. The entire plant is transported to a central location for overhaul and used fuel storage after the conclusion of a 12-year operational cycle. The life of an operating plant is 40 years. A 20,000-ton barge will be equipped with two units to accommodate outages (70% capacity factor). Kaliningrad may also make advantage of it. Convection is used in emergencies even though the reactor core is typically cooled by forced circulation (four-loop). With uranium aluminum silicide fuel and up to 20% enrichment, refueling durations of up to four years are possible. The KLT-20, which was created especially for floating nuclear plants, is a variation of this. The variant has two loops and the same enrichment, but the refueling interval is 10 years. Construction on the Akademik Lomonosov, the first floating nuclear power station, started in 2007. The factory is currently anticipated to be operational in 2019 due to the shipyard's financial instability. Another option was the NuScale design by NuScale Power Inc. Like the mPower reactor, this design also has passive residual heat removal and passive emergency systems as well as a 60 year service life. It is also smaller physically, however it must be refuelled every 4 years, equal to the mPower. A longer time span between refuelling is a major advantage for the shipping application, as when the ship is not in use, it’s not making money and therefore for any success, the ships downtime will need to be minimised. Another major disadvantage of this reactor is the power output of a mere 45MWe. As this design is more aimed at a NPP of between 1-12 modules, this small power output is not an issue, however for the ships required power output, 2-4 modules would be required, and the weight and space required for this could also cause potential difficulties on board the Emma Maersk. (IAEA, 2020).

The Westinghouse SMR by Westinghouse was another leading technology from the USA. It is based on the successful AP1000 design but on a smaller scale and with proven components. The design has passive heat removal, which Westinghouse state will ensure that no operator intervention will be required for seven days post-accident (Petrovic, B., 2021). Several disadvantages for the shipping application are present with this design, including a two year refuelling period. It is also rather large compared to the mPower reactor. At a diameter of 9.8m and height of 27m it is almost twice the size.

The power output is 225MWe, which is more than is needed to power the ship (IAEA, 2020).

Another design was the SMART reactor, by the Korea Atomic Energy Research Institute (KAERI), which is actually already licensed, but is being developed further to make the design fully passive (The Ux Consulting Company, 2013). This design has a longer fuel interval than most designs, three years, but still a year less than the mPower design but the power output is 100MWe which is a good fit to the ship’s needs (IAEA, 2020).

Other notable mentions include the Russian designed VBER-300, which is a result of the evolution of nuclear marine propulsion reactors; however, with a power output of 325MWe, it technically is not a SMR. The Argentinean, CAREM design is currently under construction, but only has an output of 25MWe. Another Russian design, the KLT-40S, also misses out under these criteria with an output of 35MWe (IAEA, 2020). There are many similarities between all these designs, as is to be expected as these are all working towards similar aims. All have a light water coolant and uranium dioxide fuel with less than 20% wt enrichment (<5% in most) which helps with proliferation resistance. In addition, these designs all run on an indirect Rankine cycle, with core outlet temperatures between 310-329°C and system pressures between 8.72-15.5MPa (IAEA, 2020).

### 4.1.3 High-temperature gas-cooled reactors (HTRs)

The second group was high-temperature gas-cooled reactors. These are relatively unproven in the marine industry and vary a lot in design.

The HTR-PM by Chinese group, Institute of Nuclear Energy and New Technology (INET) at Tsinghua University & Huaneng Shandong Shidaowan Nuclear Power Company (HSSNPC) is currently under construction, making it the most developed reactor in this group (The Ux Consulting Company, 2013). This reactor uses a different fuel to the PWRs, called TRISO (tristructural-isotropic) fuel. This consists of fuel kernels of 200-600μm of $UO_2$, $UC_2$ or UCO, coated in layers of carbon and silicon carbide which gives containment to the fission products to temperatures up to 1600°C (WNA, 2020). This reactor is a follow on from the smaller HTR-10 reactor, a 10MWe version of this reactor, which has an output of 200MWe. INET have successfully completed several experiments to prove the inherent safety measures of this design are functional which increases confidence levels, including the loss of main heat sink without any countermeasures, which could be an issue should the ship ever run aground (IAEA, 2020).

Another design was the Pebble Bed Modular Reactor (PBMR) by PBMR (Pty) Ltd, a South African company. This reactor is fuelled by TRISO fuel particles, embedded in graphite pebbles, similar to the HTR-PM, and gives a power output of 165MWe, perfect for the ship. The core consists of approximately 452,000 of these pebbles, continuously being cycled through. As with the HTR-PM, the design ensures the fuel spheres retain almost all of the radioactive products, even under emergency conditions (IAEA, 2020). Unfortunately, the specifications for passive safety place restrictions on this design. There is no prior commercial experience with this technique, which uses direct cycle helium turbines to power vertically oriented generators with magnetic bearings (Vujic, 2012). Another issue which potentially negates the selection of this reactor, it has currently been placed on hold due to financial issues and technical problems. The Gas Turbine Modular Helium Reactor (GT-MHR) by General Atomics is another similar design, and has a more than acceptable power output of 150MWe. It uses very similar fuel to the PBMR, with the same associated safety benefits. Another benefit of this revolutionary fuel is that extracting the radioactive material is an expert process, making it very proliferation resistant. General Atomics also claims that because of the high thermal efficiency, high fuel burn up and lower fertile fuel inventory of this reactor, it creates less radioactive waste and less total plutonium per unit energy produced. This is very good for the shipping application as large amounts of radioactive waste could be problematic and proliferation concern is reduced with less plutonium produced (IAEA, 2020). However, this reactor will be under the same scrutiny as the PBMR, as it uses the same questioned technology that has no commercial experience (Vujic, 2012).

A rather different reactor being developed by General Atomics is the EM, a modified version of the GT-MHR but this is a high temperature, gas cooled fast reactor, with a power output of 240 MWe (Thompson, 1977). This is slightly more than is required for this application but it is an interesting concept. Initial fuel for the EM$^2$ consists of 22 tonnes of low enriched uranium and 20 tonnes of spent PWR fuel or depleted uranium. Following processing to remove fission products, the reactor is refueled with more old PWR fuel, totaling about 4 tonnes. This might result in refueling intervals of up to a significant 30 years (WNA, 2020). However, this is only in the conceptual design stage at present and there is much development to be made before it would be a realistic selection. (Wu, 2002)

All these reactors were helium cooled; have outlet temperatures ranging from 750-900°C and system pressures of 6.39-9MPa. The HTR-PM and PBMR operate on an indirect Rankine cycle whereas the GT-MHR and EM$^2$ use a Brayton cycle (IAEA, 2020).

Also, there is another issue with the HTR-PM, PBMR and GT-MHR. All of these reactors use the TRISO fuel, with a graphite coating, which makes the fuel self-moderating. However, graphite reacts with oxygen, which can lead to the entry of air or water into the primary coolant system. This only leads to issues if sufficient natural circulation flow of air through the core occurs, yet it remains a possibility (Vujic, 2012).

### 4.1.4 Liquid metal cooled reactors (LMRs)

The third group was liquid metal cooled reactors, with either a lead alloy or sodium coolant being the most common cases. There are many varying designs in this group and most are still in the conceptual design/development stages with much work to be done, making any selection from this group unlikely.

The most progressed design in this category is the SVBR-100 reactor from Russia, which is another fast reactor and is currently being licensed. It has a power output of 101MWe with a lead-bismuth coolant and initially uses $UO_2$ fuel enriched to less than 16.4%, but is designed to be able to use a wide variety of fuels (WNA, 2020). Other fuels it can use include Mixed Oxide Fuel ($MO_X$), uranium nitride, and other uranium-plutonium fuels (Vujic, 2012). Other advantages include a long fuel cycle of 7-8 years, although this was not as long as the EM$^2$ fast reactors, and both passive safety and heat removal systems (IAEA, 2020).

There are also other fast reactors worth mentioning, but unsuitable for selection due to the power outputs. The Super-Safe, Small and Simple or 4S, is a sodium cooled fast reactor from Toshiba. This has a fantastic fuel cycle of up to 30 years without refuelling and has high levels of safety but only has an output of 10MWe (IAEA, 2020). Another sodium cooled fast reactor was the PRISM reactor from GE-Hitachi. This was another design progressing well but with an output of 311MWe, this is another that is not technically classed as an SMR (IAEA, 2020).

### 4.1.5 Molten salt reactors (MSRs)

Another interesting design was the Molten Salt Reactor type which offers some significant advantages. They operate at atmospheric pressure and therefore can avoid accident sequences driven by pressure gradients. It operates at large temperatures and with the use of appropriate plant, can give very good thermal efficiencies and power outputs. These use thorium as a fuel, of which there is an abundant world supply and can be used in its natural state, saving costs of separation and pre-processing. The fuel salt can be also contaminated which provides virtually insurmountable resistance to proliferation and hence use in nuclear weapons. (Serp, 2014)

Unfortunately, there were also several major disadvantages with these concept designs; pipes and components containing the salt must be held above the melting temperature of the salt, which is very high. Isolating the Ships structure from these high temperatures is a big issue that must be overcome to make these reactors a realistic choice. Also, the pipework and the components were obviously very highly radioactive due to the fission product activity, meaning remote maintenance is required. Due to the fuel being dispersed, the shielding requirements are much more complicated, and much more straightforward with the other technologies. These limitations probably mean that this reactor type is not applicable for this application (Carlton, 2019).

### 4.1.6 Reactor selection and justification of selected design

The initial decision made was that the reactor must be an SMR due to the power requirements, as stated in section 4.1.1 Initial Thoughts. The next logical decision to be made to enable the choices to be narrowed down, was to decide upon the type of Naval Reactor, from the four major types discussed above.

The first reactor type to be ruled out was the MSR type, discussed in section 4.1.5. These reactors have some very unique advantages associated with them, such as the use of thorium as a fuel, which is a very abundant world source and also avoids large processing costs associated with most other fuel types. However, the disadvantages discussed above will make any reactor of this type very hard to justify and license on the grounds of the complexities associated in the physical properties of the reactor and components.

The next reactor type to be ruled out was the LMR type, discussed in section 4.1.2, mainly due to the lack of development of most of the reactors in this category. For this reason, the reactors are unproven and some of the associated technologies used in the designs are also unproven. The merchant nuclear shipping application that is being investigated here, is fairly revolutionary, thus using unproven technologies is not likely to be accepted at this stage, due to the large societal doubts about the safety of nuclear power. The most developed reactor in this category, currently in the licensing stage, is the Russian design SVBR-100 discussed in section 4.1.2. The prospect of potentially using a range of differing fuels is an interesting concept and one of the advantages that this design boasts. This gives flexibility when it comes to which fuels to purchase, which is a valuable commodity. However, at this stage this design is ruled out due to the lack of experience, but could potentially be an option in the future, subject to performance. However, one significant disadvantage here, specifically for LMR types cooled by Liquid Sodium, is the fact that Liquid Sodium reacts with both air and water. When in contact with air, it spontaneously ignites and produces aerosols that are highly toxic and also cause equipment damage. It also reacts violently with water, which when at sea, is clearly a major problem when accident scenarios are considered. This may well mean that LMRs cooled by Liquid Sodium will never be suitable for this maritime application (Omar, S.L., 2012).

The final reactor type to be ruled out was the HTR reactor type, discussed in section 4.1.3. These designs give large benefits in terms of the inherent safety and proliferation resistance associated with them, because of the use of the special TRISO fuel, which can be used due to the high temperatures. The most realistic near-term choice in this category is the Chinese HTR-PM, currently under construction. This has many claimed advantages but a power output of 200MWe is slightly above what is required. This is another that could potentially be altered for the maritime application in the future, should it prove successful during operation and if it were possible to lower the power output (IAEA, 2020). For reasons similar to the LMR type, lack of experience, this reactor type is also ruled out at this time.

This has narrowed the choice down to the various PWR options, discussed in section 4.1.2, which are widely viewed as being the most likely to be deployed in the near future. This is due to the fact that of all the NPPs in operation, 60% are powered by large scale PWRs and the SMR designs are largely based on these, meaning major parts of the technology, are tried and tested, only on a larger scale. With this thesis, it was very aware that public perception is vital for success and the use of a reactor with a certain level of experience would seriously help gain the support of the public, in respect to a totally new design. As stated in section 4.1.2, there is also past experience of using small integral PWRs on various ships, which justifies the selection of a PWR type.

There are far more PWR types being developed than any other type, and the decision was made to narrow down the options to the leading designs and then examine these in more detail. Several key criteria were identified and the reactors chosen evaluated on said criteria. A spreadsheet outlining this information is shown in Appendix A and should be referred too. Boxes in red indicate unsuitable, boxes in yellow indicate an issue and boxes in green indicate suitable. Blank boxes are where the information could not be found.

The first reactor to be dismissed on the grounds was the Holtec SMR-160, purely as it was the only design which was not integral which deemed it completely unsuitable. The NuScale design by NuScale Power and Fluor was the next design to be designated unsuitable. This was due to the power output being only 45MWe. With this reactor, there is the potential for installation of multiple units, each providing the 45MWe to enlarge the power output to a suitable amount, however size and weight requirements will likely deem this impracticable and not as favourable as other potential options. The Westinghouse SMR was ruled out next, again because of an unsuitable power output.

The decision has been made to aim for a power output greater than that provided by the engine used in the Emma Maersk currently, the rationale being that faster travelling speeds could be achieved for a cost premium being charged on deliveries. But this has a limitation and a power output of 225MWe, provided by the Westinghouse SMR, will be much greater than required. This narrowed the choice down to the KLT-40S reactor by Afrikantov OKBM and the SMART reactor by South Korean based KAERI, both shown below in Figures 4.1 and 4.2 respectively.

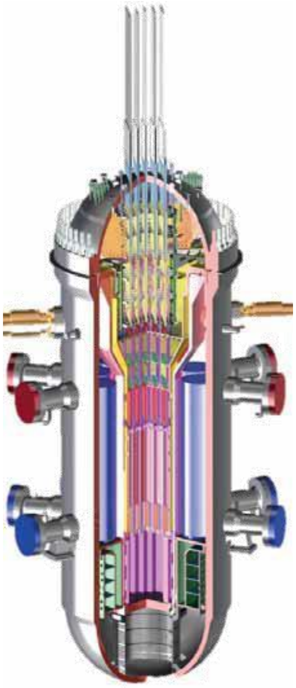


**Figure 4. 1: Smart Reactor (IAEA, 2020)**

**Figure 4. 2: KLT-40S Reactor (IAEA)**

The reactor design chosen, was the KLT-40S reactor by Afrikantov OKBM, Russian Federation. Not much separated this and the SMART design, but the KLT-40S was decided upon due to the slightly longer refuelling period and due to the track record that Afrikantov OKBM have in the nuclear shipping industry. The KLT-40S reactor has a 4 year refuelling interval, compared to the SMART reactors 3 years, which is not much different but it is an extra years profits without any stoppages and associated refuelling costs, which will be looked upon favourably by potential clients.

Afrikantov OKBM have a long history in the nuclear propulsion of maritime industry, which dates back to 1945 when they were awarded there first contract to begin the research on propulsion systems for the Russia Navy, and this has continued from then on with them being involved in the design and manufacture of reactor systems and propulsion units for various clients (Afrikantov OKB Mechanical Engineering, 2020). The rationale behind partly selecting a reactor based on the company that constructs it, is that a large margin of confidence will be attained by the selection of a reactor that is constructed by a company which has a long history of similar dealings with the military. As well as this, as Afrikantov OKBM also design and build propulsion systems, hypothetically, if this thesis should ever go ahead, some deal could potentially be agreed upon in which a reactor, tailored to suit the ship's needs, and propulsion unit could be purchased together. This would be beneficial financially and because of the expertise they have in this area, they could help with the necessary changes to the reactor, needed for it to be used in a maritime environment. Other companies may not be able to deliver such services and in which case, a reactor and propulsion system would need to be purchased separately and much work put into how they were going to combine and function to the best effect.

### 4.1.7 Layout of reactor plant and propulsion system

Once the KLT-40S reactor was selected, the layout of the plant and associated equipment was to be decided. This first entailed deciding how the power produced by the reactor would be utilised.

Fission within the core of the reactor releases a large amount of heat energy used to heat the coolant pumped upwards throughout the centre of the reactor plant, as seen in Figure 4.3 below.

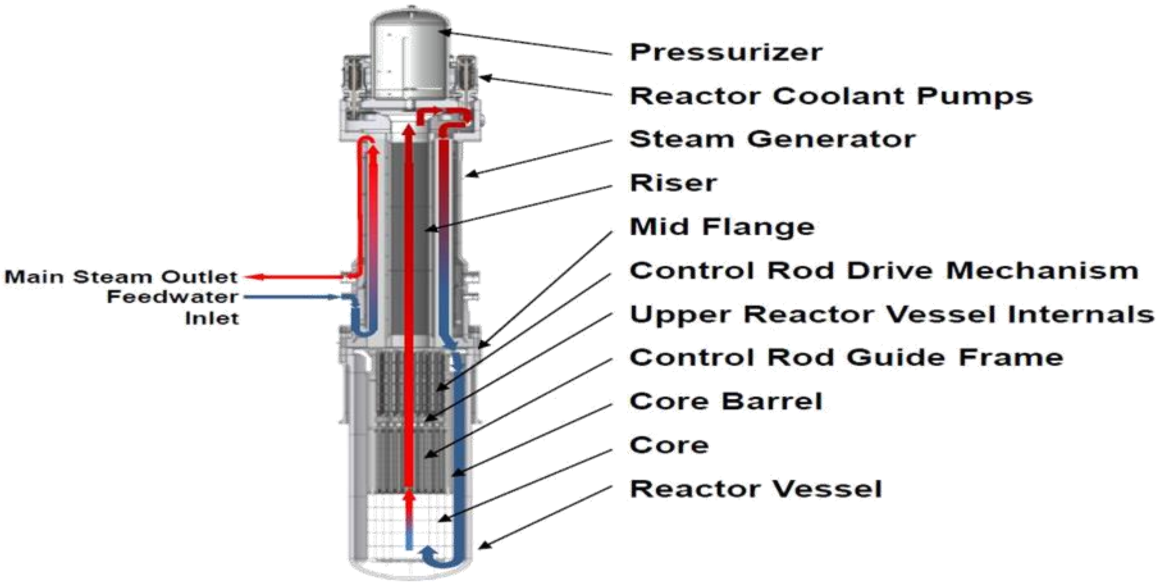


**Figure 4. 3: KLT-40S Reactor Flow**

This heated coolant inside the primary circuit will transfer heat to the feed water in the secondary circuit, shown on the left hand side of Figure 4.3. This generates steam which is employed to generate useable power (Carlton, 2019). This useable power can be used in two main ways, the first being to use the steam to power a steam turbine for direct shaft power, used predominantly by the Russian, US and British navies. The other is a technique employed by the French and Chinese in their submarines, which is to use the steam to power a steam turbine to generate electricity, which in turn will be used to provide propulsion (WNA, 2020).

This second option has been selected for the commercial shipping application and will use a turbo-generator to convert the mechanical energy produced by the steam into electrical power. Electronic motors will then convert a portion of this back into mechanical energy to drive the propeller shafts to provide propulsion (Rolls Royce, 2021). An advantage of this is that the extra electrical power produced can be used to fulfill on-board electrical needs for the ships operations, such as lighting and electricity for crew facilities, by the use of a portion of the electrical power generated by the turbo-generator not used for propulsion. This is because the current diesel engine of the Emma Maersk produces a maximum of around 82 MWe but the KLT-40S reactor can provide outputs up to 140 MWe (Rolls Royce, 2014).

Another advantage of adopting the turbo-electric system is related to the layout of the plant. As the mechanical power produced by the turbine does not directly power the propeller shaft, this allows for the reactor plant and associated shielding being located away from the propulsion unit. This will help with shielding requirements as the reactor plant may be placed in a part of the ship that is not readily accessible to the crew, thereby reducing doses. Also, if any maintenance is required on the propulsion unit, this is simplified as it is not directly attached to the reactor plant. There is also a requirement for an auxiliary means of propulsion, in order for the ship to still be able to dock in countries that are against nuclear energy, the ship would then use the auxiliary method. Another reason is redundancy, should the reactor plant fail, the auxiliary means could be used to propel the ship to dock (Carlton, 2019).

It has been decided that this secondary option shall be a small diesel engine, used in the traditional way, to enable the ship to travel medium to short distances in the case of any issues as discussed above. Other options such as large batteries or super-capacitors to store electricity generated by the reactor plant when in use, in order to propel the ship and supply electricity at a time when the reactor plant was not being used were investigated but were dismissed in favour of the small diesel engine. This is due to possible issues with size and complications with the technology, and it was decided that a diesel engine is a more reliable and trusted option and will help in regard to licensing.

### 4.1.8 Modifications to convert the reactor plant to a marine environment

The KLT-40S reactor chosen for this thesis was being developed by Afrikantov OKBM to predominantly provide a lower risk solution for the US energy needs. This showed that it has been designed for on land use and therefore may require some modifications for use in the marine environment. However, as the KLT-40S reactor is a direct descendent of the Afrikantov OKBM maritime reactor program, but with improvements to the inherent safety, major changes are unlikely to be required. The reactor is scalable by design to allow for multi-unit plants to be constructed which will consist of 1-10+ units, the ship will have two units but this will not pose an issue as the rationale for multi-unit plants on land is mainly due to higher power demands. In fact, the reactor is intended for use in an enclosed area with limited space, which is similar to the conditions of the ship. However, part of the rationale for having the on-land nuclear island fully underground was to decrease seismic response, this requires further investigation as there will be constant movement on the ship (Zverev, 2019).

A small change that is required relates to the Emergency Core Cooling System (ECCS). This system has been made passive during the design of this reactor to increase the level of inherent safety, primarily by employing natural circulation to remove decay heat by gravity instead of using pumps. However, this could be problematic in the case of the ship due to the constant pitch and bounce of the ship and in the unlikely but

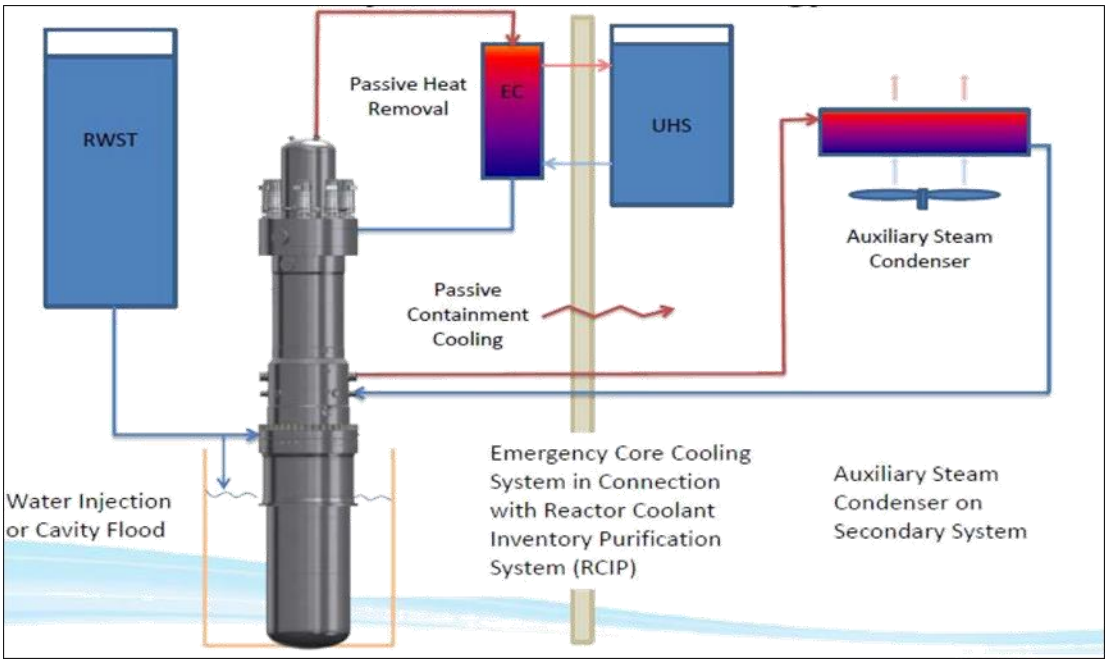


**Figure 4. 4: Decay Heat Removal Strategy**

possible chance of accident scenarios which involve the reactor losing its vertical orientation. Therefore, the change is to use pumps to circulate a coolant for decay heat removal, which will be powered by the additional diesel engine should power from the reactor ever be lost (Zverev, 2019).

Another change is to make use of the sea as the ultimate heat sink for decay heat removal; this can be seen in Figure 4.4 above, labelled UHS. It may also be required to keep the tank currently used as the Ultimate Heat Sink as an alternate UHS should the ship ever run aground.

Reactors on board a ship must be able to withstand almost continuous conditions of uneven movement due to the pitch and bounce of the ship. A suggestion for further work here is an investigation into the effects of how this movement effects reactor safety and performance, however major problems are not expected as there is history of the use of PWR technology on ships. (Kunitomi, 2004).

## 4.2. Reactor Physics: Technical Assessments

### 4.2.1 Reactor core design

For the propulsion unit design a small modular KLT-40S reactor was chosen. This design is widely used in the nuclear energy sector. As well as this, the naval nuclear submarines and civilian ships that employ this type of power production are already in use. The technical assessment section will consider the chosen reactor technology, the KLT-40S reactor by OKBM Afrikantov. This unit has an electrical output of 140 MWe (thermal output of 400 MWt) and 18.6% uranium-235 enrichment (uranium oxide is used as a fuel).

**Reactor plant layout**

The Figure illustrated a marine based KLT-40S design (Note: 2 close cycles: Reactor coolant System and Secondary System) in Figure 4.5. The same concept of the energy production process was modified for a SMR to operate on a container ship.

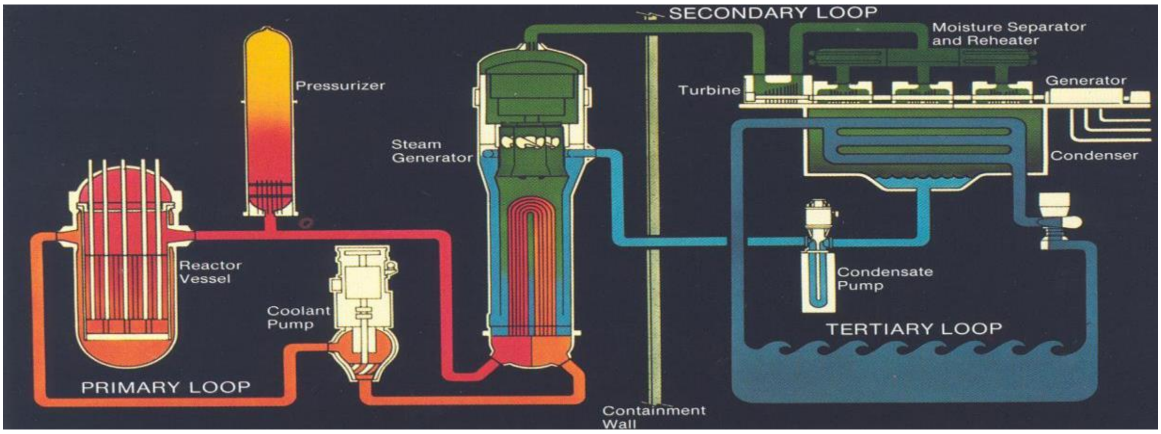


**Figure 4. 5: On-land PWR basic design**

The layout of the nuclear power station shown in Figure 4.5 is different to the layout of the SMR concept, however the principles of energy production such as critical chain reaction, neutron moderation, heat removal by coolant, steam and electricity production are the same. The main differences between a standard PWR and the SMR type are the compactness of the reactor plant, the enrichment of the fuel (higher for an SMR) and refueling strategy. The layout of the KLT-40S can be seen in Figure 4.6.

**Figure 4. 6: KLT-40S reactor layout**

### 4.2.2 Main reactor features

#### Chain reaction

A PWR is a thermal reactor, which requires the bulk of neutrons to have energy in the vicinity of 0.1eV. This allows the thermal (low energy) neutrons to cause fission of the burnable uranium-235. The absorber is split into nuclear reaction products which includes an emission of 2 to 3 high energy neutrons and is accompanied by other reaction products such as gamma-rays in Figure 4.7.

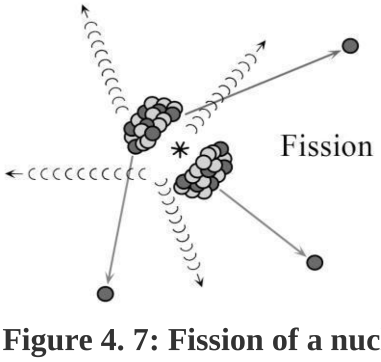


**Figure 4. 7: Fission of a nucleus**

These neutrons are used to sustain the chain reaction. However, the energy of the produced neutrons varies in the range of 0.1-1MeV which could not be used in thermal reactor, because U-235 has a very high probability of neutron absorption without fission, especially in the scattering region for 1-1000eV neutron energies in Figure 4.8, also known as the Doppler Effect (Touran, N., 2009).

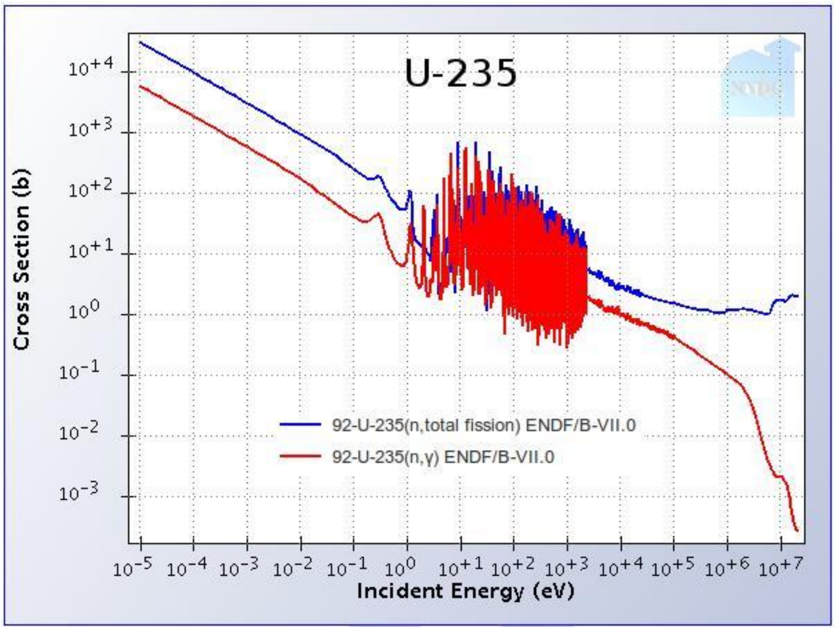


**Figure 4. 8: Cross section of fission and absorption for U-235**

Therefore, the reaction could not be sustained unless the neutrons are slowed down to lower energies and at least one of them causes the next fission, so the reaction is kept critical. Neutrons can be slowed by employing a moderator. The neutrons produced during fission can be divided into two main categories: prompt neutrons and delayed neutrons. The prompt neutrons are emitted just after the fission, while delayed neutrons occur from several milliseconds up to several minutes after the fission reaction. The later neutrons make up less than 1% of the total amount of the neutrons emitted by fission. Delayed neutrons might be emitted by a fission reaction product such as $^{87}$Br, $^{142}$Cs, $^{137}$I, $^{138}$I, $^{139}$I, etc. or any other short lived fission product. These neutrons extend the life of a neutron generation allowing criticality control.

### Moderator

In PWRs the moderation is performed by water. Moderation is obtained by the collision of the fast neutrons emitted during the fission and thus the partial loss of their energy (Lamarsh, J.R. and Baratta, A.J., 2001). This mechanism significantly reduces the neutrons energies so that the fast neutrons emitted after nuclear fission become thermal neutrons and the chain reaction can be sustained. Figure 4.9 presents a schematic of a neutron moderation mechanism.

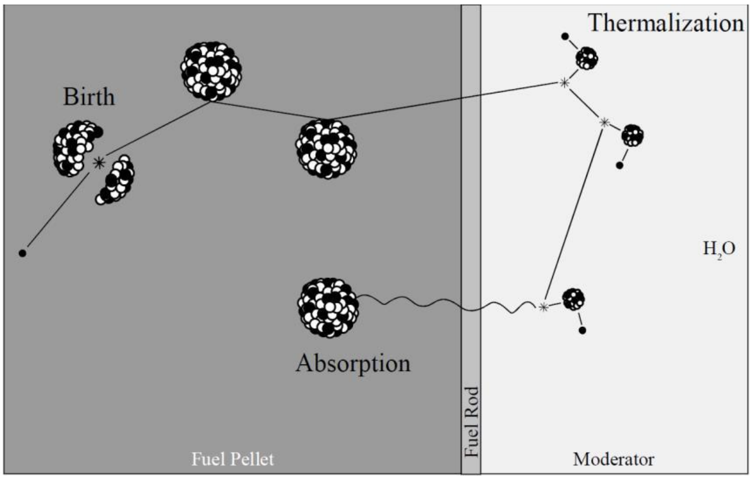


Figure 4. 9: Moderation of neutrons

As the neutron energy is lost during the collision of neutron with a moderator, the best moderating performance is achieved when the mass of the moderator atoms is as close as possible to the mass of a neutron.

Light water contains hydrogen which has a mass very close to that for neutron, so it efficiently slows down fast neutrons to thermal energies. The pressure of the coolant (150-160 bar) keeps coolant in the liquid state preventing it from boiling; this improves the uniform moderation across the length of the reactor core.

### Coolant

As mentioned above, moderation may be partially performed by the coolant, which in this case is pressurised water. Water has good conducting properties and high scattering cross-section because of hydrogen in the water molecules. It also has several beneficial properties such as transparency, low melting temperature and low cost (readily available). The disadvantage of water as a coolant is the comparably low boiling temperature. This property will cause the loss of coolant in case of depressurization of the primary circuit, because the pressurised coolant is at a significantly higher temperature than its boiling point at atmospheric conditions. Also in case of the loss of pressure in the primary circuit, water will boil as its temperature under normal operating conditions of PWR (ca. 300°C) is higher than its boiling temperature at ambient conditions (100°C). Water as a coolant allows employing a passive safety mechanism such as a negative temperature coefficient. This property enables a reduction in the moderation of the neutrons (and therefore the fission) when the temperature of the coolant increases, because the density of the water decrease with an increase in temperature. This property leads to the self-adjusting core reactivity. The table below provides information about water properties in Table 4.1.

**Table 4. 1: Water properties**

| | |
|---|---|
| Density | 767 kg/m$^3$ |
| Moderating ratio* | 72 |
| Thermal conductivity | 0.059 W/mK |
| Cp | 5.14 kJ/kgK |
| Inlet temperature | 275 °C |
| Outlet temperature | 315 °C |
| Viscosity | 102*10$^{-6}$ Ns/m$^2$ |

The parameters of the water pressure and temperature in the primary circuit for a given type of a given type of the reactor are 2200psi, 600F (KLT-40S).

### Fuel

The fuel used in PWR is uranium dioxide ($UO_2$). For the thermal fission the U-235 isotope is crucial. Naturally the uranium appears with 0.7% enrichment of U-235; however, this is not enough to sustain thermal fission. Therefore, the fuel is enriched to contain more than 2.0-2.3% of fissile uranium. The main limiting reactor lifetime factor is the increase of the fission products inside the fuel. As the chain reaction is present throughout the fuel pellet, these fission products are mainly stuck inside the fuel material. The amount of fission gases and other fission products increases during the operating time causing voids inside the fuel and swelling its volume. The pressure rise inside the created voids due to increase of fission gases leads to fuel cracks (failures). Therefore, uranium dioxide is used as a fuel, not metallic uranium, because $UO_2$ is more porous and allows the burning of more fissile isotopes as more of the fission products can be accommodated in the material. Uranium dioxide is manufactured into small cylinders of 0.7844 cm diameter in Figure 4.10. The cylinders are then placed into a zirconium tube of 0.914 cm outer diameter. Between the pellets and the cladding tube there is a gap of 0.0157 cm thickness which accommodates for fuel swelling caused by irradiation and any cracks of pellets (Buongiorno, 2021). This function is also performed by a plenum gap of 61 cm which in addition incorporates a spring allowing fuel expansion (Blair, 2003). The gap between the fuel pellets and the clad tube is filled with helium gas in order to improve heat conduction from the fuel to the cladding.

**Figure 4. 10: Fuel pellets (3.5% enrichment)**

### Fuel Enrichment

Low enriched uranium (LEU) uranium dioxide serves as the fuel (UO2). Fuel assemblies for typical PWR cores will have varying degrees of uranium enrichment. LEU is enriched to 3–5% 235U in order to be used in naval reactors. Low enriched UO2 pellets with a helium gap and zirconium alloy cladding make up the fuel rod. To attain the needed power for the anticipated four-year core lifetime, the active fuel length, fuel enrichments, and loading pattern will all be researched and tuned. Core size is therefore another variable. The fuel enrichment influences the reactor power output and its core size. As the reactor size is limited by the ship dimensions and its load capacity the reactor core size should be minimized. In order to provide the required power output, the enrichment of the fuel is optimized.

The KLT-40S reactor employs less than 5% U-235 enrichment, however for the reactor core analysis the enrichment was assumed to be equal to 5.0%. This enrichment level allows reaching an adequate core size allowing allocation of a core on a ship, leaving enough space for transportable cargo. The increase in fuel enrichment decreases the core size dimensions by a factor of 2. The increase in fissionable material in the core also increases the power output; therefore, there is the potential for higher ship travelling speeds (KLT-40S).

## Reactivity Control

As U-235 fission normally produces 2 to 3 neutrons, however the controllable chain reaction in thermal reactors requires one fission event to be caused by a preceding fission, some of the neutrons should be absorbed by the materials that absorb neutrons and do not fission (“neutron poisons”) (Muhammad 2010). Reactor criticality is expressed in terms of the multiplication factor k which represents the increase of the neutrons in a further generation and is expressed as a ratio of number of neutrons in the current generation to the number of neutrons in the previous generation:

$$k = \frac{n1 + 1}{n1} \qquad \text{………………………………..…………………(4.1)}$$

In order to keep reaction critical multiplication factor should be kept at k=1. To describe kinetics and dynamics of nuclear reactors the concept of reactivity (ρ) is used. ρ characterizes the deflection of the reactor from the critical state:

$$\rho = \frac{k - 1}{k} \qquad \text{…………………………….……………………... (4.2)}$$

The coefficient k varies throughout the reactor operation from slightly less than 1 to slightly higher than 1, therefore a negative value of ρ implies reduction in fission number, and a positive ρ corresponds to an increase in the number of fissions. Ideally ρ is kept to be equal to zero for normal reactor operating (k=1). The neutrons that escape from the fuel area or are absorbed by the non-fissile materials do not cause fission. Some of the neutrons which leak from the core are absorbed by the concrete shielding around the reactor vessel; all the neutrons that do not cause fission but remain in the core will be absorbed by the structural materials of the core, fission products and control rods.

Control rods containing boron (which absorbs neutrons) are attached to a drive mechanism in the reactor pressure vessel which allows them to be inserted or withdrawn from the reactor core moving inside the guide tubes allowing neutron absorption in order to sustain the critical reaction in Figure 4.11. Boron carbide is used as the material for the control rods, it is commonly used to control reactor chain reaction in different reactor types because of boron’s high absorption cross section. Each fuel assembly incorporates 24 control rods, each group of 24 control rods contain rods which perform the power control and rods used for the shutdown. Neutron absorbing materials (burnable absorbers) are also incorporated in to the fuel pellets. At the start of the fuel life cycle, when the fuel is more capable to produce higher power output, these materials suppress this powers surge. However, by the end of the life cycle the amount of fissile isotopes reduces and a part of the absorbing material is also transmuted into materials with negligible absorption cross section. This means that the neutrons are absorbed at a lower rate, therefore a higher amount of neutrons are available to cause fissions. Gadolinium, erbium-167 and boron-10 are used as burnable absorbers (Abram 2008), (Volkov, 1962). The temperature coefficient of reactivity in a PWR is negative under all conditions. This denotes that the increase in reactor power output (coolant temperature rise caused by the growth in reactivity) will cause a decrease in the moderation leading to the purer neutron slow down therefore decrease in the reactivity. This mechanism is inherent in the reactor design.  The KLT-40S reactor does not contain boric acid unlike other PWR reactors.

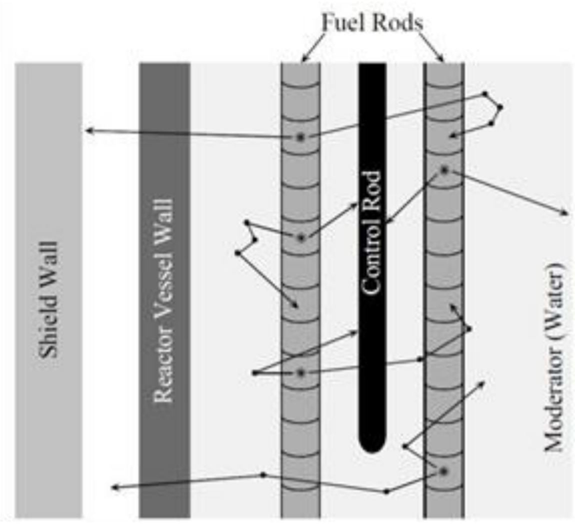


**Figure 4. 11: Schematic of control rods absorbing neutrons**

### Heat transfer in the reactor core

Figure 4.12 represents the temperatures of oxide fuel, cladding and coolant in the operating PWR reactor. The heat is generated in the fuel, therefore the temperature distribution inside the fuel pellets is uneven (parabolic). The heat obtained by fission reaction of the fuel first of all is transferred to the helium gap. The thickness of the gap is smaller than is required to allow convection, so the heat transfer from the fuel to the helium and from the helium to the cladding is performed by conduction. Helium has a low density (3.08 kg/m3) and pure thermal conductivity (0.028 W/mK), so a big temperature drop occurs in the gap between the fuel and the cladding in Figure 4.12. Heat transferred to the helium is then transferred to the fuel cladding and then to the oxide layer on the outside of the cladding, heat is then removed by the coolant.

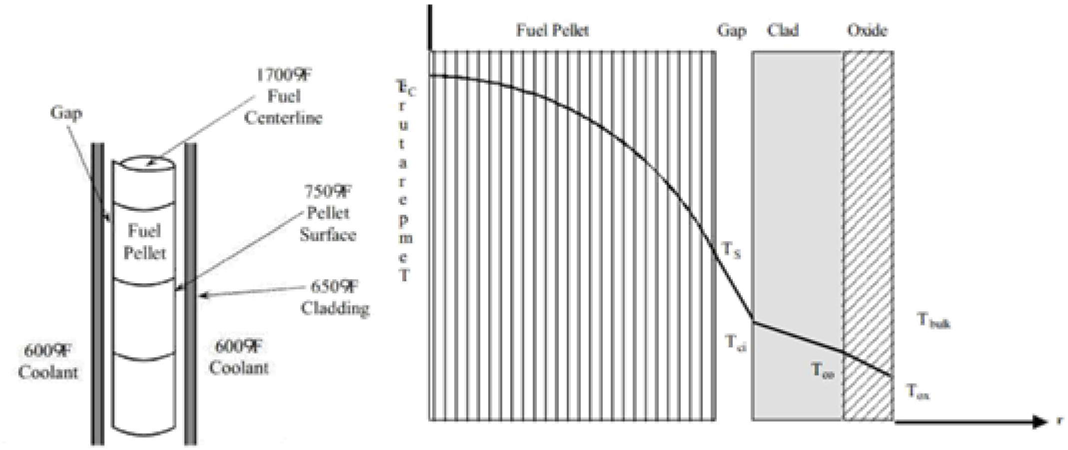


**Figure 4. 12: Temperature distributions of fuel, cladding and coolant in the operating reactor**

### 4.3 MONK Simulations

To perform neutronic design calculation the Monte Carlo computer code (MONK) was used. MONK is an industry standard code which was developed in the 1970’s and is used for the licensing of nuclear power reactors in Europe.

The computer code, based on the Monte Carlo technique, was created to promote the solutions of criticality, safety and reactor physics problems. MONK allows modelling complex geometries using Fractal Geometry (FG) which comprises of a Solid Simple Body package and a Hole geometry package.

The Solid Simple Body package includes a basic set of simple bodies such as sphere, box, rod, prism, cone, torus, etc. These are used to model basic blocks forming simple parts of the geometry. Unlike the Solid Simple Body package, the Hole package, using a technique called Woodcock tracking, allows modelling more compound geometric shapes and arrays. This significantly simplifies fuel assemblies modelling; therefore, the Hole package is extensively used in MONK.

### KLT-40S core model description

The KLT-40S reactor core is close to a cylindrical shape and is composed of 69 fuel assembles with 22 cm pitch, the resulting core diameter and height (here active fuel height) are 118 cm and 241.3 cm respectively (Zverev, 2019). The core is shielded in a steel cylinder reflector which was assumed to have 5cm radial thickness and 20cm top and bottom thickness. Shielding allows reducing neutron leakage from the reactor core and improves safety. The reactor core horizontal cross section can be seen in Figure 4.13.

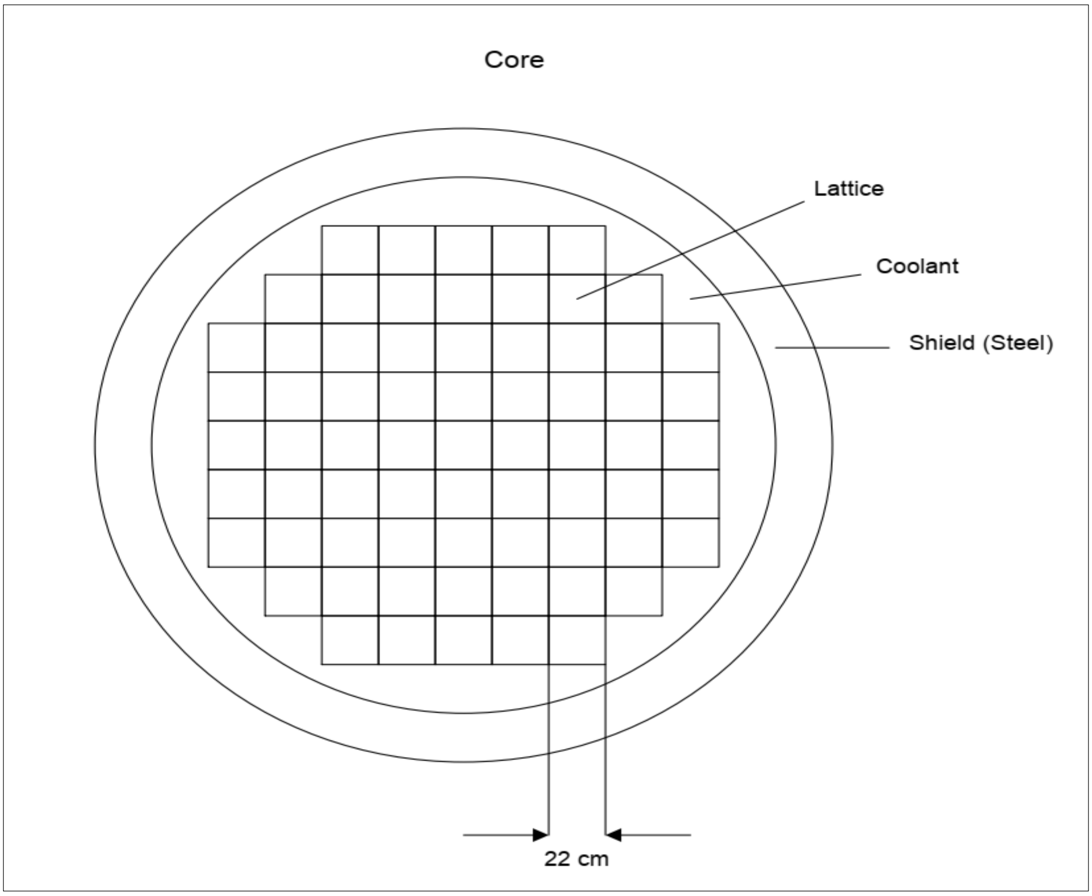


**Figure 4. 13: KLT-40S reactor core layout**

Each fuel assembly has 264 fuel rods containing fuel pellets, 24 control rods with the neutron absorber (B4C) and an instrumentation tube accommodating instruments to measure instant parameters of the reactor such as coolant temperature. The rods are assembled into a 17x17 array with 1.239cm pitch forming a fuel assembly using a spring clip grid in Figure 4.14. To simplify the analysis the spring clip grid was not modelled as it does not contribute significantly to the criticality or the fuel burn up. Westinghouse fuel assembly can be seen in Figure 4.14.

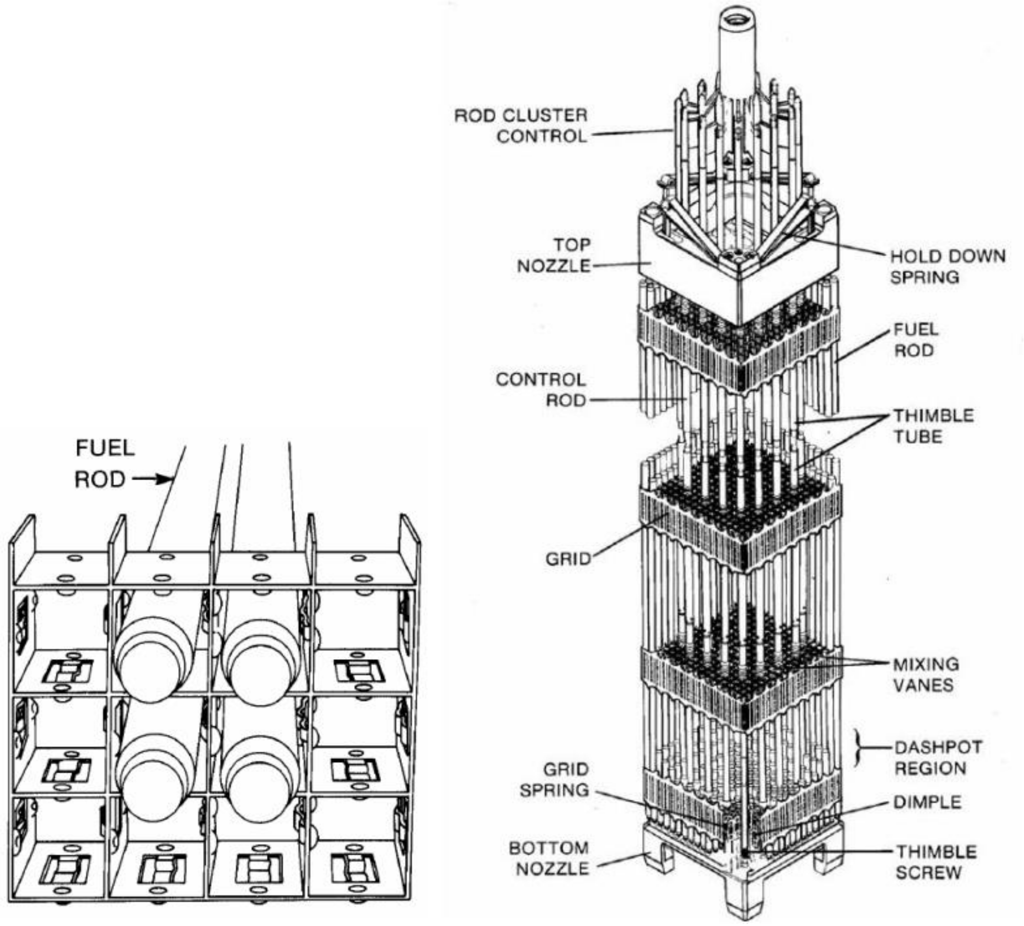


**Figure 4. 14: Part of spring clip grid, Cutaway of fuel assembly**

The rod cluster is made up of rod cluster control (RCC) assemblies, which are connected at the top by a spider-like bracket and roughly the same size as fuel rods. A separate magnetically driven driving mechanism situated on the reactor vessel head activates each RCC's drive shaft, which is linked to each RCC. Each RCC travels vertically in its tubular guide thimble (0.03556cm thickness Zircaloy), and control rods remain attached to guide thimbles at their upper ends even when fully withdrawn. RCC was represented by a simple array of control rods in zirconium cladding in order to simplify the analysis (USNRC, 2021), (Marshall, 2015). The arrangement of fuel rods, control rods and instrumentation tube in a fuel assembly is provided in Figure 4.15.

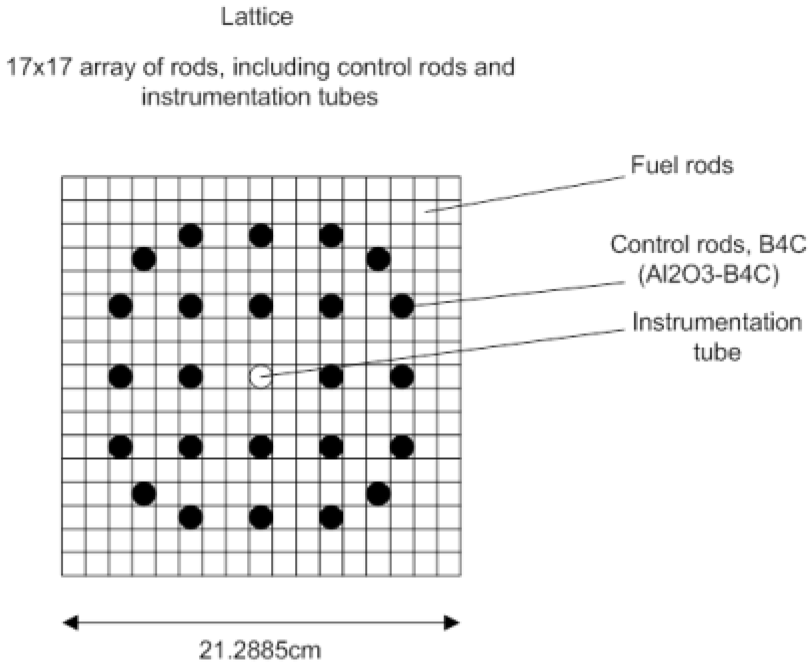


**Figure 4. 15: KLT-40S lattice layout**

Parameters of fuel rods are provided in Figure 4.16. Control rods and instrumentation tubes were assumed to have the same dimensions as fuel rods (including helium gap and cladding thickness), however the clad material is steel, and Zircaloy-4 is used as the fuel cladding. In this analysis control rods are modelled without guide tubes, only with steel cladding. Each fuel/control rod accommodates fuel pellets/burnable material of 0.3922 cm radius in a tube of 0.4079 cm inner and 0.457cm outer diameter. A pressurised helium gap of 0.0157 cm allows accommodating fuel expansion and failures due to irradiation (Zverev, 2019). The main parameters of the modelled reactor are described in Table 4.2.

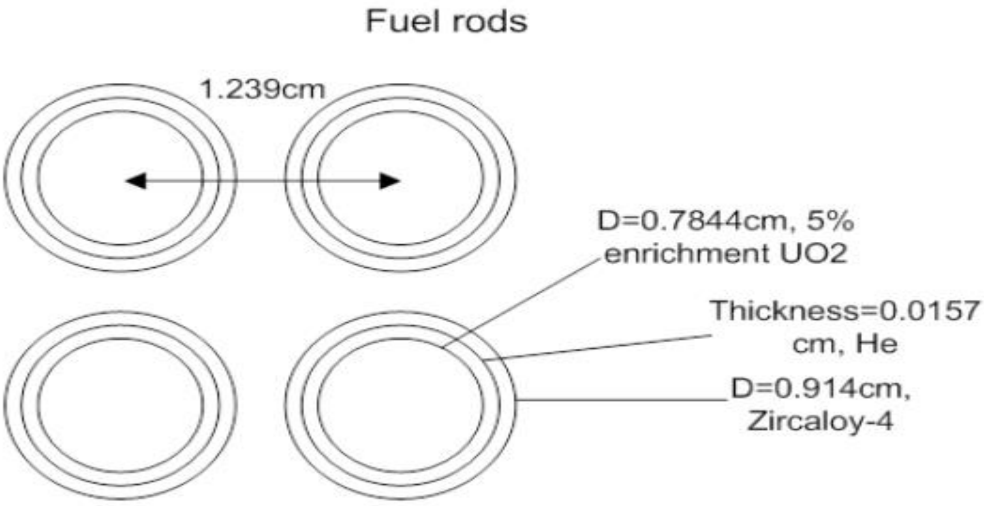


Figure 4. 16: Fuel rods

**Table 4. 2: The main parameters of the modelled reactor**

| **Parameter** | | **Value/Material** |
|---|---|---|
| Thermal output | | 450 MWt (03 units) |
| Coolant | | Pressurised Water |
| Fuel | | $UO_2$ (5% U-235 enrichment) |
| Core radius (without reflector) | | 118 cm |
| Height of fissile zone | | 241.3 cm |
| Number of fuel assembles | | 121 |
| Fuel density | | 10.97 $g/cm^3$ |
| Fuel pin radius | | 0.3922 cm |
| Fuel rods pitch | | 1.239 cm |
| Fuel cladding material | | Zircaloy-4 |
| Fuel cladding thickness | | 0.0491 cm |
| Absorber material | | $B_4C$ |
| Absorber pin radius | | 0.3922 cm |
| Absorber cladding material | | Steel |
| Absorber cladding thickness | | 0.0491 cm |
| Helium gap thickness | | 0.0157 cm |
| Fuel assembly thickness | | 21.2885 cm |
| Fuel assembly height | | 241.3 cm |

| | | |
|---|---|---|
| Total Mass of Fuel | | 23.3 Tonnes |
| Reflector material | | Steel |
| Lower reflector thickness | | 20 cm |
| Upper reflector thickness | | 20 cm |
| Radial reflector thickness | | 5 cm |
| Operating time | | 3-4 years |

The calculations were performed with a standard deviation of 0.002.

The created reactor model does not take into account a 61cm long plenum spring which is incorporated in an original design and accommodates fuel expansion and fission gases.

## 4.4 Reactor Safety Analysis

### 4.4.1 Regulatory requirements

The nuclear industry is probably the most strictly regulated of all industries. Each country that utilizes nuclear power has its own nuclear regulatory body that is legally authorized to protect the public and the environment against the dangerous effects of ionizing radiation. For this purpose, most regulatory bodies have developed a set of regulations to govern all nuclear-related installations and activities via the granting of licenses. (Bae, 2001)

This fragmented international regulatory framework has a direct impact on the development of a commercial nuclear ship engine, since the nuclear ship might have to be separately licensed for each country that would be visited during operation (Ramana, 2013). This would result in a very costly and time-consuming process, since the process to obtain a license for a new type of nuclear reactor could easily extend over more than a decade! (Elbaradei, 1995)

This section aims to establish the requirements related to safety for a nuclear propulsion unit of a nuclear powered ship. For this research, the most significant safety requirements from the IAEA Safety Requirements publication, "Safety of Nuclear Power Plants: Design", NS-R-1 (IAEA, Vienna, 2000) are used:

a. Utilize the Defence in Depth concept to ensure multiple independent layers of protection in Figure 4.17.

b. Ensure that the three Fundamental Safety Functions are always maintained:

i. Control of the reactivity.

ii. Removal of heat from the core.

iii. Confinement of radioactive materials and control of operational discharges, as well as limitation of accidental releases.

c. Two diverse reactor shutdown systems shall be provided.

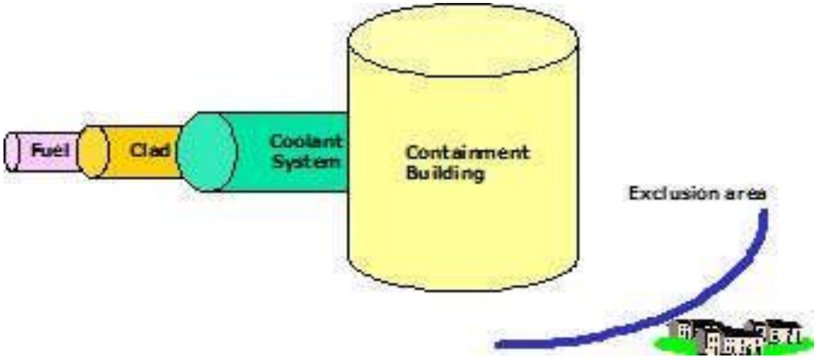


Figure 4. 17: Defence-in-depth: barriers

### 4.4.2 Reactor design safety features

The KLT-40S reactor has focused on achieving design with innovative safety characteristics. The safety analysis of the reactor must be in line with national and international regulations. Since the KLT-40S is an American design approximately three dozen general requirements of safety analysis have been identified and must be addressed before the reactor can go into production (Zverev, 2019).

Eliminating any situations that could potentially result in core damage is the first line of defense. A "safety-by-design" strategy, which may be summed up as "designing the plant in such a way to eliminate accidents from occurring, rather than coping with their repercussions," is used in most SMRs, including the KLT-40S, to put this notion into practice (Carelli, 2003). The benefit of such a strategy is that the reactor is constructed so that the possibility of an accident is drastically reduced—to the point where it would be impossible with traditional land-based reactors.

The KLT-40S builds on technology employed by over 40 years of operating PWR's with no new components/technology being incorporated into its design (Carelli, 2003). The design also uses passive safety features. The use of passive safety systems provides improvements in simplifying the plant, increased safety and reliability when compared to conventional plant designs (IAEA, 2020). The result equals a design with reduced complexity and improved operability which made it a worthy choice to be employed on the Emma Maersk (EM). The following section will address the main safety features of the KLT-40S design. Safety evaluations are carried out to ensure that a reactor's parts achieve the following goals:

- failure and abnormal operation prevention
- control of aberrant operation and failure detection
- preventing hazards within the parameters of the design
- management of adverse plant circumstances, including steps to alleviate the effects of accidents and stop their progression
- reducing radioactive material releases

Demonstrating the safety analysis of the KLT-40S reactor under accident scenarios is paramount to achieving the objectives and consequently making a case for it to be employed on a commercial ship. B&W attempt to verify and validate the objectives using scaled testing data and mathematical modelling. Testing and modelling data must satisfy the regulations stated in 10 CFR 50.43 (e) (1) which includes:

Through study, test programs, and/or experience, each safety aspect of the design has proven to work as intended. Analysis, suitable test programs, and/or experience have all determined that the design's safety features' independent effects are acceptable. It is possible to evaluate the analytical methods used for safety analysis under a variety of operational conditions, transient conditions, and specified accident sequences, including equilibrium core conditions, thanks to the availability of appropriate data on the design's safety features. The KLT-40S, as well as other SMR's, fulfil these safety objectives and regulations by:

- Exhaustive review of what accidents can occur and how the design is able to contain/mitigate the consequence.
- Minimising or eliminating, if possible, the occurrence of “cliff-edge” effects during normal operation, anticipated operational occurrences (AOOs) and accidents. (Stoiber, 2003)
    - Providing a long grace period when operator action is necessary. Simplifying the architecture of the reactor by:
    - Applying “As Low As Reasonably Achievable” (ALARA) principles to maximise the protection of workers against radiation exposure.
    - Minimising/mitigating hazards other than radiological ones e.g. chemical hazards.
    - Minimise production of waste and making suitable storage for them.
    - Preventing/minimising the consequence of sabotage and proliferation.

## 4.5 Radiation Shielding

Radiation is a serious concern in nuclear power industry. Preventing radiation from causing any harm to employees and the environment is necessary for safe operation of equipment (reactor core) that emits radiation (Blekher, 2000). Protection of surrounding structural materials is also of high importance since materials properties change with irradiation (metal embrittlement, etc.) discussed. The penetration of radioactive rays and its regulation vary depending on the type of radiation involved. This depends on the interaction between specific particles and elemental properties of the materials used as the shield; therefore, for different types of radiation different materials are better suited. (Sneve, 2013). The principle of attenuation is the base for radiation shielding. During attenuation a wave's or ray's effect is reduced by blocking or bouncing particles through a barrier material. For reactor shielding more attention is paid to neutron and gamma ray radiation, because alpha particles, beta particles, and protons have a very short range in matter due to their charge. Charged particles can be attenuated by losing energy in interactions with electrons in the shielding material. The suitable material is dependent not only on the type of radiation, but al soon its energy. The following equation describes how a shield attenuates monoenergetic x- or gamma rays exponentially over a narrow beam:

$$I = Ioe^{-\mu x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.3)$$

where I is the intensity outside of a shield of thickness x, Io is the unshielded intensity, μ is the linear attenuation coefficient of the shielding material (1/cm) and xis the thickness of shielding material. The linear attenuation coefficient represents the sum of the probabilities of interaction per unit path length by photoelectric effect, Compton effect, and pair production. The reciprocal of μ is defined as the mean free path, it corresponds to the average distance the photon travels in an absorber material before an interaction occurs

(RSSC Radiation Protection, 2011). Linear attenuation coefficients are proportional to the absorber density, which usually depends somewhat on the physical state of the material; therefore the mass attenuation coefficient is used in order to avoid density dependence:

$$\mu_{\boldsymbol{m}} \quad = \frac{\mu}{\rho} \qquad \text{…………….……………………….(4.4)}$$

where ρ is the density of absorber material (g/cm3).

For a given photon energy, µm does not change with the physical state of a given absorber. For example, it is the same for water whether present in liquid or vapour form (if the density stays constant). If the absorber thickness is in cm, then µm will have units of cm2/g [RSSC Radiation Protection, 2011]. Using the mass attenuation coefficient instead of the linear attenuation coefficient, the attenuation equation can be rearranged as follows (RSSC Radiation Protection, 2011):

$$I = Ioe^{-\mu m\rho x} \qquad \text{……………………………………….(4.5)}$$

A substance with a high atomic number is sought for gamma ray shielding, where the major interaction occurs with atomic electrons (this includes lead and iron). The material, thickness, and photon energy of the shield all affect how much attenuation is gained. Through photoemission, scattering, or pair formation, gamma and x-ray radiation is attenuated (Jones A., 2014). The primary characteristic of a shielding material is the thickness reduction by half (or half-value layer, HVL). The halving thickness is the thickness of the material at which the intensity of the entering radiation is reduced by one half. For the majority of ionising radiation (a combination of gamma rays fluxes and neutron fluxes) HVL can be approximated by the following expression:

$$d = \frac{23}{\rho}$$ ……………………….………….( 4.6)

Where corresponds to the halving thickness (cm) and is the material density(g/cm3) (Atamanyuk, 1986).

A comparison of gamma radiation half-value layers of different materials was presented in Figure 4.18. Table 4.3 summarises further properties of materials employed as shielding (material density and half value layers for gamma ray and neutron radiations).

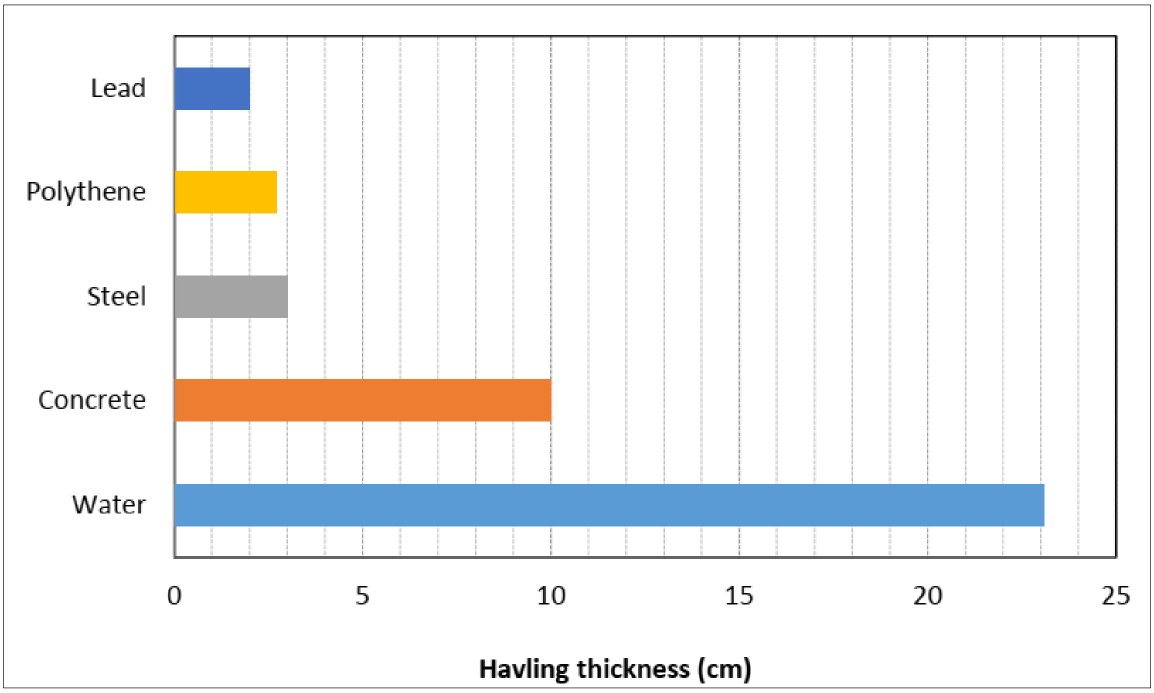


**Figure 4. 18: Halving thicknesses of different materials (ionizing radiation)**

**Table 4. 3: Properties of Shielding Materials**

| Material | Density (g/cm3) | Halving thickness (cm) (ionising radiation) | Halving thickness (cm) (neutrons) |
|---|---|---|---|
| Water | 1.00 | 23.1 | 2.7 |
| Concrete | 2.02 | 10.0 | 11.5 |
| Steel | 7.50 | 3.0 | 12.0 |
| Polyethylene | 0.95 | 2.7 | 2.7 |
| Lead | 11.34 | 2.0 | 12.0 |

Due to the high energy loss experienced when a neutron collides with an atom of the shield material, a light element is chosen for the shielding of fast neutrons (both elastic and inelastic scattering significantly reduce neutron energy). The goal is to delay neutrons close to where they came from so that they can be absorbed at thermal energy. Consequently, hydrogenous materials like concrete, polyethylene, and water are efficient neutron shields (Murray, 2014). It could be noted, that polyethylene has a comparably small halving thickness(2.7cm) for a combination of neutrons and gamma rays (ionising radiation). This is due to the fact that polyethylene is an effective neutron shield; even though its low density leads to a pure performance in gamma rays cases. Polyethylene's small neutron radiation HVL (2.7cm) and low density (0.95g/cm$^3$) (Al-Sarray, 2017) make it suitable to be employed as a shield on a nuclear merchant ship, as this allows bringing the dose rate down to a certain (acceptable) level, while keeping the volume and the mass of the shield minimized. Furthermore, polyethylene has good ease of manufacturing (Thermo Electron Corporation). Water, being a good neutron shield with halving thickness of 2.7 cm, is also one of the possible solutions. The use of liquid shield would require additional modifications do be made to the propulsion unit design with pitching of the ship taken into account. However in this case the damage of the water sink employed around the reactor core might result in a complete loss of neutron shield; therefore the use of this material as a neutron shield would decrease the safety. For gamma ray shielding lead is a possible solution, nevertheless its high density would result in high mass of the shield, however small halving thickness for ionizing radiation (2.0cm) allows saving the space on the ship. When incorporating reactor shielding it is necessary to account for generated gamma flux, caused by absorbed neutrons and beta particles in the shield. It may be required to shield with a variety of materials when various radiation types, such as beta particles and gamma radiation, are released. The more penetrating gamma radiation would need an extra layer of shielding, whereas the less penetrating beta radiation can be first insulated with a layer of plastic (such as polyethylene or plexiglass), slowing or stopping the beta particles while minimizing the generation of bremsstrahlung. This means that a gamma shield inside a neutron shield may not be as effective as the gamma shield outside the neutron shield. Therefore after placing a neutron shield, a gamma shield (which is passive to neutrons) is incorporated. Thus a combination of neutron shield (for example polyethylene) and gamma ray shield on its periphery (for instance lead) is a suitable solution.

With international practice, an obvious requirement is that personnel have to be shielded against radiation exposure. The International Commission on Radiological Protection (ICRP) publishes recommendations on the amount of radiation that is deemed acceptable. According to the ICRP publication 103, any single worker that is occupationally exposed to radiation should not receive more than 20 mSv/year, averaged over 5 years. Radiation exposure of a member of the public should not exceed 1 mSv/year.

In addition, it is important to ensure that the oil cargo (or any other cargo) does not get activated by a neutron field, since this would lead to widely distributed radioactive contamination once the oil is offloaded and distributed through the oil supply chain. A thermal neutron flux limit of $2\text{x}10^5$ neutrons cm-2 S-1 is assumed as an acceptable level, based on experience. (Vidal, J., 2009). The limits on effective dose (dose to the whole body) introduced by the IRR99 to replace the limits set previously by the IRR85 are 20 millisieverts (mSv) ina calendar year for a radiation worker and 1 millisievert in a calendar year for any other person (The Ionising Radiations Regulations, 1999). The shielding design of a reactor must allow workers protection during the reactor core operation and maintenance; therefore, neutron and gamma doses received by the worker should not exceed the allowable limit of 20mSv/year. This can be sustained by a limitation of the contact time with the shielded core within the containment, which allows minimizing the required shield thickness, therefore minimizing space and weight of the reactor plant. The allowable dose rate at the sides of the reactor shield was assumed to be of the order of 1 mSv/h. This allows attendance in the containment for 20 hours a year (if the dose rates level falls below 1 mSv/h).

## 4.6 Safety of Crew

The general safety on a nuclear propelled container ship is very different to a commercially powered ship. The risks attributed to a nuclear malfunction need to be taken into account when operating the ship and independent and redundant systems need to be employed to minimise the risk to employees and cargo.

Members of the crew can be exposed to various forms of ionising radiation; electromagnetic rays (gamma, X-ray etc) or high energy particles (alpha and beta particles). The protection and safety of the public and the environment during operation of the nuclear propelled container ship must be optimised to allow the following consequences:

- the magnitude of individual radiation doses,
- the number of persons exposed, and
- the likelihood of incurring exposure

To be as low as reasonably achievable. In addition to this, radiation doses to persons must be below the relevant dose limits set out by the IAEA and, in the UK, the “Ionising Radiations Regulations 1999 (IRR99)” (HSE, 2010).

If the ship is of UK origin the legislation on radioactive exposure, IRR99, limits any person exposure to a variable dose limit (HSE, 2010):

1. employees (18+) are subject to a maximum dose limit of 20 mSv per calendar year

2. in special circumstances the dose limit can increase to 50 millisieverts in a single year but the employee must not be exposed to more than 100 millisieverts in 5 years
3. trainees have a maximum dose limit of 6 milliseiverts in a calendar year
4. members of the public and employees under 18 are permitted a maximum of 1 mSv per annum

The dose limits for the skin is averaged over an area of skin 1cm$^2$ maximum.

The same requirements are applicable on the ship due its effectiveness. Incidents occur because of poor job planning (most notably with site radiography); failure to use adequate local source shielding (collimation); or inadequate systems of work. On the ship any of these incidents would cause catastrophic results and as such safety systems must provide diverse safety mechanisms to ensure the risk is minimised as much as possible.

The simplest form of safety which can be given to the crew is having them wear film badges; TLD's to monitor radiation levels across the voyage. Any personnel exceeding the recommended intake can be placed in a shielded room where they will receive minimal exposure.

In the event of an accident adequate preparations have to be established and maintained to enable a quick and thorough response on the ship itself. To address this multiple and diverse detection equipment, such as NaI scintillator detectors can be installed at strategic points across the ship to provide a quick emergency alarm to notify all staff of leakage.

Specialist training should be provided to engineers on board the ship to enable proper operation of the reactor as well as radioactive materials. The training must be specific and rigorous to prepare the engineer on any potential outcome which may arise.

Around the ship radiation shielding materials can be placed such as lead lined doors and windows to provide diverse means of shielding and protect workers. The extra shielding will increase the inherent safety of the crew and cargo.

The advantage of using the KLS-40S design is that it incorporates a high level of automation, including controlling start-up and shutdown. This reduces the probability of human error whilst also reducing the number of specialist staff needed which consequently reduces the total number of staff reducing the total number of staff exposed to radiation.
The reactor pressure vessel into which all the primary components are placed is the primary course of radiation mitigation as it is able to provide shielding in the event of an accident. The reactor vessel is also able to contain all the debris resulting from a rupture of melting of components (Carelli, 2003, IAEA, 2019).

The reactor can also be surrounded by emergency diesel tanks, used to power emergency diesel power. Diesel properties are good at absorbing radiation and reflecting neutrons due to the large number of hydrogen atoms in its structure. As such diesel fuel can perform two tasks; neutron absorption to limit radiation and power the ship if nuclear power is unavailable.

In the case of an incident involving radioactive leakage the ship operators/personnel are advised to follow the following procedures:

- provide first aid to injured persons;
- not touch the package;
- notify the overseeing body;

- evacuate and control access to the incident area until the arrival of appropriate personnel to control the situation;
- immediately notify the Radiation Health Unit, in the closest country, of the incident;
- follow on board instructions to control the incident given by the consignor, or an officer of Radiation Health from the country of origin;
- not eat, drink or smoke while at the incident site;
- identify persons or equipment that may have been contaminated by radioactive material or exposed to radiation; and
- provide a report to the legislative body within 7 days, advising of:
  (a) location of incident
  (b) nature and cause of incident
  (c) actions taken to contain incident
  (d) clean up procedures and environmental concerns
  (e) any person exposed or possibly exposed
  (f) proposals aimed at avoiding a recurrence.

## 4.7 Port Safety

Safety within ports is of extreme importance due to the large number of people which can be affected if an accident does occur. Therefore, if a nuclear powered ship docks at a particular port, the risk needs to be assessed and contingency measures need to be applied to mitigate the effect of release of radioactive material (Helmick 2008).

The principle aims of an emergency response, according to the IAEA, can be conveyed as:

"To ensure that arrangements are in place for a timely, managed, controlled, co-ordinated and effective response at the scene, and at the local, regional, national and international level, to any nuclear or radiological emergency." (Harrington 1992)

According to a publication released by the IAEA and IMO three problems need to be addressed when assessing the suitability of a port for nuclear powered ships (STCW, 2011):

- recognised reference doses for individuals to be used when evaluating accidents involving release of radioactive material
- assessment of the possible releases of radioactive materials and its consequence from the ship
- possible limitations of release of radioactive material by careful selection of a berth and by emergency planning

Potential ports which can be used for a nuclear propelled ship must meet set criteria. From a safety perspective these can be collated as follows (International Atomic Energy Agency and International Maritime Organisation, 1968):

- Factors influencing the likelihood of an accident occurring due to external causes. One possible method of assessing the feasibility is by evaluating the history of accidents which have occurred at the port.
- Factors influencing the dispersal capability of radioactive material. This would include environmental implications such as seasonal variations in wind/ tide etc.
- Factors influencing the potential consequences of an accident such as the population density around the port.

Using the following criteria safety is the most important aspect when picking a port for a ship to dock not only due to the potential impacts on personnel but also on the surrounding area.

# CHAPTER 5: SIMULATIONS RESULTS AND OBSERVATIONS

## 5.1 Results and Discussions (MONK)

The MONK software allowed computation of reactor criticality, the value of the obtained multiplication coefficient (keff) was computed to be keff=0.9997 with part of the control rods inserted allowing control of chain reaction. Therefore, criticality should be reduced in order to allow reactivity control. This might be done by introducing absorber material with an enriched number of burnable isotopes ($^{10}$B).

Rad Pro software was employed to perform shielding calculations. Radiation physicists, radiological researchers, radiochemists, radiation safety officers, health physics technicians, and other radiation physics specialists can benefit from the many nuclear computations that the Rad Pro calculator does. It computes, among other things, gamma emitter dosage rate and activity as well as conversions between radioactivity units (SI and US customary). The screenshots obtained using MONK software are provided below, these include reactor core radial and axial profiles and a fuel assembly cross section in Figures 5.1 and 5.2 respectively, the MONK code for this model is provided in Appendix C.

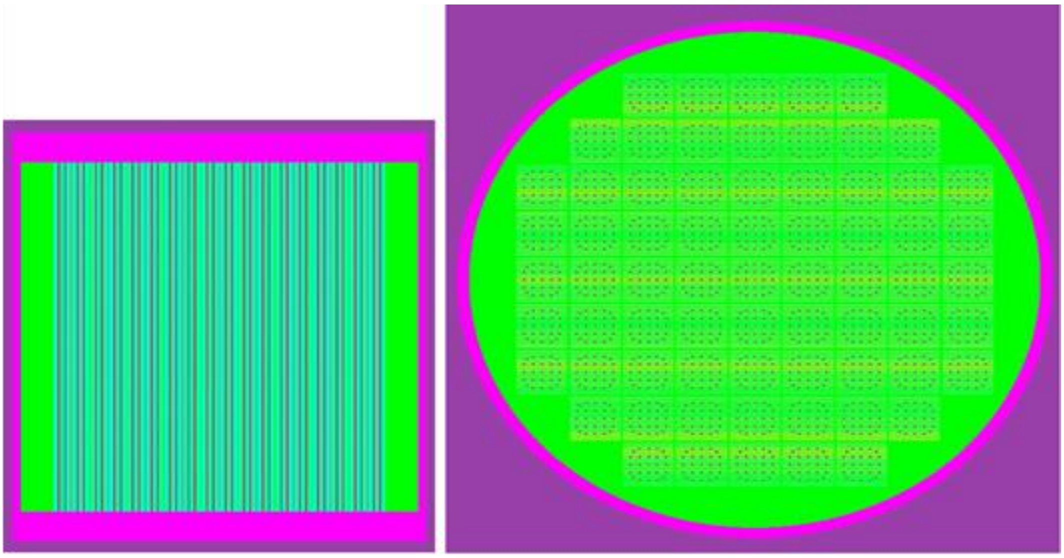


Figure 5. 1: Reactor core profiles

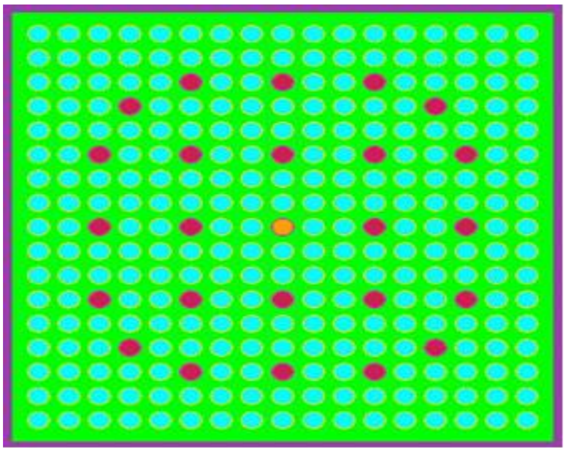
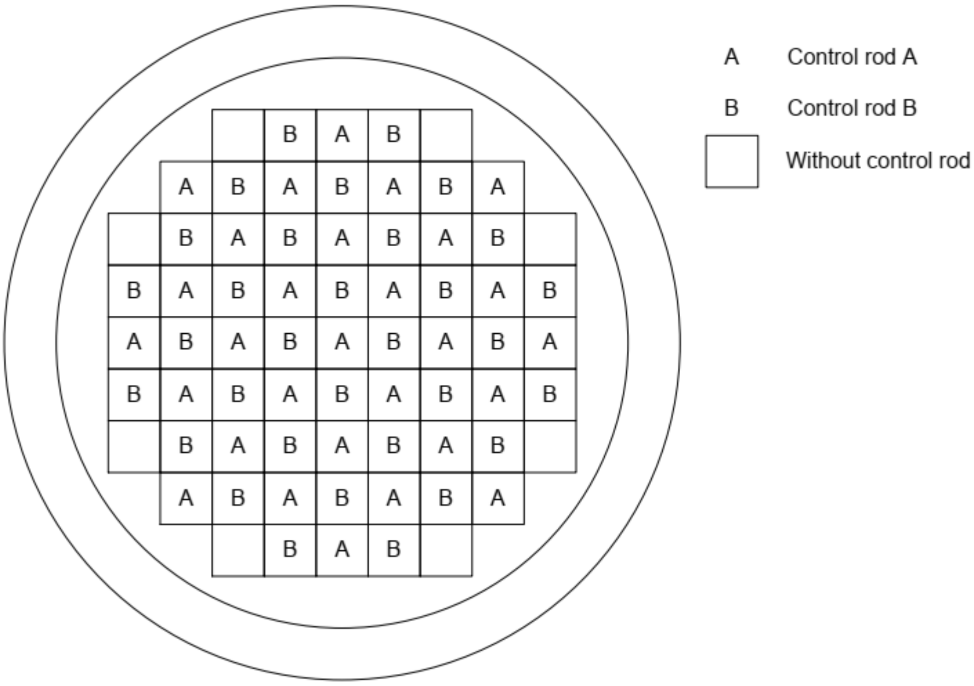


Figure 5. 2: Fuel assembly cross section

Note that not all of the fuel assembles incorporate control rods, the actual assemblies distribution is provided in the Figure 5.3 below (Erighin, 2012). There are two main sequences of control rods (marked A and B on Figure 5.3), control rods incorporated in these assemblies are used for reactor control and reactor shut down. A and B cluster also represent the variation in the fuel enrichment (lower for A assemblies and lower for B). However fuel enrichment variation was not considered in this simulation.



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | B | A | B | | | |
| | A | B | A | B | A | B | A | |
| | B | A | B | A | B | A | B | |
| B | A | B | A | B | A | B | A | B |
| A | B | A | B | A | B | A | B | A |
| B | A | B | A | B | A | B | A | B |
| | B | A | B | A | B | A | B | |
| | A | B | A | B | A | B | A | |
| | | | B | A | B | | | |

Figure 5. 3: Core with distribution of different fuel assembles

Core lifetime also could be obtained using burn up calculations. The burn-up calculation process requires special treatment, because of the variation in material compositions throughout the operating time. To accommodate these processes an extension of the methods used in deterministic calculations of burn-up was used. MONK estimated the flux at a particular time and this flux is used for estimation of reaction rates in considered materials. These reaction rates are then used to calculate the new material compositions by solving depletion equations. This method requires breaking down the calculation process into discrete steps in order to simulate continuous changes in material compositions. For a burn-up calculation each cycle (step) corresponds to a specified burn-up time.

In this particular case reactor thermal power output was set to 450 MWt (according to the original KLT-40S design X 03 units) and the operational time is 1440 days (6 steps introduced to perform the calculation) of EFPD (Effective Full Power Days), giving ≈4 years, as a first approximation. Control rods were discharged and replaced by the coolant (water).

## 5.2 Fuel Burn up

Burn up[1] calculations performed with 5% U-235 enrichment resulted in keff above 1 over almost 1440 EFPD in Figure 5.4, the equation of the line fitted into the data points in displayed on the graph). As at the start of the reactor lifecycle neutrons can be absorbed by boron (absorber rods) reducing $k_{eff}$ to 1, as well as moderating down fuel burn up, leading to the core life time extended to full 4 years. Under certain conditions (inserting more control rods at the start of reactor operation

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** Note that on the figures provided in this chapter the first value of reactor criticality is ignored in the analyses. The value provided as the first estimate of criticality is expected to be lower, however misaligns with practice due to simulation technique. The possibility of leakage at the first calculation stage is significantly lower than at further stages, because neutrons are assumed to be only presented in the fuel, but on later stages it becomes possible for them to escape, therefore neutron leakage contributes to criticality reduction.*

period and varying the amount of burnable poisons) this operating period could be extended to 4 years showed in Figure 5.4. Reactor criticality was also computed with all control rods inserted. This simulation resulted in the $k_{eff}$ value below zero in Figure 5.5.

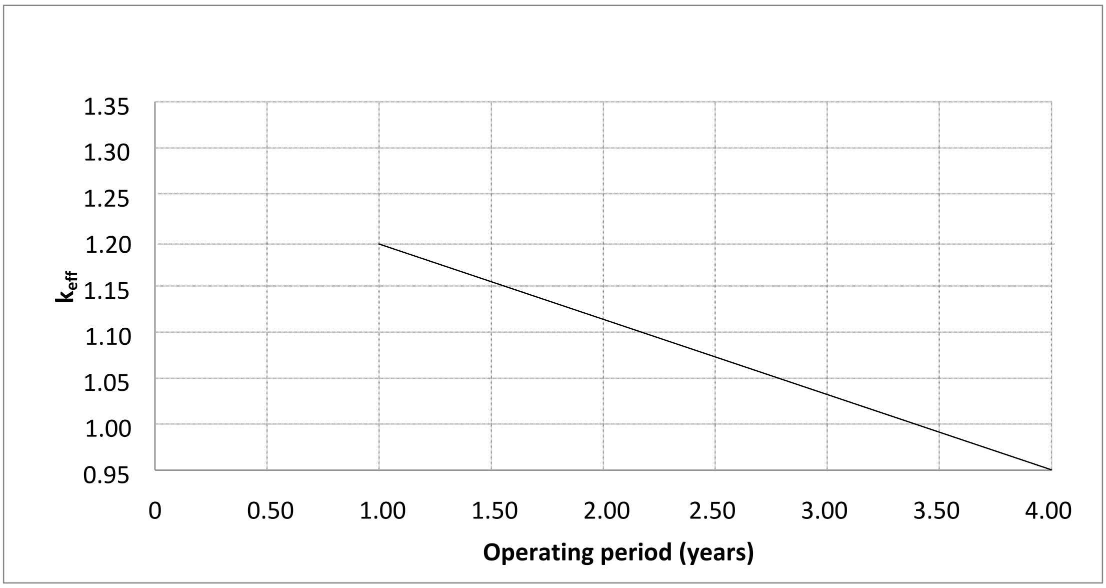

**Figure 5. 4: 5% enrichment, 15 controls rod assemblies with boron inserted**

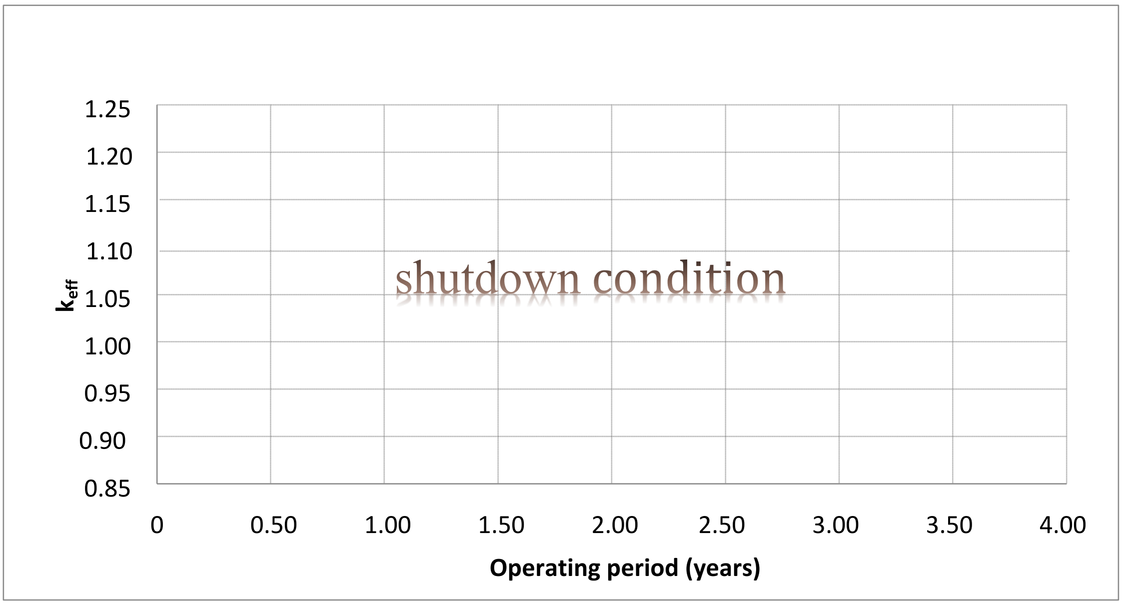

**Figure 5. 5: 5% enrichment, All control rods assemblies with boron inserted**

Fuel Burn-up simulations were performed for different U-235 enrichments. It was found that with 3.50% fuel enrichment is capable of operating for more than 3 years showed in

Figure 5.6 and, with appropriate content of burnable poisons in the reactor core materials, the operating period can be extended to 4 years showed in Figure 5.7.

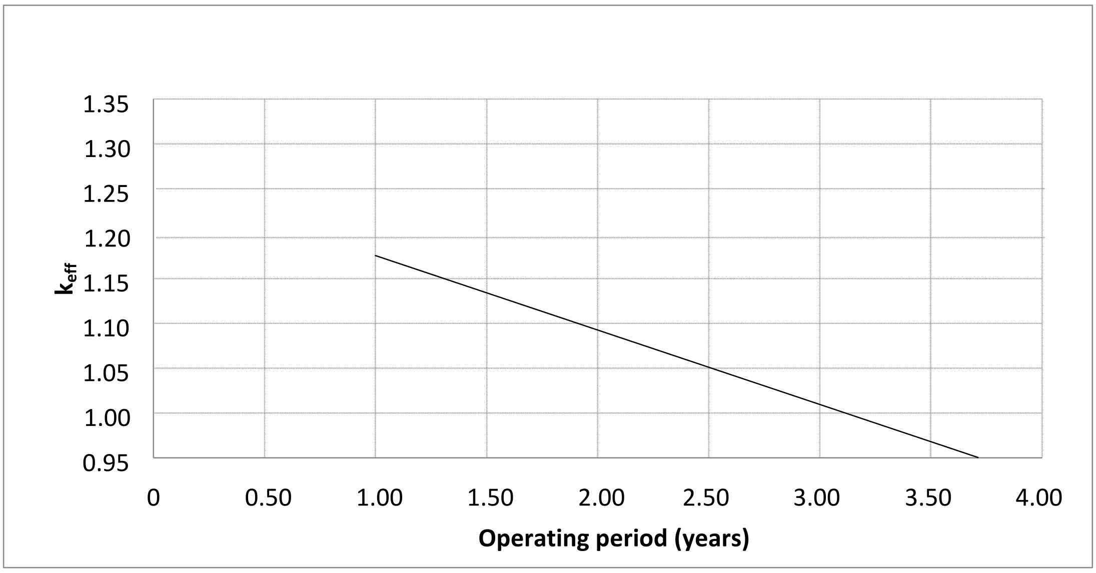

**Figure 5. 6: 3.50% enrichment, 11 control rods without boron**

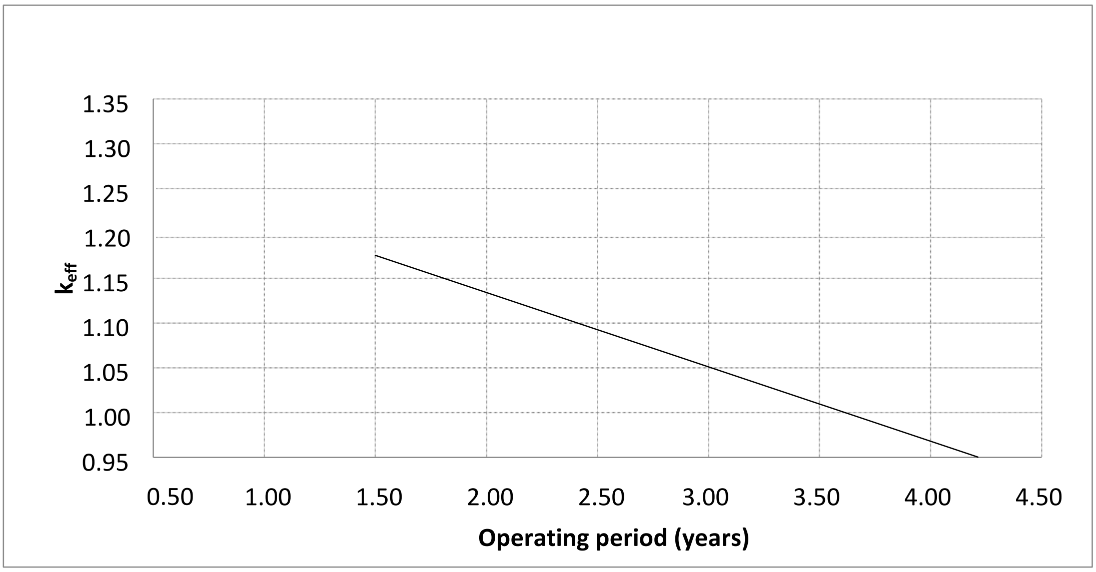

**Figure 5. 7: 3.50% enrichment, 11 control rods with appropriate boron**

The enrichment was then raised to 10% and 20% and the criticality variation with time was observed in Figures 5.8 and 5.9. It was found that with the uranium oxide fuel of 10% and 20% enrichment KLT-40S reactor criticality can be sustained for more than 7 years and 10 years respectively without refuelling, again when appropriate criticality control is performed.

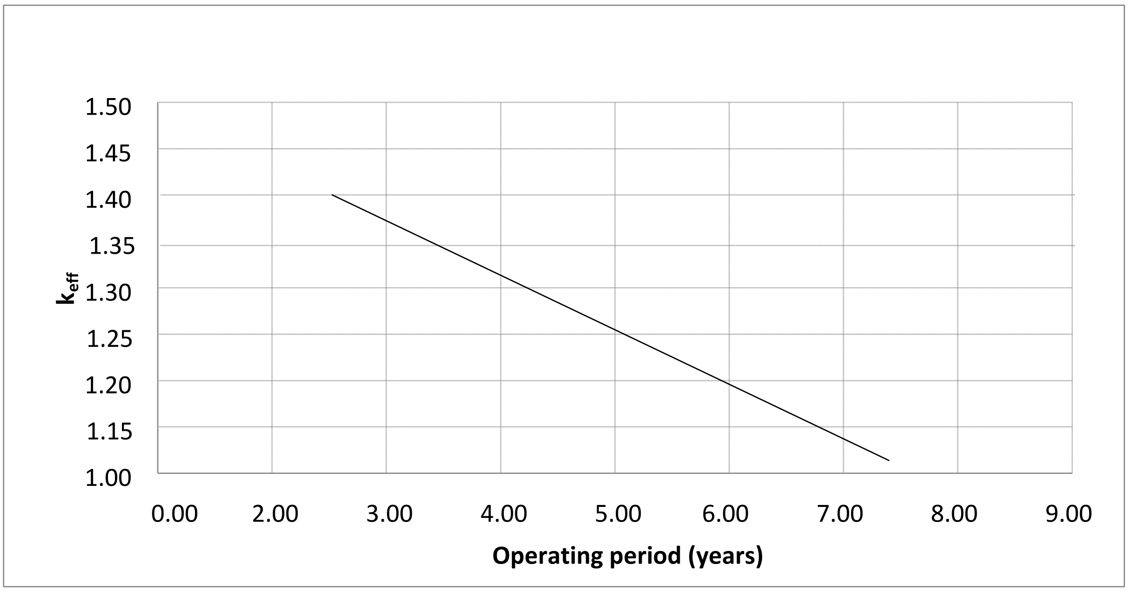

Figure 5. 8: 10% enrichment, 11 control rods with Boron

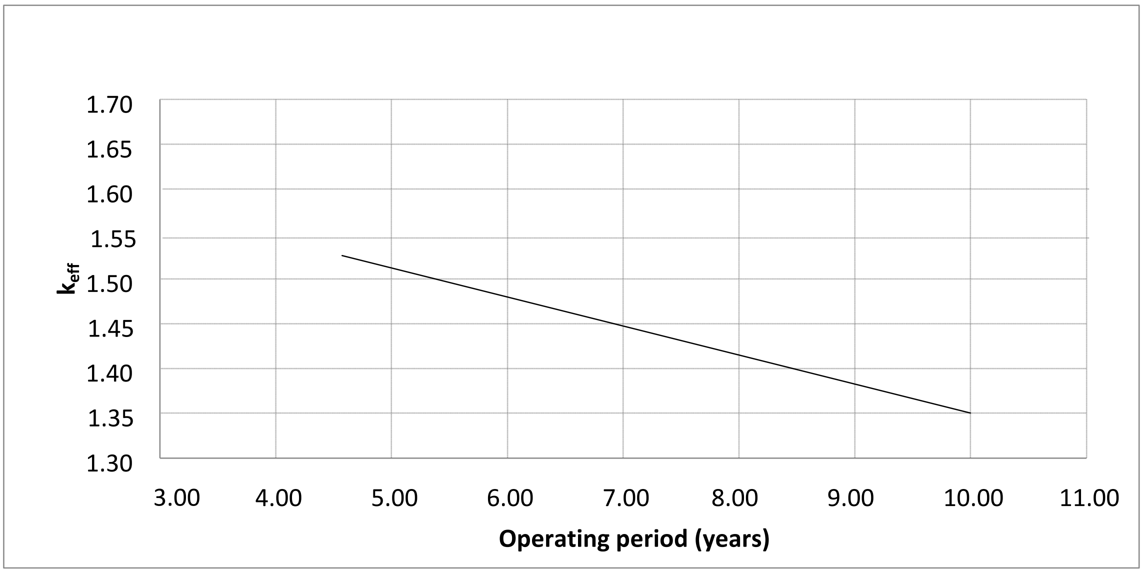

Figure 5. 9: 20% enrichment, 11 control rods with Boron inserted

## 5.3 Burnable Poisons

The significance of burnable poisons could be observed by comparing the rate of fuel burn up. The reduction in criticality for the case with boron in the coolant (water) was less rapid than for the case with no boron in the coolant in Figures

5.6 and 5.7. The same influence on the fuel burn up was observed moderating the number of control rods inserted in the core. Criticality decreased more significantly for the cases with absence or few control rods; however, with the increase of the amount of absorber in the core, criticality decrease over the operating time was reduced. Therefore, it was possible to conclude that the presence of burnable poisons and absorber in the reactor core not only allows criticality control, but also reduced waste fuel burning, therefore extends reactor core life time.

The significance of burnable poisons: The reduction in criticality for the case with boron in the coolant (water) or for the case with no boron in the coolant.

The significance Inserting control roads: Criticality decreased more significantly for the cases with absence or few control rods; however, with the increase of the amount of absorber in the core, criticality decrease over the operating time will reduced. The presence of burnable poisons and absorber in the reactor core not only allowed criticality control, but also reduced waste fuel burning, therefore extends reactor core life time. The summary of the output by MONK code is shown in Table 5.1.

**Table 5. 1: Summary of output by MONK Code**

| Fuel Burnup | Inserted Control Rods | Used Absorber | Keff | Core life | SD (%) |
|---|---|---|---|---|---|
| 5% | 15 | Boron | 1.2746 | EFPD | .0002 |
| 5% | All | Varying Boron | Below Zero | >5.5 yrs | .0002 |
| 3.50% | 11 | Boron | 1.27067 | 3 yrs + | .0002 |
| 3.50% | 11 | No Boron | 1.3056 | >4 yrs | .0003 |
| 10% | 11 | +/- Boron | 1.4982 | >7 yrs | .0001 |
| 20% | 11 | +/- Boron | 1.5495 | 10 yrs | -9E-05 |

## 5.4 Results and Discussions (Rad Pro)

Rad Pro code was run several times employing a single material as the reactor shield for both gamma and neutron radiations. These included steel, lead, water, concrete and polyethylene; runs with a void outside the core were also performed for the comparison. The thickness of the shield of the tested materials was specified as 20 cm. Dose rates were measured at the top/bottom and the sides of the core. The results obtained from Rad Pro software were summarised in Table 5.2 below.

**Table 5. 2: Fluxes obtained with different shields**

| Radiation | Position | Void | Concrete | Lead | Steel | Water | Polyethylene |
|---|---|---|---|---|---|---|---|
| Gamma dose rate (μSv/h) | Top | 4.450E+08 | 1.477E+08 | 3.018E+04 | 4.716E+06 | 2.608E+08 | 2.655E+08 |
| | Error (%) | 0.6 | 0.9 | 1.4 | 1.6 | 2.1 | 0.7 |
| | Side | 1.240E+09 | 4.279E+08 | 1.215E+05 | 1.626E+07 | 7.363E+08 | 7.508E+08 |
| | Error (%) | 0.4 | 0.4 | 0.6 | 3.0 | 1.4 | 0.4 |
| Neutron dose rate (μSv/h) | Top | 4.897E+07 | 3.214E+06 | 9.664E+06 | 9.922E+06 | 4.221E+04 | 1.508E+04 |
| | Error (%) | 3.5 | 1.5 | 1.3 | 1.0 | 13.7 | 3.1 |
| | Side | 1.742E+10 | 2.125E+09 | 5.818E+09 | 6.333E+09 | 4.528E+07 | 1.841E+07 |
| | Error (%) | 0.4 | 0.2 | 0.1 | 0.1 | 0.8 | 0.2 |

It can be observed that generally the dose rate level at the top/bottom of the reactor is considerably lower in comparison to the dose rate at the sides. This is due to the fact that there was a sufficient amount of water inside the RPV above and below the core which contributes to the shielding effect. This is easy to observe in the neutron radiation case, because water is a good neutron shield.

Polyethylene was confirmed to be an effective neutron shield. The software detected the lowest neutron fluxes around the reactor core (for both top and bottom of the core) when implementing polyethylene. The properties of polyethylene as a neutron shield can be further improved by the addition of boron (a neutron absorber); however, in this case the shielding properties will gradually decrease during the operation because of boron burning. It could be noted that in the gamma ray shielding simulation the dose rate obtained using lead as a shield was significantly reduced in comparison to the case when no shield was implemented (void case). The dose rate obtained using steel was also notably decreased.

As described in 4.5 Shielding section, two materials should be chosen to provide both gamma ray and neutron shielding. Referring to the analysis performed, polyethylene was chosen for neutrons shielding and lead was selected for gamma ray shielding (because lead is comparably an ineffective neutron moderator).

A combination of polyethylene and lead shields (polyethylene surrounded by lead, both layers were 20 cm thickness respectively) was employed in the Rad Pro calculation. The results were summarised in Table 5.3.

**Table 5. 3: Properties of shielding materials**

| Radiation | Position | Polyethylene surrounded by lead |
|---|---|---|
| Gamma flux (µSv/h) | Top | 1.595E+04 |
| | Error | 1.5 |
| | Side | 6.506E+04 |
| | Error | 0.6 |
| Neutron flux (µSv/h) | Top | 7.794E+03 |
| | Error | 1.7 |
| | Side | 5.397E+06 |
| | Error | 0.2 |

As it can be seen from the table, both neutron dose rate and gamma dose rate were reduced when employing a combination of effective neutron and gamma shield materials. This confirmed that a combination of different material layers reduces flux (therefore dose rate) more efficiently.

## 5.5 Specific Results

KLT-40S reactor core was confirmed to be capable of operating over the 4 year period without refueling when employing 5% enriched uranium dioxide fuel; however the enrichment could be decreased up to 3.50% with the core still capable to operate for 4 years. The increase in fuel enrichment up to 20% can increase core operating period to 10 years, however this modification requires increased amount of absorber material to be introduced in the reactor core. Therefore, any fuel enrichment changes would subsequently result in a necessary design reassessment of the whole reactor unit. Shielding is a necessary component of the reactor plant, which protects workers and environment from radiation. Neutrons and gamma rays are the main concerns when designing shielding. Neutron shield is placed inside a gamma ray shield, accounting for the generation of gamma flux resulting from neutron shielding. The KLT-40S reactor employed water as the coolant, therefore the amount of neutron radiation is instantly reduced due to self-shielding. Polyethylene was confirmed to be a good neutron ray shield; its properties can be improved by the addition of boron (neutron absorber). Lead was confirmed to be an effective gamma ray shield. A combination of 100 cm of polyethylene and 30cm of lead was found to be a feasible reactor shield which allowed keeping the dose rates within 1mSv/h order of magnitude.

# CHAPTER 6: DISCUSSION ON RESULT AND RELEVANCE

## 6.1 Performance Evaluation Tools (PET) Model

Perhaps the most important factor regarding the feasibility of a nuclear powered fleet of merchant ships was the economic model and its appeal to potential investors. It is believed that with the rising oil prices, the shipping industry will be looking for new, more efficient propulsion systems to introduce to the new fleets. It may be possible that with a much cheaper fuel cycle, a nuclear powered ship will be much cheaper to run, however, a naval reactor was a significant initial cost to the investment which could overshadow these savings. In terms of day to day costs of running a conventional merchant ship, fuel is by far the highest proportion of cost. A nuclear powered ship would use less than 4% of the bunker fuel of a conventional ship of the same capacity (Beaver 2009) assuming the naval reactor would not be suitable to run at a certain proximity to shore. Therefore, aside from the clear environmental benefits, there needs to be an assessment of the potential savings that this nuclear application may have to create as an incentive for further work to be done on this thesis. Since there are no current nuclear powered merchant ships in service presently, costing of the fuel, ship and maintenance of the nuclear proposal was difficult and relies predominantly on other studies into the economic feasibility of nuclear powered ships and publicly available military information. However, the Performance Evaluation Tools (PET) model only intended to quantify the feasibility of nuclear naval reactor and had been created as a comparison between the current costs of the Emma Maersk and the nuclear powered proposal ship. Over 25 design or analytic tools were used in the systems architecting, systems engineering, ship synthesis, performance evaluation, cost calculation, and operational effectiveness assessments during the study period as a result of the PET modeling development mandate. The study approach included an examination of current and emerging technologies as well as project components that were carried out based on operational effectiveness vs cost.

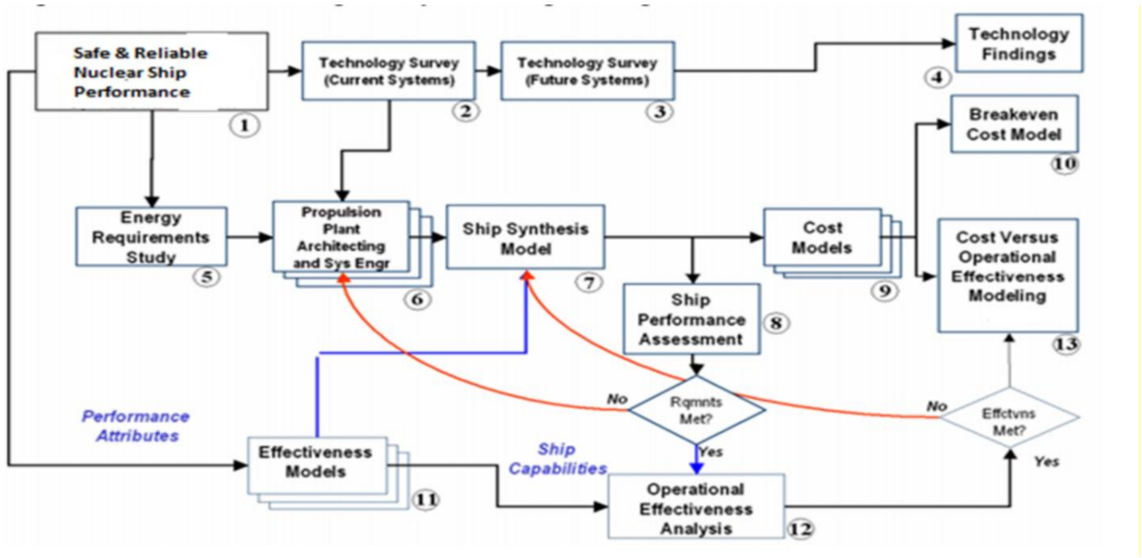

Figure 6. 1: Performance Evaluation Tools (PET)

The connections between the various project components and the overall process flow are shown in Figure 6.1. The ship and energy plant designs had to go through several iterations before performance standards were satisfied and mission effectiveness was enough. Propulsion Plant Architecting and Systems Engineering sector 6 technology models provided bodily and financial descriptions of developed technologies. The following components, whose numbers correspond to the sectors in Figure 6.1, made up the entire study process:

1. Safe and reliable nuclear ship performance: Categorized ship types to be studied and baseline warfare system performance necessities. Described baseline ships and variants of those ships with alternative propulsion systems.

2. Current technology survey: Surveyed industry and check with the Advances in Small Modular Reactor Technology Developments (IAEA) to identify and describe existing technologies relating to propulsion and power systems and architectures.

3. Future technology survey: Surveyed industry and consult with IAEA to identify and

describe future technologies relating to propulsion and power systems and architectures.

4. Technology findings: The findings of the present and future system technology surveys were summarized.

5. Energy requirements: Determined life-cycle energy requirements for each ship by NavCad software to perform missions for navigating the trade route. Exercised each variant in energy usage states to determine propulsion and electrical power demands.

6. Propulsion plant architecting and systems engineering: Determined the basic architecture for each variant. Architectures will include traditional mechanical, and electric propulsion architectures as well as “hybrid” architectures that blend integrated propulsion (electric and steam) with mechanical and electric transmissions to satisfy mobility, vulnerability and warfare system service demands. Characterized nuclear and fossil fuel power plants that meet peak, endurance, and, in the case of nuclear powered ships, the lifetime energy needs. Selected the type, number, and general location of prime movers and propulsion equipment in the ship. Determined the sizes, weights, and costs associated with various propulsion plant options appropriately scaled for the surface combatants and amphibious warfare ships under study.

7. Ship synthesis model: Identified a total ship concept for each variant that incorporates the alternate propulsion plants and defined mission systems that is suitable for cost estimating and operational effectiveness analysis.

8. Ship performance assessment: Evaluated the performance of each ship baseline/variant in all energy management system areas: energy storage, energy conversion, energy distribution, energy transmission, and thrust generation. Related the energy management system and architecture to ship speed, range, and service to warfare mission system

performance areas.

9. Cost models: Estimated ship acquisition cost and life cycle cost for each ship baseline and associated variants. Acquisition costs include actual cost return data or vendor quotes for power and propulsion system material. The life cycle cost estimated incorporate the following costs: fueling, defueling (nuclear variants only), disposal, burdened fuel costs, manpower costs, and maintenance. Non-recurring costs were not specified as they were dependent on capability growth which was outside the scope of this study.

10. Breakeven cost model: Performed breakeven cost analyses to compare the nuclear and fossil-fueled ship concepts. Performed a correlation analysis between the breakeven cost of oil with operational tempo, operational profile, and service life.

11. Effectiveness models: Developed analytical models to evaluate the vulnerability, operational, and mobility effectiveness of the ship variants in mission scenarios.

12. Operational effectiveness analysis: Evaluated each ship concept in terms of mobility, survivability, and operational effectiveness in the context of operational circumstances.

13. Cost and operational effectiveness analysis: Quantified the relationships between mission effectiveness and cost using a project of experiments approach. Developed a comparison for performance versus cost and for performance versus operational effectiveness for each ship type.

## 6.2 Economic Analysis

Real cost estimation was a very difficult task, especially for a plan like this one that had no real precursor. In order to test the cost sketch, an economic cost model was created. The cost comparison was finished based on the variations in installation and fuel expenses; all other ship costs, save the extra charges for elongation, were ignored. (Schultz, 2011). A description of some links between the major components in Figure 6.2 demonstrates how the costs varied depending on a large number of interrelated components.

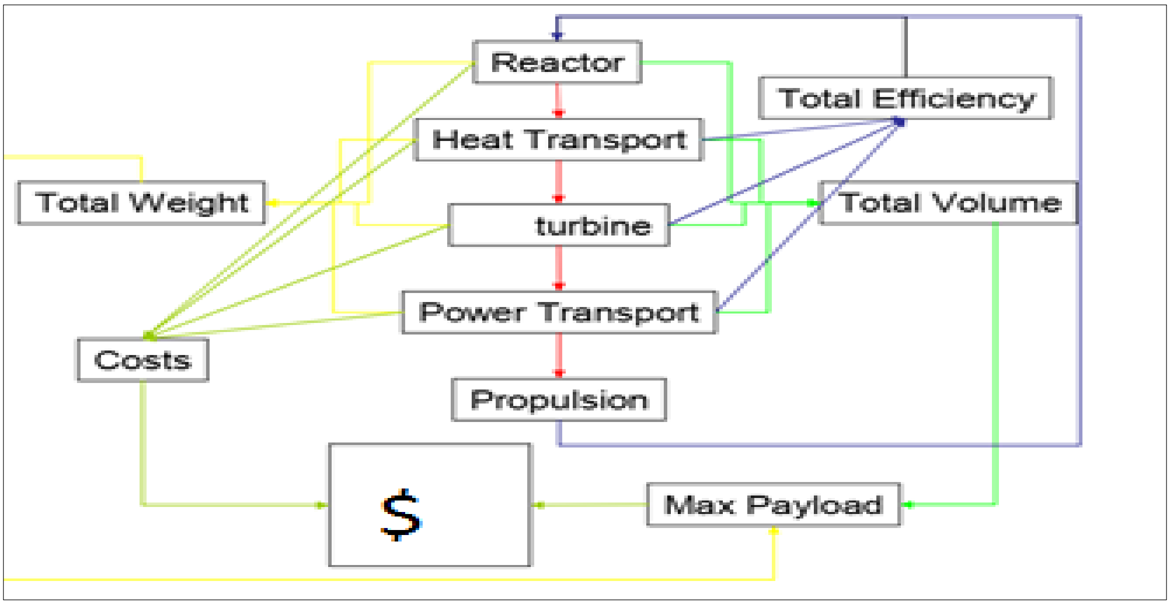

**Figure 6. 2: Schedule Possible Cost buildup**

A nuclear power plant's costs can be divided in a variety of ways, such as by the reactor's acquisition, operating, maintenance, and financing charges. These can be further broken down into several components, including as capital costs for things like fuel, shielding, piping, reactor control equipment, turbines, heat exchangers, and safety precautions.

### 6.2.1 Ship acquisition

The acquisition cost of an E-class vessel identical to the Emma Maersk was advertised by Maersk Group itself to be approximately $145 million. However, this was the cost of the ninth ship of this type and it was likely that the first ship of a fleet had a relatively large acquisition cost since the cost of a ship significantly reduced as the ship building and materials used becomes increasingly efficient. This is known as a learning curve, the curve used by the US navy in ship building be seen in Figure 6.3.

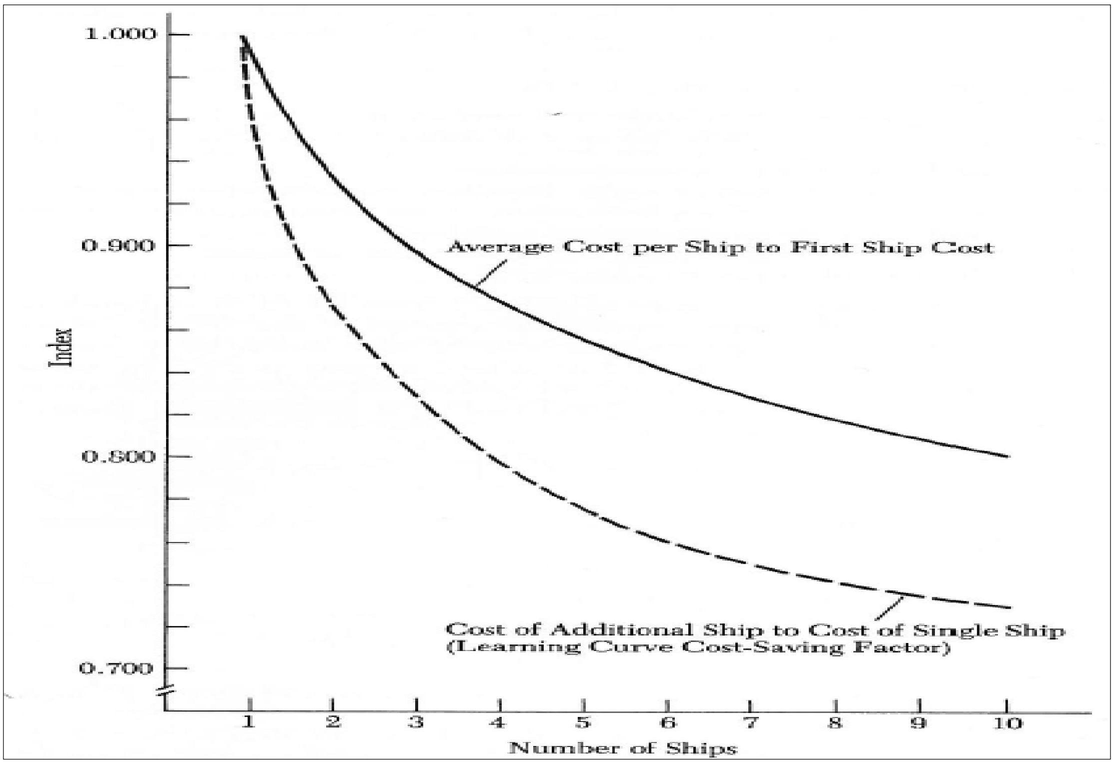

**Figure 6. 3: Example of a Learning Curve (Beaver 2009)**

From the US Navy report on alternative propulsion for surface combatant vessels (2007) an estimate for the cost of a large ship propelling reactor could be as large as $800 million, however this was the cost of the 5th ship in the fleet. Thus, with the learning curve factor of 0.76 from Figure 6.3 and the assumption that the ship itself will be modelled so similar to the Emma Maersk that it will have the same cost, an estimate of the value for the first-in-fleet nuclear container ship is up to $1.26 billion as an upper bound.

The US Navy, however, had no profit incentive in its ship building operations therefore this value may be an overestimate of the value of such a ship if it were built for commercial operation where cost-effectiveness and efficiency are much more imperative to the success of an assignment. Therefore, as a lower bound to the nuclear ship’s value the estimate of Sawyer (2008) was used, this is approximately $835 million. The US Navy used a learning curve when determining costs.

With these values, it was clear that a nuclear reactor adds enormous capital cost to an assignment which compares poorly to conventional container ships which had relatively low capital cost relative to other yearly costs.

The key assumption was that the third-party or manufacturer will make a 60% profit on the value of the vessel and reactor over the loaning period and any inclusive services such as maintenance and repair will come at a standard price. The model did not however include the potential added value of the ship associated with the design and work on special infrastructure that may be required.

Depending on the discount rate assumed, the present value of the cumulative cost with the "steady-pay" system could amount to less than the immediate payment of the ships value as a capital cost. This model assumed a 5% discount rate however if time allowed, a sensitivity study of the model dependent on discount rate and interest rate may be analysed in this thesis.

Essentially, the model assumes a 'steady' payment of the ship's value will be beneficial to a potential cost model rather than accumulating the large initial investment an outright procurement of a vessel would require. This 'steady-pay' model had been assumed for both the Emma Maersk case and the nuclear powered proposal.

### 6.2.2 Insurance

The cost of insurance according to Sawyer (2008) for merchant ships similar to Emma Maersk was less than 1% of the ship's value each year, therefore this model had taken 1%

for both vessels as an overestimate. The value of the ship for each year was calculated using the straight-line depreciation method as shown by below Equations:

$$d = \frac{(B - BVn)}{N} \qquad \text{……………………………..………………..(6.1)}$$

$$BV_k = B\text{-}\ dk \qquad \text{………………………………………………...(6.2)}$$

Where: d is annual depreciation deduction
N is the service life, and is equal to 20 years
B is the cost basis and is equal to the acquisition cost
$BV_n$ is the salvage value at the end of service life
k is the deduction year ($1 \leq k \leq N$)
$BV_k$ is the book value at the end of service year k

The ship's yearly depreciation value was modelled using a simple exponential decay curve assuming the value of the ship after 'useful' life (taken here as 20 years) is 10% of its acquisition value (Paine, 2012). The salvage value at the end of the ship's service life (BVn) was set equal to 10% of the initial acquisition cost. Once the yearly book value (BVk) was known for each vessel, the insurance premium for each year was calculated. This depreciation model was used for estimating the insurance costs of both the nuclear proposed vessel and the Emma Maersk since no data was publicly available.

### 6.2.3 Fuel

Earlier in the report, it is suggested that the nuclear powered vessel would require back up diesel power in case of reactor failure and also due to the possibility of regulations on nuclear propulsion at a certain proximity to shore. (Nian, V. 2017). This suggested that the nuclear vessel would still consume amounts of oil although still not to the extent of the

Emma Maersk which used approximately 350 metric tonnes of bunker fuel per day (Beaver, 2009). This research work estimated a usage of 4000 metric tonnes per year, allowing for usage through the Suez Canal where regulations on nuclear power may be strict and also in navigating other ports/canals. In December 2013 the oil price was US$109.69 per barrel which associated to approximately US$784 per metric tonne.

For the cost of uranium fuel for the nuclear vessel the Nuclear Energy Agency (2009) described a method of estimating the cost of each fuel cycle, where each stage is given a cost per kilogram of useful fuel and then the weight of fuel required for the reactor in each cycle is estimated from the design. As of December 2013 the price of uranium dioxide was US$36.25 per pound of ore which was estimated by Murray (2008) to equate to US$89.7 per kilogram of fuel created.

The following values are gathered in Table 6.1 from the Nuclear Energy Agency's report (2009) the WISE uranium project (Diehl, 2019) and (Beaver 2009):

**Table 6. 1: Summary of costs of fuel cycle processes per kg of eventual fuel**

| For 5% Enrichment | Cost US$/kg of fuel |
|---|---|
| Current uranium ore price | 89.7 |
| $UF_6$ conversion | 10 |
| Enrichment to 5% | 719.8 (7.198 SWUs at $100 each) |
| Fuel element fabrication | 275 |
| Transport (on land) | 50 |
| Spent fuel storage/disposal | 290 |

The weight of fuel was 23.3 tonnes per four year fuel cycle, thus giving a total cost of fuel of US$33.4 million per refuelling period, not including the cost of work.

Refuelling will take 15-30 days as estimated (Mowry 2010), which would create a loss of potential income. This fuel model shows that the cumulative cost of fuel for a nuclear powered vessel was significantly less than the diesel fuel powered Emma Maersk (approximately 10% of 20 years of bunker fuel). Figure 6.4 showed the cumulative cost over the first 20 year life of both ships, it also shows the yearly cost for the nuclear vessel to illustrate the enormous variation in costs per year caused by the uranium fuel cycle.

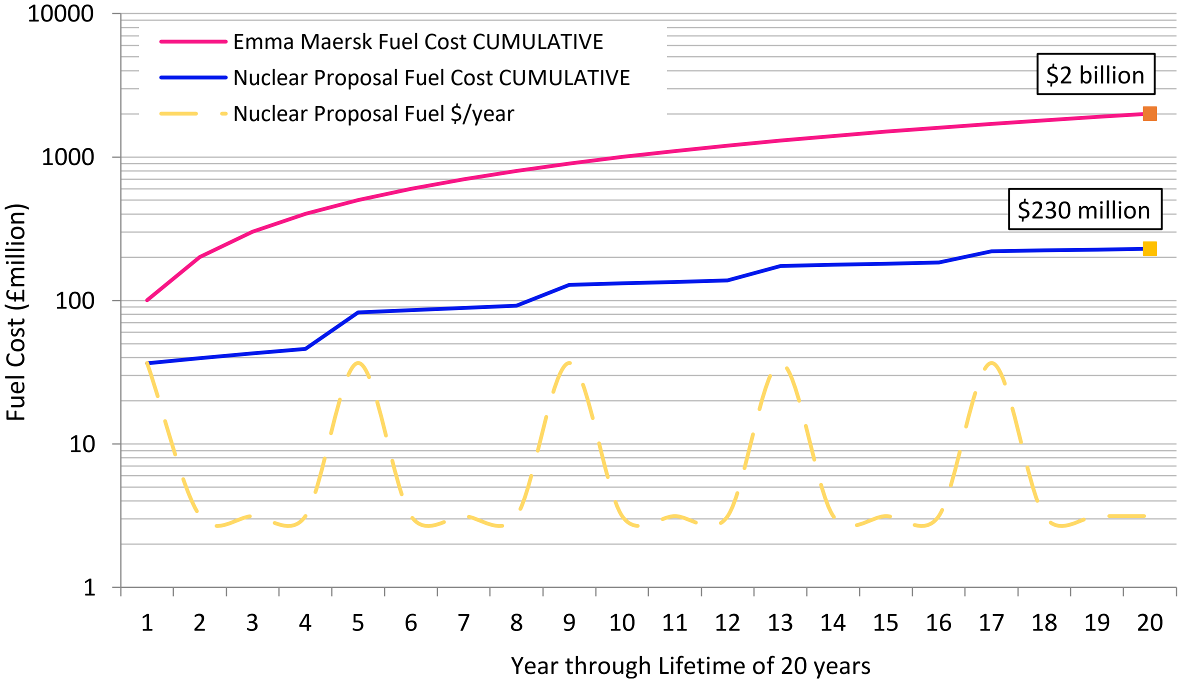

**Figure 6. 4: Cumulative Cost of Propulsion Fuel for Emma Maersk and Nuclear Proposal Vessel**

### 6.2.4 Other annual costs

A summary of all costing data is shown Table 6.2.

**Table 6. 2:Other Estimated Costs adapted from Beaver (2009)**

Amount in Million

| Costing Data | Emma Maersk | Nuclear Propelled |
|---|---|---|
| Acquisition | $145 | $1260 |
| Maintenance (US$ mill/year) | $0.80 | $1.6<br>$2.0 every 4 years for turbine overhaul & reactor maintenance |
| Dry-docking | $1.25M every 2.5 yrs<br>$1.75M every 5 yrs | $1.25M every 2.5 yrs.<br>$1.75M every 5 yrs |

| Costing Data | Emma Maersk | Nuclear Propelled |
|---|---|---|
| Fossil Fuel Burn Rate | 350 metric tons/day | 4,000 metric tons/yr |
| Refueling (per 4 years) | 0 | $2 |
| Spent Fuel Disposal | 0 | $3 million/yr beginning 10th year |
| Crew per day | $10 (20 crew) | $25 (35 crew) |
| Security per year | $1 | $3 |
| Insurance | 1% of value of the ship per year | 1% of value of the ship per year |
| Scrap Value | $10 steel only | $20 steel and copper |
| Decommissioning | 0 | $20 |
| Slot Charter Expense Refueling/Dry-docking | $19.5 per 4 year period | $71.1 per 4 year period |

Table 6.2 showed further estimates of yearly operational costs from a similar assignment by Beaver (2009), these can only be estimates due to the secrecy of the industry and the fact that a nuclear powered merchant ship is commercially unprecedented. One value to note is that Beaver estimated that maintenance will have to occur in the nuclear reactor and turbines every 5 years due to the increase in safety criticality in addition to the daily maintenance while the ship is running. This will also result in a down time of approximately 100 days (Beaver 2009).

## 6.3 Cost Comparison Between Diesel and Nuclear Propulsion

When diesel engine cost was compared with nuclear reactor cost, there were two variables that play a significant part: the oil price and the interest rate on capital cost. The interest rate played a significant role in the cost of the nuclear option, while the oil price played a large role in the diesel engine option. The cost comparison that was applied here was to convert all relevant life-cycle cost components into annual cost components at current dollar values. The capital cost of the propulsion power system was converted into an annual payment over the 20-year lifespan of the engine is shown in Table 6.3. The fuel cost was converted into an annual instalment over the 4-year refuelling cycle. It is assumed here that the same interest rate would be applicable to finance the initial capital cost, the 4- yearly fuel cost, and also to the decommissioning investment that will be built up over the life of the ship.

The Annuity Formulas for future value and present value is:

The present value of an annuity,

$$PV = P\times(1-(1+r)^{-n}) / r \ldots\ldots (6.3)$$

The future value of an annuity,

$$FV = P\times((1+r)^{n}-1) / r \ldots\ldots (6.4)$$

where,

- P = Principal
- r = Interest rate per year
- n = Number of years

Maintenance and operational costs are ignored in this comparison, because they are assumed to be similar for the two applications.

**Table 6. 3: Annual Comparative Cost Components**

| Component | Emma Maersk [$m] | Nuclear Ship [$m] |
|---|---|---|
| Capital loan repayment | $145\times(1-(1+r)^{-20}) / r$ | $1260\times(1-(1+r)^{-20}) / r$ |
| Fuel | 350 metric ton x fuel price/ day | $2\times(1-(1+r)^{-4}) / r$ |
| Lubrication oil | 0.1 | 0 |
| Decommissioning | 0 | $20\times((1+r)^{20}-1) / r$ |

These cost items were compared as a function of interest rate and fuel cost. The result was shown in Figure 6.5. From this graph it can be seen how the annual cost of the two alternatives change as a function of interest rate and fuel oil cost.

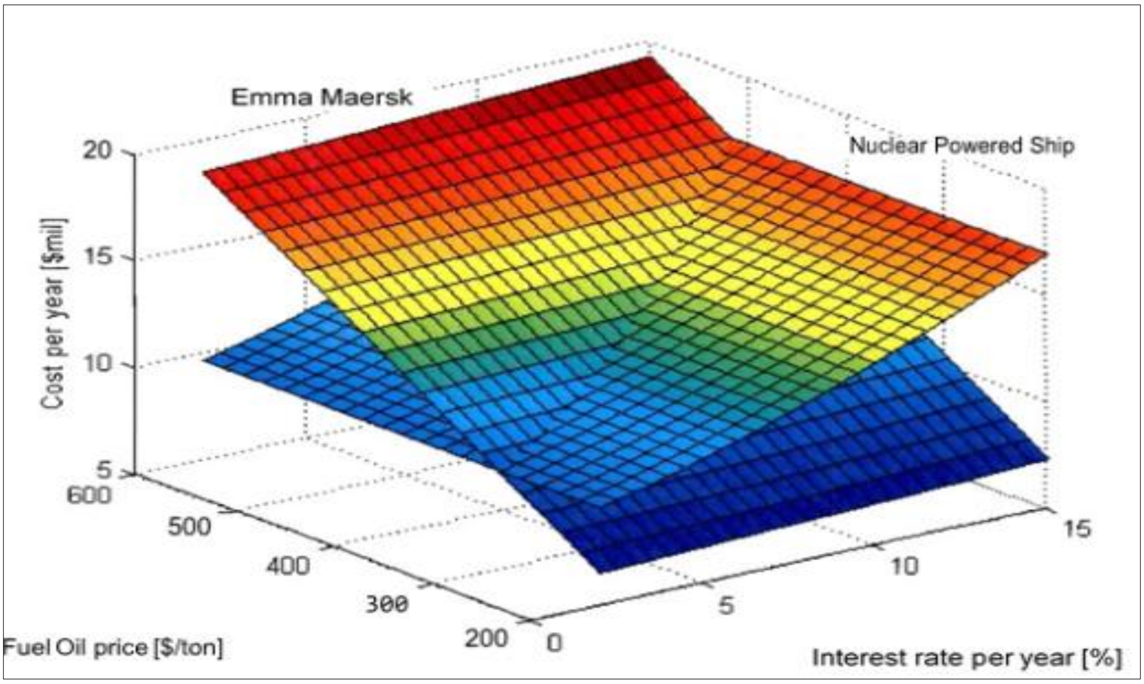

Figure 6. 5: Annual Cost Comparison between Nuclear Ship and Emma Maersk

**In Bangladesh context**

Figure 6.6 maps the relative cost competitiveness of Emma Maersk versus nuclear Ship. The deep area indicated the oil price and interest rate combinations for which nuclear would be cheaper than Emma Maersk. The horizontal dashed line indicated the fuel oil price. The dotted line shown where the equal-cost boundary between the two options would be in the absence of carbon credits. This graph showed that even if capital borrowed at a net rate of less than 12%, the nuclear ship would still cost less than Emma Maersk. This was significant, since the current interest rate in Bangladesh is only about 9%, while the interest rate in the USA is very close to zero at this stage.

The dotted curve showed that even if carbon credits were ignored, the nuclear ship would offer cost benefits at diesel prices above $791/ton at the current interest rates in Bangladesh.

This cost model was also used to calculate that the cost benefit of this nuclear ship relative to a diesel substitute would be around US$88 million per year at the current fuel oil price and 9% rate of interest in Figure 6.6.

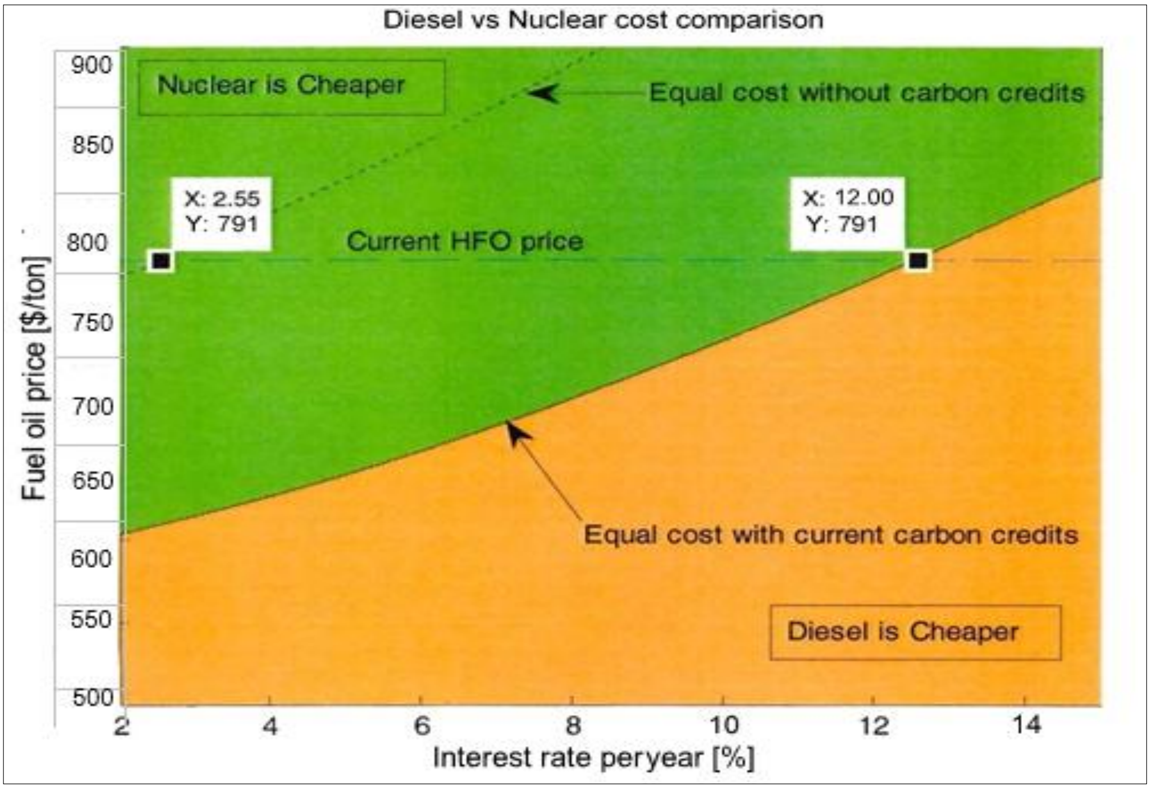

**Figure 6. 6: Comparison of Annual Cost**

## 6.4 Results of Cost Model

The results of the cost analyses above were gathered into one analysis of the yearly expenditure for each assignment resulting in a break-down of cumulative costs through the proposed 20 year life time.

Figure 6.7 showed the overall costs of the nuclear powered vessel compared to the Emma Maersk case. Again, the contrast of fuel costs and ship acquisition was evident, however, now it can be seen that the savings from using less fossil fuel, outweigh the higher ship loans. Also, the higher ‘other’ costs (crew, maintenance, insurance etc.) for the nuclear powered ship are still low enough for the overall cost to be lower.

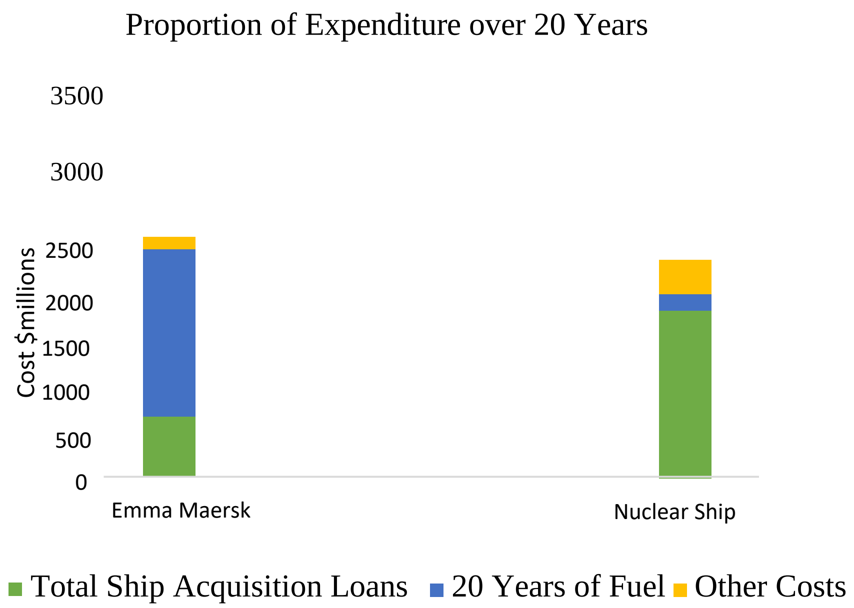

**Figure 6. 7: The cumulative cost of nuclear powered proposal as compared to Emma Maersk over 20 years**

Therefore, from this model where present value is not taken into account, the total cost of running a commercial cargo ship which was nuclear-powered was less than the Emma Maersk. Assuming that the annual profits are the same in both cases, due to similar carrying capacities and speeds of travel, then the nuclear powered ship appears to be more economically feasible.

However, to a commercial business it was the capital costs and annual profits which were attractive as an investment. Since the value of money changes over the years an investor will want minimum capital costs if these can be delayed until capital has increased in value, meaning a smaller present value (PV). This model had assumed a 5% discount rate consistent with a current average of developed countries.

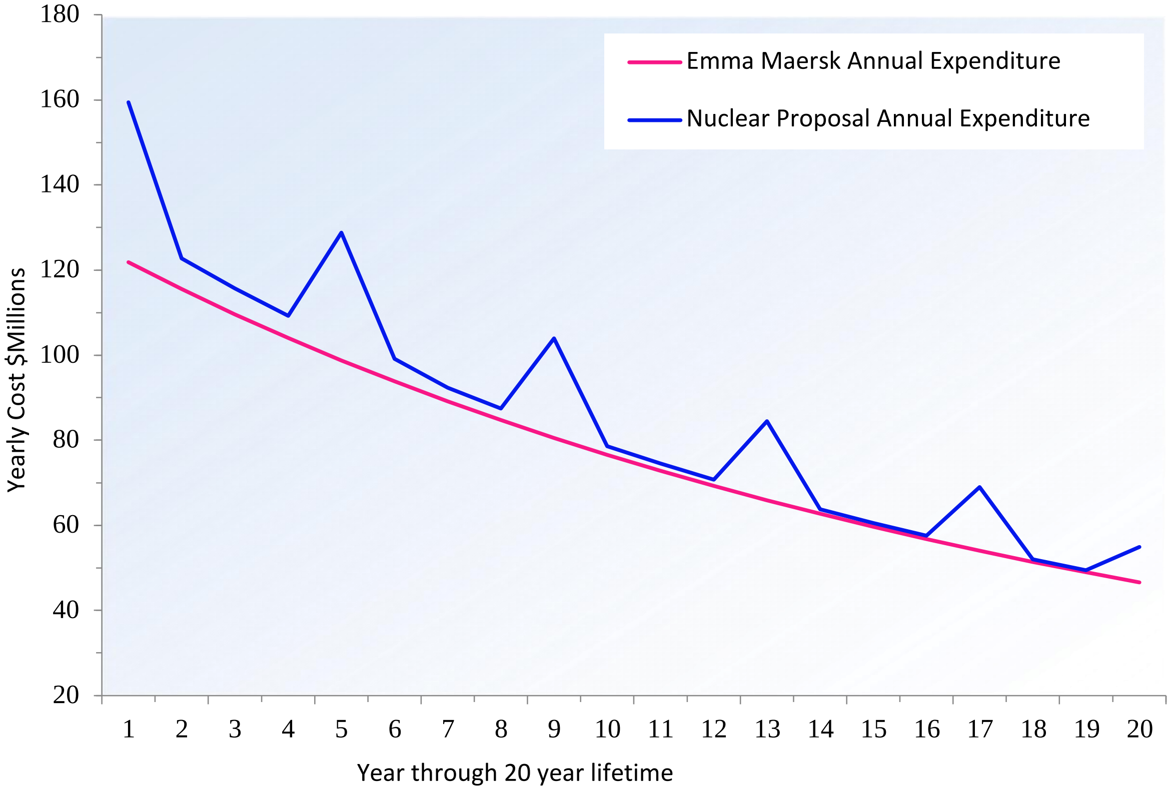

**Figure 6. 8: The present value annual costs of running the Emma Maersk compared to the nuclear propelled version over 20 year lifetime**

Figure 6.8 showed the model's predicted annual costs of running both types of merchant ship with the PV taken into account. It can be seen that the Emma Maersk had consistently decreasing annual expenditure whereas the nuclear powered vessel oscillates every four years due to the refuelling period. This could be controlled using the 'steady-pay' method for fuel loans which would average out the costs to a similar annual cost to the Emma Maersk.

It must also be noted that at periods of refuelling, the profit capacity of the ship was zero since it must stay stationary for up to 30 days, thus the maximum expenditure arises, problematically, at a period with minimum profits. This could be controlled with methods of payment for fuel that could be spread out over the period rather than incurring one sudden charge. For instance, a contract with the fuel producer would replace most outright payments with annual/monthly fees and would thus create a smoother annual costs function.

The model had thus far shown that the PV of the average annual expenditures of both the Emma Maersk and the nuclear powered vessel (upper bound) are quite similar, thus the cumulative costs of the projects must be similar when spread over the 20 years. Figure 6.9 compared the cumulative costs of these schemes, showing also the lower-bound nuclear cost and the cost if the entirety of the highest nuclear ship acquisition cost was paid for at the beginning of the life time. The out-right acquisition was clearly an unrealistic and unfeasible option for this thesis since it demands an unrealistic procurement of capital in the beginning of the assignment.

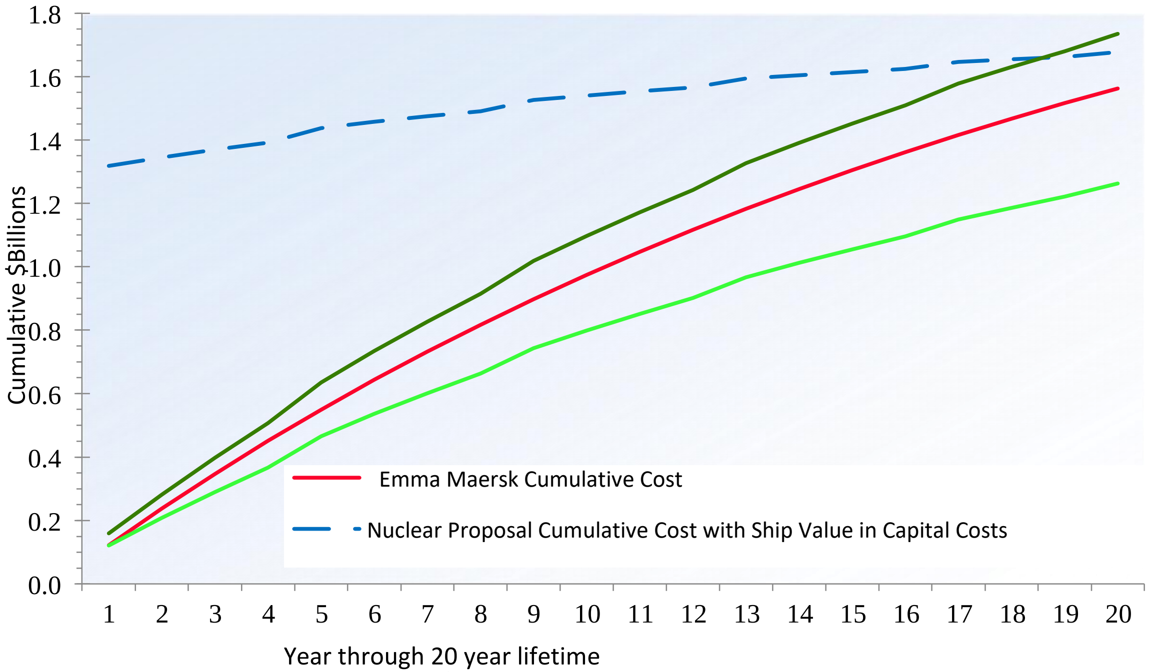

**Figure 6. 9: Cumulative costs of Emma Maersk over 20 years compared to three possible models for a nuclear powered merchant ship**

Figure 6.9 also showed the cumulative cost of the Emma Maersk to be slightly lower than the upper-bound nuclear vessel throughout the life time, however it is much higher than the lower-bound. It should be noted that the upper-bound ship cost was calculated as a first-in-fleet cost, thus the more ships that are manufactured the lower the acquisition cost will become, moving the project's cumulative costs closer and possibly lower than the Emma Maersk.

Therefore, so far the model had shown that the nuclear powered vessel was an economic feasibility provided that a manufacturer or other company can provide a leasing service similar to those in the airline industry. The model was however very sensitive to many estimated factors such as discount rate and particularly the real value of a vessel incorporating a nuclear reactor. Despite the fact that many assumptions were required and many simplifications were made to enable a like-for-like comparison, it is clear that the nuclear powered ship that was designed conceptually is economically viable for the selected Ship.

So far, it had been shown that the nuclear ship's value determined whether the merchant ship will be more or less profitable than the Emma Maersk. However, other factors such as oil prices may have an effect on the model or it may be possible for the nuclear ship to provide premium services such as refrigeration to increase revenue which would significantly affect the economic feasibility of this proposal.

# CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

## 7.1 Conclusions

In this study, the main objective was to determine whether a nuclear powered ship could be conceptual designed to be a feasible alternative to a diesel powered ship.

The Very Large Crude Carrier class of ship as Emma Maersk was selected as a suitable platform for nuclear propulsion. The required propulsion power was determined to be 81 MW.

The KLT-40S reactor, using nuclear fuel was selected as the energy source. KLT-40S reactor core was confirmed to be capable of operating over the 4 year period without refueling when employing 5% enriched uranium dioxide fuel; however the enrichment could be decreased up to 3.50% with the core still capable to operate for 4 years. The increase in fuel enrichment up to 20% can increase core operating period to 10 years, however this modification requires increased amount of absorber material to be introduced in the reactor core. The concept design therefore appears technically viable.

Safety will always be an important aspect in a nuclear powered ship. Although much attention has been given to nuclear safety in this study and inherent safety has been designed into the concept, the full scope of analysing the safety of the system was not encompassed in this study. It is thus not yet possible to determine if the nuclear ship is as safe as an equivalent diesel ship. This should be determined in future work. A feasible shield for KLT-40S reactor core, which would bring the dose rate levels below 1 µSv/hour, could be constructed using 100 cm layer of polyethylene and 30 cm of lead.

The cost estimate was compared with the cost associated with an equivalent diesel ship. The life-cycle cost comparison shows that even at the current fuel oil price and interest rates, the nuclear ship is significantly cheaper than the diesel ship. Considering trends in oil prices, this definitely justifies further investigation. Economically the project could be successful as long as the ship can be designed and manufactured below the military estimates and the oil prices continue to rise giving nuclear propulsion a profit advantage over conventional fuel ships.

Nuclear propulsion with a naval reactor as KLT-40S would be technically possible in the near future, but a lot of effort to accomplish this still has to be made. Based on the abovementioned, the research therefore suggests that nuclear propulsion should once again be considered as a viable alternative for maritime propulsion. In conclusion, the thesis found that a nuclear powered vessel will be economically and technically feasible in the near future. The technology would be found to be suitable for maritime applications as expected; however, some modifications to current technology would be required.

## 7.2 Recommendations for Future Work

a. The cost to develop and license a SMR nuclear propulsion needs to be determined to launch the feasibility of developing such a system.

b. A complete safety concept for the nuclear ship would have to be developed, based on a specific IMO-IAEA regulatory framework. The chosen regulatory framework would depend on the nationality of the launch customer.

c. One of the very important issues is to optimize the shielding around the reactor to reduce the weight and size of the shield to more acceptable values.

d. Investigate the changes that would be required to this propulsion system to make it applicable to large container ships. The economic advantages might be as attractive as or even better than calculated in this research because of the significant effect of fuel oil cost on diesel ship.

e. The risk matrix of the proposed nuclear ship has to be investigated.

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# Appendix A

## Selection of SMR (PWR) Type

## Green – Suitable, Yellow – Issue, Red – Unsuitable.

| **Reactor** | KLT-40S | Westinghouse SMR | Holtec SMR-160 | NuScale | SMART | MAERSK Engine |
|---|---|---|---|---|---|---|
| **Company** | Afrikantov OKBM | Westinghouse | Holtec | NuScale Power and Fluor | KAERI (South Korea) | |
| **Type** | PWR | PWR | PWR | PWR | PWR | |
| **Amount of Info.** | Plenty | Some | Difficult to Find | Plenty | Plenty | |
| **Track Record** | KLT-40 series | Based on AP1000, proven components of AP1000. | - | Reliance on well established LWR technology. | Proven and fully validated technologies. | |
| **Passive Safety?** | No | Yes | Yes | Two passive decay heat removal and containment heat removal systems | Yes | |
| **Life** | 40 years | 60 years | 80-100 years | 60 years | 60 years | |
| **Design Stage** | Development well | Development well advanced | Development well advanced | Development well advanced | Development well advanced | |
| **Enrichment** | advanced | <5% | - | 4.95% | 4.80% | |
| **Fuel** | <5% | UO2 | Similar to Large PWRs. (Including MOX) | UO2 | UO2 | Heavy Oil |
| **Refuelling** | UO2 | 2 years | 42 months | 2 years | 3 years | |
| **Initial Cost** | 4 years | - | $5000/kW | <$5000/kW | $5000/kW | |
| **Dimensions** | $5000/kW for a twin-unit | 9.8m diameter, 27m high (Whole Unit) | 31m high (Just RPV) | 4.3m diameter, 20m high (Containment Vessel) | 6.5m diameter, 18.5m high (RPV) | 27m long, 13.4m hi |
| **Weight** | plant | Upper Vessel package - 280 tons | - | 650 tons | - | 2300 tons |
| **Power Output (Mwe)** | 4.5m diameter, 23m high | 225 | 160 | 45 | 100 | 82-111.1 |
| **Integral?** | (Whole Unit) | Yes | No | Yes | Yes | |

# Appendix B

## Summary of Main Design Features and Status of SMRs included this thesis

| Design | Output MW(e) | Type | Designers | Country | Status |
|---|---|---|---|---|---|
| **PART 1: WATER COOLED SMALL MODULAR REACTORS (LAND BASED)** | | | | | |
| **CAREM** | 30 | PWR | CNEA | Argentina | Under construction |
| **ACP100** | 100 | PWR | CNNC | China | Detailed Design |
| **CANDU SMR** | 300 | PHWR | Candu Energy Inc (SNC Lavalin Group) | Canada | Conceptual Design |
| **CAP200** | 200 | PWR | SNERDI/SPIC | China | Conceptual Design |
| **DHR400** | 400 MW(t) | LWR (pool type) | CNNC | China | Basic Design |
| **HAPPY200** | 200 MW(t) | PWR | SPIC | China | Detailed Design |
| **TEPLATORTM** | 50 MW(t) | HWR | UWB Pilsen & CIIRC CTU | Czech Republic | Conceptual Design |
| **NUWARD** | 2 × 170 | PWR | EDF, CEA, TA, Naval Group | France | Conceptual Design |
| **IRIS** | 335 | PWR | IRIS Consortium | Multiple Countries | Basic Design |
| **DMS** | 300 | BWR | Hitachi-GE Nuclear Energy | Japan | Basic Design |
| **IMR** | 350 | PWR | MHI | Japan | Conceptual Design |
| **SMART** | 107 | PWR | KAERI and K.A.CARE | Republic of Korea, and Saudi Arabia | Certified Design |
| **RITM-200** | 2 × 53 | PWR | JSC “Afrikantov OKBM” | Russian Federation | Under Development |
| **UNITHERM** | 6.6 | PWR | NIKIET | Russian Federation | Conceptual Design |
| **VK-300** | 250 | BWR | NIKIET | Russian Federation | Detailed Design |
| **KARAT-45** | 45 - 50 | BWR | NIKIET | Russian Federation | Conceptual Design |
| **KARAT-100** | 100 | BWR | NIKIET | Russian Federation | Conceptual Design |

| | | | | | |
|---|---|---|---|---|---|
| **RUTA-70** | 70 MW(t) | PWR | NIKIET | Russian Federation | Conceptual Design |
| **ELENA** | 68 kW(e) | PWR | National Research Centre “Kurchatov Institute” | Russian Federation | Conceptual Design |
| **UK SMR** | 443 | PWR | Rolls-Royce and Partners | UK | Conceptual Design |
| **NuScale** | 12 × 60 | PWR | NuScale Power Inc. | USA | Under Regulatory Review |
| **BWRX-300** | 270 - 290 | BWR | GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy | USA, Japan | Pre-licensing |
| **SMR-160** | 160 | PWR | Holtec International | USA | Preliminary Design |
| **W-SMR** | 225 | PWR | Westinghouse Electric Company, LLC | USA | Conceptual Design |
| **mPower** | 2 × 195 | PWR | BWX Technologies, Inc | USA | Conceptual Design |
| **PART 2: WATER COOLED SMALL MODULAR REACTORS (MARINE BASED)** | | | | | |
| **KLT-40S** | 2 × 35 | PWR in Floating NPP | JSC Afrikantov OKBM | Russian Federation | In Operation |
| **RITM-200M** | 2 × 50 | PWR in FNPP | JSC Afrikantov OKBM | Russian Federation | Under Development |
| **ACPR50S** | 50 | PWR in FNPP | CGNPC | China | Conceptual Design |
| **ABV-6E** | 6-9 | PWR in FNPP | JSC Afrikantov OKBM | Russian Federation | Final design |
| **VBER-300** | 325 | PWR in FNPP | JSC Afrikantov OKBM | Russian Federation | Licensing Stage |
| **SHELF** | 6.6 | PWR in Immersed NPP | NIKIET | Russian Federation | Detailed Design |
| **PART 3: HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS** | | | | | |
| **HTR-PM** | 210 | HTGR | INET, Tsinghua University | China | Under Construction |
| **StarCore** | 14/20/60 | HTGR | StarCore Nuclear | Canada/UK/US | Pre-Conceptual Design |
| **GTHTR300** | 100 - 300 | HTGR | JAEA | Japan | Pre-licensing |

| | | | | | |
|---|---|---|---|---|---|
| **GT-MHR** | 288 | HTGR | JSC Afrikantov OKBM | Russian Federation | Preliminary Design |
| **MHR-T** | 4 × 205.5 | HTGR | JSC Afrikantov OKBM | Russian Federation | Conceptual Design |
| **MHR-100** | 25 – 87 | HTGR | JSC Afrikantov OKBM | Russian Federation | Conceptual Design |
| **PBMR-400** | 165 | HTGR | PBMR SOC Ltd | South Africa | Preliminary Design |
| **A-HTR-100** | 50 | HTGR | Eskom Holdings SOC Ltd. | South Africa | Conceptual Design |
| **HTMR-100** | 35 | HTGR | Steenkampskraal Thorium Limited | South Africa | Conceptual Design |
| **Xe-100** | 82.5 | HTGR | X-Energy LLC | USA | Basic Design |
| **SC-HTGR** | 272 | HTGR | Framatome, Inc. | USA | Conceptual Design |
| **HTR-10** | 2.5 | HTGR | INET, Tsinghua University | China | Operational |
| **HTTR-30** | 30 (t) | HTGR | JAEA | Japan | Operational |
| **RDE** | 3 | HTGR | BATAN | Indonesia | Conceptual Design |
| **PART 4: FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS** | | | | | |
| **BREST-OD-300** | 300 | LMFR | NIKIET | Russian Federation | Detailed Design |
| **ARC-100** | 100 | Liquid Sodium | ARC Nuclear Canada, Inc. | Canada | Conceptual Design |
| **4S** | 10 | LMFR | Toshiba Corporation | Japan | Detailed Design |
| **Micro URANUS** | 20 | LBR | UNIST | Korea, Republic of | Pre-conceptual Design |
| **LFR-AS-200** | 200 | LMFR | Hydromine Nuclear Energy | Luxembourg | Preliminary Design |
| **LFR-TL-X** | 5~20 | LMFR | Hydromine Nuclear Energy | Luxembourg | Conceptual Design |
| **SVBR** | 100 | LMFR | JSC AKME Engineering | Russian Federation | Detailed Design |
| **SEALER** | 3 | LMFR | LeadCold | Sweden | Conceptual Design |
| **EM2** | 265 | GMFR | General Atomics | USA | Conceptual Design |
| **Westinghouse LFR** | 450 | LMFR | Westinghouse Electric Company, LLC. | USA | Conceptual Design |

| | | | | | |
|---|---|---|---|---|---|
| **SUPERSTAR** | 120 | LMFR | Argonne National Laboratory | USA | Conceptual Design |
| **PART 5: MOLTEN SALT SMALL MODULAR REACTORS** | | | | | |
| **Integral MSR** | 195 | MSR | Terrestrial Energy Inc. | Canada | Conceptual Design |
| **smTMSR-400** | 168 | MSR | SINAP, CAS | China | Pre-Conceptual Design |
| **CA Waste Burner 0.2.5** | 20 MW(t) | MSR | Copenhagen Atomics | Denmark | Conceptual Design |
| **ThorCon** | 250 | MSR | ThorCon International | International Consortium | Basic Design |
| **FUJI** | 200 | MSR | International Thorium Molten-Salt Forum: ITMSF | Japan | Experimental Phase |
| **Stable Salt Reactor - Wasteburner** | 300 | MSR | Moltex Energy | UK / Canada | Conceptual Design |
| **LFTR** | 250 | MSR | Flibe Energy, Inc. | USA | Conceptual Design |
| **KP-FHR** | 140 | Pebble-bed salt cooled Reactor | KAIROS Power, LLC. | USA | Conceptual Design |
| **Mk1 PB-FHR** | 100 | FHR | University of California at Berkeley | USA | Pre-Conceptual Design |
| **MCSFR** | 50 - 1200 | MSR | Elysium Industries | USA and Canada | Conceptual Design |
| **PART 6: MICRO MODULAR REACTORS** | | | | | |
| **Energy Well** | 8 | FHTR | Centrum výzkumu Řež | Czech Republic | Pre-Conceptual Design |
| **MoveluX** | 3~4 | Heat Pipe | Toshiba Corporation | Japan | Conceptual Design |
| **U-Battery** | 4 | HTGR | Urenco | UK | Conceptual Design |
| **Aurora** | 1.5 | FR | OKLO, Inc. | USA | Conceptual Design |
| **Westinghouse eVinci** | 2 -3.5 | Heat Pipe | Westinghouse Electric Company, LLC. | USA | Under Development |
| **MMR** | 5-10 | HTGR | Ultra Safe Nuclear Corporation | USA | Preliminary Design |

# Appendix C

## MONK Code

```
NCYCLE 1 8
BEGIN MATERIAL SPECIFICATION
TYPE WIMS
BURN
READ FROM INTERFACE 1
WRITE TO INTERFACE 2
PRINT 0 !PRINT ERRORS
NORMALISE
GOTO 1 2-100
ATOMS
MATERIAL 1 DENSITY 10.045
U235 5.0
U238 95.0
O 200.0
FISSILE
WEIGHT
MATERIAL 2 DENSITY 6.57
ZR 0.9826
SN 0.015
FE 0.0008
CR 0.001
NI 0.0006
NONBURNABLE
ATOMS
MATERIAL 3 DENSITY 0.72746
H1INH2O 1.0
NONBURNABLE
WEIGHT
!CONTROL ROD CLADDING
MATERIAL 4 DENSITY 7.9
FE 0.73
CR 0.17
NI 0.09
MN 0.01
NONBURNABLE
ATOMS
MATERIAL 5 DENSITY 2.52
B 32.0
```

```
B10 8.0
C 10.0
BURNABLE
WEIGHT
MATERIAL 6 DENSITY 0.1786
HE 1.0
NONBURNABLE
LABEL 1
GOTO 2 1
ATOMS MATERIAL 1=1 FISSILE
WEIGHT MATERIAL 2=2 NONBURNABLE
ATOMS MATERIAL 3=3 NONBURNABLE
WEIGHT MATERIAL 4=4 NONBURNABLE
WEIGHT MATERIAL 5=5 BURNABLE
WEIGHT MATERIAL 6=6 NONBURNABLE
LABEL 2
END
BEGIN BURNUP DATA
READ 2
WRITE 1
RATING 6 530 !POWER OUTPUT 530MWt OF THERMAL ENERGY
STEPS 6 30.0 !STEP MODE AND DAYS
PRINT 4
END
BEGIN MATERIAL GEOMETRY
!FUEL ROD
PART 1 NEST
BOX H1 0.0 0.0 0.0 1.239 1.239 241.3 !TO ALLOW SPACING
MVOLUME 1 1 1 116.6
!CONTROL ROD
PART 2 NEST
BOX H2 0.0 0.0 0.0 1.239 1.239 241.3 !TO ALLOW SPACING
!CONTROL ROD DISCHARGED
PART 3 NEST
BOX H3 0.0 0.0 0.0 1.239 1.239 241.3 !TO ALLOW SPACING
!INSTRUMENTATION ROD
PART 4 NEST
BOX H4 0.0 0.0 0.0 1.239 1.239 241.3 !TO ALLOW SPACING
!ARRAYS OF RODS
PART 5 ARRAY 17 2 1 (1)*34
```

```
PART 6 ARRAY 17 1 1 (1)*5 3 1 1 3 1 1 3 (1)*5
PART 7 ARRAY 17 1 1 (1)*3 3 (1)*9 3 (1)*3
PART 8 ARRAY 17 1 1 (1)*17
PART 9 ARRAY 17 1 1 1 1 3 1 1 3 1 1 3 1 1 3 1 1 3 1 1
PART 10 ARRAY 17 1 1 1 1 3 1 1 3 1 1 4 1 1 3 1 1 3 1 1
PART 11 ARRAY 17 1 1 (1)*5 3 1 1 3 1 1 3 (1)*5
PART 12 ARRAY 17 1 1 (1)*3 3 (1)*9 3 (1)*3
PART 13 ARRAY 17 1 1 1 1 3 1 1 3 1 1 3 1 1 3 1 1 3 1 1
PART 14 ARRAY 17 1 1 1 1 3 1 1 3 1 1 4 1 1 3 1 1 3 1 1
PART 15 ARRAY 17 1 1 (1)*5 3 1 1 3 1 1 3 (1)*5
PART 16 ARRAY 17 1 1 (1)*3 3 (1)*9 3 (1)*3
PART 17 ARRAY 17 1 1 1 1 3 1 1 3 1 1 3 1 1 3 1 1 3 1 1
PART 18 ARRAY 17 1 1 1 1 3 1 1 2 1 1 4 1 1 3 1 1 3 1 1
!FORM FUEL ASSEMBLY A
PART 19 CLUSTER
BOX P5 -10.5315 8.0535 0.0 21.063 2.478 241.3
BOX P6 -10.5315 6.8145 0.0 21.063 1.239 241.3
BOX P7 -10.5315 5.5755 0.0 21.063 1.239 241.3
BOX P8 -10.5315 4.3365 0.0 21.063 1.239 241.3
BOX P9 -10.5315 3.0975 0.0 21.063 1.239 241.3
BOX P5 -10.5315 0.6195 0.0 21.063 2.478 241.3
BOX P10 -10.5315 -0.6195 0.0 21.063 1.239 241.3
BOX P5 -10.5315 -3.0975 0.0 21.063 2.478 241.3
BOX P9 -10.5315 -4.3365 0.0 21.063 1.239 241.3
BOX P8 -10.5315 -5.5755 0.0 21.063 1.239 241.3
BOX P7 -10.5315 -6.8145 0.0 21.063 1.239 241.3
BOX P6 -10.5315 -8.0535 0.0 21.063 1.239 241.3
BOX P5 -10.5315 -10.5315 0.0 21.063 2.478 241.3
BOX M3 -11.0 -11.0 0.0 22.0 22.0 241.3
!FORM FUEL ASSEMBLY WITHOUT CR
PART 20 CLUSTER
BOX P5 -10.5315 8.0535 0.0 21.063 2.478 241.3
BOX P11 -10.5315 6.8145 0.0 21.063 1.239 241.3
BOX P12 -10.5315 5.5755 0.0 21.063 1.239 241.3
BOX P8 -10.5315 4.3365 0.0 21.063 1.239 241.3
BOX P13 -10.5315 3.0975 0.0 21.063 1.239 241.3
BOX P5 -10.5315 0.6195 0.0 21.063 2.478 241.3
BOX P14 -10.5315 -0.6195 0.0 21.063 1.239 241.3
BOX P5 -10.5315 -3.0975 0.0 21.063 2.478 241.3
BOX P13 -10.5315 -4.3365 0.0 21.063 1.239 241.3
```

```
BOX P8 -10.5315 -5.5755 0.0 21.063 1.239 241.3
BOX P12 -10.5315 -6.8145 0.0 21.063 1.239 241.3
BOX P11 -10.5315 -8.0535 0.0 21.063 1.239 241.3
BOX P5 -10.5315 -10.5315 0.0 21.063 2.478 241.3
BOX M3 -11.0 -11.0 0.0 22.0 22.0 241.3 !TO MAKE IT 22CM
!FORM FUEL ASSEMBLY B
PART 21 CLUSTER
BOX P5 -10.5315 8.0535 0.0 21.063 2.478 241.3
BOX P16 -10.5315 5.5755 0.0 21.063 1.239 241.3
BOX P8 -10.5315 4.3365 0.0 21.063 1.239 241.3
BOX P17 -10.5315 3.0975 0.0 21.063 1.239 241.3
BOX P5 -10.5315 0.6195 0.0 21.063 2.478 241.3
BOX P18 -10.5315 -0.6195 0.0 21.063 1.239 241.3
BOX P5 -10.5315 -3.0975 0.0 21.063 2.478 241.3
BOX P17 -10.5315 -4.3365 0.0 21.063 1.239 241.3
BOX P8 -10.5315 -5.5755 0.0 21.063 1.239 241.3
BOX P16 -10.5315 -6.8145 0.0 21.063 1.239 241.3
BOX P15 -10.5315 -8.0535 0.0 21.063 1.239 241.3
BOX P5 -10.5315 -10.5315 0.0 21.063 2.478 241.3
BOX M3 -11.0 -11.0 0.0 22.0 22.0 241.3 !TO MAKE IT 22CM
!arrays of fuel allocated according to the lines
PART 22 ARRAY 5 1 1 20 21 19 21 20
PART 23 ARRAY 7 1 1 19 21 19 21 19 21 19
PART 24 ARRAY 9 5 1 20 21 19 21 19 21 19 21 20
21 19 21 19 21 19 21 19 21
19 21 19 21 19 21 19 21 19
21 19 21 19 21 19 21 19 21
20 21 19 21 19 21 19 21 20
!ALLOCATE ARRAYS INTO BOXES
PART 25 CLUSTER
BOX P22 -55.0 77.0 0.0 110.0 22.0 241.3
BOX P23 -77.0 55.0 0.0 154.0 22.0 241.3
BOX P24 -99.0 -55.0 0.0 198.0 110.0 241.3
BOX P23 -77.0 -77.0 0.0 154.0 22.0 241.3
BOX P22 -55.0 -99.0 0.0 110.0 22.0 241.3
ZROD M3 0.0 0.0 0.0 118.0 241.3
PART 26 NEST
ZROD P25 0.0 0.0 0.0 118.0 241.3
ZROD M4 0.0 0.0 0.0 123.0 241.3
END
```

```
BEGIN ENERGY DATA
WIMS
SUBGROUP 172 !NUMBER OF AVALIABLE SUBGROUPS
SCORING
BASIC GROUPS
END
BEGIN HOLE GEOMETRY
!FUEL ROD
HOLE 1 SQUARE
ORIGIN 0.6195 0.6195 0.0
1.239
-0.0 -0.0
MORE 3
0.3922 0.4079 0.457
WRAP
1.0 1.0
0.6195 0.6195
0.6195 0.6195
M1 M6 M2 M3 M0 M0
!CONTROL ROD
HOLE 2 SQUARE ORIGIN 0.6195 0.6195 0.0
1.239
-0.0 -0.0
MORE 3
0.3922 0.4079 0.457
WRAP
1.0 1.0
0.6195 0.6195
0.6195 0.6195
M5 M6 M4 M3 M0 M0
!CONTROL ROD DISCHARGED
HOLE 3 SQUARE ORIGIN 0.6195 0.6195 0.0
1.239
-0.0 -0.0
MORE 3
0.3922 0.4079 0.457
WRAP
1.0 1.0
0.6195 0.6195
0.6195 0.6195
```

```
M3 M6 M4 M3 M0 M0
!INSTRUMENTATION ROD
HOLE 4 SQUARE ORIGIN 0.6195 0.6195 0.0
1.239
-0.0 -0.0
MORE 3
0.3922 0.4079 0.457
WRAP
1.0 1.0
0.6195 0.6195
0.6195 0.6195
M3 M6 M4 M3 M0 M0
END
BEGIN CONTROL DATA
STAGES -1 100 1000 STDV 0.002
END
BEGIN SOURCE GEOMETRY
ZONEMAT ALL / MATERIAL 5
END
FINISH
```

# Appendix D

## Absorbed Dose Rate Calculation

Assume that the isotropic point source has a half-life of 30.2 years and contains 1.0 Ci of 137Cs. Note that the link between half-life and the quantity of a radionuclide needed to produce an activity of one curie is illustrated below. The decay constant of a specific nuclide, λ can be used to determine the amount of material:

$$N(atoms)\ x\ \lambda(s^{-1}) = 1\ Ci = 3.7\ x\ 10^{10}\ Bq$$

A metastable nuclear isomer of barium, barium-137m, is produced in around 94.6 percent of barium's beta emission decays. Ba-137primary m's photon peak has a 662 keV energy. Assume for the purposes of this calculation that all decays pass through this channel.

The principal photon dosage rate at the outer surface of a 5 cm thick lead shield should be calculated in gray per hour (Gy.h-1). All secondary particles are ignored by the primary photon dosage rate. Assume that there is a 10 cm effective distance between the source and the dose site. Additionally, we'll suppose that the dose point is soft tissue that can be accurately represented by water using its mass energy absorption coefficient.

Solution: Taking into consideration the shield, the dosage rate from primary photons is given by the exponential attenuation of the primary photon dose rate:

$$\dot{D} = \frac{kSE\frac{\mu_t}{\rho}e^{-\mu D}}{4\pi r^2}$$

where

- k is a collective constant to convert energy fluence rate to dose rate; for gray/hour, k will have a value of 5.76 x $10^{-7}$
- S is the source strength in $s^{-1}$
- E is the photon energy in MeV
- $\frac{\mu_t}{\rho}$ is the mass absorption coefficient for the material at the dose (values are available at NIST)
- $\mu$ is the linear attenuation coefficient for the photons in the shield material (values are available at NIST)
- D is the thickness of the shield
- r the effective distance of the source from the dose point

As can be seen, we do not take the accumulation of secondary radiation into consideration. In the event that secondary particles are produced or the initial radiation changes in energy or direction, the effective attenuation will be significantly reduced. Despite the fact that this assumption simplifies the computations, it frequently understates the true dosage rate, especially for thick shields and in situations when the dose point is close to the shield surface. In this instance, the actual dosage rate will be greater than twice as high due to the accumulation of secondary radiation.

To calculate the absorbed dose rate, we have to use in the formula:

k = 5.76 x 10-7

S = 3.7 x 1010 s-1

E = 0.662 MeV

μt/ρ = 0.0326 cm2/g (given value)

μ = 1.289 cm-1 (given value)

D = 5 cm

r = 10 cm

Result: The resulting absorbed dose rate in grays per hour is then:

$$\dot{D} = \frac{5.76\ x\ 10^{-7}\ x\ 3.7\ x\ 10^{10}\ x\ 0.662\ x\ 0.0326\ x\ e^{-1.289\ x\ 5}}{4\pi\ x\ 10^{2}}$$

$$= \frac{0.46\ x\ 10^{3}\ x\ e^{-1.289\ x\ 5}}{1256} = 0.582\ mGy/h$$

If to account for the buildup of secondary radiation, then we have to include the buildup factor. The extended formula for the dose rate is then:

$$\dot{D} = \frac{kSE\frac{\mu_t}{\rho}Be^{-\mu D}}{4\pi r^2}$$

where

- B is the buildup factor (tabulated), which depends on the photon energy, the shield material and thickness, the source and shield geometry, and the distance from the shield surface to the dose point.

# Appendix E

## Dissemination

Hoque, M., Salauddin, A.Z.M. and Khondoker, M.R.H., 2018, “Design and Comparative Analysis of Small Modular Reactors for Nuclear Marine Propulsion of a Ship”, *World Journal of Nuclear Science and Technology,* China, 8(3), pp.136-145.

Juwel, M. M. H., Khondoker, M. R. H. and Khan, R. A., 2018, “*Performance Analysis of a Naval Reactor for Nuclear Powered Ship”*, Journal of Nuclear Engineering & Technology, India, 8(1), pp.1-6.