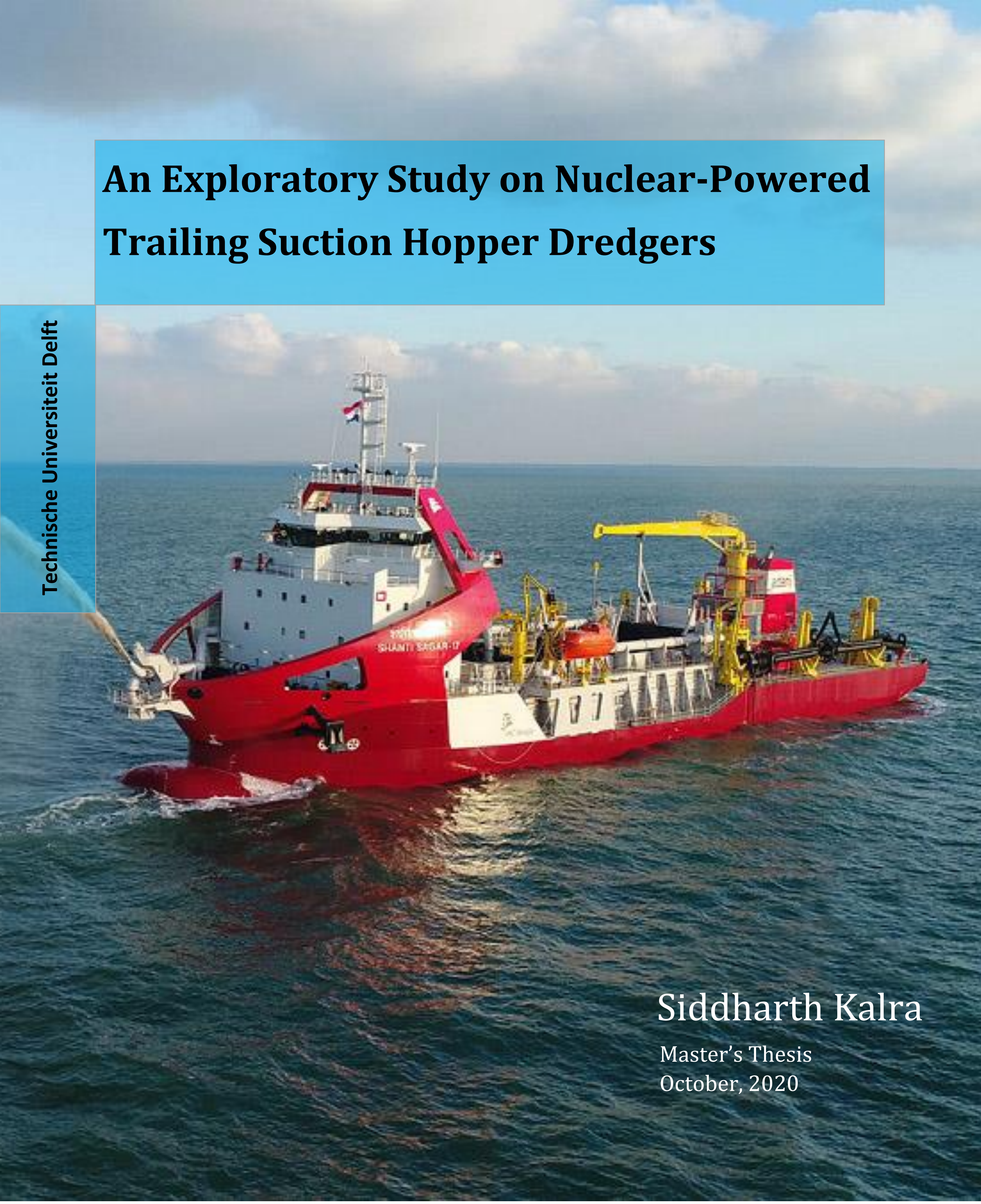
An Exploratory Study on Nuclear-Powered Trailing Suction Hopper Dredgers

Technische Universiteit Delft



Siddharth Kalra

Master's Thesis
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TU Delft Delft University of Technology

Challenge the future

An Exploratory Study on Nuclear-Powered Trailing Suction Hopper Dredgers

by

Siddharth Kalra

in partial fulfillment of the requirements for the degree of

Master of Science
in Mechanical Engineering

at the Delft University of Technology,
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This thesis is confidential and cannot be made public until October 31, 2022.

Delft
University of
Technology

”If I have seen further it is by standing on the shoulders of Giants” [1]

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[1] Isaac Newton in a letter addressed to Robert Hooke dated 5 February 1675.

Preface

This master thesis, as it lies before you, marks the end of my time as a M.Sc. student at Delft University of Technology. This fulfills the final requirement in order to receive my Master of Science degree in Mechanical Engineering (Energy, Process and Flow Technology) and double annotations in Technology in Sustainable Development and Entrepreneurship.

My master's was a whirlwind in the most positive sense of the word. I'm incredibly grateful for all the opportunities that I was given and putting me on this path of accelerated learning. I had the chance to do a board year, an amazing international internship, experience the startup environment, learn from 170+ ECTS of coursework and publish two papers. However, the icing on this "cake" was this research work.

Of course, this work would not have been realised if it was not for the support of others. Therefore, I would like to take this opportunity to express my gratitude to the people who made this work possible. First off, I would like to thank Prof. dr. ir. Cees van Rhee and Prof. dr. ir. Jan-Leen Kloosterman for giving me the opportunity to work on this topic, being extremely approachable, and guiding me amidst their busy agendas. I have learnt a lot from our discussions. I want to thank Prof. dr. P.V. Aravind for helping me navigate the process and for his feedback on the report. And lastly, I would like to extend my gratitude to Prof. dr. ir. E.L.V. Goetheer for agreeing to be a part of my thesis committee.

I would like to end this word of thanks on a personal note, by thanking my family and friends (you know who you are). Thank you for supporting me through thick and thin, keeping me sane, motivating to do my best and distracting me from work. A special thanks to Marlinda for continuously being there, serving me reminders and going on all those walks with me that you did not want to. In the end, I would like to thank my parents, who have always supported me and moulded me to continuously strive to get the most out of every aspect of life. Whatever I achieve in life, it is as much theirs as it is mine.

As I look back, this journey was filled with highs and lows but nevertheless, left me with great stories to tell and experiences to share. Enjoy reading!

Siddharth Kalra
Delft, September 2020

Abstract

Dredging is an energy-intensive operation and, due to the nature of the process, there are large and rapid fluctuations in the power requirement. With the signing of the Paris Agreement, implementation of IMO 2020 and expansion of ECAs, the external pressures for the reduction of different emissions (CO_2, SO_x, PM, and/or NO_x) in dredging are rising. Additional motivating factors are the rise in the fuel expenses which form a major component of dredging project costs and the incentives from regulatory authorities to reduce the carbon intensity in dredging operations. Often, the achievement of one objective leads to deterioration of another, for example, the use of IMO-compliant fuel can increase the overall carbon emissions. In recent years, alternative fuels like LNG and biofuels have been explored. However, they suffer from their own set of issues and with the predicted trends, the usage of these alternative fuels would imply lower production and earnings, especially in large dredging projects.

In this work, a marine power plant concept that has been rarely discussed in the context of dredging is explored and forwarded: a nuclear-based system. Fundamentally, such a power plant addresses the issues related to the emissions and essentially eliminates bunkering stops. This was the first study focused on nuclear-powered Trailing Suction Hopper Dredgers (TSHD), the most common type of dredging vessel. In this work, a system-level study was carried out to ascertain the retrofittability of a nuclear-based system on four existing TSHDs. The feasibility of retrofitting the nuclear-based system has been studied by comparison of mass and volume requirements of the nuclear power plant, with the mass and volume of the engine and fuel storage system of current dredging vessels. No re-design of the vessel was considered here.

The ”inherently safe” High Temperature Gas-cooled Reactor (HTGR) with Nuclear Air-Brayton Cycle (NABC) was determined as the nuclear power system of choice. It appeared that for such a system, the TSHD sizes that are interesting for the deployment starts around 12000 m^3 hopper capacities. The bigger the hopper capacities than this baseline, the better the nuclear system performed. It was found that despite the satisfaction of the mass and volume constraints, a redesign of the TSHD is required for the placement of the reactor and for the compliance with the nuclear related regulations.

In addition to the nuclear power plant, the retrofitting of the TSHDs with Proton Exchange Membrane Fuel Cell (PEMFC) in combination with solid, compressed and liquid H_2 storage and batteries was considered. With the current commercially available offerings, PEMFC with liquid or 500 bar compressed H_2 storage were found to be suitable for maintenance dredging or capital dredging for a short duration (couple of days). However, it was established that the realisation of endurance level of current dredgers is not possible without a reduction of hopper capacities or factorial increase in energy density of storage. Further, the smaller TSHDs were found to be better suited to use PEMFC or battery-based systems.

A part of this work also tried to answer the pertinent question of the third party liability insurance premiums for a nuclear-powered vessel and the regulations such a ship would be subjected to. Further, a preliminary business case was developed and the sustainability of the concept was evaluated. It was realised that the technological forces and trends like the development of Small Modular Reactors, deep-sea mining and autonomous ships, could favour the development of a fleet of nuclear-powered dredging vessels in the future. However, the regulations and the support for these vessels would be highly dependent on the flag country and operational location.

Keywords : Dredging, Trailing Suction Hopper Dredgers, Nuclear, HTGR, NABC, PEMFC, H_2 storage, Battery, Nuclear third-party liability insurance

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Nomenclature

Abbreviations

AC	Alternating Current
AGR	Advanced Gas cooled Reactor
AHTR	Advanced High Temperature Reactor
Bkse	Nuclear Installations Fissionable Materials and Ores Decree
BWR	Boiling Water Reactor
CFR	Code of Federal Regulations
CONAS	Combined Nuclear and Steam Propulsion
CSD	Cutter Suction Dredger
DC	Direct Current
DoD	Depth of Discharge
DWT	Deadweight tonnage
ECA	Emissions Control Area
EEDI	Energy Efficiency Design Index
EPA	Environmental Protection Agency
ESS	Energy storage system
EuDA	European Dredging Association
FC	Fuel Cell
FOAK	First-of-a-Kind
GHG	Greenhouse Gases
HFO	Heavy Fuel Oil
HPDF	High Pressure Dual Fuel
HTGR	High-Temperature Gas-Cooled Reactor
HTR	High Temperature Reactor or also High Temperature Resistant
HX	Heat Exchanger
IADC	International Association of Drilling Contractors
IAEA	International Atomic Energy Agency
IEP	Integrated electric propulsion
IFO	Intermediate Fuel Oil
IHX	Intermediate heat exchanger
ILG	Intermediate Loop Gas
IMO	International Maritime Organization
JIP	Joint Industry Programme
KEW	Kernenergiewet "Nuclear Energy Legislation"
LBE	Lead-Bismuth Eutectic
LCOS	Levelized Cost of Storage
LFR	Lead-Cooled Fast Reactor
LHV	Lower Heating Value
LMTD	Log mean temperature difference
LNG	Liquefied Natural Gas
LPDF	Low Pressure Dual Fuel
LS	Low sulphur
LWR	Light-water reactor
MARAD	Maritime Administration
MARPOL	International Convention for the Prevention of Pollution from Ships
MGO	Marine Gasoil
SDR	Special Drawing Rights

NABC	Nuclear Air Brayton Cycle
NIMBY	Not In My Back Yard
NRC	Nuclear Regulatory Commission
NS	Nuclear Ship
PBR	Pebble bed Gas Cooled Reactor
PCHE	Printed Circuit Heat Exchanger
PEMFC	Proton Exchange Membrane Fuel Cell
PHE	Plate Heat Exchanger
PHX	Primary heat exchanger
PWR	Pressurised Water Reactor
RPM	Revolutions per minute
SMES	Superconducting magnetic energy storage
SMR	Small Modular Reactor
SoC	State of Charge
SOFC	Solid-Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea
SOx	Sulphur Oxides
TRISO	Tristructural-isotropic
TSHD	Trailing Suction Hopper Dredger
UCO	Uranium Oxycarbide
UNCLOS	United Nations Convention on the Law of the Sea

Symbols

β	Area Density of Heat Exchanger	m^2/m^3
λ	Scaling Factor	$-$
W	Weight	kg
P	Power	W
V	Volume	m^3
E_k	Kinetic Energy	J
ω	Angular Velocity	m^2/s
I	Moment of Inertia	kgm^2
k	Radius of Gyration	m
Δt	Temporal Resolution	s
$\dot{Q}$	Heat Transfer Rate	W
U	Heat Transfer Coefficient	$W/(m^2K)$
A	Area or Overall Heat Transfer Surface Area	m^2
c	Specific Heat Capacity	$J/(kgK)$

1

Introduction

Maritime transport is responsible for 90% of the global trade. Shipping is the most cost-effective and environment-friendly means for the transportation of goods and raw material around the world [1]. Without dredging, there is no global trade and consequently, no economic development [2].

Dredging is an activity to remove material from under water. But the objective of dredging is not limited to the creation and maintenance of deeper waters for maritime trade. Dredging is also carried out for coastal protection, land reclamation, extraction of construction materials, wreck clearance, offshore renewables, undersea cable laying, and even picking up shellfish from the sea floor. All in all, infrastructure that is constructed or maintained in connection with water almost always requires dredging.

The most common dredger vessel type is the Trailing Suction Hopper Dredger (TSHD). These dredging vessels have hoppers and are self-propelled. Due to their characteristics advantages [3], they are regarded as the workhorses of the dredging industry. These advantages include :

- Independent operations
- Working in congested areas
- Handle relatively harsher weather and sea conditions
- High production rates
- Cheaper mobilisation

Essentially, Trailing Suction Hopper Dredgers are giant vacuum cleaners that remove the material from the ocean floor. TSHDs are used for all forms of capital and maintenance dredging, and especially, for land reclamation. The vast volumes of sand, often mined far away from the fill site, have resulted in the rapid expansion in the hopper capacities to well over 20,000 cubic metres. This has consequently, also increased the fuel requirements for undertaking dredging operations. Hence, Trailing Suction Hopper Dredgers are considered for analysis in this work.

Dredging is typically considered the most extreme work that an engine can be subjected to [1]. With the signing of the Paris Agreement, implementation of IMO 2020 and expansion of ECAs, the external pressures for the reduction of different emissions (CO_2, SOx, PM, and/or NOx) in dredging are rising. In light of the various emissions regulations and the increased dredging needs, the dredging industry needs to find better solutions to comply with the regulations and continue to service the world's dredging needs. For the time being, dredging vessels have been exempted from the mandatory Energy Efficiency Design Index (EEDI) by International Maritime Organization (IMO), due to the complexity of engine setup and energy demands [4]. Nevertheless, the industry has been moving towards reduction of CO_2 emissions. Over the past few decades, with technological changes/improvements, average reduction

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[1] For use aboard dredgers, manufacturers derate their engines by 10% (See Appendix C.2.1)

of 7.5% in CO_2 emission per m^3 sand loaded has been achieved per decade in TSHDs [5]. Blue Carbon has been suggested for offsetting of carbon emissions [6]. Such a strategy can also yield negative carbon emissions if a carbon neutral dredger is used. However, this is not an effective strategy against other emissions.

(a) Optimus (b) Willem van Oranje

(c) HAM 318 (d) Cristóbal Cólon

Figure 1.1: Visual representation of selected TSHDs used in this work

Image Courtesy: a) Marinetraffic b) Dredgepoint c) Vesselfinder d) Flickr

To date, the most realistic (technical and economic) solution for Sulphur Oxides (SOx) compliance (0.10%) by dredgers would be to run on Marine Gasoil (MGO) [5]. Emissions compliant fuel like MGO is about 40% more expensive than Low sulphur (LS)[2] or even up to 50% more expensive than regular Intermediate Fuel Oil (IFO) grade fuels. Considering that the cost of fuels can easily represent thirty percent of dredging cost [7], the use of emission compliant fuel increases the cost of operation substantially. For example, with a 30% increase in the fuel costs, the project execution costs would be escalated by 5-10%. Therefore, the financial impact of fuel on the margins is considerable and this has incentivised the search for fuel economy and alternate fuels.

In recent years, alternative fuels have been explored. These include : Liquefied Natural Gas (LNG), biofuels, methanol, ammonia among others. Much valuable research has taken concerning these energy sources and their propulsion concepts. Vessels utilising LNG and biofuels are already plying the oceans and working on the seabed. However, the alternative fuel and power technologies suffer from their own set of issues (supply, energy density, gravimetric density, low TRL, captive and life cycle emissions etc.). Further, with the predicted increase of distances between the loading/dumping sites and increased frequency of bunkering calls, the usage of these alternative fuels would imply lower production. Especially in large dredging projects this would imply depressed earnings.

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[2] 1% sulphur

Hence, there is an urgent need for an emission compliant, energy-dense and cheap fuel in the dredging industry.

A nuclear-powered dredger has the potential to reduce the emissions (CO_2, SO_x, PM, NO_x and HC) to zero. Nuclear fuel prices are relatively stable (See Appendix C.13) and the ”once-in-years” refuelling of nuclear reactors essentially eliminates the bunker stops. In the past 15 years, works have been carried out on the topic of nuclear-powered tankers [8], container ship [9] and short sea concept [10]. However, Murden et al.'s work [11] from 1970 is the only work done on nuclear-powered dredgers and this too, considered a cutter suction dredger. Big strides have been made in the dredging industry and the ecosystem has changed completely in the last 50 years. On the nuclear energy front, there is a better understanding of certain reactor concepts, increased focus on the development and commercialisation of the Generation IV (Gen IV) reactors. These reactors have the concrete goals for the improvement of sustainability, efficiency, safety and costs related to nuclear energy [12]. The discussion around Small Modular Reactor (SMR) has gathered momentum in the past decade and currently, these are in various stages of deployment. All of these developments necessitate a re-look into the potential of using nuclear energy to power dredging vessels.

1.1. Research Objectives

The objective of this work was exploration of powering of Trailing Suction Hopper Dredger vessels by nuclear energy. There are two ways in which this can be achieved : placement of the nuclear based system on board of the vessel (”direct”) or the indirect use of shore-based nuclear energy which stores electricity in the batteries or generate nuclear H_2 for fuel cells (”indirect”). This is one of the first works in the direction of powering dredging vessels by placement of nuclear energy source aboard the dredger. The driving questions in this work were :

1. What could be a potential conceptual design for the powerplant of a nuclear-powered dredging vessel?
   Numerous nuclear and power conversion technologies exist. There are a variety of different design choices available (fuel, coolant, moderator, reflector, and neutron spectrum etc.) for nuclear reactors, even within the same reactor technology. The conceptual design is not limited to the generation of power but also includes the transmission and distribution of power.

2. What sizes of TSHDs are interesting to be powered by a nuclear system?
   The placement of nuclear power onboard of a vessel or the installation of PEMFC based or battery based system is not interesting for every TSHD. TSHDs are designed for certain hopper capacities and endurance [3]. These factors dictate the available volume and mass for placement of the powerplant. To avoid a redesign of the TSHDs, systems need to fit into these mass and volume constraints.

3. What are rules and regulations that a nuclear-powered dredging ship has or would have to comply with?
   At present, most of the nuclear propelled vessels are owned by navies but the civilian nuclear-powered vessels would not have the same treatment as naval nuclear-powered vessels. Because nuclear-powered merchant ships have sailed and nuclear icebreakers continue to sail, some regulations and guidelines already exist. After the development of some of these regulations, no civilian nuclear-powered vessel has sailed. There certainly is no precedent for a nuclear-powered dredging ship and no prior works have focused on the regulations in light of operating a dredging vessel.

4. What is the possible premium for third party liability for a nuclear-powered dredging ship?
   To cover the risk to a third party from a nuclear accident, nuclear third party insurance is a mandatory feature of nuclear installations. The nuclear third party liability insurance premium for a nuclear-powered vessel is either skipped from the discussion or for example is referred to as being ”expensive” [13].

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[3] Endurance can be defined as the maximum length of time that a ship can sustain at specific conditions. In this report, it is defined as the maximum length of time, the vessel can sustain without making a bunker call (port visit for refueling).

5. Based on today's commercially-available technology, to what extent can battery-only system or H_2 fuel cell-only systems power a TSHD and what is the best role for TSHDs powered by these technologies?

This work will try to answer the aforementioned questions.

1.2. Approach

Finding hard limits for how well an energy source performs aboard a dredging vessels would require generating vessel plans of different TSHDs (hundreds of permutations) and missions (related to the dredging cycle and the parameters enforced by restrictions such as draft, speed etc.) and then carrying out a feasibility of each of these.

The objective of this study is to provide a rough estimation on the TSHD sizes that may/can have a potential for adoption of nuclear energy based powersystems (direct and indirect). With this first study, the sizes which favor the systems can be examined in detail while unfavourable areas can serve for undertaking a trajectory for future development.

In this work, rather than conducting a full design of each of these vessels, the power and energy requirements are translated into the volume and mass of the systems employed. The volume and mass of the systems are then compared with the volume and mass available with the dredger. This work provides an easy-to-use method for estimating the suitability of nuclear based systems, PEMFC based systems and battery packs. No re-design of the vessel or change in operating procedure was considered here.
A typical dredging cycle does not exist. Therefore, to mirror reality, dredging cycle data of a jumbo diesel-electric dredger was obtained. The data covered two discharge types (pump ashore and dumping) and consisted of 11 variables (approximately 2 million values). The data set was cleaned, analysed and normalised. Next, the normalised data was used to develop power profiles for four TSHDs that are in service today. The selection of these TSHDs was carried out so as to cover a spectrum of sizes (based on the Gross Tonnage, Deadweight Tonnage, Hopper capacity etc.). The specifications of four vessels can be found in Table 4.3. The relative sizes of the TSHDs in question are visualised in Figure 1.2.

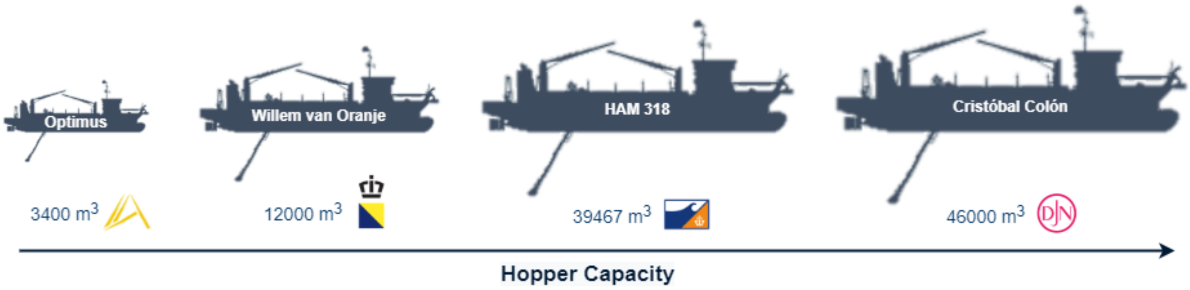

Figure 1.2: Visual representation of the relative sizes of the selected TSHDs used in this work

Since there are a lot of nuclear reactor designs, a selection of the nuclear reactor technology was considered and followed by the selection of the power conversion system. Then, the nuclear reactor and the auxiliary systems were sized to cater to the power demands. This was achieved through MATLAB® code and Aspen Plus simulation. Heat Exchanger design was carried out in Aspen Exchanger Design and Rating (EDR).

The computation of mass and volume of the nuclear energy based power systems (direct and indirect) for replacement of current fossil based power plants required data on the individual components of the systems. The mass and volume of nuclear reactor and shielding was estimated from a current design. Single and multiple reactor units were considered in the analysis. The Heat Exchanger volume and mass were computed based on area density and a gravimetric factor based on literature. Current commercial data on turbo-compressors, generators, PEMFC and battery packs was gathered and correlations were formed. To accurately represent commercially available technology, data on mass, volume, energy capacity, peak power, unique features was compiled from manufacturers (websites, product presentations or specification sheets) or previous works. Sometimes, there were holes in the data and not all information was found to be directly available. In such cases, other derived parameters (for example specific energy, energy density etc.) were used to calculate the required parameters. If the derived parameters could also be not found, the required parameters were estimated. Fuel cells require a fuel storage system for the energy requirements. Three types (compressed, solid and liquid) of storage systems were considered. Figure 1.3 visually represents the various cases that are considered for evaluation of the four dredgers.

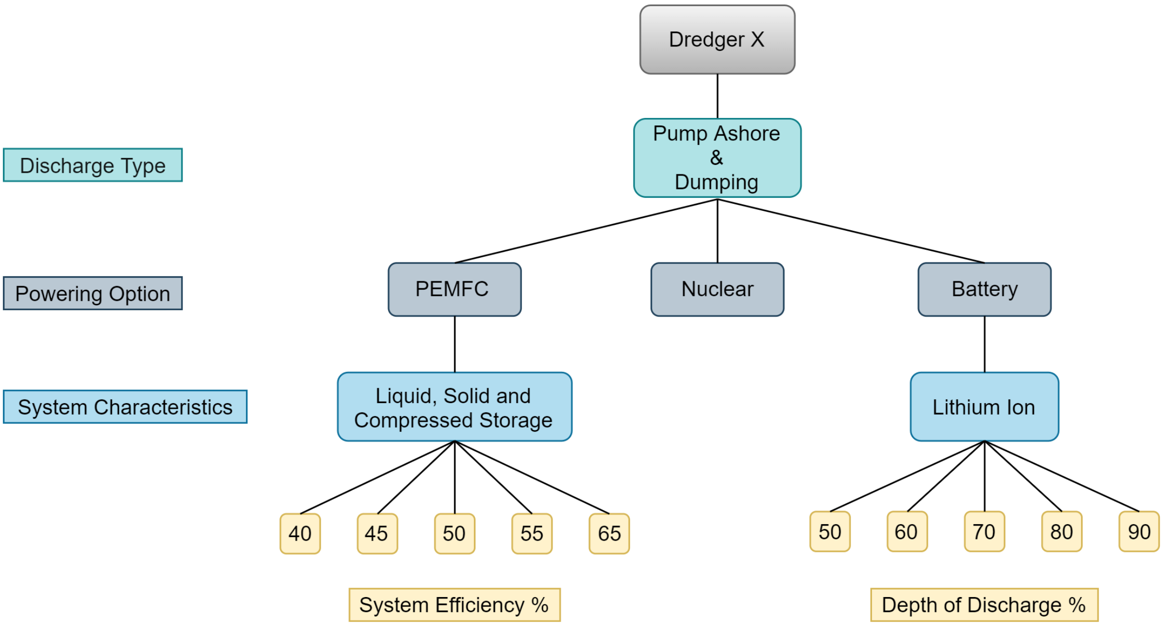

Figure 1.3: Different cases considered in this work for each of the four TSHDs

The information on the regulations was collated mostly from multiple primary sources (text of laws) and seldom, from secondary sources. For the determination of the third-party liability insurance premiums, the known third-party liability amount and multiple accident frequencies were used to determine a premium value. This premium was compared to a known nuclear third-party liability premium to ascertain the ”fairness” of the premiums and a multiplicative factor was arrived at. Then, the premium for the different dredgers was calculated by considering the multiplicative factor.

1.3. Thesis Outline

The thesis is structured into multiple chapters, sections, subsections and subsubsections. At the start of each chapter is the information about the contents (section-wise) of the concerned chapter.

Briefly, the topics that are covered in each of the chapter are given as follows :
Chapter 2 discusses the present scenario and trends that affect/are affecting the dredging industry, the various emission compliance options, the nuclear option and about nuclear-powered vessels.
Chapter 3 describes the regulations that a nuclear-powered TSHD would encounter/have to comply with. Some of the ramifications on vessel design due to some of these regulations is also discussed.
Chapter 4 covers the dredging cycle data, different system design possibilities and the selection of the components for the marine nuclear powerplant.
Chapter 5 discusses the power control philosophy, sizing of nuclear reactor and energy storage system, modelling of the power cycle, development of mass and volume correlations and computation of total system mass and volume.
Chapter 6 discusses the results of simulation and modelling.
Chapter 7 provides an idea on the safety of the vessel taking into consideration some possible events, sustainability aspects (fuel, emissions, nuclear decommissioning), economics (including possible third party liability premiums) and other necessary things that have to be taken care of.
Chapter 8 summarizes the conclusions of this work and provides recommendations for future research.

In addition to the main body, this report has 6 Appendices. Each of the appendix is based on a specific theme.
Appendix A is the report for the work that was carried out in partial fulfillment of the requirements for the Master Annotation in Entrepreneurship. This involved understanding the value of a nuclear-powered TSHD to dredge operators, the market potential, the possible geographical beachhead market and identified the stakeholders for a nuclear-powered TSHD.
Appendix B comprises of data that have been used in the report.
Appendix C includes the supplementary information on topics covered in this thesis.
Appendix D contains portions of the methodology that are not a part of the main report.
Appendix E covers some of the theoretical background that might be necessary to understand the report. Additionally, it harbors the glossary.
Appendix F contains some low priority/supplementary results.

As the convention dictates, when the name of a vessel appears in the text, it is capitalised.

2

Why a Nuclear-powered TSHD now?

This chapter tries to provide a background of the the dredging industry, the developments and rounds up with a review on nuclear-powered vessels. In Section 2.1, the non-emission related trends affecting the dredging industry are identified and discussed. These include increase in number of jumbo and megatrailers, population growth and urbanisation, increase in diesel-electric, autonomy of ships. Some possible future trends include new dredger concepts, anticipated increase in travel distance, megaprojects, and deep sea mining. In Section 2.2, dredging related emissions (CO_2, NO_x SO_x, heavy metals are quantified, soot & noise emissions are treated qualitatively. In Section 2.3, the obligatory emissions regulations, the government impetus to move towards lower emissions and current/proposed carbon taxation is discussed. Section 2.4 discusses the fuel options that are being currently used and/or considered. Nuclear fuel is identified as a potential option in Section 2.5 that is a ”blind spot” with the potential to be an interesting option for consideration. In Section 2.6, some nuclear-powered vessel concepts like nuclear icebreakers, merchant ships, other concepts (floating/submerged) are discussed. It is realised that nuclear-powered dredging ship has not been evaluated or given proper consideration.

The dredging industry is a highly competitive, labour intensive and specialised industry. Four of the biggest dredging companies are from Belgium and Netherlands [14]. European dredging companies have 66% market share of dredging in worldwide markets (open and closed) [15]. In 2015, European dredging companies had a turnover of more than € 9.2 billion and employed directly over 75,000 people (direct and indirect) [16].

2.1. Trends

This section discusses some of the developments and the non-emission related trends that affect/have the potential to affect the dredging industry (directly or indirectly). The understanding of these developments is necessary to realise why the introduction of a nuclear-powered TSHD could make sense at this point of time.

2.1.1. Population Growth and Urbanisation

The urban population has grown from 751 million to 4.2 billion between 1950 and 2018. By 2050, more 2.5 billion people would live in urban centres of the world [17].

Due to the population growth and urbanisation, the construction needs of the world will continue to grow. Presently, this need for construction material is fulfilled by river aggregates and in general, unsustainable. To satisfy the need for construction material, there is an imminent move from the river aggregates to sea sand [18].

2.1.2. Embracing Diesel-electric

In 2018, the world’s first diesel-electric aggregate dredger, 5450 m^3 TSHD was launched [19]. In the dredging industry, there is a move towards switching to the diesel-electric propulsion systems. With such a powertrain, power is generated by diesel generator sets and all the major drives are electrically driven. In an ideal case, there would be no installation of latent engine power. This would essentially imply that when the dredger is trailing, engine power is distributed over propulsion and pumping; when sailing full, power is directed for propulsion and when pumping ashore most of the power is directed to drive the inboard pumps. A control system automatically starts and stops the sets depending on the power requirement. If multiple diesel engines exist, then there's also an opportunity for load sharing which can lead to optimal load distribution over the diesel generator sets. Further, the frequency controllers help in making each system can operate at its optimal speed and power.

There are several benefits adoption of diesel-electric propulsion [20]. These include :

- Noise and vibration reduction.
- Flexibility in the placement of diesel engine
- Reduction in the occupied space due to elimination of auxiliary diesel generators
- Reduced maintenance
- A lower fuel oil consumption, usually the best in their class [21]
- Constant maximum torque over a large range of RPM

2.1.3. Escalating Costs

There are various cost drivers for a dredging project [22]. These include but are not limited to :

1. Permits : for dredging, disposal, waste and water management
2. Mobilisation cost : This is a one time fixed cost to the project location.
3. Nature of removed material : The thicker the sediment face, better are the production rates (less relocation). The denser the material, more power is consumed and hence, more fuel. Harder material is more difficult to unearth. This also causes more equipment wear and tear.
4. Operating Time : In general, run time consists of 10-12 hours shifts lasting for 5-6 days a week. 24 hour shifts are most cost effective as the dredger does not need to startup and mobilise.
5. Transport : Distance and the means.
6. Disposal method : Restrictions on the method of disposal for example : requirement for water treatment, formation of a settling basin etc.

Weather downtime or any other downtime (mechanical/"passing vessel") not factored for, also affects the economics. Except for the costs of permit, other factors influence the costs by the way of increasing fuel consumption or decrease of productivity.

Fuel Cost and Volatility

Fuels can easily represent thirty percent of dredging cost [7]. The volatility in the price of fuel makes fuel costs the most variable portion of the cost. The operational profile of a dredging vessel affects the fuel consumption [23]. The properties of the dredged material, depth, speed limitation and the amount of manoeuvring etc. affect the operational profile. This in turn effects the fuel consumption. In addition to the operational profile, the fuel consumption is also related to the design and the age of the vessel.

With the implementation of IMO 2020, the fuel component in the total project cost has increased and hence, the total project costs have escalated too. This is because emissions compliant fuel like MGO is about 40% more expensive than LS380 (1% sulphur) or even upto 50% more expensive than regular IFO 380 grade fuels.

Longer travel distances

In some countries like Belgium, there is a greater need to extract materials from the sea for construction and fulfill the demand for housing and infrastructural works. The sea is becoming more crowded and bigger distances have to be travelled to obtain the required raw materials [24]. This increases the fuel consumption, costs and emissions.

2.1.4. Rise of Jumbo and Mega Dredgers

The average growth rate of deadweight tonnage of dredgers for the period from 2004-14 was 3.3% p.a. [25]. Figure 2.1 displays the Gross Tonnage with the year of building of the dredger vessels. It is clear that larger vessels have been built in the past 30 years and the size of dredging vessels has increased.

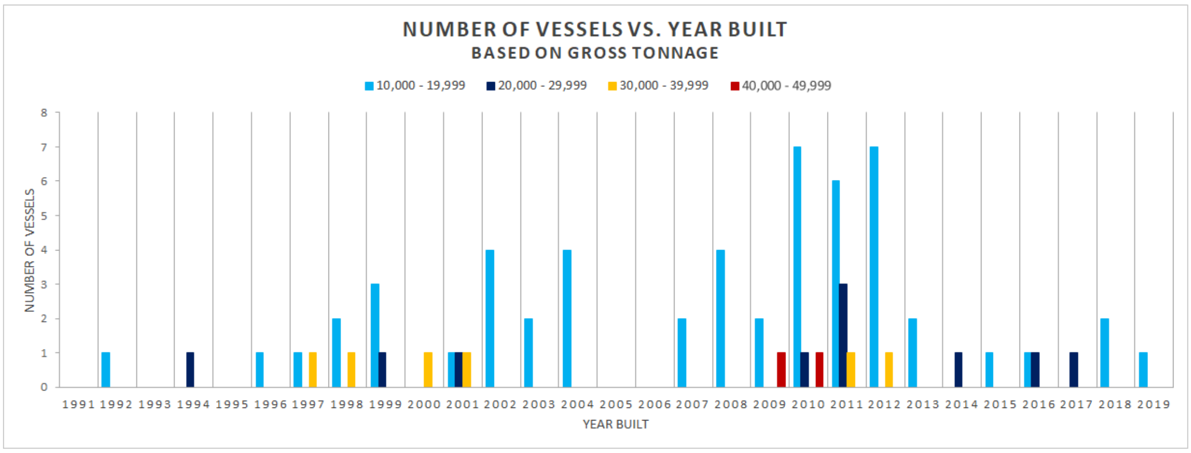

Figure 2.1: Gross Tonnage of TSHDs vs. Year built

Source: Data from Clarksons Research [26]

In particular, the TSHD was developed in response to the need for extraction of huge quantities of easily-won fill material in realistic time scale and affordable prices [27]. For a period of time, the development of dredging equipment was decoupled from economics. The delivery of Jumbo Hopper dredge class PEARL RIVER in 1994 to DEME accelerated the creation of a new market in dredging, the land reclamation work [28].

Size matters in the dredging world, jumbo trailers (35k cubic metres) are shown to make better economical sense than smaller ones. In 1988, the largest TSHD was LELYSTAD (hopper capacity of 10,000 m^3) while in 2000, the largest TSHD was VASCO DA GAMA with a hopper capacity that was more than triple of ”LELYSTAD” (33,000 m^3). In the 1990s, a tipping point was reached w.r.t. the increasing size of the TSHDs [29].

With this increase in the hopper size came the increase in the power requirements. CRISTÖBAL COLÓN, the largest TSHD today has a total installed power of 46,000 kW. In comparison, a 8,000 cubic metre dredging ship (for example, SHANTI SAGAR -17) has only 8769 kW of installed power [30].

Jobs that formally could be conducted only with cutter suction dredge are now being performed by TSHDs. One such example is the D.R.A.C.U.L.A.®system (high-pressure water jet) that was equipped in the TSHD, LANGE WAPPER to dredge cemented sand [1][31].

2.1.5. Megaprojects

Large projects that require removal of millions of m^3 of sand have been undertaken in the past 25 years. Such projects were not a regular feature of the dredging industry earlier. A non-exhaustive list of large dredging projects that have been carried out in the past 10 years and the m^3 of sand removed is tabulated in Table 2.1.

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[1] (uniaxial compressive strength of 5-8 MPa)

Table 2.1: Non-exhaustive list of big Dredging Projects

Project	m^3 **of sand**
Maasvlakte 2	240,000,000
Suez Canal Expansion	258,000,000
Port of Hamburg Channel Deepening	32,000,000
Palm Jumeriah	120,000,000
Dangote Refinery	50,000,000

Source: [16], [32], [33]

There are plans to build megaprojects that would require moving billions of m^3 of sand. In the recent past, four proposed mega-canals have been proposed/re-proposed.

- Interoceanic Grand Canal(Nicaragua)
- Kra Canal
- Kanal Istanbul
- Caspian-Persian Canal

Inter-oceanic Grand Canal in Nicaragua is a 273 km channel that is expected to cost $50 billion[2]. This canal would be three times as long and twice as wide as the Panama Canal [34]. One estimate [35] puts the dredged material amount to 5 billion cubic metres requiring 5 billion litres of fuel. However, the bankruptcy of the businessman sponsoring the project has put the project on hold.

Kanal Istanbul, also referred to as the Bosphorus Strait project is a 45 km channel linking Black and Marmara sea. The 45 km will run from the Durusu region on Istanbul's Black Sea coast to Lake Küçükçekmece on the Sea of Marmara. The canal will be 25m deep and depending on the dock location between 250m-1,000m wide [36]. This would require an excavation of 1.5 billion cubic metres of soil [37] and cost around 17.3 billion Euros [38]. The environmental clearance for the project was obtained in January 2020 [39].

Kra Canal is a proposed canal that would serve as an alternative to the Straits of Malacca and shorten transits from East Asia to West Asia/Africa. The canal would connect the Gulf of Thailand with the Andaman Sea. For the twin-channel (350m wide) Kra Canal it is estimated that about 2,000,000,000 m^3 of soil and broken rock [3] would have to be removed. The total cost of the Canal is expected to be approximately $25,000,000,000 in terms of 2005 USA dollars [40]. However, how these numbers have been arrived at is not clear from the work. As of 16 January 2020, the Thai Canal Project is being considered by the Thai House of Representatives [41].

Caspian-Persian Canal is a planned 700 km canal connecting the Caspian Sea to Persian Gulf. The plans for these were discussed in 2016 between Russia and Iran [42].

2.1.6. New Dredger Designs

In 2019, a submerged maintenance dredger design emerged [43]. For the same dredging depth, transit speed and almost same hopper capacity, this design referred to as AUMD (Autonomous Underwater Maintenance Dredger) claims to decrease the power requirements for propulsion (>55%) and dredging (~80%). Additionally, it was claimed that the operational costs are much lower and in 15 years, the owners can expect twice the profits (in comparison to conventional dredgers).

Constructed in 2017, BLANEW, a small 565 kW Cutter Suction Dredger (CSD) is fully electric. It is powered by a floating electric cable that is connected to shore based electricity [44].

2.1.7. Autonomous Ships

The autonomy aboard a vessel has been rising. There are cost savings due to reduced crew costs and the possibility to change the vessel's design changes [45]. As part of IMO's Strategic Plan (2018-2023), IMO is considering the issue of introduction of marine autonomous surface ship (MASS). Interim

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[2] Unless explicitly stated, in this work $ implies US $

[3] In comparison, Cape Cod Canal, the widest canal in the world built in the 1940s required displacement of 42,000,000 m^3 of material.

guidelines for Maritime Autonomous Surface Ships (MASS) trials. (MSC.1-Circ.1604) have already been published by IMO [46]. Some operational trials of autonomous vessels has already been conducted. In December 2018, the car ferry FALCO navigated autonomously (without any human intervention from the crew) [47]. In mid-September 2019, a Ro-Ro vessel successfully completed its journey travelled between Xinsha, China and Yokohama, Japan while navigating autonomously [48].

Dredging can be an extremely complex and sensitive operation. However, carrying out dredging operations autonomously is also being tried out in the sector. In 2019, TIAN KUN HAO, a 6,000 $\frac{m^3}{hour}$ cutter suction dredger (operated by Tianjin Dredging, a subsidiary of China Communication Construction) carried out dredging operations without human intervention [49]. ARZANA, a TSHD, operated by National Marine Dredging Company features an integrated forward-looking system which combines various sensors [50]. A 3D image of the seabed is generated via sonar and this is operated in conjunction with the navigation system. This enables the dredger to ascertain the composition of the dredging surface, optimising its speed and reducing overall fuel consumption. This system is capable of allowing the dredger to navigate by itself along designated dredge tracks.

2.1.8. Deep Sea Mining : New Market?

Six growth drivers [4] are recognised for the dredging industry by the EuDA [51]. However, there is a possibility of a 7th factor coming up in the near future : Deep Sea Mining. Deep Sea mining is the process of mineral retrieval from the ocean floor. Deep Sea mining may be a lucrative market for dredging vessels and near a breakthrough [14]. Deep Sea mining can be a crucial field to satisfy the thirst for critical raw materials [5] especially those that have the possibility of powering the energy transition. Some deep sea mining capable vessels exists already [52] [53] [54]. In particular [6], rock phosphates (for example, in Chatham Rise - New Zealand), iron sands and diamonds (for example, in New Zealand, Papua New Guinea and Namibia) can be mined with the capabilities of current TSHDs.

For Deep Sea mining, a contractor willing to acquire a license must do so under a sponsoring state. The Netherlands is not yet a sponsoring state for the license, however, Dutch companies are involved [55]. Deep Sea mining can be a crucial field to satisfy the thirst for critical raw materials that power the energy transition. However, Deep sea mining represents a green-green dilemma, where biodiversity conservation conflicts with renewable energy [56].

2.2. Emissions

Most of the environmental impact of a TSHD is during its operational phase and the usage of fossil fuel causes the majority of the impact [57]. In the next parts of this subsection, emissions from the dredging industry and dredging operations would be discussed.

Carbon

A global estimate was made by European Dredging Association (EuDA)/International Association of Drilling Contractors (IADC) on the basis of the 2008 IADC plant list "Dredgers of the World" [7] [15]. The emissions by EuDA members were based on actual fuel consumption figures as reported by the individual EuDA members. This data is presented in Figure 2.2. More recent data (till 2017) is only available for the emissions of the EuDA members and can be found in Appendix Figure C.1.

The majority of carbon emissions from dredging companies is attributable to the utilisation of their dredging equipment. In general, there is a lack of clarity on the reported carbon emission's Scope (1,2 or 3). Out of top 10 dredging companies in the world, Boskalis seems to have the most comprehensive carbon reporting mechanism. However, the industry seems to be more carbon efficient than the shipping industry [8]. More details on the company level carbon emissions, carbon reporting and carbon

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[4] see A.3

[5] For more on critical raw materials, see C.4.

[6] due to the depths they are found at and the state they are found in.

[7] This list also contained small dredging equipment that is not ocean-going and not IMO-registered.

[8] With an approximate value of carbon intensity is 600 tons per million $ revenues in comparison to 1000 tons per million $ revenues.

intensity can be found in C.3.1.

The need for the development of an alternative CO_2 index for dredging ships arises from the fact that the carbon emissions from dredging are dependent on a variety of factors. The emissions highly dependent on the borrow pit/dredging site, transport distance, the type of soil, operation etc. [15].

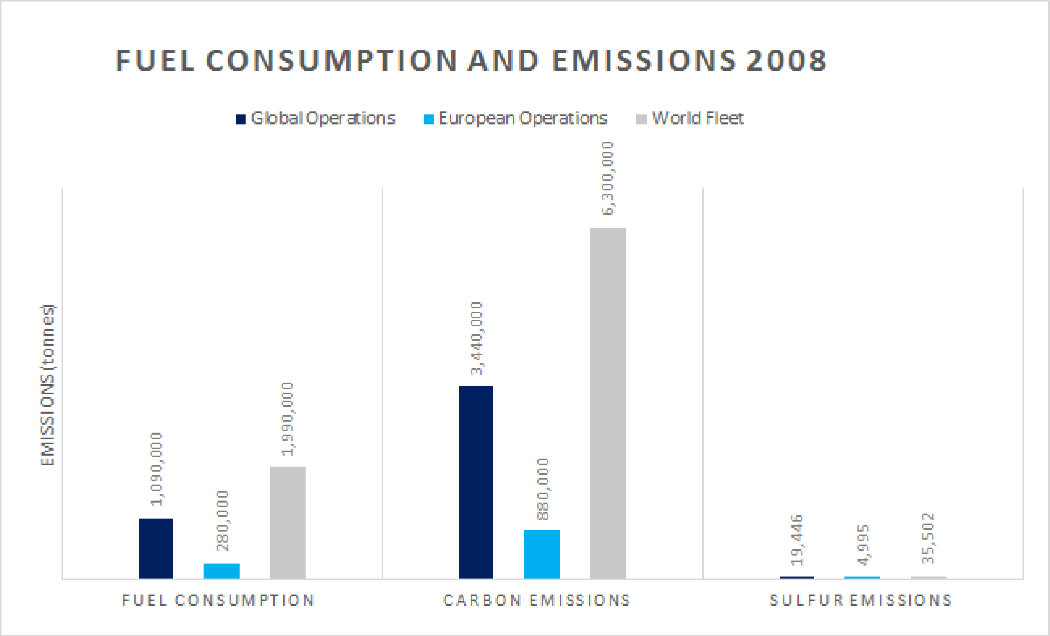

Figure 2.2: Global estimate of fuel consumption with CO_2 and SO_2 emissions from dredging operations

A comparative study concluded that, during dredging process, dynamic loads lead to higher and fluctuating power specific fuel consumption and exhaust emissions [58]. In most of the dredging projects that have transportation in the range of 10-20 km, the CO_2 emissions per m^3 of sand dredged is about 2-5 kg [59].

Vessel selection is an important aspect of emissions and costs reduction and should be mission-driven [60]. For example : smaller vessels can match and even outperform larger dredgers in projects with limited navigational depth, very short transport distances or with smaller dredged material quantities. Due to sailing with limited payload that is enforced by depth restrictions or manoeuvrability issues, the large size dredgers cannot work in an optimal energy efficient mode. Further, the mobilisation and demobilisation emissions are much smaller from a smaller dredger.

Heavy Metal Emissions

The long term accumulation of heavy metals causes acute and chronic toxicity to all living organisms. This leads to disability and ultimately, the death of the organism. Heavy metals are released into the air as a consequence of fuel combustion. The heavy metal emissions (specifically Mercury, Arsenic and Lead) from the dredging activities [9] is given in Figure 2.3. For comparison the entire UK road transport 39.4 million motor vehicles [61] [10] emits 550 kg of As [62], 33000 kg of Pb [63] and 300 kg of Hg [64].

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[9] Fuel data source based on 2008 IADC plant list "Dredgers of the World" and Emission Factors from Table C.2.

[10] (cars, trucks buses, ambulances etc.)

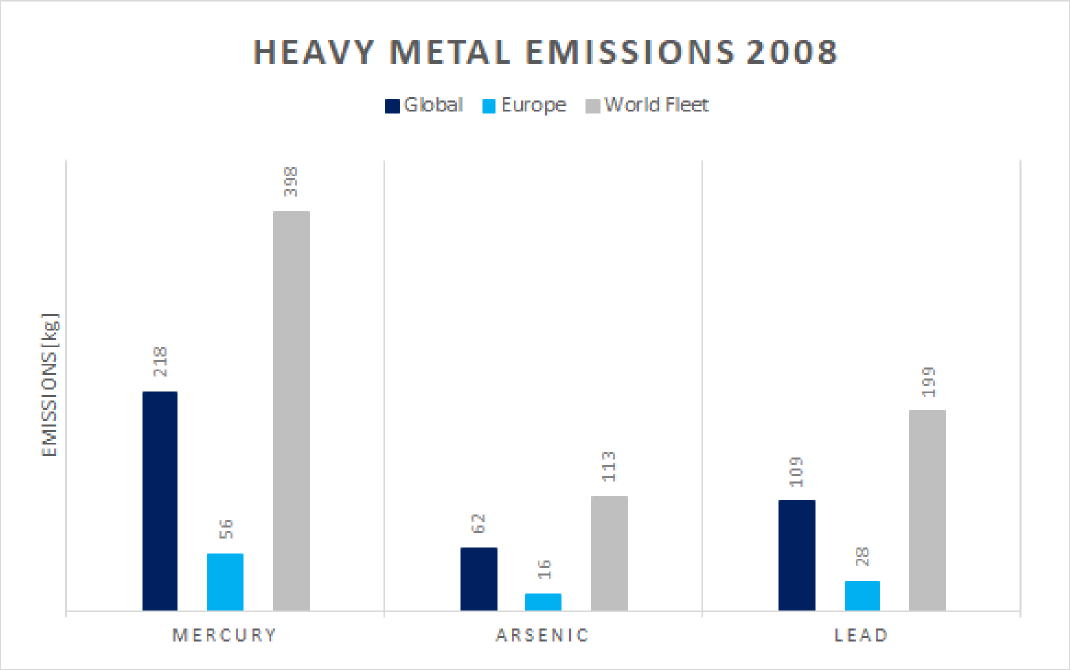

Figure 2.3: Estimated Heavy Metal Emissions (2008)

Soot/Black Carbon

After CO_2, black carbon (BC) is a major contributor to shipping's climate impacts. Over a 20-year period, soot contributes to more than 20% of CO_2 equivalent emissions from ships [65]. Discussions about Black Carbon emissions were part of IMO's Pollution Prevention and Response Meeting that was held from 18-22 February 2019 [66]. Hence, there seems to be a strong possibility that a regulation on BC emissions can be enacted in the coming years.

Soot formation can be reduced by usage of cleaner fuels (LNG or distillate fuels like MGO). Exhaust soot removal is also possible by using diesel particulate filters (DPFs) or electrostatic precipitators (ESPs), each of which reduces black carbon by more than 90% [67].

Underwater Noise

Underwater noise has adverse impacts on marine life [68]. TSHDs are one of the loudest vessels [69] [70]. TSHDs produce sounds intermittently as they move between the dredging and discharge sites. The constant (frequency) and higher intensity sounds from the vessel engines are transferred through the ship hull. The gears produce substantial amount of sound [69]. TSHDs emit sounds of <500Hz which is similar to cargo ship travelling between 8-16kt [71]. No formal regulations have been proposed for control of underwater noise. IMO guidelines on the reduction in generation of underwater noise exists. Of the measures prescribed, the diesel-electric propulsion is stated to be an effective solution [72]. This is due to the possibility to configure vibration isolation measures like resilient mountings and the lack of a gearbox mechanism.

2.3. Emissions Regulations

The Paris Agreement on Climate Change, that entered into force on 05/11/2016, is the first legally binding universal agreement at global level to enforce the urgent action on anthropogenic GHG emissions. However, this was not the first legally binding climate change treaty since the Kyoto Protocol. This was at MEPC 62 (July 2011) where MARPOL Annex VI was amended to make the Energy Efficiency Design Index (EEDI) mandatory for new ships and the Ship Energy Efficiency Management Plan (SEEMP) mandatory for all ships. The aim of the amendment was the promotion of energy efficient equipment aboard vessels. Depending on the ship type and size, the EEDI sets a minimum energy efficiency level per capacity mile. This amendment was entered into force on 1st January 2013 [73].

EEDI is not applicable to dredging vessel in its present form [60]. In Europe, EU's main legal instrument for CO_2 emissions from shipping is the Monitoring, Reporting and Verification (MRV) regulation. Similar to EEDI, dredgers are exempted from the first phase as it is understood that the most suitable approach to optimise their emissions is project based rather than ship-based.

Although, dredgers are currently insulated from carbon emissions related measures, they are not immune from the NO_x and SO_x emission regulations. There are global caps on NO_x and SO_x emissions and then, there are more stringent requirements in Emission Control Areas or ECAs. Inside an Emissions Control Area (ECA), all vessels have to comply with the emission regulations. Currently, there are four Emission Control Areas designated by IMO :

- Baltic Sea area (SO_x only)
- North Sea area (SO_x only)
- North American area (SO_x, NO_x and PM)
- United States Caribbean Sea area (SO_x, NO_x and PM).

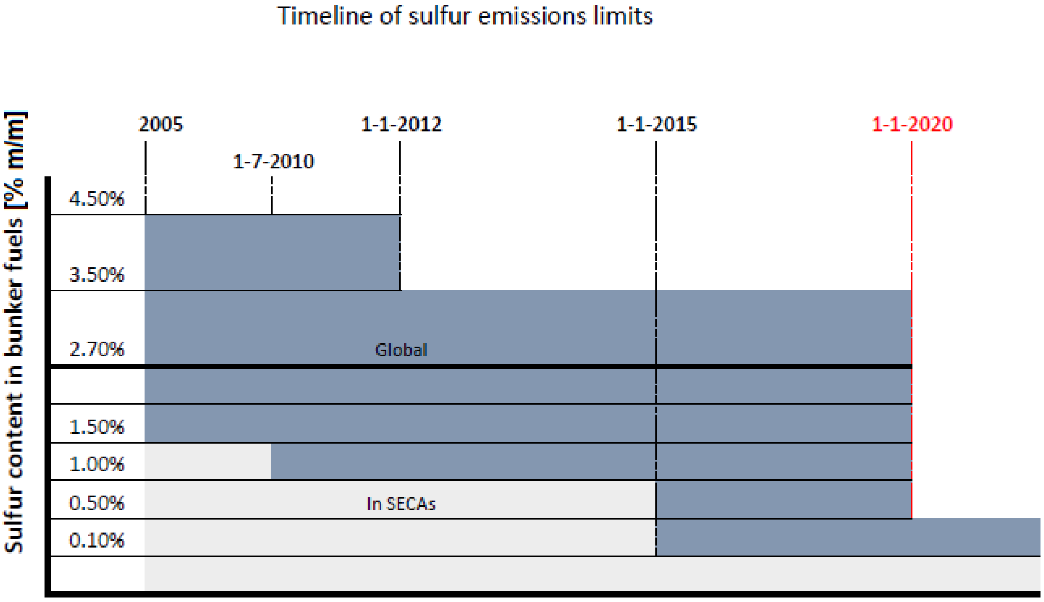

Figure 2.4: Timeline of Sulphur Content Limits in Fuel

Figure 2.4 shows the evolution of the different sulphur limits (inside and outside ECAs) for fuel over time. From 1 January 2020, the global sulphur cap was cut to 0.50% (from 3.5% m/m). This is referred to as the IMO 2020.

In SECAs [11], the sulphur cap is 0.10% m/m (mass/mass). Ships in Baltic Sea, North Sea and English Channel as of 1st January 2015 had to ensure that sulphur content is no more than 0.10%. From 1 January 2021, Baltic Sea and North Sea ECAs will have the NO_x Tier III standards in effect [74]. Since January 1, 2010, only fuel with 0.1% or less sulphur content has been used in EU inland waterways or ports.

Unlike the absolute limits of SO_x emissions, the NO_x limits are based on the rated speed (in Revolutions per minute (RPM)) of the engine. The emission limits as a function of the engine's RPM along with the applicable Tier is given in Figure C.2 [12]. This is based on Regulation 13 of International Convention

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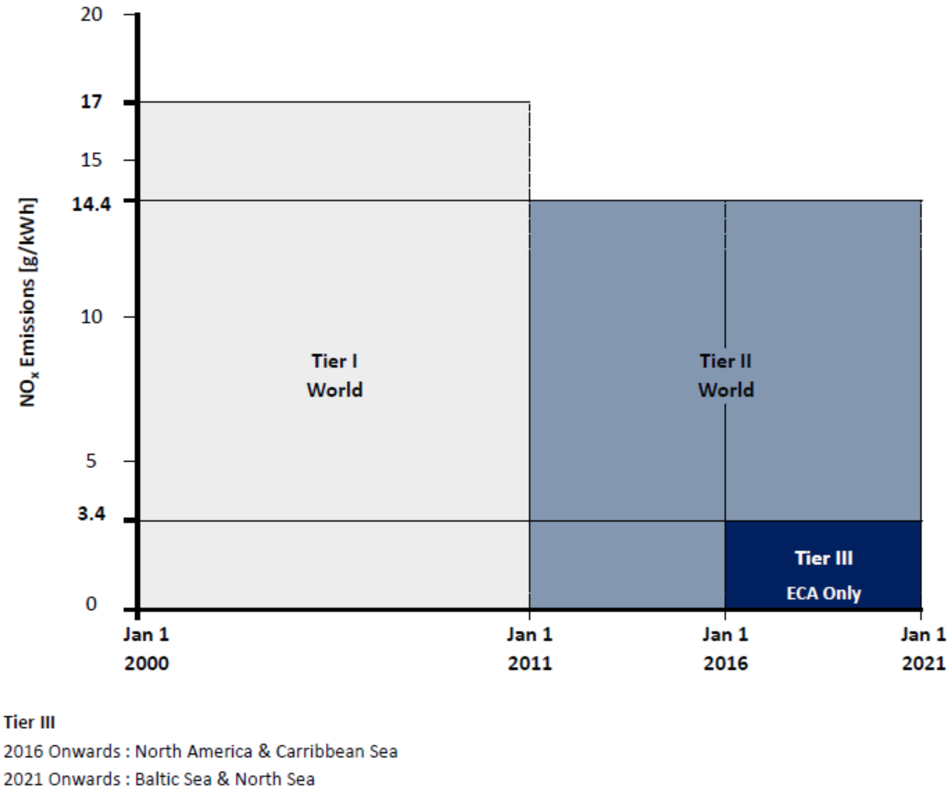
[11] The ECAs with sulphur limits are referred to as Sulphur Emission Control Areas or SECAs and those with NO_x limits are referred as Nitrogen Oxide Emission Control Areas (NECAs).

[12] Data in Appendix B.1

for the Prevention of Pollution from Ships (MARPOL) [75]. The evolution of the NO_x limits is given in Figure 2.5. As per the European Stage V standards were entered into force in July 2016 in Europe, the NO_x limit for inland waterway vessels (with power greater than 1000 KW) is 0.40g/kWh [76]. In United States, Environmental Protection Agency (EPA) Tier 4 emission regulations [77] are the norm and led to the reduction of emissions, especially for NO_x.



Tier III
2016 Onwards : North America & Carribbean Sea
2021 Onwards : Baltic Sea & North Sea

Figure 2.5: NO_x Emissions timeline

2.3.1. Incentive-based Regulations

Incentive-based regulations give an additional impetus to move along a certain pathway. The two regulations that are going to be discussed here is the preferential treatment and direct rewarding.

The Dubocalc (Sustainable Construction Calculator) and CO_2 Performance scale was developed by Rijkwaterstaat in 2009. The CO_2 Performance scale of Rijkwaterstaat gives additional advantages in public tenders to the bidders with the best CO_2 records [78]. Recently, the Rijkwaterstaat with its ”Innovations Coastal Care Program” envisages the deployment of more sustainable solutions for dredging by 2024 [79]. Further, Rijkwaterstaat envisages to develop methods that significantly reduce greenhouse gases for regular coastal maintenance and in 2030 bring it down to zero. In 2019, the Flemish Government also started the three-year pilot project for testing the CO_2 performance ladder for government contracts [80].

World Ports Sustainability Program is a commitment by the world’s key ports to reduce GHG emissions. The Environmental Ship Index (ESI) [81] is one of the voluntary initiatives under the program. The index is intended for rewarding ships by the ports. The ship owners/shippers can also use the Index as a promotion of their ”clean” ships. The ESI score ranges from 0 to 100 [82]. A vessel that is in compliance with the mandatory IMO regulations for NO_x and SO_x emissions is scored as 0. While, on the other extreme, the vessel which have zero emissions (NO_x, SO_x, and CO_2) are scored as 100.

2.3.2. Penalty-based Regulations

The most identifiable penalty-based regulation is the taxation of carbon. In these set of regulations, the use of carbon-based sources invites additional taxation. In 1990, Finland became the first country to tax carbon emissions. In 2019, there were 57 initiatives already implemented/planning to be implemented a charging carbon tax or involving an emission trading system [83]. The tax rate is based on per tonne of CO_2 equivalent emissions (t-CO_2eq). The number of countries that are enacting such carbon emission taxation laws is increasing. Further, tax rates are planned to increase in all of these countries. Table 2.2 gives the carbon tax rate for certain implementations. For more on carbon tax, see C.3.3.

Table 2.2: Carbon tax rates in different countries

Country	**Carbon tax per t-CO_2eq**
Canada	13.8 €
Sweden	114 €
France	45 €
Estonia	2 €
The Netherlands (proposed)	12.30 €

0.69 € = 1 CA$

The implementation of carbon tax on dredging operations is a looming eventuality and in a business as usual (BAU) scenario would have a negative effect on the dredging industry.

2.4. Emissions Compliance Options

The two broad options for complying with the regulatory regime are :

- Scrubber installation
- Switching to cleaner fuels and/or power generating technologies

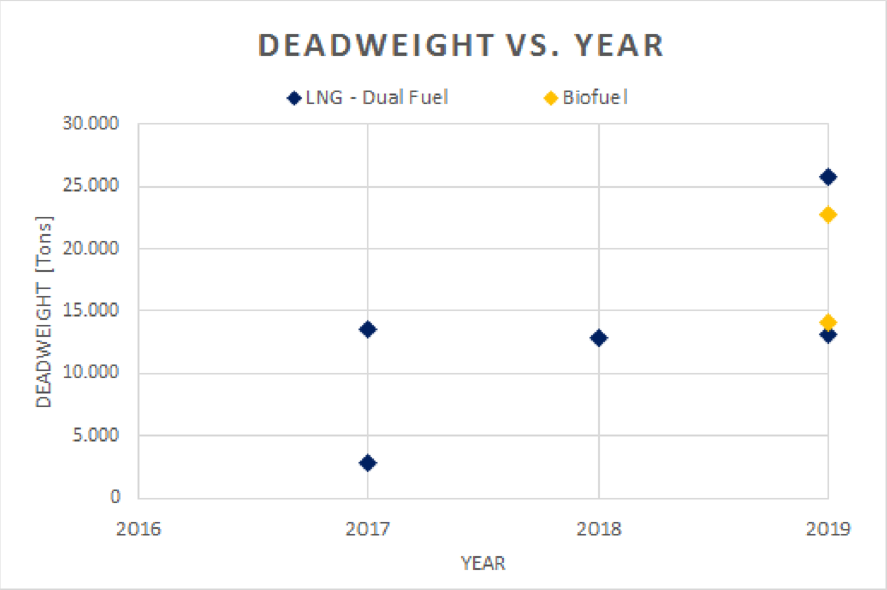


Figure 2.6: Deadweight vs Year of TSHDs powered with LNG-Dual Fuel and biofuels

When switching to cleaner fuel, LNG-Dual Fuel and biofuels are most relied upon. Before 2017, no TSHD was built for or had consistently utilised fuels other than HFO/MDO-based marine fuel. Figure 2.6 gives the deadweight of the TSHDs and year[13] of TSHDs that were powered with LNG-Dual Fuel and biofuels.

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[13] Built year in case of LNG/Dual-fuel vessels.

In the following text, various fuel/technology options would be discussed that can realise the compliance of the current emissions regulations.

2.4.1. LNG-Dual Fuel

The use of Liquefied Natural Gas (LNG) brings substantial benefits and automatic compliance with the current emissions regulations [84]. Compared with diesel, it produces 30% less direct CO_2 emissions [85], and much lower levels of particulate matter, NO_x and no SO_x. Additionally, the ignition can be done with 99% LNG and 1% MDO [86] and cost savings of 5-10% cost per cubic metre [86] can be realised depending on the price differential of the bunker oil and LNG.

ECODELTA owned by Van der Kamp with a hopper volume of 5900m^3 was one of the first LNG-based dredger [87]. In 2017, MINERVA a 3,500 m^3 TSHD became the first dredging vessel to be equipped with dual fuel engines [88]. Complying and exceeding the most strict international emission requirements, the vessel has a "Green Passport" and "Clean Design" notation. The SCHELDT RIVER with a 7950 m^3 hopper capacity is a dual fuel hopper dredger (installed with a 630m^3 LNG tank). Its first LNG bunkering in 2018 became the largest LNG bunkering operation in Germany [89]. Van Oord has ordered three new trailing suction hopper dredgers with 10,500 m^3 hopper capacity. Two of these are scheduled to be delivered in 2021 and another one in 2022 [90]. These would be powered by dual-fuel engines (Marine Gas Oil and LNG) with a total installed power of 14,500 kW [91]. Both these vessels would qualify for Tier III vessels as per the IMO emission standards and eligible for the "Green Passport" and "Clean Ship" Notation.

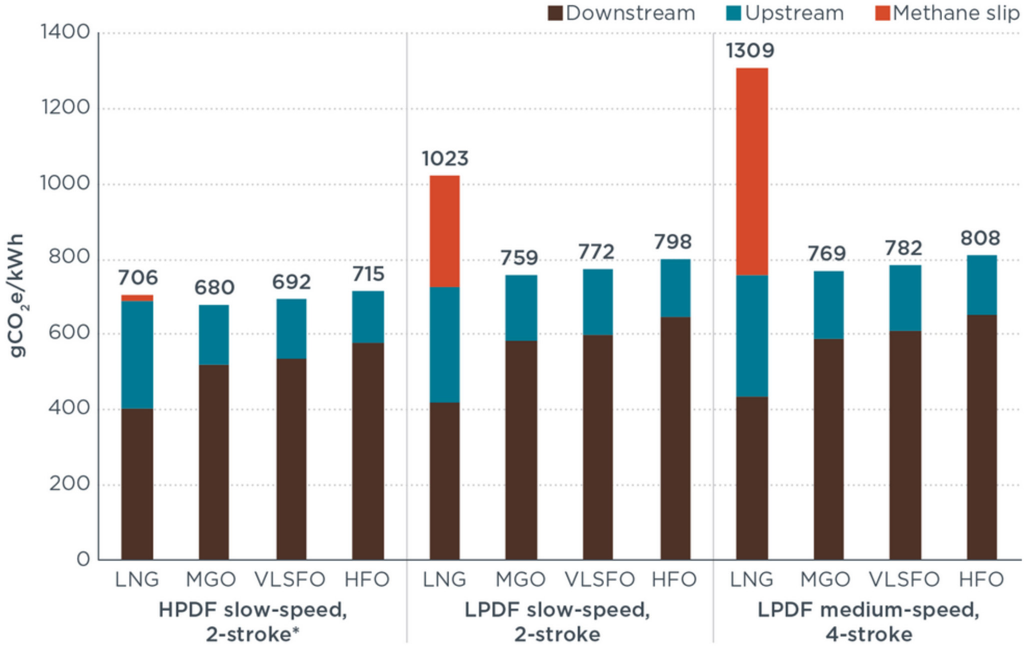
The retrofit of a MGO to a dual fuel LNG/MGO propulsion has already been carried out, for example, the 8,500m^3 TSHD Samuel de Champlain. "SAMUEL DE CHAMPLAIN" was also the first LNG powered vessel to operated in France [92]. Non-TSHD vessels have also embraced LNG. Van Oord's first LNG powered vessel was WERKENDHAM, a crane vessel and with gas oil as backup [93]. SPARTACUS, a 44,180kW self-propelled cutter suction dredger (CSD) and owned by DEME is the world's first LNG-powered powered CSD [94]. In France, grab hopper dredger LA MAQUELINE was replaced by L'OSTREA, a water injection dredger. This was the first dual-fuel newbuild vessel in France [95].

There are encouraging developments in terms of availability for fuelling of LNG. In the last five years, bunkering facilities have been growing. There are 77 ports worldwide that offer LNG bunkering [96] and LNG Bunker ships are upcoming. For example, in Rotterdam-Antwerp cluster three LNG bunker vessels owned by Shell [97] and one by NYK [98] have become operational. The first LNG bunkering vessel in Greece and Eastern Mediterranean is being built [99]. However, LNG bunkering still has a lot to catch up with bunker oil.

As per Royal IHC [84], to accommodate LNG capability into dredgers, adjustments were needed to be made to vessel's design. According to previous IMO regulations and the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), the tank couldn't be placed too close to the hull. For easing the installation a change in the IGF code by Bureau Veritas in 2014 allowed for the placement of the tank closer to the hull (for a limited length). There are additional safety provisions [100] required for using such low temperature fuel for example : double-walled piping. A diesel engine can take load steps like when a dredge pump is activated, the power can jump from 20% to 80% in a short time [86]. Dual-fuel engines are not capable of achieving this and this has been achieved by making direct driven systems. The direct driven systems reduce the flexibility for the placement of the engines and leads to installation of redundant power.

A LNG tank requires twice the volume of a Heavy Fuel Oil (HFO) tank. If the entire mission has to be done on only LNG, the space requirements would be huge. Hence, LNG powered dredgers are operated as dual-fuel where LNG is in combination with another fuel (HFO/MDO/MGO). This gives the vessel certain autonomy period to run on LNG (as per requirements). The emissions (in grams of CO_2 eq/kWh) caused by natural gas in the form of LNG is about 20% higher than in non-LNG form. All of the excess comes from the supply chain side. Additionally, for the same amount of power of delivered, overall Greenhouse Gases (GHG) emissions from usage of LNG increases. This increase is anywhere between 4-80% more (depending on the engine type) as presented in Figure 2.7. Hence, unless the

CH_4 leakages are plugged, there is a detrimental effect of using LNG on GHG emissions.



Life-cycle GHG emissions by engine and fuel type, 20-year GWP, higher methane scenario

Figure 2.7: Life-cycle GHG Emissions of some marine fuels and engines

Source: [101]

2.4.2. Drop-in Biofuels

Biofuels combust more efficiently, can achieve 25% reduction in the CO_2 footprint, reduced PM, NO_x and SO_x emissions [102] and contribute to circular economy [80].

Drop-in biofuels are the liquid fuels produced from biomass that are equivalent to petroleum fuel and compatible with the existing infrastructure [103]. Boskalis has pioneered the use of biofuels in dredging vessels. 30% biofuel blend was used on the Marker Wadden project in 2016 in the Netherlands. EDAX, a cutter suction dredger dredged for six months using a 50% biofuel blend utilising the residual products from the paper industry. PRINS DER NEDERLANDEN, a jumbo trailer suction hopper dredger is utilising blend consisting of up to 30% biofuel [104]. This resulted in a substantial CO_2 reduction for the realization of the Borssele offshore wind farm project [105]. In a pilot project, WILLEM VAN ORANJE was powered by a blend of diluted cooking oil in the past. Following these earlier successful tests with 'drop-in' blends of light biofuel and marine gas oil, Boskalis' WILLEM VAN ORANJE is the first dredging vessel in the world to operate on 100% bio-fuel oil [106].

In 2016, Dutch Dredging B.V.'s Reclamation dredger ALOUETTE started using 30% biofuel blend [102]. In second half of 2019, Jan de Nul announced its plan to start using drop-in biofuels [107]. Since the end of 2019, there are three Jan de Nul vessels (MAGELLANO, VERRAZZANO and ALEXANDER VON HUMBOLDT) that can and are utilising biofuels [108]. The SANDERUS, the new build ULEv can also utilise biofuels. Van Oord is planning to utilise "second-generation" biofuel made from waste products such as cooking oil as pilot during a dredging project in Germany on HAM 316 [109], a trailing suction hopper dredger with a hopper capacity of $9535 m^3$.

Biofuels compete for land with agriculture and depending on the supply chain they can have even worse emission characteristics than fossil fuels. Hence, biofuels that are certified for their sustainability will only deliver the overall carbon emission reduction as is advertised. One such certification scheme is through the International Sustainability and Carbon Certification (ISCC) [110], where the entire supply chain is third party certified.

2.4.3. Fuel Cells and Batteries

Depending on the source of H_2 or electricity, Fuel Cells and Batteries have the potential to become virtually zero emission technologies. IHC BEAVER 40 CSD with a total installed power of 483 kW and 55 kW cutter power at shaft was tested with Fuel Cell in 2010. This test was also the first instance of use of alternative fuels on a dredger. The PEM fuel cell was used for 120 hours to power electrical equipment on board. The unit proved to be able to handle the typical dredge circumstances (vibrations, frost, humidity and continuous use) [111]. However, no TSHD has ever been fitted with Fuel Cells.

Batteries have not been used to power any dredging ship until now. However, a underwater maintenance dredger design proposed in 2019 by C-Job is envisioned to run on 16 MWh battery packs [43].

2.4.4. Diesel Optimisation and After-Treatment

The optimisation of diesel engines and improvement of the after-treatment of exhaust gases [14] is another technological solution Jan De Nul chooses not to invest in LNG [32] and instead launched six Ultra-Low Emissions Vessels (ULEv) TSHD in 2018 [112]. These TSHDs are 3x3500, 2x6000 and 1x18000 and all are diesel-electric. Accessing the Fleet Register of Clarksons Research [26], it was found that only one dredger has had a scrubber retrofitted, the LELYSTAD (operated by Van Oord). Additionally, the new build BIN GANG JUN 8 with a hopper volume of 7,200 m^3 has a scrubber installed.

Methanol

Methanol is a liquid fuel whose combustion produces no SO_x and reduced NO_x emissions. In comparison to fuel oil or natural gas, high power output is possible from engines utilising methanol [113].

The methanol use produces emissions not just during combustion process but also in the upstream. This is because most of the methanol produced in the world is sourced from natural gas and this produces CO_2 as a byproduct. In the recent years, the focus has shifted to manufacture methanol using sustainable energy sources and CO_2 feed from flue gas, biogas or direct air capture. This process produces what is referred to as ”green methanol”. As part of the Green Maritime Methanol nine ships have been selected for research [114]. There are vessels of Boskalis and Van Oord and at least one dredger exists. However, the exact details are not yet know. DEME is also a part of this consortium. There are plans to construct a W2C (waste-to-chemicals) project with a production capacity of 270 million litres of biomethanol from plastic waste. This project is led by a consortium consisting of Shell, Nouryon, Enerkem and Air Liquide [115]. For the same amount of energy content, the space requirements for methanol fuel are about 2.5 times and the mass requirements are around 2 times that of diesel.

2.4.5. Ammonia

Ammonia is a carbon and SO_x emission-free fuel. Ammonia is an interesting option as there’s an experience of 100 years on working with it. Ammonia is easily liquefiable in comparison to other gaseous fuels (-33.4°C at 1 bar pressure).

Ammonia can be burnt in an Internal Combustion (IC) engine where H_2 cracked from NH_3 is used to ignite and is burnt along with it [116]. H_2 from fully cracked ammonia can be used in a PEMFC or a Solid-Oxide Fuel Cell (SOFC) can directly use ammonia. Research in this field in ongoing and promising. 23,000 TEU Ultra-Large Container Ship (ULCS) concept design utilising ammonia has started in December 2019 [117]. However, in the dredging industry, such projects are not yet under consideration. High NO_x emissions may be a concern but special techniques can be used to reduce these emissions [118]. For the same amount of energy content, ammonia weighs twice as much and requires three times more space in comparison to HFO.

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[14] The after-treatment consists of a Selective Catalytic Reduction (SCR) system and a Diesel Particulate Filter (DPF) [21].

2.4.6. What do the companies think?

The biggest dredging companies of today : Boskalis, DEME, Jan De Nul and Van Oord are concentrating on different fuels to for toeing the regulatory regime around emissions. The possible solutions and different things they are working upon tabulated in Table 2.3. The table was compiled by accessing the primary sources (Annual Reports and Sustainability Reports etc.) of information from the dredging companies.

Table 2.3: Company view on different fuel options

Company Name	Diesel Optimisation with after treatment	Biofuel	Methanol	LNG
Jan De Nul	+	+	∼	−
Boskalis	∼	+	+	−
DEME	∼	∼	+	+
Van Oord	∼	+	+	+
CCCC Dredging	∼	∼	∼	∼
DCI	∼	∼	∼	∼
Great Lakes Dredge and Docks	∼	∼	∼	∼
Inai Kiara	∼	∼	∼	∼

2.5. Nuclear Option

Section 2.4 discussed various emissions compliance options. However, a natural option in the quest for achieving compliance (and much more) has been left out : nuclear energy. This is true for the dredging industry too. Discussion with representatives of one of the world's biggest dredger manufacturers and world's biggest dredging company confirmed that nuclear option is "a blind-spot". Further, this option has not (in the recent past) and is not being considered by the industry. Some of the benefits of the use of nuclear energy source for powering of vessels are :

- Compliance with the current and other future emission regulations (SO_x, NO_x, CO_2, PM, HM, VOC etc.)
- There are no constraints for ships operating with Nuclear under the EEDI.
- Nuclear propulsion is at least an order of magnitude quieter in comparison to diesel [119]. Stealth is one of the desired traits of naval submarines. Hence, nuclear propelled submarines have been inducted in the most advanced navies of the world. The 2009 collision of British and French nuclear ballistic missile submarines [120] proves how quiet the submarines using naval propulsion are.
- As per the classification under the ENVIRONMENTAL CLASS, PART 6 CHAPTER 12 of the RULES FOR CLASSIFICATION OF SHIPS NEWBUILDINGS of DNV GL [121], a nuclear dredger or a ship complies with the requirements of the class notation CLEAN and CLEAN DESIGN. It would also comply to the IMO Green Passport criteria [122].
- Nuclear fuel costs are stable and cheapest on per kWh basis.
- Refuelling frequency can be 10 years or even 20 years.

It is clear that a nuclear-powered dredger could be a clear pain reliever and gain creator the dredging operators (For more, see Appendix A.4).

2.5.1. Generation IV concepts & Small Modular Reactors

The arguments against nuclear energy almost always revolve around the high capital costs and long construction time.

In the past 20 years, on the nuclear energy front, there is a move for the development and commercialisation of the Generation IV (Gen IV) reactors. These reactors have the concrete goals for the improvement of sustainability, efficiency, safety and costs related to nuclear energy [12]. One of the target goals is to have a clear life cycle cost advantage over other energy sources.

The discussion around small modular reactors (SMR) has gathered momentum in the past decade. As per IAEA [123], SMRs are advanced reactors that are rated for <300MW_e with inherent and passive safety features, better upfront capital cost affordability. These can be built in factories and shipped to the location.

In the nuclear industry, there is a strong belief in the economies of scale but this is not supported by data. An example is analysed by Grubler [124] for the French case. The author showed that an increase in the size increased the time required for construction without the benefits of economy of scale. Further, the concept of economies of scale apply if and only if the comparison is made between 1 Large vs. 1 Small reactor of a similar design [125]. However, current SMRs have very different characteristics from larger reactors. There are technical solutions that can be only achieved by size reduction of the nuclear reactors. Examples of this is the ability to remove heat passively, utilisation of an integral vessel (with incorporated heat exchangers and natural circulation of coolant). Due to the modular construction, the capital costs and construction times are reduced [126]. Rolls Royce claims [127] that each of their small modular reactors is more affordable than a large standalone nuclear reactor of equivalent power. This is attributed to the 'production line' like manufacturing environment. Currently, 50 SMR designs and concepts exist globally [128]. These concepts are at various development stages and at least 4 SMRs are in advanced stages of construction [123].

2.6. Nuclear-powered Vessels

Currently, there are about 100 operating reactors on sea and there have been around 700 in total [129]. Most of the current operating reactors are naval nuclear ships and a very small portion of it are the nuclear icebreakers. Except for the some Soviet submarines [15] all marine nuclear reactors have been Pressurised Water Reactor (PWR). In a Congressional hearing of 1973 on Nuclear Vessel Incentive [130], it was noted that the benefits of nuclear power are in higher horsepower ranges (>120,000 hp/90 MW). All the civilian merchant ships that have been built had power requirements of less than 25,000 hp [16].

2.6.1. Nuclear-powered Tankers

In 1957, it was hypothesised that the first nuclear ship would be a tanker because the first cost of a nuclear ship will be much higher than conventional ships [131]. However, the world is yet to see a nuclear-powered tanker. Although there have been instances where this almost became a reality. For example, there were talks of a possible British tanker based on the Atomic International organic reactor concept by English Electric Co. [132]. Newport News Shipbuilding & Drydock Co. (Virginia) was contracted by Globetik Tankers Ltd. for building two large nuclear-powered tankers [133]. Recently, a preliminary nuclear propulsion concept based on 70 MW_{th} (23.5 MW shaft power) Lead-Cooled Fast Reactor (LFR) (with Lead-Bismuth Eutectic (LBE) coolant) to drive a 155,000 Deadweight tonnage (DWT) Suezmax tanker was evaluated. For this concept, a refueling period of ten years was considered and this was found to be feasible. However, the viability is dependent on an increase in the maturity levels of the nuclear technology [8].

2.6.2. Nuclear Icebreakers

The diesel icebreakers cannot provide enough power in ice conditions especially those in Kara sea [134]. Currently, only Russia owns nuclear-powered icebreakers. Cumulatively, it has 400 reactor-years of experience with them [135].

The 16,000 ton icebreaker, LENIN commissioned in 1957 was Soviet Union's first nuclear surface ship. By 2035, Russia plans to operate 9 nuclear-powered heavy-duty icebreakers [136]. This is a bet based

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[15] 7 Alfa-class submarines and K-27 submarine which were Lead coolant based nuclear reactor

[16] Nuclear Ship (NS) Otto Hahn and NS Mutsu were both 10,000 hp ships and NS SAVANNAH had a 20,000 hp power.

on the opening up of the Northern Sea Route (NSR) due to the rising temperatures that would make the Arctic more navigable. With the intention of reinforcement of its leadership in the Arctic and keeping the Northern Sea Route open all year round [137], Russia launched the SIBIR nuclear-powered Icebreaker in September 2017. The 33,500 ton and 173.3 meters long SIBIR is built under Project 22220. The lead ship of the project, the ARKTIKA, was commissioned in 2016. URAL [17], the third vessel is planned for delivery in 2021. Together, they would become the world's largest and most powerful nuclear-powered icebreakers. Russia eventually plans to build 120 MW LEADER Icebreakers and commission the first of the series by 2027 at Zvezda Shipbuilding complex [139]. Current icebreakers TAYMYR and VAYGACH will continue to sail until 2026 and 2027. The larger YAMAL and 50 LET POBEDY will sail at least till 2030 and 2039 [140]. These icebreakers also offer passenger cruises to the North Pole.

In 2018, China National Nuclear Corporation called for bids to make the first Chinese nuclear-powered icebreaker [141]. In 2019, China General Nuclear Power Group (CGN) invited bids for an "experimental ship platform" which would feature two 25 MWe PWR, 152 metres long and displacement 30,000 tonnes [142].

2.6.3. Nuclear Merchant Ships

NS SAVANNAH was the first nuclear-powered merchant ship. During its commercial operations (August 1965-July 1970), NS SAVANNAH visited 77 ports [143].

NS SEVMORPUT was designed for for servicing shallow high-volume ports [18] in the North Soviet. NS SEVMORPUT has some ice-breaking capabilities and can make through 1 metre of ice [145]. With the aim to keep the vessel in operation until 2024, the reactor's service life was prolonged by 150,000 hours in 2015 [146]. At the end of 2020, it is planning to sail to Antarctica to supply material Vostok research station in Antarctica [147].

2.6.4. Other Concepts

Floating

MH-1A aboard STURGIS barge was a floating nuclear reactor prototype which operated from 1968-1976 supplied electricity in the Panama Canal [148]. In late 1970s, a floating nuclear power plant had been considered for New Jersey [149].
Russia is home to half of the 4 million people who live in world's Arctic regions. To supply electricity in its remote Arctic regions, Russia started the first of its floating power units (FPUs), AKADEMIK LOMONOSOV. The FPU is equipped with two KLT-40C generating about 70 MWe and heat for Pevek (a city in Russian Arctic). AKADEMIK LOMONOSOV needs refueling every 3 years and has a lifespan of 40 years (extensible up to 50 years). There are special on-board compartments for storing spent nuclear fuel. Work is already in progress for second generation of floating power units (FPUs) referred to as OPFU (Optimised Floating Power Units) [150]. These would possibly be powered by two RITM-200M reactors and are expected to be compacter, with higher power capacity (100 MWe), with longer refueling time and flexible load following capabilities [135].
China is engaged in designing and developing floating vessel to be equipped with SMRs for supplying electricity [151]. There are plans to eventually build 20 floating nuclear plants in South China Sea [152].

Submerged

There is a submerged nuclear reactor concept called as Flexblue®. The underwater siting provides security against extreme weather events, does away with the need for containment or strict biological shielding [153].
The technical feasibility of baseline designs for commercial cargo submarines 181,400 DWT submarine oil tanker and a 140,000 m^3 submarine LNG tankers have been developed earlier [154]. In the late 1960's, General Dynamics had proposed technically and economically feasible designs for a family of nuclear-powered submarine oil tankers (170,000-300,000 dwt) that could be used to transport Arctic oil [155].

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[17] The URAL will be powered by RITM-200 reactors and able to smash through ice that is ten feet thick [138].

[18] This required barges for unloading and transporting cargo inland [144].

In 2019, ”MALAKhIT” (Malachite Design Bureau) [156] suggested a 4 MW nuclear-powered submarine with ice-breaking capabilities. The submarine is envisioned for underwater installation works and potentially, mining the Arctic sea floor. The same design bureau also developed a 90 MW nuclear submarine gas-carrier concept for transporting LNG from Arctic fields. This concept has been presented to potential customers - Gazprom and Novatek [157].

As per the 98th Session Hearings of U.S. Congress [158] (1984), studies on various nuclear-powered vessels for Arctic were conducted by Maritime Administration (MARAD) between 1970 and 1980. These studies include :

- Icebreaking Support Ship (1973) - To be used for offshore Arctic drilling operations - based on average yearly costs the nuclear option would fare better than a fossil fueled concept between 5-10 years of its life already.
- Submarine Tankers (1975) - To be used for delivering crude oil from Arctic. The concept was found to be technically feasible and viable economically.
- Nuclear-powered icebreaking tanker (1977) - To be used for moving crude oil from Alaska to US East Coast technical feasibility was established The freight rates were favorable and the concept feasible.
- Nuclear-propelled surface tanker - To be used for transporting oil from Alaska Arctic. This concept was found to be unfeasible due to the under utilisation of the nuclear power plant installed onboard the surface tanker.

2.6.5. Nuclear Dredging Ship

In the book, ”Nuclear Propulsion for Merchant Ships” [159] (1962) there was a passing remark about nuclear energy being applied to dredging operations might be feasible where high energy output or remoteness of the location or functioning away from land for long periods of time is required. The design of a nuclear-powered cutterhead pipeline dredge was proposed at the third World Dredging Congress & Exposition (WODCON) in 1970 [11]. In 2008, a work discussed some of the details of having the Kra Canal (Thailand) excavated by nuclear-powered [40]. Utilising four 100 MW nuclear-powered dredges the work is envisioned to be competed in 5 years. In 2005 USA dollars terms, the nuclear-powered dredges for Kra Canal Project would cost 100,000,000 each. There are no other work(s) that mentions nuclear as an option or evaluates a nuclear-powered dredger.

The operation of nuclear-powered dredgers can lead to benefits that have been outlined earlier (see 2.5). With these realised benefits, a nuclear-powered dredger can be used for building the mega-canals (as discussed in 2.1.5) or other macro-engineering projects (Blue Carbon, Palm Jumeriah, coastal defense etc.) or for carrying out the continuous dredging works at Straits of Malacca and Singapore [19] or accomplish deep sea mining (see 2.1.8).
In case of unavailability of the enough dredging work, these vessels can also act as floating power plants. In this work, a conceptual design of a nuclear-powered TSHD was explored. In addition to working as a TSHD, the First-of-a-Kind (FOAK) vessel would serve as a multipurpose vessel to :

1. demonstrate that civilian nuclear-powered ships are safe and reliable
2. to test/achieve the acceptance of nuclear-powered dredgers
3. to serve as a first for insurance and regulations.

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[19] for maintenance of depth of the straits that gets reduced due to large scale siltation [160].

3

Treaties, Conventions and other Regulations

This chapter discusses the Regulations, Authorisations, Insurance and other requirements for a nuclear powered vessel. Most of the discussed aspects are of generic nature and applicable for all the nuclear propelled vessels. However, some of these are specific to nuclear powered dredging vessels. In the Section 3.1 vessel classification, access to territorial waters & port access, decommissioning, safety, construction and operation and security related regulations specific to nuclear powered vessel are discussed. Section 3.2 discusses the various international third-party liability conventions and third-party liability insurance thereof. In Section 3.3 the requirement related to backup generators, double hulls and reactor vessel placement is discussed.

3.1. Regulations and Authorisations

As mentioned in the previous chapter, powering dredgers with nuclear systems substantial potential benefits and is a ”blind-spot” for the dredging industry. One of the reasons for not considering nuclear-power as an option is related to the lack of understanding and knowledge about the regulations.

Since there has not been a civilian nuclear ship in recent times, regulatory aspects and concerns from the past have not been addressed. Because nuclear-powered ships have sailed and some vessel categories continue to sail, there already exists certain regulations. When these regulations or laws exist, they are generally targeted and/or developed for the naval fleet in mind. Even these regulations are often buried in bulky maritime codes, international law, conventions and treaties. The terminology on how a nuclear-powered vessel is referred to in these documents is itself not straightforward. A nuclear-powered vessel could be referred to as ”nuclear propulsion ship”, ”nuclear ship”, ”atomic powered”, without or with a hyphen. Eventually, these terms are all variations of something that is the same thing. There are no specific authorisations/regulations for nuclear powered dredgers. As for a nuclear-powered dredger, depending on the country, these vessels could also be referred to as nuclear powered dredgers, nuclear dredgers, nuclear propelled dredgers etc.

3.1.1. Classification

Classification societies are non-governmental organisations that set the benchmark and standards for vessel design, construction, maintenance and machinery. Classification societies classify, validate designs and certify the vessel construction. Marine insurance cannot be obtained without a classification certificate issued by a classification society.
In 1962, American Bureau of Shipping (ABS), the classification society in the United States published the ”Guide for the Classification of Nuclear Ships” in 1962 [161]. However, the ABS does not presently classify nuclear-powered ships. In 1966, Lloyd’s Register had released ”Provisional Rules for Nuclear Ships” which covered the hull design, construction material, protection against collision/grounding, and design criteria for rapid vessel accelerations. However, these rules were withdrawn in 1976 due to lack of application [162]. In 2010, a goal-based framework of principles for the design, construction and

operation of nuclear-powered ships were developed by Lloyd's Register [129]. Under the "Rules for the Classification and Construction of Nuclear Ships and Floating Facilities" [163], the Russian Maritime Register of Shipping seems to be the only classification society that maintains a register for nuclear vessels.

3.1.2. Access

Territorial waters

Dredging projects often require mobilisation of dredgers from one part of the world to another. The flag state of the dredger might be different than the country where the operations are carried out. Such a mobilisation would often require navigation through and access of another nation's territorial waters. The access to territorial waters is governed by United Nations Convention on the Law of the Sea (UNCLOS) [164].

As per Article 17 of Section 3 (Part II) "Innocent Passage in the Territorial Sea" [1], the "right of innocent passage", a concept allowing for a vessel to pass through territorial water of another state may be exercised. The meaning of passage and innocent passage is topic of Article 18 and Article 19. The term "innocent passage" can be interpreted as the navigation through territorial sea which is not detrimental to the peace, good order or security, further, this passage should conform with the Convention and with any other international law. As per Article 38 "Right of transit passage", the right to transit can be exercised in straits that are between one part of high seas of Exclusive Economic Zone (EEZ) [2] and another part of high seas. There cannot be suspension of transit passage as per Article 44. Article 45 guarantees right of innocent passage for straits that are used for international navigation which are excluded in Article 38 or are between high seas/EEZ and the territorial sea of a foreign State. Article 52 guarantees right of innocent passage through archipelagic waters, though temporary suspension of innocent passage can occur.

Article 21 gives the Coastal State [3] the power to adopt laws and regulations that conform to the provisions of this Convention and other rules of international law. A passage by nuclear-powered ships would also be subjected to Article 22 and Article 23 of UNCLOS. Foreign ships need to comply with all such laws. Hence, a more in depth check would be needed before deciding on the path of mobilisation.

Article 22 (2), "Sea lanes and traffic separation schemes in the territorial sea" states that like vessels that can pose a danger (for example, tankers), nuclear-powered vessels maybe required to confine their passage to designated sea lanes.
Article 23 ("Foreign nuclear-powered ships and ships carrying nuclear or other inherently dangerous or noxious substances") When exercising the right of innocent passage through the territorial sea, foreign nuclear-powered ships and ships carrying nuclear or other inherently dangerous or noxious substances are required to carry documents and observe special precautionary measures established for such ships as per international agreements.

Earlier, the passage of Nuclear powered ships was excluded for Suez Canal [165]. However, in the recent years the passage is being allowed with prior permission is required for the entry of nuclear powered vessels to enter the contiguous zone [4] [166]. Even though a notification/authorisation is not required when exercising the right of innocent passage, some countries like Saudi Arabia, Malaysia, Oman and Yemen require prior authorisation [167]. Djibouti and Pakistan require prior permission for passage in their territorial waters [168]. Ships entering territorial water of the USA must carry a valid certificate of inspection by US Coast Guard for a nuclear ship [161].

Port Access

The access to ports is needed for replenishment of supplies and/or manpower and maintenance/repair work.

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[1] Article 3 of Section 2 (Part - II) defines the territorial sea as extending 12 nautical miles or 22,224 km from the baseline. Waterbodies inside the baseline are referred to as internal waters.

[2] This is the area extending 200 miles from the coast. In this area, a coastal state can explore and exploit the marine resources

[3] A country with access to the coast

[4] Article 33 of Section 4 (Part - II) defines the contiguous zone as not extending beyond 24 nautical miles from the baseline.

Bilateral agreements might be needed to abate the risks of nuclear ships to a foreign land. Such agreements were made between the United States and other countries where NS SAVANNAH visited [5]. A compensation was also part of these agreements in case any incident occurs. Prior approval from the national government and subjection to principles and procedures applicable to nuclear ships under Safety of life at Sea Convention 1960 [167]. Similar agreements were also made for OTTO HAHN [169].

International Convention for the Safety of Life at Sea (SOLAS) [170] is regarded as the most important international treaty relating to ship safety [171]. There have been 5 different versions of the document (1914, 1929, 1948, 1960 and the latest version is 1974). Like all other vessels, all the general regulations would be applicable to a nuclear ship unless overruled in the dedicated chapter for nuclear ships, Chapter VIII ”Nuclear Ships”. The 12 regulations in the Chapter are applicable to all nuclear ships except for naval nuclear ships. As per Regulation 7 ”Safety Assessment”, there is a requirement to make a Safety Assessment available well in advance to the countries where the ship intends to visit. Regulation 10 is related to Safety Certificates for Nuclear Cargo ships and Nuclear Passenger ships. A certificate, called as Nuclear Ship Safety Certificate (Passenger or Cargo) is issued after inspection and survey of the nuclear ship which complies with the relevant requirements of the Convention (Structure, Stability, Machinery and Electrical installations, Fire, Life-saving appliances, Radio-communications etc.) These certificates are not valid for a period of more than 12 months. Regulation 11 ”Special Control” is an additional control for nuclear ships before they enter the ports. This control is for verification of a valid Nuclear Ship Safety Certificate and to ensure that the vessel does not cause unreasonable radiation or other hazards to others. Similar requirements could be expected in case of Nuclear Dredgers as under SOLAS, all ships which are not passenger ships are classified as cargo ships.

The threat of radiological pollution from the ship in distress can warrant a suspension of the Ports Convention. In such a case, the ship in distress could be denied access to the port where it would otherwise be permitted for the ship in distress to access the port [172]. IMO Guidelines on places of refuge for ships in need of assistance (adopted in 2003) [173] are intended to be used when assistance is required by the ship and safety of life is not threatened. As per the section 3.12 of these guidelines, there is no absolute and unequivocal obligation for states to grant access to a ship in need of assistance. The International Convention on Maritime Search and Rescue adopted in 1979 also referred to as the SAR Convention covers the ships in distress and responding to ships to save lives [174].

Examples

Access laws and procedures for specific countries is briefly discussed to give an idea of what it can entail. There is some historical precedence of access laws, this is also included in the discussion.

Belgium

The access of nuclear powered ships to territorial sea and ports is regulated by Royal Decree of 30 December 1923. In addition, the Royal Decree of 28 February 1963 that is related to the protection of population against danger of radiation 11 May 1971 needs to be complied too. For non-Belgian nuclear-powered vessels entering into the territorial waters, permission is required from the Minister of Public Health upon the advice of the Minister of Transportation. NATO vessels are allowed entry into the territorial waters as per a 1962 law [175].

United States of America

Based on the experience of NS SAVANNAH, the entry to port was granted by AEC’s Director of Licensing and Regulation and subsequently, referred to the commission. The decision was taken based on the port facilities, safety hazard and population density [176]. A safety assessment made by the US Coast Guard is used as the basis of establishing the negotiation between the United States and countries where the nuclear vessel intends to visit [177].

Russia

Government of the Russian Federation has determined 22 seaports of the Russian Federation where calls can be made by ships powered by nuclear energy. These ports have the facility and appropriate measures to accommodate vessels transporting nuclear materials, radioactive substances and products containing them. The latest amendment was made on September 17, 2018. Table 3.1 provides a

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[5] During the commercial operation of NS SAVANNAH (August 1965-July 1970), out of the 77 ports that were visited, 45 were foreign ports [143].

comprehensive list of the same. The procedure for the entry to port or territorial waters for foreign nuclear-powered vessels is not clear.

Table 3.1: List of Russian ports where nuclear-powered vessels can call

No	Name of Port	Location	Order Number
1	Arkhangelsk Commercial Sea Port	Arkhangelsk	
2	Bolshoy kamen	Primorsky Krai	
3	Vladivostok Commercial Sea Port	Vladivostok	
4	Vostochny Seaport	Primorsky Territory	2010 N 2089-r (Dated November 27, 2010)
5	Vysotsky Commercial Sea Port	Vysotsk	
6	Seaport of Dikson	Dikson	
7	Seaport of Dudinka	Dudinka	
8	Seaport of the Caucasus	Krasnodar Territory	2009 N 1934-r (Dated December 14, 2009)
9	Sea Trade Port of Kaliningrad	Kaliningrad	
10	Kandalaksha Commercial Sea Port	Kandalaksha	
11	Murmansk Commercial Sea Port	Murmansk	
12	Seaport of Nakhodka	Primorsky Territory	2010 N 2089-r (Dated november 27, 2010)
13	Pevek Commercial Sea Port	Pevek	
14	Provideniya Commercial Sea Port	Chukotka Autonomous Okrug	
15	Commercial Sea Port of St. Petersburg	St. Petersburg	
16	Taganrog Seaport	Rostov Region	2008 N 999-r (Dated February 6, 2012)
17	Seaport of Ust-Luga	Leningrad Region	
18	Seaport of Kholmsk	Sakhalin Oblast	2012 N 152-p (Dated February 6, 2012)
19	Seaport of Magadan	Magadan Region	2016 N 1288-r (Dated June 22, 2016)
20	Seaport of Astrakhan	Astrakhan Region	2017 N 695-p (Dated April 14, 2017)
21	Sea port Olya	Astrakhan Region	2017 N 695-p (Dated April 14, 2017)
22	Seaport of Korsakov	Sakhalin Oblast	2018 N 1951-r (Dated September 17, 2018)

Brazil

To access Brazilian ports an agreement (”Agreement concerning nuclear ships in Brazilian waters”) dated 7 June 1972, was signed between Germany and Brazil [178].

SOLAS provisions were taken as central standard for inspection. The entry into the Brazilian waters and port was based on CNEN [179] Rules (especially setup for this purpose) and Brussels Convention on the Liability of Operators of Nuclear Ships (1962).

South Africa

National Nuclear Regulator (NNR) Act allows nuclear-powered vessels to operate or access ports after filing an application. The application has to be made to the CEO of the NNR for a nuclear vessel license. The application is published and open for comments from the public. Several such applications [180] [181] [182] can be found on their website with the title ”NOTICE OF APPLICATION FOR NUCLEAR VESSEL LICENSE IN TERMS OF SECTION 21 (3) OF THE NATIONAL NUCLEAR REGULATOR ACT (ACT No. 47 OF 1999)”.

Vietnam

As per the National Assembly Law No. 95/2015/QH13 [183], foreign nuclear-powered ships, ships used for carrying nuclear materials can be allowed to operate in internal waters and territorial waters if the the Prime Minister grants permission.

3.1.3. Licensing, Construction & Operation

The quick and hassle-free licensing of the nuclear reactor would be a beneficial trait for the nuclear-powered dredger. The expedition of licensing of first nuclear plant has been covered by IAEA's International Nuclear Safety Group (INSAG) [184]. The regulations around SMR are developing in some countries and the rapid licensing is on the agenda. In January 2019, the US Congress passed Public Law No: 115-439 (01/14/2019) Nuclear Energy Innovation and Modernization Act [185] and one of the requirements in the Bill is development of new processes for faster licensing of advanced nuclear reactors, establishment of framework that encourages greater innovation.

The Ministry of Economic Affairs and Employment of Finland has setup a working group for development of laws relating to licensing of SMRs [186]. The Canadian Nuclear Safety Commission and US NRC are also collaborating on technical reviews of SMR technologies and advanced reactor to help speed up design review and licensing process.

The regulations for construction and operation of nuclear-powered vessels differ from country to country. As an example of what the potential requirements could be, the requirements for some countries is stated as follows.

Belgium

Basic nuclear safety and radiological protection regulations are governed by the The Royal Decree of 20 July 2001. As per the Chapter VIII–"Nuclear Propulsion" [187], the construction of any ship powered by nuclear energy needs prior authorisation by the King. The right to remain in Belgian waters or passing through are subject to prior licensing.

Netherlands

In the Netherlands, the permit system according to KEW (Kern Energie Wetgeving). In general, there are no nationally developed nuclear codes and standards in the Netherlands. As per Article 14 and section i) 14.(i) "Assessment of safety", Operational safety review must be performed once every two years and a more comprehensive safety review must be conduced once every 10 years. In the latter, it is required to carry out a review of the plant's design basis taking into consideration any new developments in research, safety, risk etc.

South Africa

Prior to the granting of an authorisation, the applicant is required to apply to the National Nuclear Regulator (NNR), in the prescribed format, detailing the intended activities and providing a demonstration of safety and compliance to the NNR requirements. The standard conditions are enlisted in Appendix C.6.

United States

U.S. Nuclear Regulatory Commission issues license for nuclear installations. As per the Part 37 Special Construction, Arrangement and other provision for Nuclear Vessels [177] a certificate of inspection is required to be renewed yearly.

3.1.4. Safety

Some attempts for the development of nuclear merchant ships have been carried out in the past. Code of Safety for Nuclear Merchant Ships - Res. A.491(XII) [188] was adopted by Inter-Governmental Maritime Consultative Organization (now, IMO) in 1981. This code was developed to assist in providing internationally accepted safety standards for the entire life-cycle [6] of a nuclear merchant ships. The code was developed for PWR reactors and has not been updated since. A re-look might be necessary due to changes in the understanding about nuclear safety. However, the regulations for a different type of reactor should not change very much. The Code is based on defence-in-depth concept [7] (for more information, see Appendix E.3.2).

Depending on the likelihood of the condition and the consequences, there are four plant process conditions (PPCs) as described in the Code [8]. These conditions are numbered 1 (continuously occurring/likely to occur often) to 4 (extremely small). For examples of each of the PPC, see C.5.1.

Section 2.1 refers to three safety criteria that must be observed at all PPCs :

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[6] design, construction, operation, maintenance, inspection, salvage and decommissioning.

[7] Fuel, fuel cladding, primary pressure boundary, containment/safety enclosure are generally regarded as the four barriers of the concept.

[8] Table 1.1 of the Code of Safety for Nuclear Merchant Ships

- As low as is reasonably achievable (ALARA) exposure to radioactivity.
- Mechanisms for removal of decay heat from the reactor core.
- Mechanisms for controlling reactivity and maintaining safe shutdown of the reactor.

Section 2.2 discusses the division of various systems into safety classes. This is based on the importance of these systems. Based on their importance, these are referred to as SC-1, SC-2, SC-3 and SC-4. Some of examples of the systems under different safety classes is given in C.5.2. Each Safety Class is further subdivided into 4 Design Classes (referred to as DC-1, DC-2 and so on..). These design classes define specific standard of designing, manufacturing and quality assurance of the system/component. Section 2.3 provides guidelines for considering the environment into the design. This is described in the number of days which the components of different Safety Classes have to withstand. As a guideline, the inertial forces brought about in the North Atlantic seaway is considered. The number of days ranges from 15,000-150 days between SC-1 to SC-4 respectively (including hull and equipment and machinery not covered by international/national standards). Further, the reactor safety system should work in list up to 30°, roll angles of 45° and 10° in fore and aft (individually or in combination). However, there is a possibility of less strict requirements as prescribed by Administration if the ship operates only in restricted areas.
Section 2.7.5 and 2.7.6 mention about the need to analyse and consider concentrated energy projectiles from rotary equipment, pipe whipping (unpredictable movement of a ruptured pipe) and effects of pressure waves from explosions to reactor safety.

Chapter 3 "Ship design, construction and equipment" discusses about Ship Arrangements (3.01), Collision protection (3.05), Grounding and stranding (3.06), Security of the ship (3.10). Some of the major features mentioned are :

- The reactor compartment needs to be bound by bulkheads (watertight, gas tight/fire resistant).
- The design of the reactor compartment should facilitate salvage activities (3.1.4).
- At least two-compartment standard of subdivision should be obtained.

Section 4.03 discusses the reactivity control and the reactor fast shutdown system that should be capable of shutting down reactor at angles of up to 90°. Section 5.07 "Emergency Propulsion" mentions that an emergency source of propulsive power should be provided. This should be located outside the reactor compartment and remain operable in a reactor incident event.

As per the Part 37 Special Construction, Arrangement and other provision for Nuclear Vessels [177] of the US Coast Guard, some of the relevant safety rules for dredging vessels could be :

- Full double-bottom hull
- Not less than two-compartment standard.
- Structural supports designed for taking into the effects of possible grounding, collision or holing of the hull.
- Collision analysis statistics should be carried out for the placement of the reactor.
- Arrangement for bilge system.

As per SOLAS requirements, ships need to have transverse watertight bulkheads. If hull penetration leads to water ingress, this provides the ship with certain survivability. The forward bulkhead or the collision bulkhead is meant a second barrier [189].

3.1.5. Ballast Water

Ballast water helps maintain safe operating conditions on a voyage. As per IMO [190], proper ballast water management reduces hull stress, improves transverse stability, propulsion and manoeuvrability, and compensates for weight changes (cargo load levels, fuel and water consumption). Ballast Water Management Convention entered into force in 2017. The prime motivation for this Convention is to prevent the introduction of invasive species. These invasive species have the potential of serious ecological, economic and health problems. The size of a ballast water is expected to be much reduced in a nuclear-powered dredger as the rebalancing due to consumption of fuel is not required.

3.1.6. Security

In relation to physical protection of nuclear material and facilities, the Convention on the Physical Protection of Nuclear Material [191] and its Amendment are the only international legally binding undertaking. The Convention was adopted at Vienna on 26 October 1979 has been into force since 8th February 1987. An Amendment was made in 2005 for strengthening the Convention and the name was replaced to Convention on the Physical Protection of Nuclear Material and Nuclear Facilities [192].

As per the Fundamental Principle E (”Responsibility of the Licence Holders of the Amended Convention”), the operator or the licensee is responsible for the physical protection and coordination of activities related to physical protection of nuclear material/nuclear facilities.
Fundamental Principle H calls for an approach that takes into account the potential consequences of sabotage and unauthorised removal of nuclear material based on the attractiveness relative to other sabotage worthy materials/facilities and threat evaluation.
Fundamental Principle I calls for a defence in depth strategy for physical projection involving structural, technical, personnel and organisational methods of protection.

In the aftermath of September 11, 2001 attacks and bombing of LIMBURG, a French oil tanker, International Ship and Port Facility Security Code (ISPS) was signed in London in December 2002. As per the ISPS code, every ship must have a Company Security officer and Ship Security Officer cargo ships of over 300 GT on international voyages. International Ship Security Certificates are issued to ships that are in compliance with International Ship and Port Facility Security Code.

New modifications were made to SOLAS Chapter V (Safety of Navigation) for the fitting of Automatic Information Systems (AIS). The operation of AIS is to be maintained at all times barring a few exceptions. Regulation XI-2/6 requires all ships to be provided with a ship security alert system. When activated the ship security alert system initiates and transmits a ship-to-shore security alert. This alert helps in identifying the ship, its location and indicating that the security of the ship is under threat/has been compromised. The system does not raise any alarm on-board the ship. The ship security alert system is capable of being activated from atleast two locations.

3.1.7. Decommissioning

Decommissioning can be defined as the necessary activities (administrative and technical) to restore the area to a greenfield status. International Atomic Energy Agency (IAEA) [193] defines three types of decommissioning strategies :

- Immediate dismantling : This is the preferred decommissioning strategy. The implementation starts within two years of permanent stoppage of activities. The philosophy of this strategy is to release the facility for unrestricted use as soon as possible.

- Deferred dismantling : In this strategy, complete dismantling is delayed and a safe condition is maintained by placing the facility into long term storage (a Safe Enclosure). The dismantling has to happen within 50 years. This is referred to as SAFSTOR (SAFe STORage). This is usually exercised in multi-facility sites where only some of the facilities are shut down and the facilities share some common systems.

- Entombment : In case of entombment, a Safe Enclosure (SE) is maintained for a period of time until the radioactivity decays to a ”safe” level. The dismantling occurs after this period. This is the least expensive strategy.

Only a handful (~10%) of the retired nuclear reactors have been fully decommissioned until now. Of the 160+ power reactors including experimental and prototype units, at least 17 have been fully dismantled, over 50 are being dismantled, over 50 are in SAFSTOR, three have been entombed, and for others the decommissioning strategy is not yet specified [194].

Decommissioning nuclear reactors is usually described to be a long-term and costly process [195]. However, it does not imply that decommissioning has to always be a long and lengthy process. The site of the Shippingport reactor (USA), a 60 MWe nuclear plant and one of the world's first reactor was released for other use in around seven years.

IAEA favors direct dismantling. The Dutch regulations now require immediate dismantling [196]. While in United States, Safe Storage and Decontamination are both accepted strategies for nuclear reactor decommissioning. A combination of two methods can also be used.

In Netherlands, the nuclear operator is responsible for all aspects of decommissioning. As per Nuclear Installations Fissionable Materials and Ores Decree (Bkse) , as part of the licensing documentation for the design and construction of the plan, the operator is obliged to submit a decommissioning plan. As per the April 2011 amendment of Bkse, the decommissioning plan needs to be updated every five years throughout the lifetime of the nuclear facility [197]. As per Article 15g of the Kernenergiewet "Nuclear Energy Legislation" (KEW) (Nuclear Energy Act) requires the nuclear facility operator to financial security for the later decommissioning of that facility [198].

In United States, Nuclear Regulatory Commission (NRC) requires the owners to set aside funds for decommissioning. 70% of the licensees are authorised to accumulate decommissioning funds over the plant's entire operating life. These are generally the traditional utilities. These decommissioning funds are placed in a nuclear decommissioning trust (NDT). Remaining licensees (approximately 30%) must provide financial assurance through other methods, such as prepaid decommissioning funds and/or a surety method or guarantee [199].

3.2. Insurance

There are certain risks that are outside the financial resources or the risk appetite of an entity. In such cases, there are several risk management options :

- Retention
- Avoidance
- Control
- Transfer

The retention of risk is done with an industry mutual while the transfer of risk is involves agreements between the private players and/or to the state. The purchase of insurance is one of the techniques for the management and mitigation of risk.

No commercial insurer provides risk coverage for nuclear facilities. The commercial insurers categorically exclude nuclear incidents under their insurance policies. An example of such a clause from German Insurance Association [200] excludes "the loss, damage, liability or expenses (direct and indirect) that arises from the risk of nuclear power plant". Nuclear risks in insurance (marine and transportation) have been discussed at IUMI conferences at San Francisco, Stockholm and Venice [201]. Protection and indemnity (P&I) insurance is the insurance for risks that are usually not covered as part of marine insurance companies. P&I insurance is provided via P&I clubs and is mutual insurance where the members are usually operators and owners of ships. Hull & Machinery (H&M) insurance is covered through marine insurers. Nuclear risks are not covered as part of P&I insurance and none of the marine insurance policies cover nuclear-related risks as they are considered beyond the scope of cover.

The primary reason for the exclusion of nuclear damage from marine and non-marine policies is the long term and cumulative consequences of the accidental release of radioactive nuclides [202]. The unknown risks and a limited number of insured installations adds to the issue. The solution to this was found in establishment of Nuclear Insurance Pools [203]. Hence, the nuclear insurance is considered as specialist insurance market.

The frequency of a radiation accident is low but the catastrophe potential is high. Nuclear Insurance Pools are association of insurers who jointly insure a particular risk related to nuclear energy. Pools spread the risk, enhance capacity, increase cost efficiency due to their market wide nature and reciprocal reinsurance arrangements with other country's pools [204]. There seems to be a possibility for expansion in the future, and marine nuclear reactors can be clubbed with the land based reactors. An updated list of nuclear insurance pools can be accessed in Appendix C.7.

3.2.1. Third-party Liability Insurance

Nuclear third-party liability insurance covers the costs related to the damage of a radiological nature that is caused to entities that are not related to the nuclear site/operator. These liabilities are strict, implying that the nuclear operator is held responsible for the loss irrespective of the nature of occurrence of the damage.

Ever since the dawn on nuclear energy, it was clear to have some sort of rules around liability coverage and cap. The international conventions related to this are :

- Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960 (also referred to as the Paris Convention), entered into force on 1 April 1968
- Convention Supplementary to the Paris Convention of 26 July 1963 (also referred to as the Brussels Supplementary Convention, BSC)
- Convention on Civil Liability for Nuclear Damage of 1963 (also referred to as the Vienna Convention), entered into force on 12 November 1977
- Convention on Supplementary Compensation for Nuclear damage (CSC), entered into force on 15 April 2015

All of the conventions were amended by protocols. The Paris Convention was amended three times (1964, 1982 and 2004), the Vienna Convention and Brussels Supplementary Convention on Third Party have been amended once. The latest amendments to the conventions are given under as :

- 2004 Protocol to amend the Paris Convention on Nuclear Third Party Liability
- 2004 Protocol to amend the Brussels Supplementary Convention on Third Party Liability
- 1997 Protocol to Amend the Vienna Convention on Civil Liability for Nuclear Damage

As per Article VII (b) of the Paris Convention, the lowest amount should not be lower than 5 million Special Drawing Rights (SDR)[9]. Under the Vienna Convention, the liability should not be less than USD 5 million. Both the conventions have limitation of ten years from the date of the nuclear accident. However, extension of the period is allowed if the operator is covered by insurance or other financial security (Article VIII, the Paris Convention; Article VI (1), the Vienna Convention). The Vienna Convention or the Paris Convention focuses only on nuclear installations based on land.

The 1962 Brussels Convention on the Liability of Operators of Nuclear Ships was created specifically to address the nuclear liability rules for nuclear ships. By Article 2 of 1962 Nuclear Ships Convention the operator of the ship "shall be absolutely liable for any nuclear damage upon proof that such damage has been caused by a nuclear accident involving the nuclear fuel of, or radioactive products or waste produced in, such ship". It is an obligation of the licensing state is to ensure that payments are made for the claims. According to Article III, the liability of the operator is limited to 1500 million francs [10] for one nuclear incident. This amount is equal to $\sim$ 4.66 billion \$ today (see Appendix D.5) which is

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[9] The SDR is a unit of account. Currently, it is based on a basket of U.S. dollar, the euro, the Chinese renminbi, the Japanese yen, and the British pound sterling. The basket of currencies is reviewed every five years.

[10] The franc or Franc Poincaré is a unit of account equal to 65.6 mg gold of 900 fineness

around 10 times the size of the first tier of US pool. However, the inclusion of the warship as per Article X into the Convention led to disagreements and the Convention was never ratified.

On top of the plethora of international third-party liability conventions that countries are party to, the countries choose to also have personalised rules and regulations. The nuclear third-party liability regime in some countries is discussed next.

United States

United States is home to the most comprehensive and oldest nuclear liability regime [205]. This regime is enforced by the Price Anderson Act which channels the obligation to pay for damages to the reactor licensee [11]. Price-Anderson Act was first passed by Congress in 1957 and has been renewed four times since. Via the Energy Policy Act of 2005 the Price-Anderson Act was extended till December 31, 2025. The Act ensures that adequate funds are available for liability claims arising out of nuclear installations and was enacted to encourage the development of private nuclear power [206].

There is 13 billion US$ of liability insurance protection available through the Act and this is also the liability cap. The Act provides for two tiered liability coverage. The first tier is private liability insurance coverage (upto 450 million $ per site) which is made available by the American Nuclear Insurers, a pool of US insurance companies. The second tier is made up by retrospective assessment on nuclear power plant operators. In case the first tier does not cover the liability, the second layer of protection comes into play. The second tier requires all the reactor owner's commitment to pay up to 131.056 million dollars per reactor. If the second tier is depleted, the Act calls on Congress to decide whether any additional disaster funds are required. In such a case, each reactor side is assessed for a maximum of 5% as surcharge on the Tier 2 maximum deferred premium.

As per 10 Code of Federal Regulations (CFR) 50.54(w) licensees are required to maintain a minimum of 1.06 billion $ in onsite property insurance at each site so as to cover for stabilisation and decontamination of the reactor and site after an accident. Nuclear Electric Insurance Limited provides this insurance for licensees.

The Act and NRC regulations only require reactors designed for the production of electrical energy with a rated capacity of at least 100 MWe to maintain retrospective premium insurance [12]. Electricity-generating reactors with a rated capacity less than 100 MWe or for non-electricity-generating reactors, where the amount of required financial protection is less than $ 560 million, the Act requires the NRC to enter into an indemnification agreement with the licensee [13].The maximum amount of government indemnity provided under an agreement of indemnification under the Act is $ 500 million. As per Code for Federal Regulations 10 140.11(a)(4), financial protection for SMR up to 100 MW_e ranges from 1 million $ to 74 million $ [205].

UK

As per Section 16 (1) (a) of the Nuclear Installation Act [207], a nuclear propelled dredging ship can qualify as a "low-risk nuclear licensed site" with a liability limit of 70 million Euros.

Netherlands

The liability in Netherlands is enforced by the Act on the liability for nuclear accidents ('Wet Aansprakelijkheid Kernongevallen', WAKO. A recent development is the increase of the maximum liability of operators of nuclear installations from €340 million to €1.2 billion (effective since 1st of January 2013).

Belgium

The operator liability and financial security limits for nuclear installations is 1.2 billion €. Belgium, however makes the distinction in case it is "low-risk installation" where the financial limits is 297 million and the liability maybe anything between 70-297 million USD.

Spain

According to Article 57 under Chapter 8 ("CAPITULO VIII. De la cobertura del riesgo nuclear"), the Ministry of Industry, Tourism and Commerce may impose another limit (> 30 million euros) in case the

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[11] The claimant need not sue all the parties.

[12] U.S. Code Title 42 Section 2210 - Indemnification and limitation of liability b(1)

[13] U.S. Code Title 42 Section 2210 - Indemnification and limitation of liability (c)

risk by a nuclear activity (opinion of the Nuclear Safety Council) does not require high coverage.

The Nuclear operators' third-party liability amounts and financial security limits [208] by OECD gives information on the operator liability amount and the financial security limit to cover the operator's liability amount for a number of countries. In general, there is no fixed operator liability limit or the requirement for financial security to cover the liability amount. Unlimited operator's liability with a financial security of 1 billion CHF (~1 billion $) in Switzerland to 100 million Mexican Pesos (~5 million $[14]) and indirect requirement for equal amount to Korea with a flat operator liability amount of SDR 300 million (~244,000 € [15]) with the financial security amount depending on the type of installation (for reactors under 10 MW, the amount is ~15500 $[16]).

3.3. Additional Commentary

Backup Generators

Nuclear Safety regulations[17] require the presence of redundant and independent backup power systems. Emergency diesel generators are the primary source of such backup power [209]. "Independent" implies the physical and electrical separation of the emergency power system and "redundant" refers to the fulfillment of power requirement even with one unit out of service.

Double Hulls

Double bottom are a requirement of the regulations, however, double hulls offer better protection. Double hulled ships have two skins with a cofferdam in between them. This void is typically two meters wide. As part of SOLAS, double hulls or double bottoms are required for all passenger ships. Double hulls are a requirement for tankers [210] [211] and LNG ships [212]. Icebreakers are designed as double hulled ships due to the tasks that they accomplish. Double-hulled dredging ships have never been constructed and are not normal, however, a double hulled design would be required for nuclear-powered dredging vessel. Figure 3.1 shows the cross section of hull for different hull types.

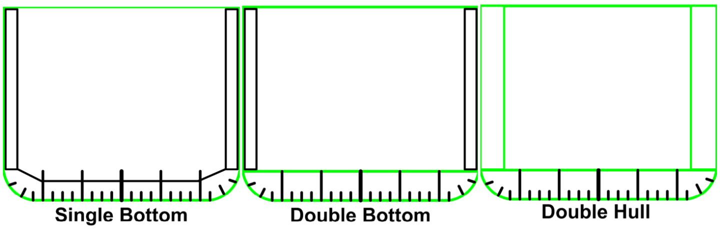

Figure 3.1: Cross section of hull for different hull types

Reactor Vessel Placement

The placement of the reactor along with the primary system components as per Part 79-Special Construction, Arrangement and other provision for nuclear vessels of the Code of Federal Regulations [213] is shown in Figure 3.2.

The main engines and pumps are generally located aft of the hopper in a TSHD. The placement of the reactor should be at the aft side of the dredger ship where the diesel engine is situated, due to the metacentric height (GM) and Center of Gravity (COG) related aspects. The amount of reinforcement and the actual placement should be based on the incident frequency and incident nature for dredgers of similar types and carrying out similar missions.

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[14] 0.05 $ = 1 Mexican Peso

[15] 1.23 € = 1 SDR

[16] 1300 KRW = 1 €

[17] (For example : As per 10 CFR 50 Appendix A of the General Design Criterion (GDC) 170); Code of Safety for Nuclear Merchant Ships etc.

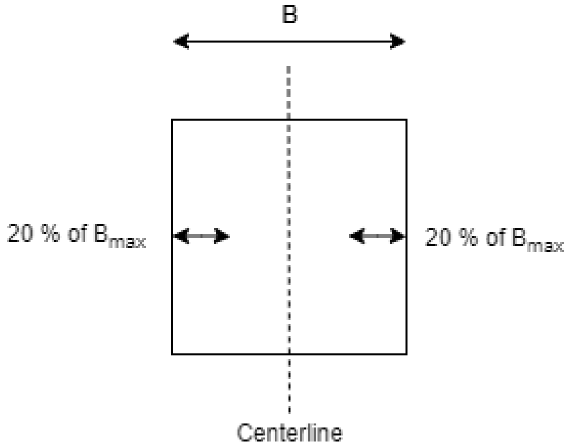

Figure 3.2: Reactor Vessel Placement

3.4. Chapter Summary

In summary, the regulations that a nuclear-powered dredger would be subjected to are tabulated in Table 3.2.

Table 3.2: Guidelines and Regulations

Application Area	**Regulations/Guidelines**	**Year**	**Notes**
Pollution from Vessels	International Convention for the Prevention of Pollution from Ships (MARPOL)	1973	
Underwater Noise & Radioactive Waste Dumping	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other matter	1972	London Convention/London Protocol
Ballast Water Treatment etc.	Ballast Water Management Convention	2004	Entered into force on 8 September 2017
Port Access	International Safety Of Life At Sea (SOLAS) Convention	1974	Self propelled ships 500 GT
Definition of Territorial Seas etc., Passage rights	United Nations Convention on the Law of the Sea (UNCLOS)		
Health Protection and Minimum Requirements for Working Conditions	Maritime Labour Convention	2006	Effective 20 August 2013
Rescue of Persons in Distress	International Convention on Maritime Search and Rescue (SAR)	1979	
Training of Seafarers	Standards of Training, Certification & Watch keeping (STCW)	2005	
Load Line fixation	International Convention on Load Lines (ICLL)	1966	For L 24 m
Vessel Design	Guidelines for the Assignment of Reduced Free boards for Dredgers (DR-68)	2010	Intact and Damage Stability calculations. Developed by Joint Working Group
Vessel Design	Code of Safety for Special Purpose Ships (SPS Code)	2008	Previously IMO Res. A.534(13), adopted 17 November 1983
Vessel Security	International Ship and Port Facility Security Code	2004	
Vessel Design and Safety	Code of Safety for Nuclear Merchant Ships		
Nuclear Third Party Liability	Convention on Third Party Liability in the Field of Nuclear Energy	1960	Paris Convention
Nuclear Third Party Liability	Convention Supplementary to the Paris Convention	1963	Brussels Supplementary Convention BSC
Nuclear Third Party Liability	Convention on Civil Liability for Nuclear Damage	1963	Vienna Convention
Nuclear Third Party Liability	Protocol to amend the Paris Convention on Nuclear Third Party Liability	2004	
Nuclear Third Party Liability	Protocol to amend the Brussels Supplementary Convention on Third Party Liability	2004	
Nuclear Third Party Liability	Brussels Convention on the Liability of Operators of Nuclear Ships	1962	Not yet in effect
Licensing and Set-up of Nuclear plants	National/International Nuclear Energy Act/Regulation		
Nuclear Material/Facility Protection	Amendment to Convention on the Physical Protection of Nuclear Material		

4

System Possibilities and Design

Section 4.1 discusses the raw data for the dredging cycle, the sanity check of data and subsequently, data cleaning and normalisation. Further, computation of the power and energy requirements from the data is described. Section 4.2 examines the system possibilities starting with the design consideration, moving onto the power train arrangement, nuclear reactor, thermodynamic cycles, heat engines, energy storage options. Section 4.3 covers selection of the individual components (nuclear reactor, power conversion system, energy storage) and power train arrangement.

4.1. Power Profile

Four phases characterise the dredging cycle of a TSHD. These are sailing empty-dredging-sailing loaded-discharge. A TSHD keeps on going back and forth about these four phases. Typical dredging cycle load profile are difficult to define. The load profile depends on the distance between the borrow and discharge sites, dredged material, TSHD size etc. Data on load profiles is unavailable in public domain.

4.1.1. Data

Raw data of a diesel-electric dredger operated by one of the world's biggest dredging operators was obtained. The dredging cycle status is captured through Programmable Logic Controller (PLC) that receives inputs from sensor and actuator positions [214]. In this diesel-electric dredger, the power from two main engines is routed to either the dredge pumps (pumping ashore) or propulsion (sailing loaded/empty) or both (dredging). Sometimes, a compromise in the operating parameters is made for the reduction of the power demand (limitation of power generation due to the size of the power generators).

The raw data had 11 variables in dataset which included time (s), distance from project origin, fuel rack settings (%), speed ($\frac{m}{s}$), dredge pumps power (kW), dredging state status, pitch of Controllable Pitch Propeller (%) etc. The data logging system recorded the value of each variables with a resolution of $\sim$ 1 second. In total, the data set consisted of over 1.8 million values. These values represented data from two different discharge conditions, pumping ashore and dumping. The different discharge conditions lead to two different Dredging Cycles (I and II). The Dredging Cycle I consisted of sailing empty-dredging-sailing loaded-pump ashore. While, the Dredging Cycle II [1] consisted of sailing empty-dredging-sailing loaded-dumping. A visual representation of the two dredging cycles is given in Figure 4.1 and 4.2.

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[1] Henceforth, the subscript I and II denotes parameters of the two dredging cycles respectively.

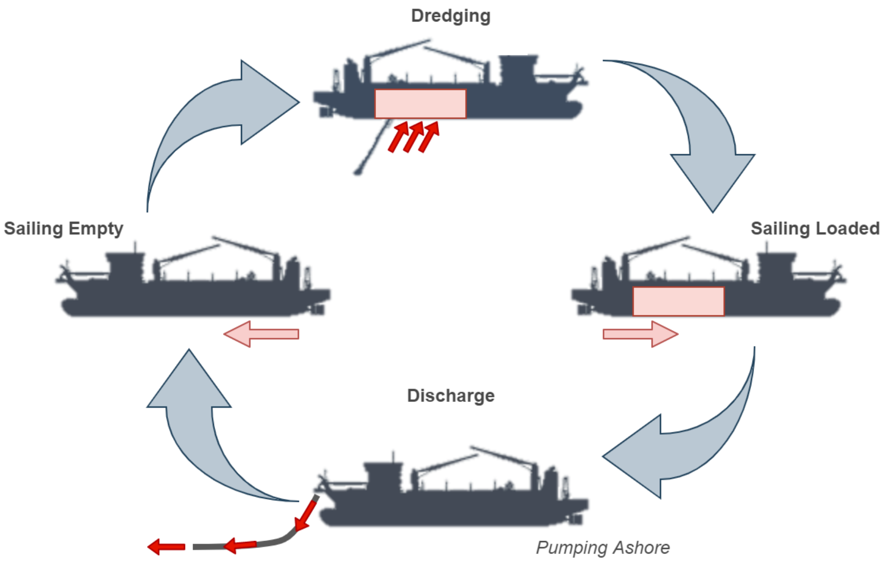

Figure 4.1: Dredging Cycle I

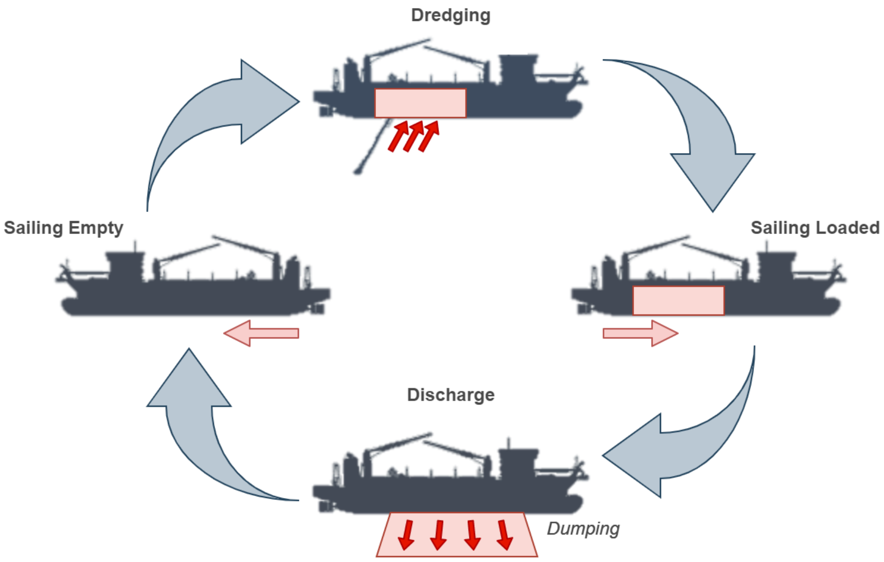

Figure 4.2: Dredging Cycle II

4.1.2. Data : Normalisation & Cleaning

Sanity check on the data was performed. This was carried out for example, by checking for values of fuel rack settings, dredge pumps power when the dredging cycle status was ”sailing empty” (This is a dredging state where the dredger is not dredging). In this particular case, there was indication of utilisation of dredge pump (albeit at much lower power). One of the possible reasons for the operation of the pump could be for flushing the hopper. Industry representatives confirmed that there are certain circumstances when the dredge pump will be used while sailing empty or sailing loaded or dumping. Hence, for making an analysis as close as possible to the dredger operations in real conditions, it was assumed that the pump was actually in use.

Further, it was found that at some points, the value of dredge pumps power were negative (see Figure 4.3 for normalised dredge pump power) and the fuel rack settings were > 100% (see Figure 4.4 for normalised fuel rack setting).

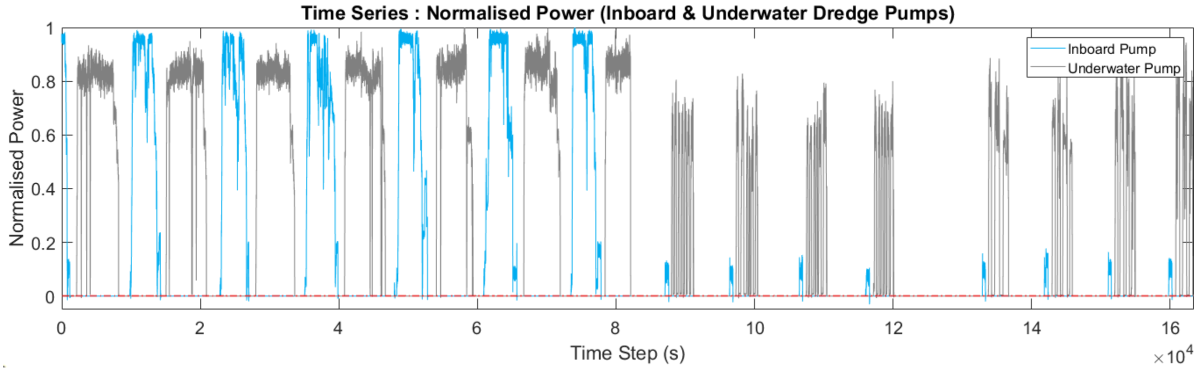

Figure 4.3: Raw Data - Normalized Inboard Underwater Dredging Pump Power

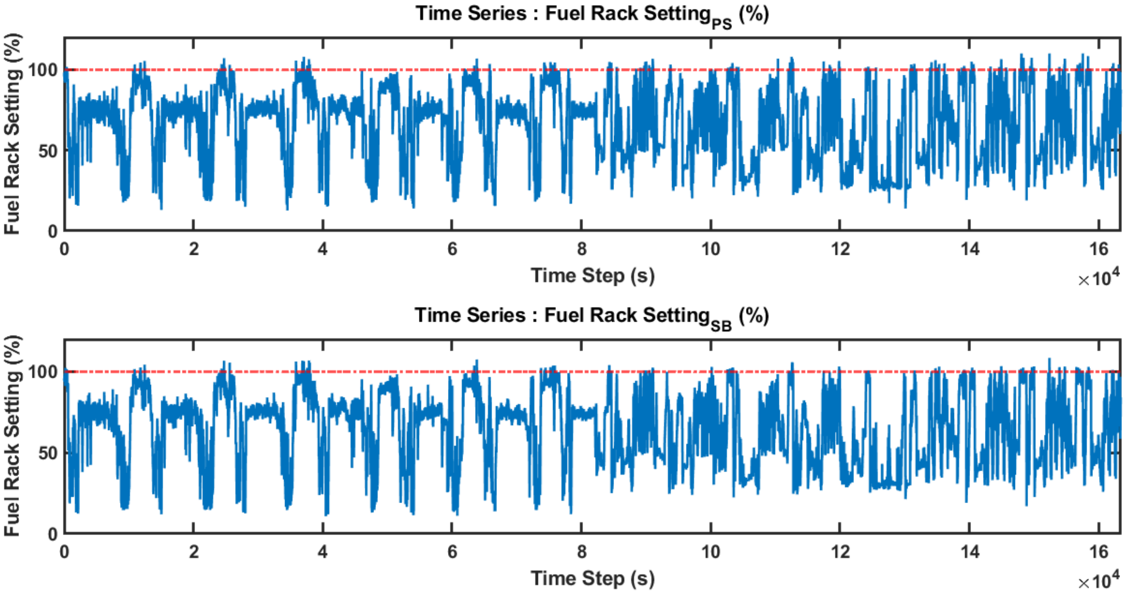

Figure 4.4: Raw Data - Normalised Fuel Rack Setting

One of the possible reasons for this could have been the noise in the signal (due to loose connections, vibrations etc.). The maintenance logs were not accessible to establish this with conviction. These negative values were relatively very small (~1%) in comparison to the total power of the dredge pumps), momentary (~10 seconds), very infrequent (<100 occurrences) to have a substantial effect on the analysis. However, these values would still lead to wrong conclusions about the data. Therefore, the requirement of data cleaning arose. To clean the data, the Fuel rack settings were normalised by ceiling the values to 100% (see Figure 4.4) and the negative values for the dredge pumps power were set to zero. By the end of this exercise, a data structure with clean data was obtained and ready for utilisation for further analysis.

Normalised data can be used as a basis for generation of power profile of dredgers of different sizes. The power demand profile is normalised as per Equation 4.1. In Chapter 5, these normalised profiles would form the basis of computation for energy, power requirements and affect the mass/volume considerations.

$$Normalised\ Power = \frac{Power\ at\ each\ instance}{Maximum\ Power} \tag{4.1}$$

In conclusion, the data was cleaned and normalised.

4.1.3. Power & Energy Requirements

In dredging vessels, energy and power is required for propelling the vessel but also for carrying out dredging work. There were two fuel racks on either side of the vessel. The two sides are referred to as Port (PS) and Starboard (SB), in nautical parlance). For generation of the load/power profile, linearity between the fuel rack setting and power generation by main engines was assumed. This is given in Equation 4.2.

$$P_D = P_{Nominal} \times \frac{(Rack\ position_{PS} + Rack\ position_{SB})}{2} \tag{4.2}$$

where,

P_D = Power Demand
$P_{Nominal}$ = Nominal engine power
$Rack\ position_{PS}$ = Port Side Fuel Rack position
$Rack\ position_{SB}$ = Starboard Side Fuel Rack position

The temporal resolution (time step) of the data was found using Equation 4.3.

$$\Delta t = \frac{24 \times 3600}{Number\ of\ data\ points}\ [s] \tag{4.3}$$

Now, the total energy requirements is the area under the load curve and given as per Equation 4.4.

$$Energy\ Requirements = \Delta t \times P_D \tag{4.4}$$

It is to be noted that the power requirements relate to the engine sizing whereas the energy requirements govern the size of the fuel tank.

4.2. System Possibilities

Before proceeding to the conceptual design of the nuclear system, it was necessary to understand the design considerations and constraints for the nuclear system. Discussion on the possibilities that exists for the power train arrangement, nuclear reactor, power conversion system and the energy storage follows next in this section.

4.2.1. Design Considerations

General Consideration

The power-to-weight and power-to-volume ratio are of primary importance because of the mass and volume limitations (retrofit scenario) and practical economic reasons (not leading to a reduction in the amount of material that can be loaded). High values of both of these metric is a desirable feature.

Load Following Operations

Nuclear power is considered as a baseload generator. However, the proposition is not entirely true. The ramp-up rates of Nuclear Power plants of around $\frac{5\%}{minute}$ are regularly carried out in Nuclear Power Plants [215].

The ramp-up depends on the type of nuclear reactor and the power level it is at. For example, for the PWRs and BWRs operating above 80% of nominal power, the ramp-up/ramp down rates can be 10% per minute [216]. German NPPs are considered as one of the most flexible in the world. The Emsland Nuclear Power Plant a single unit PWR of 1355 MW (net electrical output) had made a 140 MW per minute maneuver [217] which equates to ramp rate are close to $\frac{10\%}{minute}$. However, the ramping (up and down) comes at a cost : material fatigue. The material fatigue limits the number of cycles that a ramping maneuver can be undertaken. For the 100-80-100 [2], 100,000 cycles are possible, the 100-40-100 cycle cannot be run more than 12000 times while for the 100-0-100, the permissible cycles is 400 [216].

In a dredging ship, such maneuvers occur at least a quarter million times over the lifetime of the

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[2] The power reduction from 100% of nominal power to 80% and back to 100%, this is referred to as 100-80-100.

ship. Hence, to ensure that the system does not prematurely fail and/or require replacement, the ideal way to operate a nuclear reactor aboard a dredging vessel would be to keep the reactor running at a constant /semi-constant power. Energy storage system (ESS) or auxiliary energy generator(s) should cope with the fluctuations.

However, this is not the only reason to have an energy storage system/spinning reserve aboard a nuclear-powered dredger. The ”safe” ramp rates of nuclear reactor are slow in comparison to the change of power demand of the TSHDs (which can go from 30% to 100% and vice-versa within 10 minutes). If there is no spinning reserve and frequency changes even by ±1% of the standard frequency (50Hz/60Hz) persists, this risks damaging equipment and infrastructure. Further, the maintenance of constant load on pump is necessary when discharging over longer distances as the slurry in the pipe can sink to the bottom. This can cause operational issues [218]. An advantage of using another energy generating source or an energy storage is that these can also act as emergency power systems in case of outage and fulfill the regulatory requirement.

In the course of this work, it was realised that there exists a possibility to operate the system without an energy storage system. However, due to the speculative nature of the design, this was not looked into. More information on the design can be found in Appendix C.11.

Other Considerations

Other considerations that were understood through discussions with the industry representatives are :

- The vessel endurance [3] is generally about 2 weeks.
- It takes about 12 hours for refueling operations.
- The filling times of hoppers is generally 1.5-2 hours for the dredger vessels (at least up to 30,000 m^2).
- Regular maintenance stops are taken every month or so. These are sometimes at a shipyard and sometimes at an anchorage.
- For a TSHD, utilisation of 38-45 weeks per annum is considered healthy.
- Major overhauling of diesel engines is carried out around 15 years of its life.
- To avoid restocking runs and visit to repair yards, maintenance at sea and supply of logistics can be considered for nuclear-powered dredgers.

Some of the constraints on the continuous operation of a nuclear-powered dredger vessel would be :

- Stoppage every month for the regular maintenance (preventive and predictive) check.
- Refuelling period (as per design).
- Economic constraint : The cost of sand dredging (Dutch coast) ranges from 2.5-4 $\frac{€}{m^3}$.
- TSHD vessel inspection check is carried out every 2 years.
- Nuclear regulators require check of nuclear reactor every 2 years (in Netherlands).

Nuclear-power generation requirements

It is clear from the discussion in 4.2.1 that the nuclear generation cannot alone satisfy the power requirements for the operation of the TSHD. The nuclear reactor sizing is dependent on the amount of nuclear power generation required. The nuclear generation should be enough for the dredger to undertake mobilisation relying solely on the nuclear power source. This would be the minimum amount of nuclear-power generation level. Additionally, there should be some excess generation capacity that is enough to keep the energy storage system charged. This is to ensure that when the dredging cycle starts, the operations can go uninterrupted and unrestricted. On top of this, a factor of safety of 10-15% should be considered.

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[3] In industry, some companies also define this as ”autonomous working/operational period.”

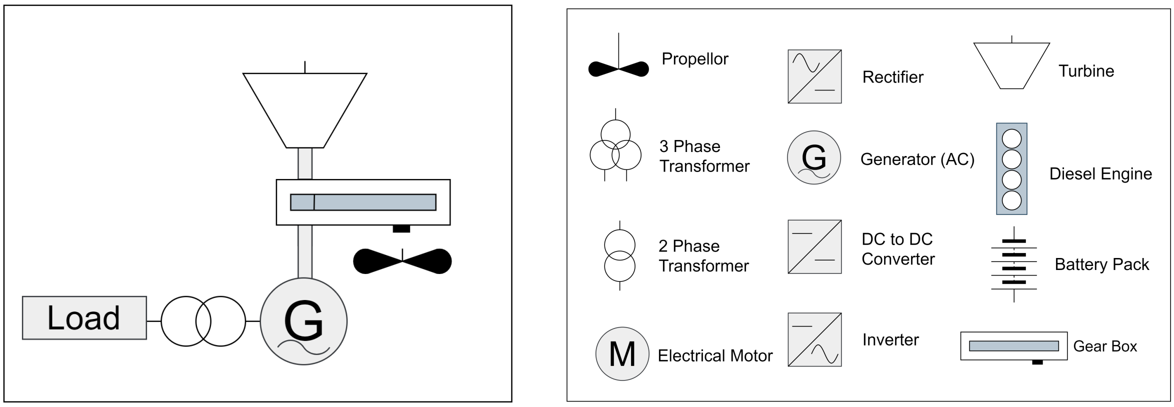
4.2.2. Powertrain Arrangement

In general, powertrain arrangement decides the way to deliver power to the propellers from an energy source. When relating to vessels, this is referred to as propulsion arrangement. In this case, it is also the way to deliver power to pumps. There are various propulsion formats that can be thought for a nuclear powered dredger.

Integrated Electric Propulsion (IEP) or Full Electric Propulsion utilises turbines or generators or both to generate electricity which powers electric motors. This eliminates the need for gearboxes, increases the freedom of placement, makes the ship less noisy and leads to reduction of weight and volume. Capital and maintenance costs are also reduced as the number of engines required reduces and the engines can run at optimal load. Diesel-electric/turbine-electric systems are types of Integrated electric propulsion. Propulsion relying on fuel cells or batteries would always be IEP.

Nuclear aircraft carriers have coupling between the shaft and the steam turbines via a series of gears. Nuclear submarines have direct coupling or electric-drive propulsion. An example of the latter is the Columbia Class submarines [219] or French Navy's Barracuda class [220]. Another possibility is the Combined Nuclear and Steam Propulsion (CONAS), a feature of the the Russian Kirov-class guided missile cruisers [221]. The propulsion system gives Kirov-class cruisers the possibility of powering the propeller shaft with the nuclear reactor and the oil-fired boilers together.

For nuclear-powered TSHDs, a possible power train arrangement could be the direct coupling of the propeller shaft with the turbine via gearbox (Figure 4.5a). However, the dredging pumps require about 50% of the total power and coupling propellers, pumps and generator(s) would require long shafts/complex gearbox arrangement. This would make the whole arrangement very cumbersome. Another possibility would be splitting the total generated power over multiple smaller nuclear reactors. Such a format would require continuous ramp-up and ramp down of the nuclear reactors that could be detrimental to the life of the nuclear reactors. Further, in order to supply emergency power to the propeller, either the gearbox would need to be decoupled and coupled to an electric motor or an additional propeller would have to be coupled with an emergency motor. The former is an arrangement that would require intervention, while the latter case would entail an unused propeller that cause additional drag on the vessel (in normal operations).



(a) Direct turbine propulsion arrangement

(b) Legend

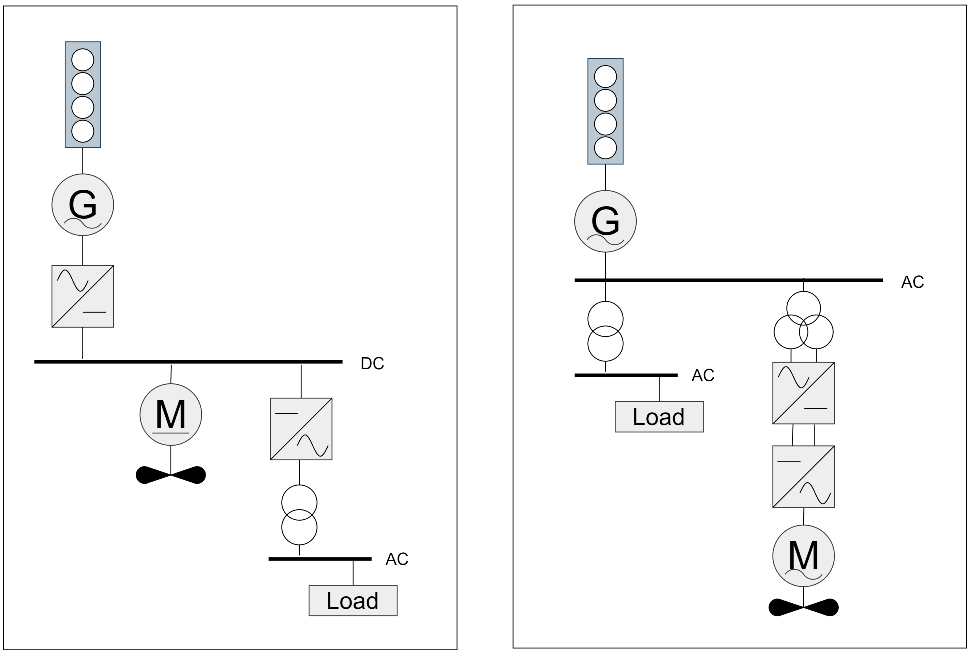
Figure 4.5: Single Line Diagram for Direct turbine propulsion and Legend for Single Line Diagrams

AC or DC grid?

The electric power system aboard a vessel could be based on Direct Current (DC) or Alternating Current (AC). In general, vessels have AC grids (Figure 4.6b). If diesel-battery hybrid powertrain is used with AC grid, conversion of AC to DC for charging of batteries needs to happen. A rectifier would be needed for charging the batteries and for discharging applications, an inverter for conversion of DC to AC. A bidirectional inverter can do both the things in a single piece of equipment. In case the grid is DC (Figure 4.6a), depending on the type of generator and motor, rectifier/inverter might be required.

DC grid based system with energy storage systems are commercially available (for example from MAN Energy) to a total installed power of 20 MW [222]. The integration of energy storage system with diesel/turbine generator leads to the following benefits :

- Peak shaving of the load demand
- Load equalisation among engines/turbines
- Dynamic response to power demand
- Reduction of required number of standby engines/turbines
- Reduction in operating hours
- Possibility to use smaller engines/turbines
- Zero emission mode possible (for example in harbours)
- Reduction of fuel consumption due to operation near the design point.



(a) Diesel Electric DC (b) Diesel Electric AC

Figure 4.6: Single Line Diagram for Diesel-Electric Propulsion with AC/DC grid

4.2.3. Nuclear Reactors

As per the Database on Nuclear Power Reactors (IAEA) [223], there are 442 land based reactors, generating about 390.6 GW of electricity (~10.5% of the global electricity generation). Combined together, they have accumulated about 18,435 reactor years. Further, 53 reactors with a combined electricity generation of 56.3 GW are under construction.

Marine reactors differ from land based reactors and as per Ragheb [224] some of the distinguishing features of marine reactors are :

- Compact core.
- Higher fuel enrichment [4].

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[4] Some marine reactors alsot run on low enriched fuels.

- Usage of higher burnup fuels [5].
- Incorporation of burnable poisons.
- Internal neutron and gamma shield.
- Ensuring that ship motions should not cause any abnormality in the operation.
- Non-gravity driven reactor shutdown mechanisms.
- Prominent salt water corrosion.

These features lead to benefits like low Xe dead time and reduced refueling frequency but also has some drawbacks such as greater stresses and lower thermal efficiencies.

Pressurised Water Reactors (PWRs) are the most common technology used for nuclear power generation. They have found themselves into the nuclear navies of the world due to their compactness, experience and maturity. Water is used as a moderator and coolant in this reactor technology. Boiling Water Reactor (BWR) are the second most common type of nuclear reactors. In a BWR, the heat from the reactor core converts water into steam and this is used to drive a steam turbine.

2.5.1 discussed about the Generation IV concepts and SMRs. A lot of these nuclear technologies have low Technology readiness levels (TRLs). Therefore, the deployment timeline of the nuclear-powered dredger will eventually dictate the nuclear reactor technology that can be used. Some of these nuclear technologies are discussed forthwith.

Supercritical water cooled reactor (SCWR) is a proposed Generation IV nuclear reactor which would function above the thermodynamic critical point of water (374°C & 22.1 MPa). The supercritical water would function as a coolant, moderator and working fluid. Similar to a BWR, steam will directly be used to drive the steam turbine. The efficiency can approach 44% or more, better fuel utilisation and lower capital costs are expected [225]. Combined, these characteristics give a potential for plant simplification.

High-Temperature Gas-Cooled reactor (HTGR) is a graphite-moderated, helium-cooled nuclear reactor technology powered by coated-particle fuel (also called as Tristructural-isotropic (TRISO) fuel). High efficiency is achievable in this low power density reactor. There is a potential for low operation and maintenance cost. Helium is a coolant that is inert, does not get activated and stays in a single phase [226]. The two main configurations are the prismatic block reactor (PR) and the pebble bed reactor (PBR). In the PR, reactor core is made up of graphite blocks while in PBR, graphite pebbles form the reactor core.

Molten Salt Reactors (MSR) use molten salts as coolant. Some of the characteristics are operation at atmospheric pressures, high operation temperatures, higher burnups & homogeneous fuel composition possible. The coolant (molten salt) has high boiling point, heat capacity and thermal conductivity [227]. There are two types of design : fuel dissolved in the coolant, and separate fuel and coolant. Online refueling is possible in some designs.

All modes of power generation requires some form of cooling. Using cooling water is one of the most effective, cheapest and hence, a very common way to cool the power generators. The temperature of the cooling water which is almost always taken for granted affects the power generation capacity of power plants [6]. The operational area for dredgers is not pre-defined and can range from equatorial water to Arctic sea. Between these extremes, the water surface temperature can vary from 30°C to -2°C [228]. If the dredger operates in same localities (latitudes, oceanic currents and temperatures), the sizing of the intercoolers/condensers can be based on the temperature of operational area.

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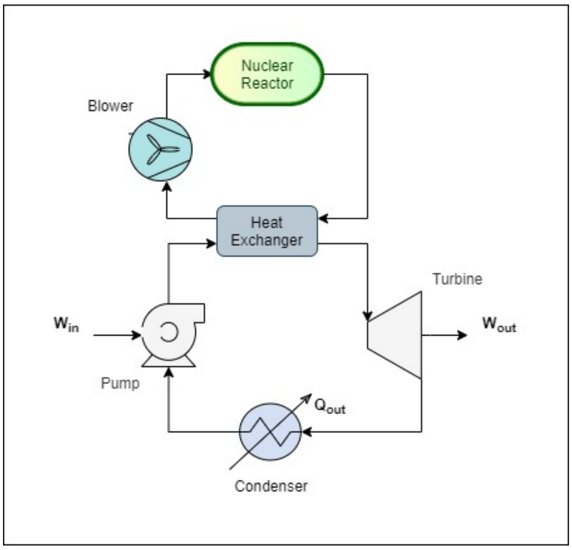
[5] uranium-zirconium, uranium-aluminum, and metal ceramic fuels.

[6] See C.16 for specific examples.

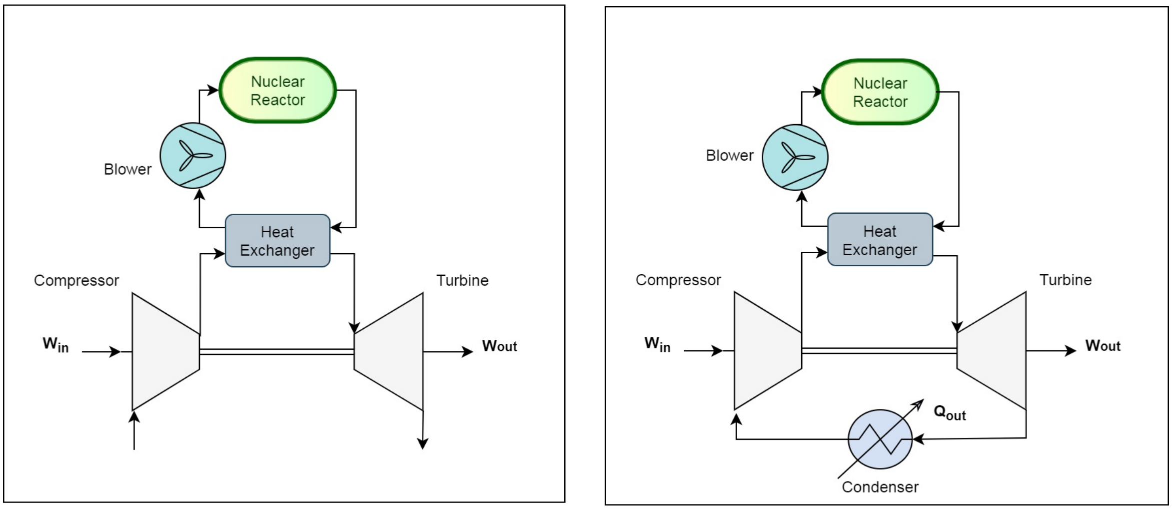
To simplify the design and make the concept reproducible, it is imperative to utilise commercial SMR models or already designed nuclear reactors. Possible options (depending on the technology) could be : CAREM, 4S, NuScale, U-Battery and HTTR etc.

4.2.4. Thermodynamic cycles

The conversion of heat into mechanical work is achieved by the use of a heat engine. The working of a heat engine can be described/modelled by the thermodynamic cycle. Hence, the heat engines and thermodynamic power cycles are interlinked. The Rankine and Brayton cycles are the most common of these cycles and would be discussed.



(a) Rankine cycle



(b) Open Brayton cycle

(c) Closed Brayton cycle

Figure 4.7: Schematic for various indirect thermodynamic cycles with Nuclear reactor as the heat source

A Rankine cycle is the thermodynamic cycle where mechanical work is produced from heat and this is accompanied by a phase change. The working fluid is generally water or an organic fluid. For water based systems, the heat engine is the steam engine or steam turbine. The Rankine cycle's advantages include low pumping power requirements and the ability for low temperature heat rejection. For high inlet temperature, a supercritical Rankine cycle is better suited and it has superior efficiency (due to reduced irreversibilities in heat transfer process). The load following response is faster than subcritical units. Commercial supercritical Rankine cycle systems are generally >150 MW and the maintenance of water chemistry (pH, Total Dissolved Solids etc.) is of utmost importance in these systems.

Brayton cycle a cycle that models the constant-pressure heat engines. The cycle usually runs as an open system and in general, is simpler than Rankine cycle. Gas turbine is a type of Brayton engine and performs very well at temperatures of even 1300 K. An open Brayton cycle uses air as the heat transfer fluid. The use of air as a heat transfer fluid [7] has certain advantages [229] :

1. Availability
2. Negligible cost
3. Well developed thermodynamics and turbomachinery

While, the major disadvantage of air is its low heat transfer coefficient.

Another important variant is the closed Brayton cycle. The use of CBC has been suggested for use with Supercritical CO_2 as a working fluid for nuclear energy system [230] [231]. In a closed Brayton cycle, the working fluid is recirculated continuously and instead of a combustion chamber, a heat exchanger is used.

For a closed Brayton cycle, the compressor power requirements are lower than open cycle, heat rejection is possible at lower temperatures and, high efficiencies can be achieved over a wide range of power demand [232]. The load-following capability of closed Brayton cycle turbo-machinery is low but a nuclear reactor with negative temperature feedback is inherently load following. Hence, the entire system can be partially load following and without an active control the changes in load demand can be met (depending on the design, this could be $\pm$ 5-15%) [233].

There can be two ways to carry out the heat transfer from a nuclear reactor : indirect cycle and the direct cycle. In the indirect cycle, the heat transfer fluid of primary cooling loop of the reactor is separated from the working fluid of the power cycle. Indirect cycle provides intermediate heat-transfer loop(s) through the intermediate heat exchanger(s). This is advantageous because it provides a radioactive-free environment for the turbomachinery, simplicity and possibility of utilising nuclear heat. Figures 4.7a, 4.7b and 4.7c represent indirect Rankine, open Brayton and closed Brayton cycles. Current Boiling Water Reactors are example of closed direct cycle, the Pressurised Water Reactors are example of closed indirect cycle.

The thermochemical generation of hydrogen is not taken into consideration here due to the extra requirements and added complexity of having such a system. However, such a system can serve as H_2 source for the emergency system (fuel cell/turbine based) for the on-board nuclear power generator.

4.2.5. Energy Storage

In marine applications, energy storage systems are used for dynamic support, peak shaving, power plant stabilisation and elimination of idle capacity (for example in tugs).

A fast acting system is required to handle the variations in a dredging cycle. The usual response time varies from seconds to minutes. A look at Figure 4.8 convinces that the options that are available for usage in this case are batteries, super-capacitors, flywheels and Superconducting magnetic energy storage (SMES). These options are the only ones that can respond quickly to a change in load. Strictly speaking, Fuel cells are not energy storage devices. However, PEMFC have high ramp-up rates and fast response times.

SMES

Energy is stored in a magnetic field in SMES systems. The source of this magnetic field is the current travelling in the superconducting coil that is cooled below its critical temperature [8]. Hence, there is

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[7] Air is also being considered in Concentrated Solar Tower power plants at a heat transfer fluid.

[8] Electrical resistivity drops to zero at critical temperature

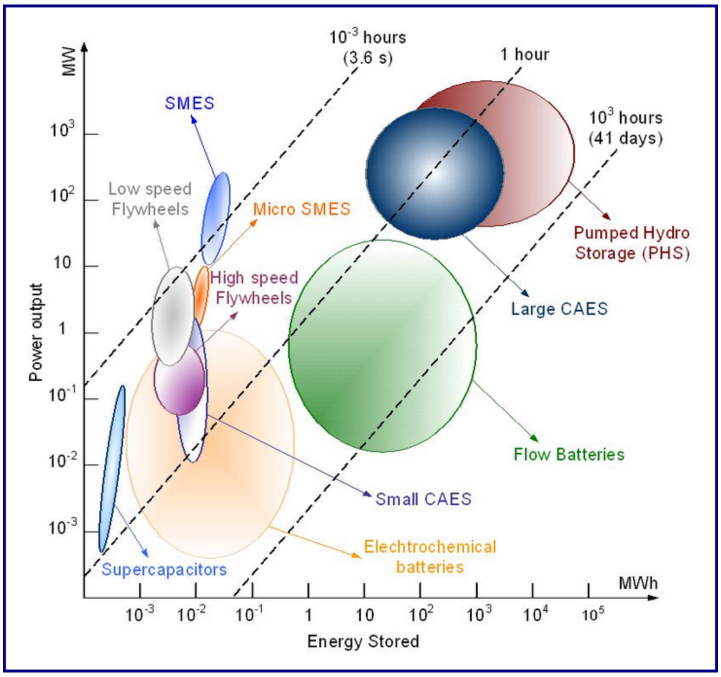

Figure 4.8: Output Power vs. Stored Energy for various Energy Storage Systems

Source: [234]

near instantaneous delivery of large amounts of power with almost zero energy loss in the storage and high efficiency grid reliability [235].
There has been limited commercial successes of SMES till date. There are specific niches where they are suitable for example : power factor improvement, providing reactive/active power, voltage support, and stabilising utility transmission lines [236]. However, they need large surface areas for installation and maintenance of cryogenic temperatures [237]. In an application like this work, they are not suitable.

Batteries

Currently, batteries are the most dominant form of energy storage devices. Figure 4.9 gives a schematic of how a the battery works. Two important and relevant metrics for this work are the C-rate and Depth of Discharge (DoD) of batteries.

The C-rate is the ratio of instantaneous rate of discharge of the battery to its nominal capacity[9]. Another way to look at it is that a battery with α C-rate charges/discharges its full capacity after $1/\alpha$ hours of discharge. C-rate is given as :

$$C - rate = \frac{Discharge\ Current}{Nominal\ Battery\ Capacity} \tag{4.5}$$

The higher the C value, the higher the power that can be delivered. This implies faster charge/discharge of the battery but also more stress [238]. The higher C-rate batteries are referred to as Energy cells as they deliver more energy delivered per weight. While, the low C-rate batteries are called as power cell.

The Depth of Discharge (DoD) is inverse of State of Charge (SoC). This is expressed in % as

$$Depth\ of\ Discharge = \frac{Discharging\ Capacity}{Battery\ nominal\ capacity} \tag{4.6}$$

There is a correlation between the DoD and the life of the battery. Manufacturers generally supply maximum DoD values, the term cycle life quantifies the number of cycles that a battery would last

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[9] A battery does not discharge at constant power.

at particular DoD(s). Discharging batteries too deeply results in an increased amount of accessible stored energy but also increases the Levelized Cost of Storage (LCOS) due to reduction of the life of the battery [239]. Hence, the usable capacity of batteries is given by Equation 4.7

$$Usable\ Capacity\ (Ah) = Depth\ of\ Discharge\% \times Nominal\ Capacity\ (Ah) \tag{4.7}$$

Two major battery technologies are the Li-ion and lead acid batteries. Table 4.1 gives the comparison of Li-ion batteries w.r.t. Lead acid batteries. This is based on information from different manufacturers [240] [241] [242] [243]. It is clear from Table 4.1 that Li-ion batteries have improved capacities, performance, reliability and reduced life cycle costs.

Lead-acid batteries have been the major battery technology for use in marine applications. However, Lithium-ion batteries are being accepted for use aboard marine vessels. In 2019, the first Lithium-ion battery based submarine was built [244]. Lithium catches fire when exposed to water, these fires are hot and release hydrogen gas which can be explosive. However, Li-ion batteries don’t contain sufficient Lithium to have this effect [245] and water can be used to put off such fires and prevent the thermal runaway.

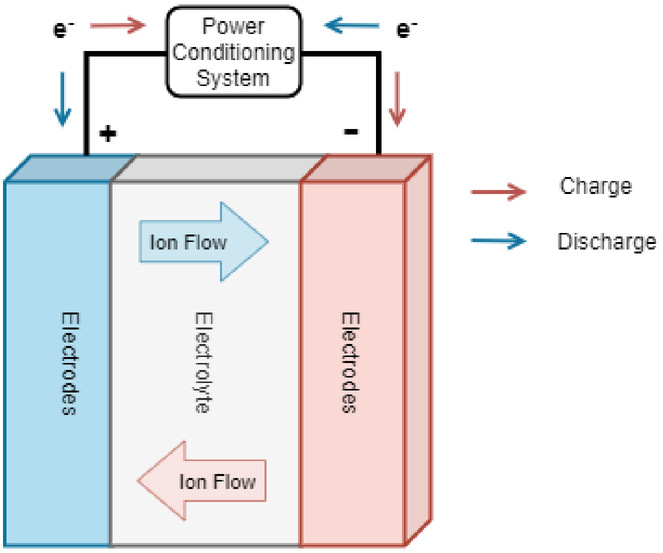


Figure 4.9: General schematic of working of a battery

Some application for the use of battery-hybrid include :

- Instances where low engine loads exist, for example : dynamic positioning applications. Due to requirements of system redundancy, multiple engines run continuously. This results in lower efficiency and and high maintenance costs.

- Icebreakers [246] : Icebreakers need a power reserve in case thicker than usual ice is expected or if they hit an ice ridge.

The round trip efficiency of the battery system (charger and battery) is around 83%. A periodic full discharge is not needed to increase the lift and there is no memory. Partial discharges are acceptable for Li-ion and rather reduce the stress, prolonging battery life. For example, partial charging reduction of 0.10V/cell can double the cycle life of a 4.2 V/cell battery [247].

Table 4.1: Comparison of Li-ion and Pb-acid Batteries

	Battery Technology	
Parameter	**Li-ion**	**Lead Acid**
Depth of Discharge	Capable of 100 % Manufacturers often advise 80 %	50 %
Purchase cost	Expensive (3.5-5 times)	Cheap
Cycle Life	Long	Short
Specific Power	High	Low For the same power 4 times heavier
High load performance	High Low to no Peukert effect	Low Considerable Peukert Effect
Charging rate and efficiency	Fast and ~95% charging efficiency	Slow and ~85% efficiency
Maintenance cost	Low to none	High
Energy Density	High	Low For the same power 4 times heavier
Total cost of ownership	Low	High

Flywheels

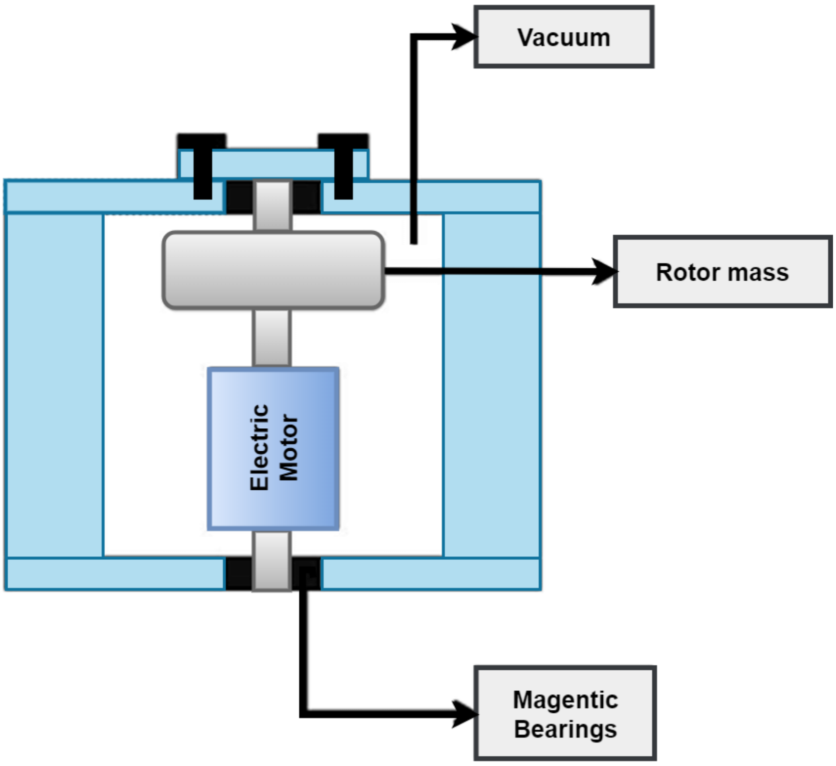


Figure 4.10: Schematic of a modern flywheel

Flywheels are one of the oldest energy storage devices. They are a mechanical energy storage device in which energy is stored as kinetic energy of the rotating wheel. The stored kinetic energy can be released by coupling it to a load to produce a rotary motion. Modern flywheels have magnetic bearings, operate in vacuum chambers and rotate at high speeds (>15,000 RPM) [248], composites are used to achieve this. Most commercial flywheel systems use a vertical drum-like shape and the same magnetic coil does the power generation or act as a motor. Flywheel kinetic energy is given as :

$$E_k = 0.5 \times I \times \omega^2 \tag{4.8}$$

where,
I = Mk^2 = Moment of Inertia (kgm^2)
ω = Angular velocity (m^2/s)
k = Radius of gyration (m)

Flywheels have operational life of 20+ years, 100% Depth of Discharge for an unlimited number of cycles, round trip AC to AC efficiency of 85-95%, are tolerant operating temperatures, don't have any temporal degradation [249] and do not develop a memory. Onboard of a marine vessel, the flywheel can find an additional (limited) use as ship stabilisers for anti-rolling.
Flywheels are cost competitive when providing power in the range of few seconds to 5 minutes at power levels > 100 kW. The systems cost of carbon fiber based flywheels is 1200$/kWh. For batteries the energy to power ratio is fixed by the cell chemistry. Hence, $/kWh is a scalable metric. However, $/kWh is not a scalable for flywheels (see Appendix C.8.1 to see the cost elements of a flywheel)

The power-to-weight ratio of commercial flywheels is low. The high rotational speeds (which can be in excess of 50,000 RPM) combined with their high mass poses an additional hazard.
Flywheel(s) in conjunction with Fuel Cells or batteries can be considered as a viable option. Data for Flywheels has been compiled and can be found in the Appendix B.4. The data was not used in this work but can serve as a starting point for future work that considers flywheels as an energy storage option.

Supercapacitors

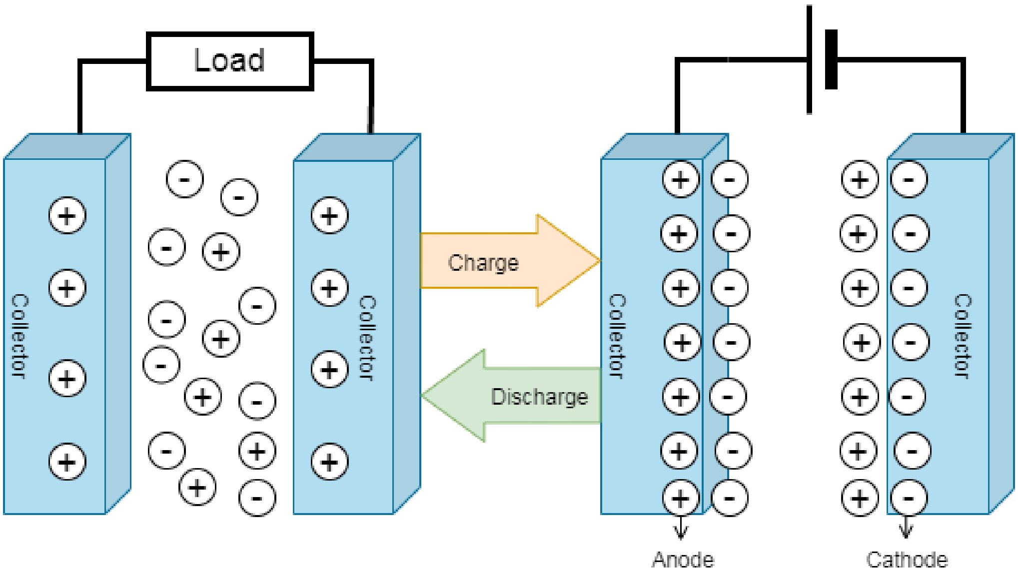
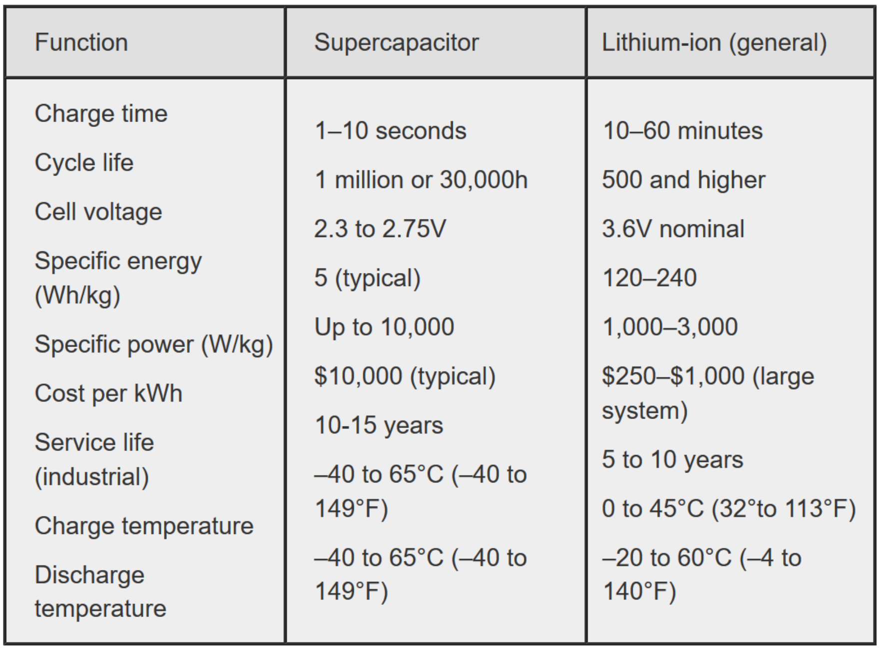


Figure 4.11: Schematic for Supercapacitor charge and discharge cycles

A supercapacitor stores energy as static charge instead of chemical energy. In some applications that require quick short-term power, super-capacitors are seen as an alternative to batteries. Rated in Farads, the super-capacitors don't overcharge or require charge detection. Super-capacitors, ultra-capacitors or electric double-layer capacitors (EDLC) can undergo 100 fold more cycles than batteries, and have more power density but much lower energy density (10-50 times). They have no risk of thermal runaway but are very expensive in comparison to batteries or flywheels. Cycle depth does not cause performance degradation and they are almost maintenance free [250]

The linear discharge characteristics reduces the usable power. If suitable voltage limit is used to charge super-capacitor at constant current there is no need for a full-charge detection in super-capacitors. Supercaps can be charged within seconds and have a longer life than batteries. More specifically Table 4.12 gives the comparison between Super-capacitors and general Li-ion batteries.



Function	Supercapacitor	Lithium-ion (general)
Charge time	1–10 seconds	10–60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6V nominal
Specific energy (Wh/kg)	5 (typical)	120–240
Specific power (W/kg)	Up to 10,000	1,000–3,000
Cost per kWh	$10,000 (typical)	$250–$1,000 (large system)
Service life (industrial)	10-15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)

Figure 4.12: Comparison between a Supercapacitor and a typical Li-ion Battery

Dielectric determines the maximum allowable voltage while for electrochemical cells, the cell chemistry determines the operating voltage. Currently, voltages of 2.8 V and higher are possible, but at a reduced service life. Series arrangement of three or more capacitors are used for higher voltages but this requires voltage balancing for prevention of over-voltage in any cell. This is similar to Li-ion battery.
Super-capacitors are not economical if charge and discharge times < 60 seconds [251], hence, super-capacitors are similar to flywheel in its qualities.
Achieving higher energy density is a possibility by the use of Asymmetric Electrochemical Double Layer Capacitor(AEDLC) which uses battery-like electrodes. However, AEDLC shares the partially the burdens of a battery like shorter cycle life.

Proton Exchange Membrane Fuel Cells (PEMFC)

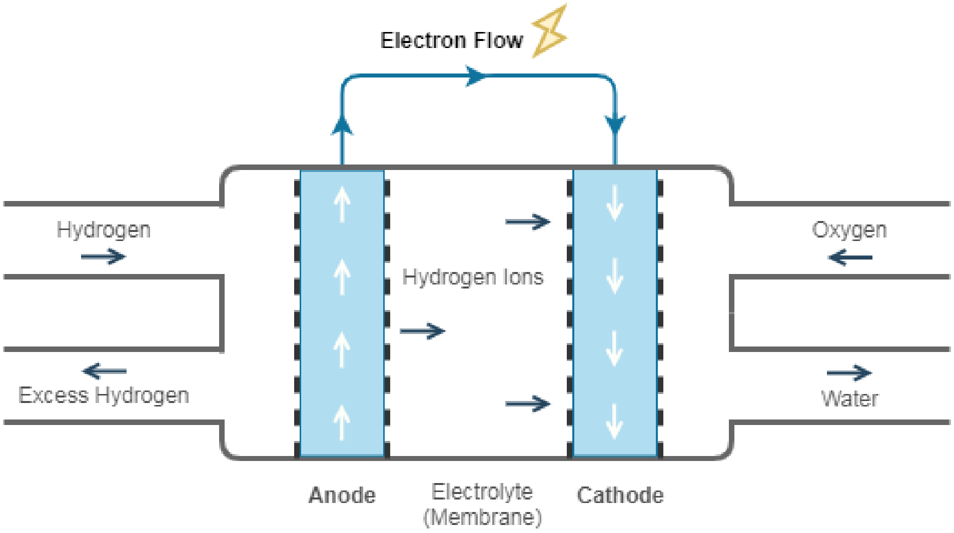


Figure 4.13: Schematic for working of a Fuel cell

A fuel cell is a energy conversion device that utilises the chemical potential energy into electricity by conduction of ions. Various fuel cells have been developed and serve different application needs by taking advantage of different electrolytes [252]. Proton Exchange Membrane Fuel cell or PEMFC is one such type of fuel cell. In a PEMFC, a Polymer electrolyte membrane serves as an electrolyte for conduction of protons from the anode to cathode. Generally, H_2 is used as fuel and O_2 is used as an oxidiser to produce electricity and heat/water as a byproduct.

The reaction at the electrodes is given as :

$$\begin{array}{ll} \text{Anode} & 2H_2 + 2O^{2-} \longrightarrow 2H_2O + 4e^- \\ \text{Cathode} & O_2 + 4e^- \longrightarrow 2O^{2-} \\ \hline \text{Overall} & 2H_2 + O_2 \longrightarrow 2H_2O \end{array}$$

Figure 4.13 illustrates the working of a PEM Fuel cell. H_2 enters the fuel cell from the anode side. On coming in contact with the catalyst (Pt), H_2 splits into two H^+ ions and electrons (e^-). Via the anode, the e^- are conducted through the external circuit to the cathode. The O_2 is forced through the catalyst where O_2 is reduced to form two negatively charged oxygen ions. The negative charge of the oxygen ions attracts the H^+ ions through the membrane to form water. Meanwhile, on the cathode side of the fuel cell, oxygen (O_2) forced through the catalyst forms two oxygen atoms. Each of these atoms has a strong negative charge. Negative charge attracts the two H^+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O). All these reactions occurs in the cell stack.

Fuel cells are similar to batteries except for the need to have a continuous source of fuel. Electricity production continues as long as there's availability of fuel. Operating at lower temperature, PEMFC can ramp up and down quickly unlike most other types of fuel cells. In case of non availability of H_2, a fuel reformer can be used to convert hydrocarbon fuels to hydrogen which can be then used in a PEMFC [252]. The maximum theoretical efficiency of a Fuel cell is 83%. However, in operation ~ 40-60% efficiency are achievable due to various losses [253]. The catalyst used is usually Pt or Pt based alloys with carbon supports. The Pt-based electro-catalysts contributes 45% of the cost of stack [254].

Hybrids

Several hybridised energy storage options can be considered :

- Super-capacitors with batteries : This combination provides the longer-term energy supply and an increase in the system's resilience to cope with sudden power demands. The overall configuration also reduces the battery stress which results in a longer battery life. A hybrid of capacitors and batteries can be especially beneficial for usage in dredger where elevated power levels are required for a very short period of time.
- Combination of chemistries : Direct combination of the chemistries of ultracaps and Li-ion batteries has been done and there are at least two companies, JSR Micro [255] and IOXUS Inc. [256] that commercially market such a device. The hybrid is capable of 100,000 cycles and has more than thrice the energy density of a conventional ultra-capacitor. Recent work by Zhang et al. [257] on hybrid super-capacitor reported to have achieved energy density equivalent to Li-ion batteries and power density of a super-capacitor.
- Fuel cell and capacitors : Fuel Cells coupled with super-capacitors can be considered as a viable combination. Capacitors can provide the power during surges and a fuel cell can act as a 'range extender'. The hydrogen for Fuel Cell (FC) usage and the electricity for capacitors can be sourced from the nuclear reactor.

4.3. Selected System Design

4.3.1. Nuclear Reactor

For nuclear reactors even within the same reactor technology, a variety of different design choices are available (fuel, coolant, moderator, reflector, and neutron spectrum etc.)

Table 4.2: Pugh Analysis : Nuclear Reactor Technology

	Molten Salt	**High-Temperature Gas**	**Supercritical Water Cooled**
Burnup	++	+	+
Start-up (criteria)	−−	0	−
Primary Circuit Pressure	+	+	−
Thermal Performance	+	+	+
Control	−	+	−
Corrosion Issues	−	++	−
Safety	++	++	−−
Maturity	−−	−	−−
Maintenance	−	+	−
Estimated Cost	+	+	+

In this work, the fast reactors are removed from this analysis because of the complexity that operation of such reactors bring [10] and the inherent goal of this work being analysis groundwork for preliminary analysis. Additionally, non-uranium based fuels are not considered in this analysis. Only Generation IV reactors are considered.

Multi Criteria Decision-making Analysis (MCDM) or Multi criteria Decision analysis (MCDA) has been used in earlier studies for arriving at choices in the nuclear sciences such as siting of nuclear reactors [258], site selection of nuclear waste disposal [259], decommissioning of nuclear reactors [260], sustainability of Nuclear Fuel Cycle systems [261] etc. For a complete MCDM, inputs of experts from various field (nuclear reactor, nuclear safety, law and dredging experts) would be required. This is beyond the scope of this work. Instead, a Pugh matrix was made based on the personal understanding and estimates that could be made from literature.

Assigning weights to the criteria is a test for robustness. However, the weights are assigned depending on the priority of the stakeholder (as different stakeholders have different priorities). Hence, this decision matrix is subject to change depending on the criteria chosen and the importance assigned to the criteria/sub-criteria. The weights can help make subjective opinions into objective ones by knowing the sensitivity of how much of the opinion would have to change in order for a lower-ranked alternative to outrank a competing alternative.

The Pugh matrix for the selection of nuclear reactor is given in Table 4.2. The Pressurised Water Reactors (PWR) are given ”0” as the benchmark. + or - indicates if the reactor is better or worse, while ++ and – indicate if the reactors is much better or much worse.

Overall, the High-Temperature Gas-Cooled Reactor (HTGR) does better than the competing options. The HTGR is the only nuclear technology that is classified as ”inherently safe” by the IAEA [262]. Under any circumstances there are no catastrophic failure modes [263]. HTGRs in the range of 80-100 MWe are considered ”walk-away” safe because the decay heat can always be released to the environment without fuel damage [264]. The TRISO fuel particles that the HTGR utilises remains intact upto 2000°C and there is no radiation leak below 1600°C from these fuel particles.

Gas-cooled reactors had been proposed for nuclear propulsion 60 years ago [265] [159]. A gas-cooled reactor was suggested to be interesting in the range of 26,000-40,000 shp range for vessels and for $>$ 70,000 shp plant, PWR starts to be economical [161]. Direct coupling of a gas turbine with HTGR for merchant ships was suggested by Crommelin [266]. However, system information and design is lacking in the work. In one proposed design for ship propulsion with a 180 MW_{th} HTGR coupled to a Rankine cycle system, it was ascertained that the design would likely fit in the space constraints and, the maximum temperature at loss of coolant can be limited to less than 1300°C [267]. Another work [10], looked at the implementation of HTGR for satisfaction of the propulsion needs of a containership.

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[10] Additional issues are that they are costly to build/operate and have not had much success commercially. However, a higher price of Uranium favours them.

Even though a Pebble Bed Reactor allows for online refuelling [11] which improves the reactor control, a pebble bed reactor is not being considered as a choice of HTGR. This is because the motion and recycling of pebbles due to ship motions is a concern. Further, the dust production in the prismatic reactor is much lower than Pebble bed reactor [268]. An Ordered Bed Modular HTGR (OBMR) has been proposed recently. It is claimed to have greater structural stability [269] and be suitable for ship applications. However, no prototypes exist and currently, there is no commercial interest in the concept. Therefore, a Prismatic HTGR is considered as the choice in this work.

For the Prismatic-type HTGRs, commercial models that are under development or have been developed were considered. Two such options are the U-Battery and HTTR. Numerous possibilities for the design of U-Battery have been analysed in the work of Ding et al. [270]. A lot of those could be applicable for the design of a nuclear-powered dredger due to the different design philosophy than required by the U-Battery. There are cases that have lower EFPY and rejected in the work which would be acceptable in this case.

For the HTTR, the burnup period is 660 days (EFPD) [271], EFPY of approximately 1.8 years. Hence, if full utilisation of the fuel occurs, the refuelling would correspond with the periodic check of the reactor and big maintenance stop for the dredging vessel. The refuelling period could take around 6 to 18 weeks. A workaround for this could be the use of nuclear reactors that have more EFPDs. An example in this case is the use of a HTGR like U-Battery which are designed for EFPY of 10 years. So, the refuelling has to be done every 10 years and this does not hamper the productivity. However, currently the fuel availability of HTTR is better than fuel availability for U-Battery like nuclear reactor (see 7.2.2 for more).

4.3.2. Power Conversion System

The choice for the power conversion system is heavily dictated by the choice of the nuclear reactor. The selection of HTGR as a nuclear reactor makes Brayton cycle a better choice as the power conversion system. Another argument in favor of Nuclear Air-Brayton cycle is that historically, the commercial interest in development of nuclear concepts has been weak and one of the reasons is the requirement for significant extrapolation of existing concepts [158]. Unlike the components of closed Brayton cycle (there are no helium compressor/turbine manufacturers for a closed cycle), the components of Open Brayton Cycle are off-the-shelf. The turbomachinery (compressors and turbines) and the heat exchangers require no major development or re-engineering efforts. An indirect system is opted. Molten salt has been used as an intermediate cooling in the Advanced High Temperature Reactor (AHTR). However, this suffers from the same issues as the molten salt reactor. Hence, the intermediate cooling loop is chosen to be gaseous (He).

Load banks [12]are attached to the power conversion system, in case there is a need to absorb the nuclear energy and dissipate it as heat. This can be expected to happen when there is sudden unplanned drop in power demand. This measure helps the system to cope with overfrequency.

4.3.3. Energy Storage

Li-ion batteries is a mature technology and has found its way into marine applications. Batteries have higher energy density and specific energy than any of the other energy storage devices. They are a favorable option over other storage devices because of the importance of having low volumetric and gravimetric footprint. A battery has a favorable discharge curve in comparison to other energy storage devices (see Appendix Figure C.8.2). The addition of a fast-acting source like battery gives the design more flexibility and resilience. Further, because the application aboard the TSHD requires an energy capacity enough to last at least 15-30 minutes, batteries are a very good fit. Hence, Li-ion batteries are used as energy storage devices. For similar reasons, the Li-ion batteries are also used for the emergency propulsion/backup power for the design considered in this work.

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[11] Reactor shutdown is required for refuelling of Prismatic reactor.

[12] For further information on load banks, refer C.9.

Battery systems are chosen over FC-based system as the FC-based system would require stops to fill the H_2 tanks every once in a while. This problem can be overcome if hydrogen production onboard is carried out which is a possibility in HTGRs. However, in this work, hydrogen production is not considered.

4.3.4. Propulsion Arrangement

Due to the difficulties that direct coupled arrangement or any other possible arrangement would bring, an integrated electric propulsion format is best suited for a nuclear-powered dredging vessel. In this arrangement, power is generated by the nuclear system and fed into a common electrical bus. The common bus supplies and (re-)distributes the power as necessary. Other necessary components as described and discussed in preceding subsections are added to arrive at the single-line diagram given in Figure 4.14.

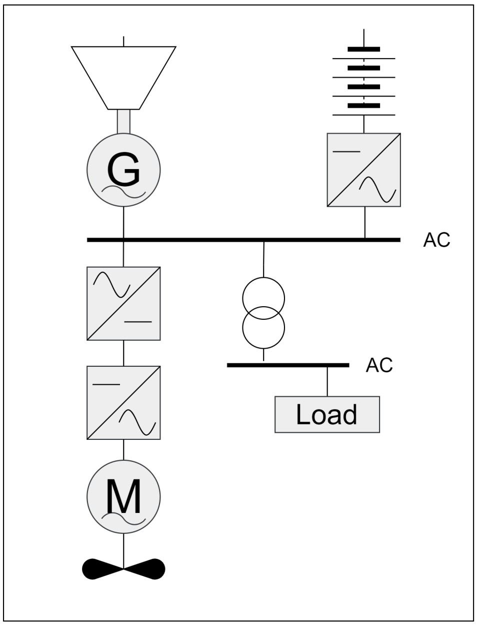

Figure 4.14: Selected Propulsion Arrangement with battery storage

4.4. TSHD Selection

Based on the decreasing hopper volume, TSHDs can be classified as :

- Mega (>30,000 m^3)
- Jumbo (15,000-30000 m^3)
- Large (8,000-15,000 m^3)
- Mid-size (4000-8000m^3)
- Small (>4000m^3)

Since, an objective of this work was to also establish if the systems that were designed were feasible for a dredger of different sizes. Four TSHDs that are in service today were selected. The selection of these TSHDs was carried out so as to cover a spectrum of sizes (based on the Gross Tonnage, Deadweight Tonnage, Hopper capacity etc.).

The power of different components is superimposed on the corresponding normalised power demand profile (total, dredging pump and underwater dredging pump) is used. This is adjusted on the normalised power profile to form the power profiles of four different dredgers. The corresponding power for the power demand elements (Propulsion power and Dredge Pumps) are loosely based on the information of dredgers that are tabulated in Table 4.3.

The following text discusses on why the superimposition of power demand on the normalised power profile is a reasonable estimate.

The power requirement for propulsion scales with the weight of the vessel (W) and the speed (s).

$$P_{propulsion} \sim W,\ s \tag{4.9}$$

Since, the speed of the dredgers are more of less constant, the propulsion power scales with the weight of the vessel. Now, the net tonnage and hopper volume scale with the displacement (see D.3). Hence, the

$$P_{propulsion} \sim V_{hopper} \tag{4.10}$$

Table 4.3: Trailing Suction Hopper Dredger Data

			Dredger Name			
			OPTIMUS (Formerly OSTSEE)	**WILLEM VAN ORANJE**	**HAM 318**	**CRISTÓBAL COLÓN**
Company Name			Archeon Akti Navigation	Boskalis	Van Oord	Jan de Nul
Gross Tonnage			3785	13917	33515	59466
Carrying Capacity	*tons*		5428	22000	61280	78500
Hopper Capacity	m^3		3400	12000	39467	46000
Dredge Pump	*kW*	Inboard	960	7500	5500	6500
Output	*kW*	Submerged	3600	3500	5000	6500
Jet Pump Output	*kW*		972	2500	4300	4300
Propulsion Power	*kW*		5280	12000	25200	38400
Length Overall	*m*		99.83	143.53	227.20	223
Breadth	*m*		17.75	28	32.05	41

Source: [272] [273] [274] [275]

The power requirement for the pumps scales with differential pressure (Δp) and mass flow rate ($\dot{m}$).

$$P_{pump} \sim \Delta p, \dot{m} \tag{4.11}$$

Now, differential pressure scales with velocity (v).

$$\Delta p \sim v^2 \tag{4.12}$$

However, velocity is more or less constant in suction tubes of different dredgers. Then,

$$P_{pump} \sim \dot{m} \tag{4.13}$$

The time (t) taken to fill the hopper is given by

$$\frac{V_{hopper}}{\dot{m}} = t \tag{4.14}$$

In general, the loading/unloading time stays constant irrespective of the size of the hopper. So, power requirement scales with volume of the hopper

$$P_{pump} \sim V_{hopper} \tag{4.15}$$

Hence, the choice of superimposing the normalised power profiles with power (from different sized dredgers) is justified on the condition that the dredger design does not change very much. A larger trailer is optimised for missions that have longer distances between sand winning area and discharge site.

5

Simulation and Modelling

Section 5.1 covers the power control scheme, algorithm for determination of nuclear power generation requirements and sizing of the ESS. Section 5.2 discusses the modelling of Nuclear Air Brayton Cycle (NABC) in Aspen Plus, heat exchanger and material selection. Section 5.3 discusses the mass and volume constraints, the total and component mass and volume of the HTGR-NABC powered, Fuel Cell-powered and Battery-powered TSHD concept. Section 5.7 presents the simulation and modelling flowchart.

5.1. System Integration

The design has to provide a dynamic and adaptable power supply in all operating conditions. There has to be a balance in the power supply and demand at every time interval.

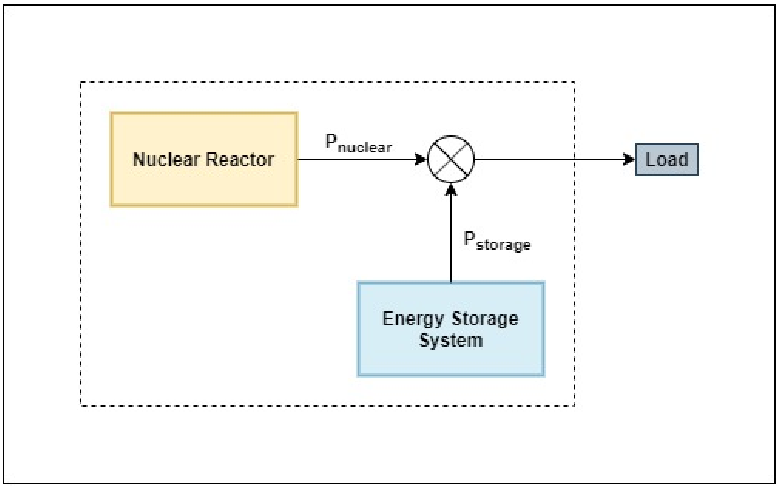

Figure 5.1: Power Control Scheme

The power control scheme for the integrated system is given in Figure 5.1. The nuclear reactor power and power from ESS is to balance out the electrical load. When the load requirements are lesser than the power generated from nuclear reactor, the ESS is charged [1]. While, when the load requirements are larger, the ESS gets discharged.

5.1.1. Model

A MATLAB® code was made to simulate the operation of the system. Power balance calculation at each time step (~1 second) was performed. At each time step, the program compares the total load

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[1] If the ESS is fully charged, the power is routed to the load bank.

demand with the generation. In case of a shortfall, the energy storage pitches in and discharges the required amount while when there's a surplus, the generation energy is used for charging the energy storage. At each time step, the state of the energy storage medium is calculated based on the energy balances. If the energy storage device is already overcharged, then the energy is rejected in the form of heat (connection to load bank) or absorbed by having higher frequency of generation.

Assumptions

The following is assumed for the code :

- Nuclear-power generation level is kept constant.
- The charging/discharging of the energy storage system (ESS) is without lag.
- The switching of ESS is without a lag.

Constraints

As per the discussions in 4.2.1, the constraints are given as

$$P_{Nuclear} \geq P_{sailingempty} \tag{5.1}$$

$$P_{Nuclear} + P_{ESS,charged} \geq P_{Demand} \tag{5.2}$$

5.1.2. ESS Sizing

The exact sizing of the ESS is an optimisation problem subject to constraints of ramp-up and cycles of the nuclear power system. Further, it depends on the adaptability and flexibility that can be imbibed in operation of different equipment. It is imperative to choose a battery capacity so that the nuclear reactor has minimum ramping up and ramping down.

The sizing requirement of the ESS is based on the dynamic calculations. This is because the size requirements for the ESS from direct calculations is grossly overstated. For example, for OSTSEE, the ESS requirement based on static system is 42910 kWh. But in every dip of power demand, the ESS can be charged. Hence, the actual size requirement for the ESS is much lower than static calculation (~ 856 kWh) [2].

Table 5.1: Requirements for Power Generation and ESS Capacity

	Nuclear Power (kW_e)	**Nuclear Power Generation** (excess of empty propulsion)	**Energy Capacity Requirements** (kWh)	
			$ESS_{charging}$	$ESS_{nocharging}$
OSTSEE	4236.3	34%	856	42910
WvO	8457.6	37%	1773	91492
HAM 318	17788	31%	3700	189930
CRISTÓBAL COLÓN	27062	32%	6590	397000

For the dredging cycle, the difference between time period where ESS charging would/can occur and the discharging needs of the ESS is computed. This is the margin to store energy and referred to as *margin of storage*. The nuclear power generation is ascertained to the nearest integer percentage in excess of the average power demand (propulsion only) such that the *margin of storage* is not negative. It was found that the margin to store energy is much bigger for dumping cycle than for pump ashore cycle. Hence, the ESS sizing is based on Pump ashore cycle. To take into account the DoD, round trip efficiency and stay conservative, the energy capacity of the battery system is increased by a factor of 3.

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[2] When nuclear reactor is sized to 40% excess in comparison to energy required for free sailing

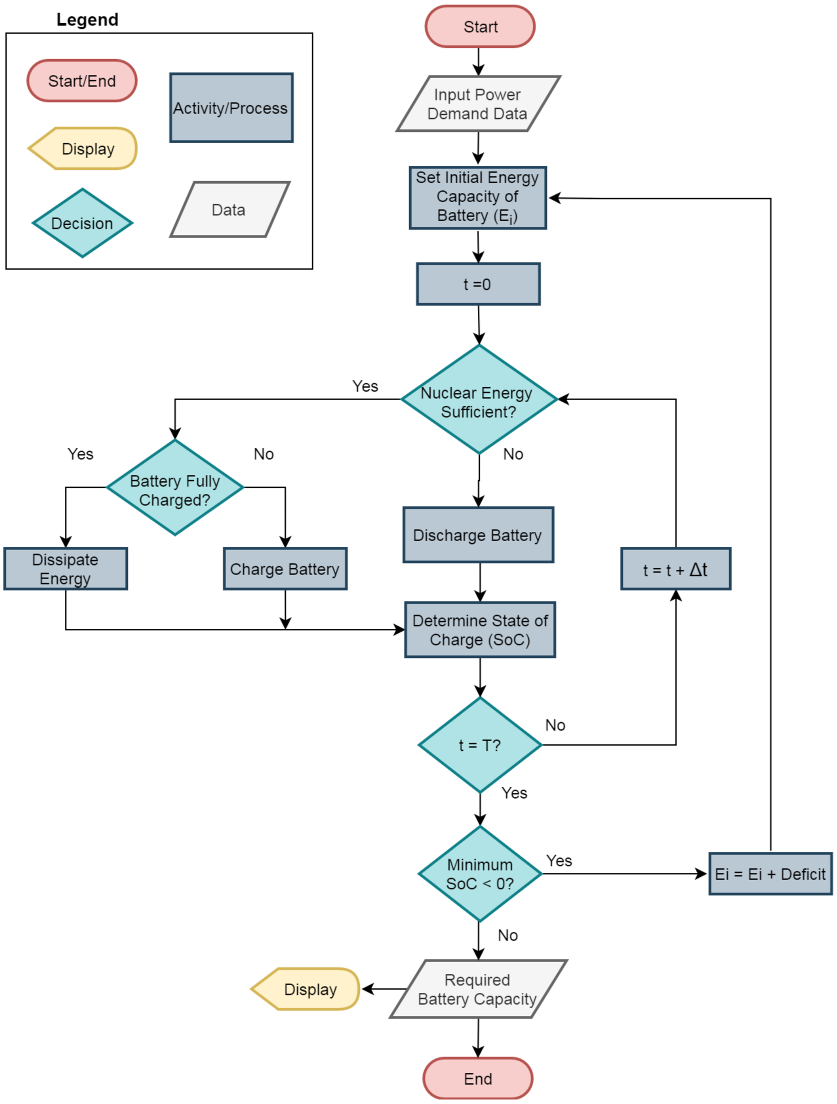

Figure 5.2: Algorithm Code for Sizing of the Energy Storage System

The nuclear power generation requirements and energy storage system capacity requirements for the the four dredgers considered in this work is given in Table 5.1. The algorithm for sizing of the energy storage system is given in Figure 5.2.

5.2. Nuclear Air-Brayton Cycle

A variation of the Indirect Open-Brayton cycle is the Nuclear Open Air-Brayton cycle, also known as the Nuclear-Air Brayton cycle (NABC).

Historically, the commercial interest in development of nuclear concepts has been weak. The requirement for significant extrapolation of existing technological solution has been one of the reasons [158]. This is where NABC has an edge over others, the components of Nuclear Air-Brayton Cycle are off-the-shelf, there is no requirement for any major development or re-engineering efforts. For the HTGR and heat transfer loops, the Helium blowers have been made in the past and there are at least two companies that have the capability to deliver helium blowers for nuclear applications. Submerged Helium Blowers for Advanced Gas cooled Reactor (AGR) were supplied by Howden Group [276]. While the Shanghai Electric Blower Works Co., Ltd. has supplied the Helium blowers for the High Temperature Reactor or also High Temperature Resistant (HTR) prototype and HTR-PM [277].

Nuclear Air-Brayton has been in the limelight recently with a good deal of works on the concept. There are some which have also used combined cycle [278] [279], reheat [280], recuperative bottoming cycle [281]. Most of the analysis has been limited to liquid metal or molten salt systems [282]. There is at least one work [10] which has analysed Nuclear Air-Brayton cycle with HTGRs.

In the current work, the cycle is evaluated for a High-temperature Gas Reactor. Two heat exchange loops are employed (primary and intermediate) between the working fluid and reactor. An intermediate loop provides an additional barrier between the primary coolant circuit and the environment. NABC designs without an intermediate heat exchange circuit risks that a puncture in the primary coolant circuit leads to contamination of piping to the rotating equipment, rotating equipment and casing and, the environment. However, the addition of another heat exchange loop comes at a cost and leads to an efficiency penalty of 2% - 3%.

The study by Zohuri [281] uses multiple turbines (three or four) to extract the work. The volume of power conversion system that is arrived at in the study does not corroborate with the volume requirements of commercial turbogenerators. As far as it could be found, there seems to have been no work conducted which established the mass requirements. The work on establishing mass requirements of such systems has not been undertaken by any of the above mentioned works or any work, as far the author's own search could find In none of the previous studies, the power requirements of the Primary Loop blower or the Intermediate Heat Exchange Loop blower have been evaluated.

5.2.1. Modelling in Aspen Plus

An Aspen Plus model was developed for the High Temperature Gas-Cooled Reactor-Nuclear Air-Brayton Cycle (HTGR-NABC) system. Figure 5.3 gives the schematic of the Aspen Plus model. The values from the model are for steady state operation.

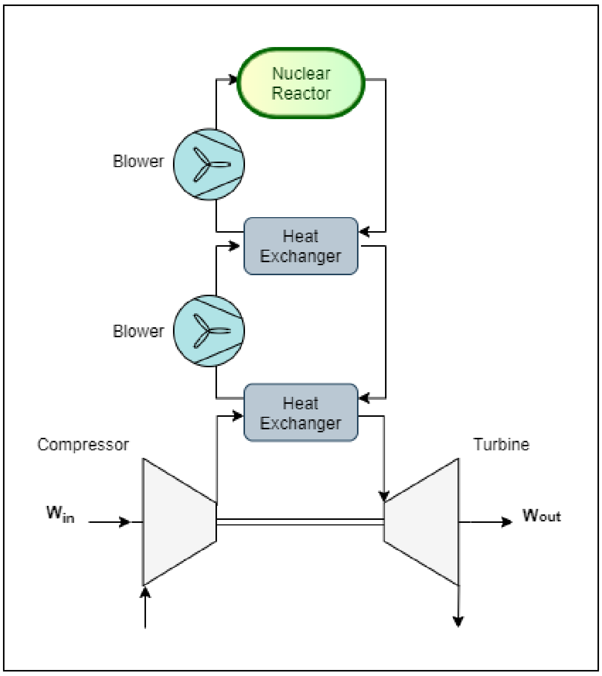

Figure 5.3: Schematic for Nuclear Air-Brayton Cycle

The different components that have been modelled and the parameters or conditions that have been used are described in the following subsections.

Nuclear Reactor

The Nuclear Reactor is modelled as a furnace with a power of 100 MW. The pressure drop is taken as 6%. From an earlier work [283], computation of the pressure drop in the nuclear reactor yields a value of 3.2%.

Primary Heat Exchanger (PHX)

The Primary heat exchanger (PHX) is modelled as a counter-current heat exchanger. On the hot side of the heat exchanger is the primary coolant (He). On the cold side of the heat exchanger is the Intermediate Loop Gas (ILG). An approach temperature of 10°C is considered. The cold and hot stream temperatures are arrived at (iteratively) so that there is no temperature cross inside the heat exchanger. The pressure drop is taken as 4% on both the sides of the Heat Exchanger.

Intermediate Heat Exchanger (IHX)

The Intermediate heat exchanger (IHX) is modelled as a counter-current heat exchanger. On the hot side of the heat exchanger is ILG. The ILG can be N_2, Ar, He, s-CO_2 etc. On the cold side of the heat exchanger is pressurised air. In the model, the approach temperature of 10°C is considered. The cold and hot stream temperatures are arrived at (iteratively) so that there is no temperature cross inside the heat exchanger. The pressure drop is taken as 4% is taken on the hot side and on the cold side a pressure drop of 8% is considered.

Air Compressor

A three stage centrifugal compressor with intercoolers is modelled. The exit temperature of compressed air stage 1 and 2 are taken as ambient temperature (25°C) as would be expected under "perfect intercooling" conditions. The polytropic efficiency of the air compressors is taken as 90%.

He-Blower

The He-Blower is modelled as a centrifugal compressor with a pressure ratio of 1.07 and 90% polytropic efficiency.

Intermediate Loop Gas Blower

The ILG Blower is modelled as a centrifugal compressor without intercooling. The pressure ratio is 1.07 and polytropic efficiency is 90%.

Expansion Turbine

The expansion turbine is modelled with an isentropic efficiency of 85 % with an outlet pressure of 1 bar. In many systems, a Free Power Turbine (FPT) and a turbine to drive the compressor are common. This is done so as to decouple the power turbine's RPM from the compressor RPM. In this model, only one turbine is considered because the interest is in the total amount of work produced.

Calculator Block

A calculator block is used for calculation of efficiencies for each run of the simulation and another one to calculate the volume of the Heat Exchanger based on different area densities.

5.2.2. Heat Exchangers

Because of the selection of HTGR with a NABC based power conversion, the heat exchangers are possibly the most important component of the system. This is because they not only have to be leakage-proof, thermal and corrosion resistant but also have the same advantageous features as the other parts of the system (like high power-to-mass and power-to-volume ratios)

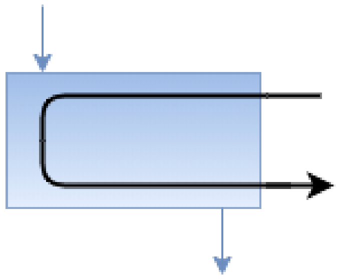

Figure 5.4: 1 Shell 2 Tubes Heat Exchanger

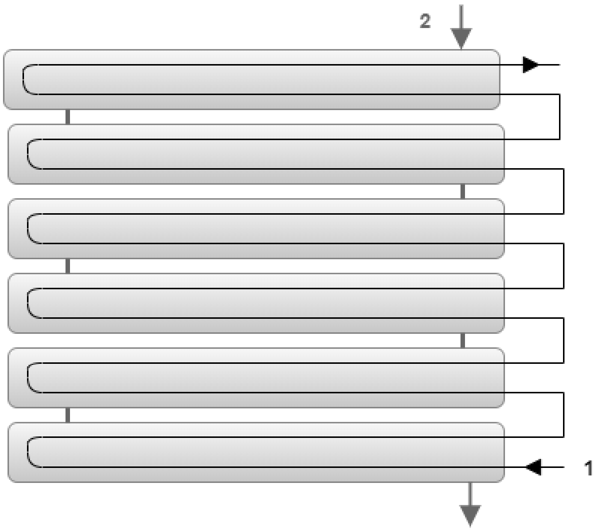

Figure 5.5: 6 Shells 12 Tubes TEMA E Heat Exchanger

The heat transfer rate is given as per

$$\dot{Q} = U \times A \times F \times LMTD \tag{5.3}$$

F (< 1) is interpreted as a geometric correction factor, that when applied to the Log mean temperature difference (LMTD) of a counter-flow heat exchanger, provides the effective temperature difference of the heat exchanger under consideration. It is a measure of the heat exchanger's departure from the ideal behavior of a counter flow heat exchanger having the same terminal temperatures. Therefore, the closer the heat exchanger design to a counter-current heat exchanger, the closer the F value is to 1. For example, F value of 6 shell 12 tube TEMA[3] E is 0.9978 while it is 0.9149 for 1 shell 2 tube TEMA E.

Various types and designs of heat exchangers exist today. In the following text, some of these heat exchangers along with their characteristics would be described.

Shell and tube Heat exchangers

The most common type of heat exchangers are the Shell and tube Heat exchangers. To increase the heat transfer, fins can be attached and baffles can be constructed (shell side). They are capable of handling the necessary high pressures and temperatures (~ 1000 bar and 1100°C) [284].

Plate Heat Exchangers

PHE are the most common compact heat exchangers. They are a better choice in heat transfer in gas-gas applications. There are two major Plate Heat Exchanger (PHE) : Brazed PHE and Plate and Frame PHE.

In a Plate and Frame Heat Exchanger, the plates are pressed to form a frame. Gaskets provide the sealing between each plate and the maximum service temperature is around 200°C [285]. In a Brazed PHE, the plates are brazed. This makes is even compacter, lighter than a Plate and frame PHE. PHEs for high temperature applications (>900°C) exists commercially. However, the sizes are limited to 1 MW and low pressures [286] [287]. As the temperature rises, the allowable working pressure decreases, for example at 750°C, the pressure is limited to 2 bar [288].

Bavex heat exchanger is a hybrid welded-plate heat exchanger that is capable of operating at 900°C and pressures up to 6 MPa on the plate side [289]. A maximum of 0.35 m wide and 16 m length plates can be manufactured.

Solid Block Heat Exchangers

Solid block heat exchangers are also commercially available. They are reported to be compact, have long life, are easier to install, clean and manufacture [290]. Graphite [291] and Silicon Carbide [292]

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[3] Tubular Exchangers Manufacturers Association or TEMA are a set of standards for shell and tube HX. The standards cover the style of heat exchanger and tolerances for machining and assembly.

are used as materials for manufacture of these heat exchangers. Graphite solid block heat exchangers are not suitable (See Appendix F.5.1). However, currently, the maximum service temperature is limited to 400°C and pressure to 16 bar. These units are also heavier.

Printed Circuit Heat Exchanger (PCHE)

The PCHE is a relatively new heat exchanger concept. PCHEs are robust, compact, have low pressure drop characteristics, and the ability to operate at high Δ P (hot and cold sides) [293]. Heatric and Alfa Laval are the two major companies who build these commercially. Alfa Laval claims [294] that their PCHE can handle pressures of up to 650 bar, temperature of 800°C and achieve approach temperature of even 1°C. The specialised joining ('diffusion-bonding') creates a heat exchanger with no joints and hence, no points of failure. Due to the size reduction, significant savings occurs (reduced piping, framing, structures etc.) Further, the chances of a leakage are two orders of magnitude lower than other heat exchangers [295]

However, PCHE is still not a part of the ASME Nuclear codes and work on this particular aspect is ongoing [296] [297] [298].

Ceramic Heat Exchangers

Due to their excellent temperature resistance and low costs, ceramics are often touted as the choice of material for high temperature heat transfer applications. However, except for SiC and SiN, ceramics are prone to thermal shocks. Further, their fabrication and joining is still a concern when it comes to reliability [299] as is the brittle fracture [300].

Fin and Tube Heat Exchanger

Fin and tube heat exchangers can support high working pressure (550 bar), high temperatures (1250°C) and have very low pressure drop – 0.1 Pa [288]. Most Steam boilers are fin and tube heat exchangers. The fins and tubes can be manufactured from range of material SS 316, INCONEL®, etc. The process of attaching the fin to the tube is a mechanical process leading to a better longevity and reliability. The manufacturing method for the fin and tube heat exchanger has a lower cost than for the other heat exchangers mentioned.

In the past, one of the barriers for using the fin and tube heat exchanger for these types of industrial applications was the lack of ability to provide a thermal design. Due to recent advancements, this barrier has been lifted and thermal and mechanical design for most working condition (corrosiveness, high temperature, and pressure) can be provided.

Plate and Shell Heat Exchanger

Since the high temperature/pressure operation could lead to pressure and thermal fatigue of the material, a Plate and Shell Heat Exchanger could be a good choice. The Plate and Shell Heat Exchanger marries the compactness Plate Heat Exchanger with the temperature and pressure capability of Shell and Tube heat Exchanger. They are suitable for use for 900°C and 100 bar pressure. They were first introduced a little more than a decade ago. An excellent comparison on the IHX has been done by Penfield et al. [301]. However, this HX had been left out. One possible reasons could be as pointed out by Javelin [302] on why Plate and Heat Exchangers are not more common could be the lack of knowledge and operating experience on these. The heat exchange is performs excellently in cases where thermal shocks and pressure/thermal fatigue are a concern [303]. These are capable of being manufactured with equivalent S&T surface area of upto 35,000 m^2. There are more than 350 large Plate and Shell heat Exchangers mainly in petrochemicals and refineries [304].

For a 30MW_{th}, Jacobs [10] HX weighed 75 ton for the 21 MW_{th} He-He and He-Air Plate Heat Exchanger (HX). PCHE was proposed to be the best solution for the IHX of VHTR [305]. While as per Penfield [301], if metallic compact HXs are used, the rate of oxidation would imply that the material thickness of compact heat exchangers would be eaten away in a few years. Using Multi-Criteria Decision-Making, the choice of heat exchanger for AHTR was fixed at Shell and Tube HX [306].

The Shell and Tube HX is the heat exchanger with the least technological and development risk. Further, because of the penalty on the mass and volume on using a Shell and Tube HX would be chosen as the type of HX.

Material

Manufacturing of an optimal and acceptable design requires taking into account the service temperature, length of operation, high temperature strength, creep and creep-fatigue resistance, thermal/pressure cycling, gas diffusion and the fabricability. All of these properties are affected by the choice of material. The resistance to oxidation and corrosion is dictated by the amount of Cr (Chromium). There are significant cost differences between a proprietary brand (INCONEL® or HASTELLOY® etc.) and generic stainless steel [307]. Some of the possible material choices are discussed here.

Austenitic steels with Cr >18% can be used up to 870°C [308].

INCONEL® alloy 625 [309] has excellent fabricability, strength and corrosion resistance. The service temperature is up to 982°C. It is used in the reactor core and control rods of PWRs/BWRs. Because of the allowable design strength at high temperatures, Alloy 625 is also being considered in use for Generation IV reactors.

INCONEL® alloy 617 [310] has high strength and oxidation resistance for temperatures over 980°C. Conventional techniques can be used to form and weld the alloy.

INCONEL® 600 [311] can be used at temperatures up to 1093°C. It has high strength, high weldability and workability.

Grade 304 Stainless Steel is resistant to oxidation damage at temperatures of up to 952°C. However, at 1093.3°C, there's a significant loss of tensile strength and corrosion resistance [312]. The inclusion of nickel in 304 (8 – 10.5%) makes the metal more corrosion resistant however, it is an expensive element and there's twice the cost difference between 304 and a grade with say 0% Nickle like 430 [313].

Grade 330 Stainless Steel has high chromium and nickel content and can be used for continuous use at 1037°C This stainless steel alloy is specifically formulated to resist the effects of scaling and oxidation at high temperatures. For use at 1093°C, INCONEL® is a better choice.

Stainless Steel (Grade 253MA) is easy to fabricate and high strength in comparison to other alternatives up to 900°C. The service temperature limit for continuous and intermittent application is 1150°C [314].

INCOLOY® 800H and 800HT are used in for high temperature heat exchangers in Gas cooled reactors [315].

For the AHTR, the material candidates were HASTELLOY® N, 800H, and INCONEL® 617 [306]. 2111 HTR was considered as the material of choice by Jacobs [10]. Based on a review of 8 materials, alloy 617 and alloy 230 were found to be the most suitable for the IHX of VHTR [305]. For the IHX, Grade 430 could be a good choice as it is suitable for 815°C of continuous use and 870°C in intermittent use.

5.3. Volume and Mass Considerations

Instead of going for an approach where design/thermodynamic correlations were used to find the volume of the equipment or to use an intuition based approach to finding weights where density would have to be ascertained, data of commercial equipment was collected. This approach led to a faster and better estimation of the mass and volume of the equipment.

In this study, the retrofit of the current dredgers is considered and not a re-design. Hence, the mass and the volume of the current system aboard a dredger serves as the constraint for the new alternative system. This work represents a first approximation for the mass of a Nuclear Air-Brayton cycle. For application on a vessel, except for the work by Coleman [316], there is no known work where the physical dimensions of the power plant were found.

The value of the maximum available on board mass and volume is required so as to set a hard limit for calculations and carry out comparison between the designed system vs. the present system. These limits would be based on the Mass and volume which is occupied by the fossil fuel engine, fuel tanks, the fuel treatment system, the clearances (safety, access and maintenance) etc. The clearances are an integral part of the engine room. This type of information is not available in the open literature. Minnehan et al. [317] set the available volume to 500% of the volume of the bare engine. General Arrangement of a few dredgers were accessed and it was realised that for dredgers the engine rooms typically occupy at least 6-8 times the volume of the bare engine.

The maximum available on-board mass is given as

$$w_{constraint} = w_{engine} + w_{fuel} + w_{foundation} \tag{5.4}$$

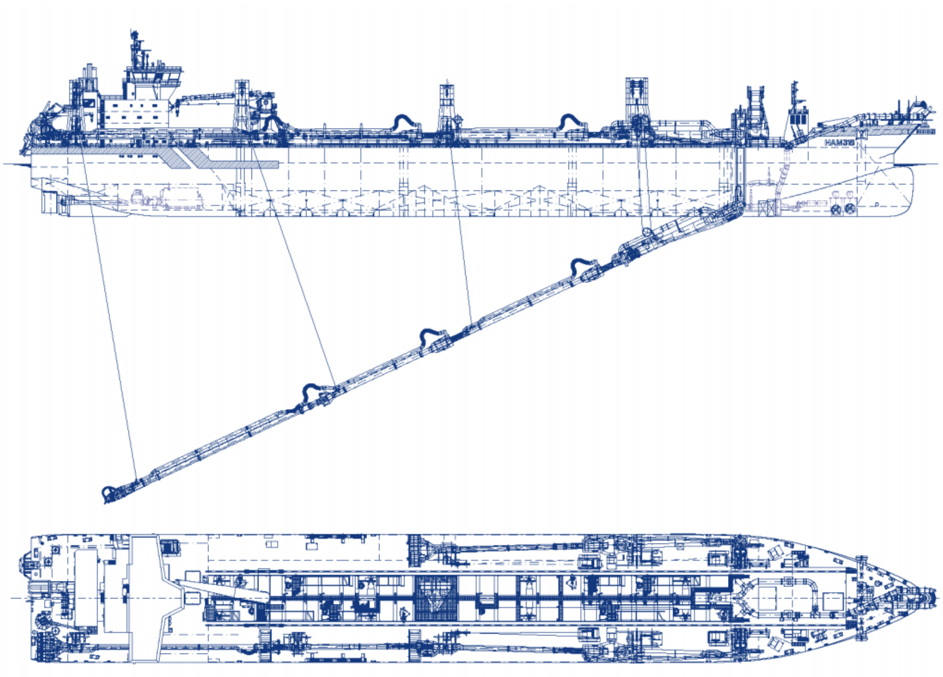

Figure 5.6: General Arrangement of HAM 318 (without dimensions)

Source: [274]

While, the maximum available volume is given as

$$V_{constraint} = V_{engineroom} + V_{fuel} + V_{clearances} \tag{5.5}$$

The General Arrangements of the dredgers also gave an idea on the size of the fuel tank/bunker tank. In the industry, the sizing of the fuel tank is based on the endurance requirements[4] of the vessel. In general, the expected endurance of a Jumbo sized or bigger sized dredgers is at least 15 days of endurance.

The mass of the required fuel (w_{fuel}) [5] based on the endurance is found by :

$$w_{fuel} = \frac{Endurance \times \frac{Energy\ requirements}{day}}{0.3 \times CV_{fuel}} \tag{5.6}$$

While, the volume of the required fuel based on the endurance is calculated as

$$V_{fuel} = \frac{w_{fuel}}{0.9 \times \rho_{fuel}} \tag{5.7}$$

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[4] Endurance can be defined as the maximum length of time that a ship can sustain at specific conditions. As a reminder, endurance is defined as the maximum length of time, the vessel can sustain without making a bunker call (port visit for refueling).

[5] The fuel used here is HFO. HFO is characterized by a maximum density of 1010 $\frac{kg}{m^3}$ at 15°C. This is taken as the ρ_{fuel}.

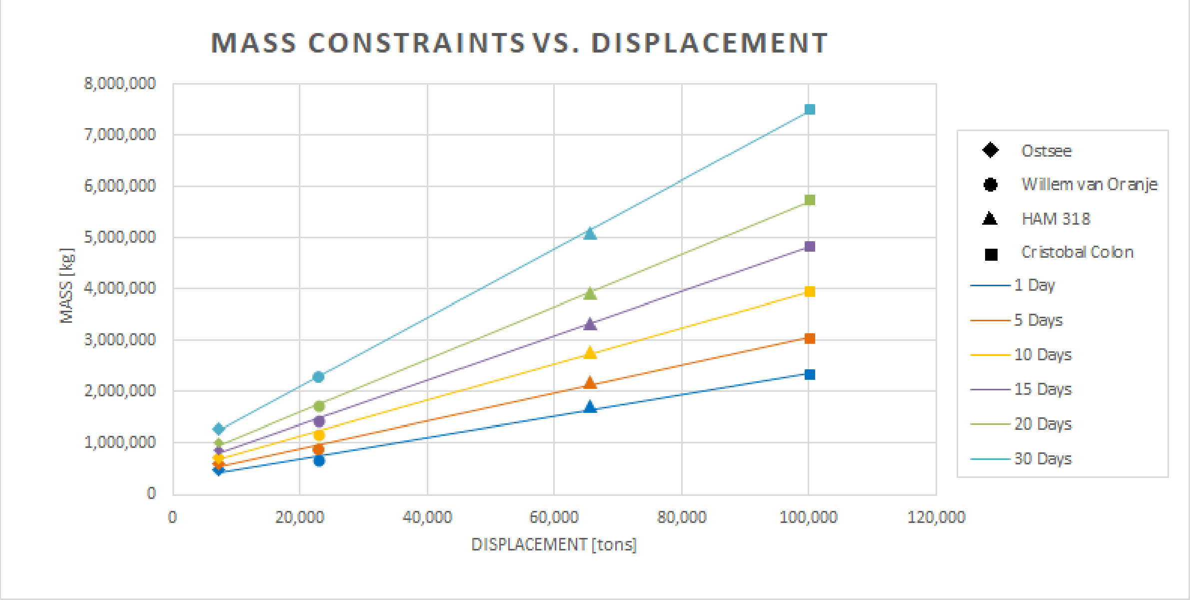

Figure 5.7: Mass Constraints vs. Displacement

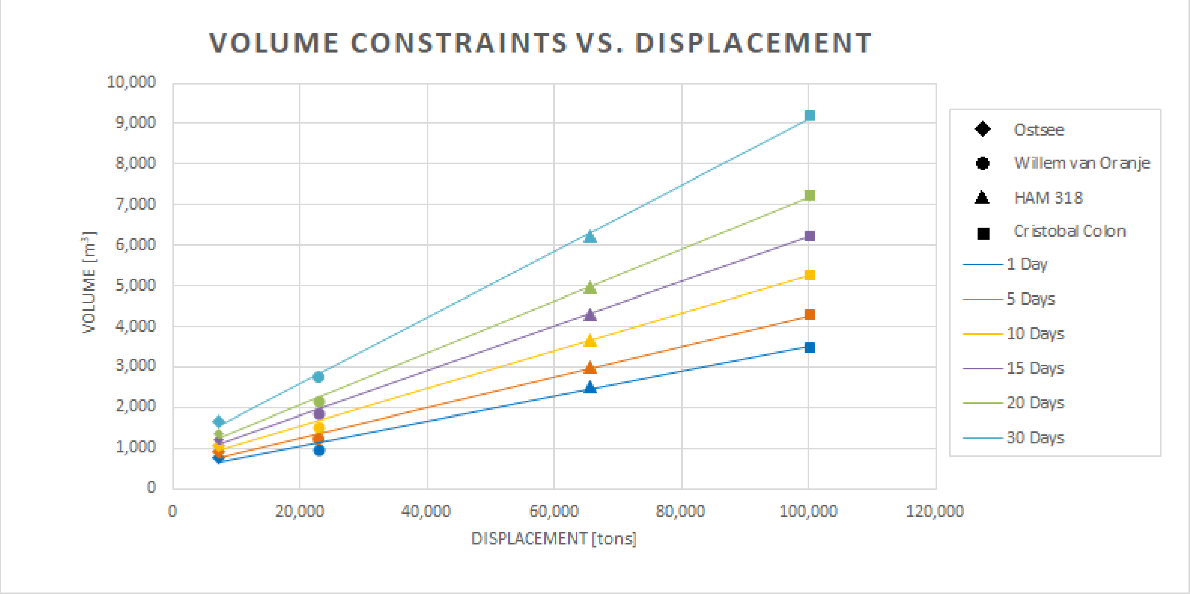

Figure 5.8: Volume Constraints vs. Displacement

The filling capacity for bunker tanks is usually 90% but it may be lesser due to formation of airlocks or pockets (due to internal configuration or unusual shape) [318]. This has been factored in as the ”0.9” that shows up in the denominator of the volume of the required fuel.

The mass of the foundation depends on the number of cylinders in a diesel engine. For example, the mass of the foundation of a six cylinder diesel engine is more than twice the mass of the engine [319]. The mass of the foundation as a multiple of mass of the engine varies between 2.75-1.90 for 2 to 8 cylinder engine types. Diesel engines >1000 kW in size cannot be skid mounted and need concrete foundations. Large foundations are required due to the reciprocating mass. Skid mounting is possible for turbines of all sizes [320]. Properly balanced rotating mass exerts no forces on the foundation and hence, vibrations are not an issue unlike the diesel engines. The exact mass of the foundation depends on the foundation design, type of machinery supported, material, acceptable vibration level etc. However, a rule of thumb for the mass of the foundations is that the mass of the foundation should be 4 times for reciprocating machines and 1.5 for rotating machines [321].

The mass and volume constraints for retrofitting in vessels with endurances of 10 days, 15 days, 20 days and 30 days is given in Figure 5.7 and Figure 5.8 respectively. These endurances would be referred to as *original design endurance*. Since, Fuel cell systems and battery based systems are built up of many small modules, the access, maintenance clearances and repair areas are reduced significantly. Further because they don't have high speed reciprocating or rotating mass, safety clearances are not as substantial as diesel engines or turbines. Hence, the utilisable volume (% of volume constraints) is set at 70% for the Fuel Cell stacks and the associated fuel tanks for FC only systems as well as for battery only systems.

5.4. On-board Nuclear System

The mass and volume of the on-board nuclear system would depend on the configuration that is chosen for generation of power and the characteristics of the nuclear reactor. Main components of the NABC systems would be PHX, IHX, expander turbine and compressor.

5.4.1. Nuclear Reactor

The mass and volume data for nuclear reactors is given in Appendix (Table B.8). This data consists of three HTR based technologies. From this, only the data for the HTTR will be used and multiple modules of the HTTR reactors will be assumed to be fitted in case one is not enough to cater to the power demand. This data will be used in the model to give an estimation on the mass and volume of a nuclear reactor. One advantage of having multiple modules is the redundancy and independence that such a system offers. The schematic diagram of HTTR nuclear reactor with different components is given in Figure 5.9.

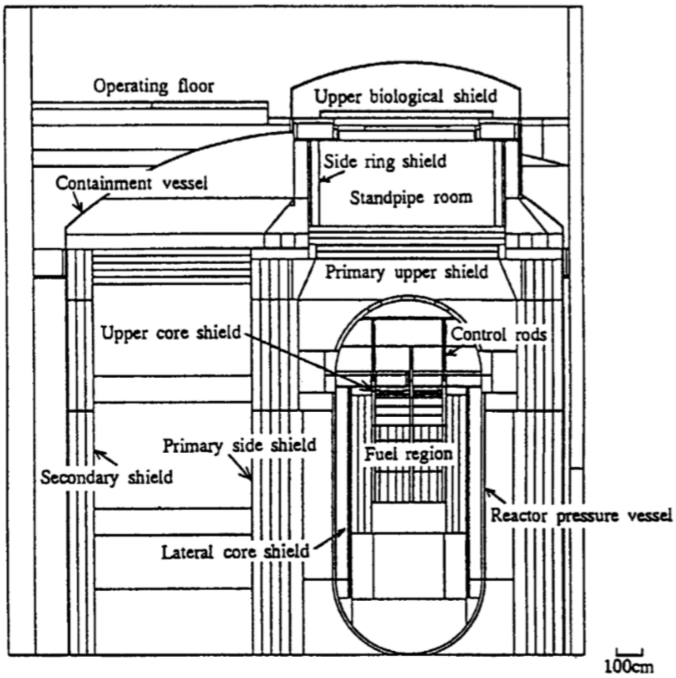

Figure 5.9: Schematic of HTTR nuclear reactor

Source: [271]

Nuclear Reactor Scaling

In addition to the deployment of multiple modules of HTTR, the scaling of the reactor was looked into [6]. This was to check the effect of having one reactor instead of say, three reactors.

It is assumed that while scaling the power density of the core remains constant [7]. The power of the nuclear reactor scales with the volume of the core. Therefore, the volume of the core is fixed from the nuclear power requirements (TSHD-specific). For the scaling of the reactor, the thickness of the reflector was not needed to be increased. This is because reflector thickness above $2 \times L_d$ [8] is enough.

The constraints of diameter, D and height, H are as fixed per the HTR Design Criteria [323]. For the diameter, D and height, H of the reactor, the constraints would be :

- $D < 6.5\ m$ due to road transportation consideration
- Maximum H is limited to 30×M (migration length) which is about 8 metres for prismatic HTR.

As the $\frac{Surface\ Area}{Volume}$ decreases, P_L (the non-leakage probability decreases). If the $\frac{H}{D}$ ratio remains fixed, P_L would stay constant and not require any change in the design.

The height of the RPV depends on a number of aspects. The height of the RPV is estimated by adding dimensions of these aspects. This is given in Equation 5.8.

$$\begin{aligned} Height_{RPV} = & Reflector_t + Reflector_b + Plenum_t + Plenum_b + Support\ Structure + \\ & Core\ Support\ Plate + Insulation_t + Insulation_b + 2.5 \times Core\ Height \end{aligned} \tag{5.8}$$

where the subscripts t and b refer to top and bottom.

The Diameter of the RPV is estimated as

$$\begin{aligned} Diameter_{RPV} = & 2 \times Reflector_r + 2 \times Insulation_r + 2 \times Vessel\ Thickness + \\ & 2 \times Barrel\ and\ Gap\ thickness + Core\ Diameter \end{aligned} \tag{5.9}$$

where the subscript r stands for radial direction.

The dimensions of reflector, plenum, core support, insulation etc. that were used can be found in Appendix Table B.12. For the total dimensions of the nuclear reactor, the shielding thicknesses are added to the axial and radial dimensions of the RPV. The mass of the nuclear reactor is estimated by using density values of the three different zones (core, reflector and shielding). The densities used are given in Appendix Table B.13.

5.4.2. Turbines

The generic power-to-mass-ratio and power density is not used in this work as these values differ significantly based on the power range that the turbine operates at. The data about mass and volume of large turbo-expanders/expander turbines is unavailable in public domain from commercial manufacturers. Hence, in this work marine gas turbines have been used as a close approximation to the compressor-turbine combination. Aero-derivative gas turbines were used for deriving the volume requirements of Nuclear Air-Brayton Combined Cycle by Zohuri [282].

The mass and volume data for turbines is given in Table B.6 of Appendix B. This data consists of marine turbines from different manufacturers. The data is further segregated as turbines with and without generators. Since, a turbine with generator is a better approximation to the mass and volume that would be required in a realistic case. Hence, trendlines for marine gas turbines with generators will be

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[6] This was necessitated because the power requirements of OSTSEE were lower than the HTTR module and the reactor needed to be downscaled for OSTSEE.

[7] For HTTR, this is 2.5 $\frac{MW}{m^3}$. For power density of other reactors, see Appendix B.8

[8] The Neutron Diffusion Length of HTGR is 10.6 cm [322].

used in the model for computing the mass and volume of the turbines. Trendlines between Power vs Mass and Power vs Volume for the dataset were made and are given in Figure 5.10 and 5.11 respectively.

Aerodynamic and mechanical similarity in compressor and turbine can be maintained by decreasing/increasing the RPM of the machine. Because of this similitude, one model can be scaled up or down into another model by using scaling factors. Similarity was used as a basis for developing the scaling between power and mass of the turbine by Coleman [316]. In this work, in addition to mass, volume is an important consideration due to the space constraints. Hence, the same similarity is taken as a basis to extend the relation between power and volume.

$$P \sim W^{1.5} \tag{5.10}$$

$$V = V_0 \times \lambda^3 \tag{5.11}$$

$$P = P_0 \times \lambda^2 \tag{5.12}$$

Hence,

$$P \sim V^{1.5} \tag{5.13}$$

$$\tag{5.14}$$

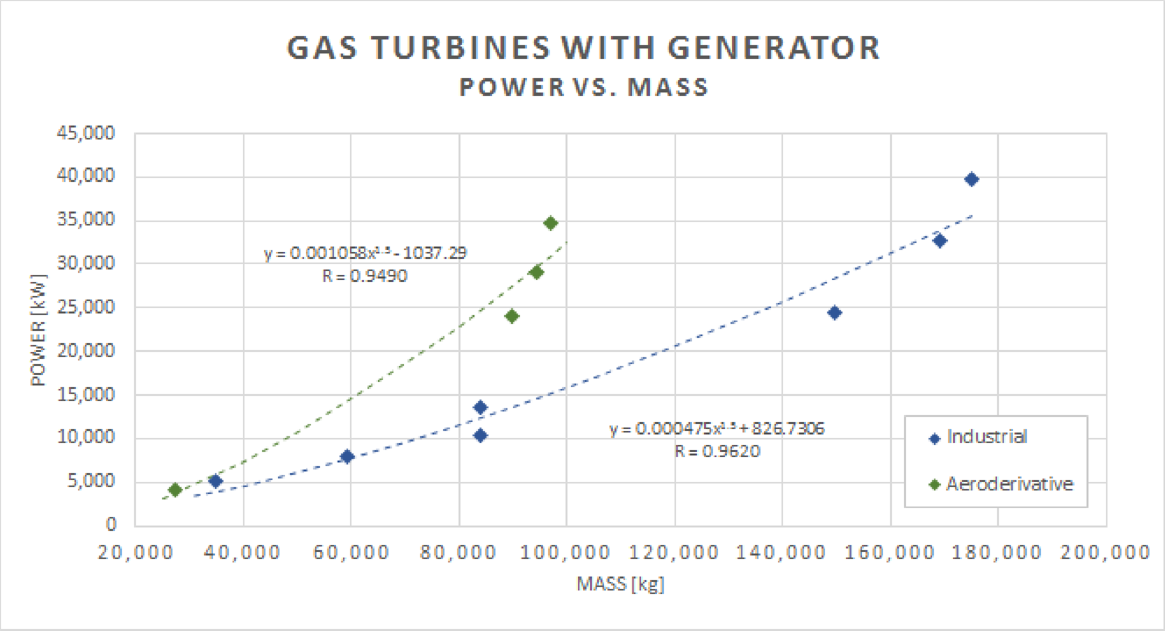

Figure 5.10: Gas Turbine with Generator Power vs. Mass Data

For Aeroderivative Gas Turbines, the relation between Power and Mass is given by Equation

$$Power[kW] = 0.001058 \times Mass[kg]^{1.5} - 1037.29 \tag{5.15}$$
$$R^2 = 0.9490$$

While, the relation between Power vs. Volume is given by Equation 5.16.

$$Power[kW] = 10.45873 \times Volume[m^3]^{1.5} - 3026.168 \tag{5.16}$$
$$R^2 = 0.9745$$

The mass and volume data for steam turbines is given in Appendix (Table B.7). This data consists of steam marine turbines from Kawasaki. This data already includes the generator dimensions and mass.

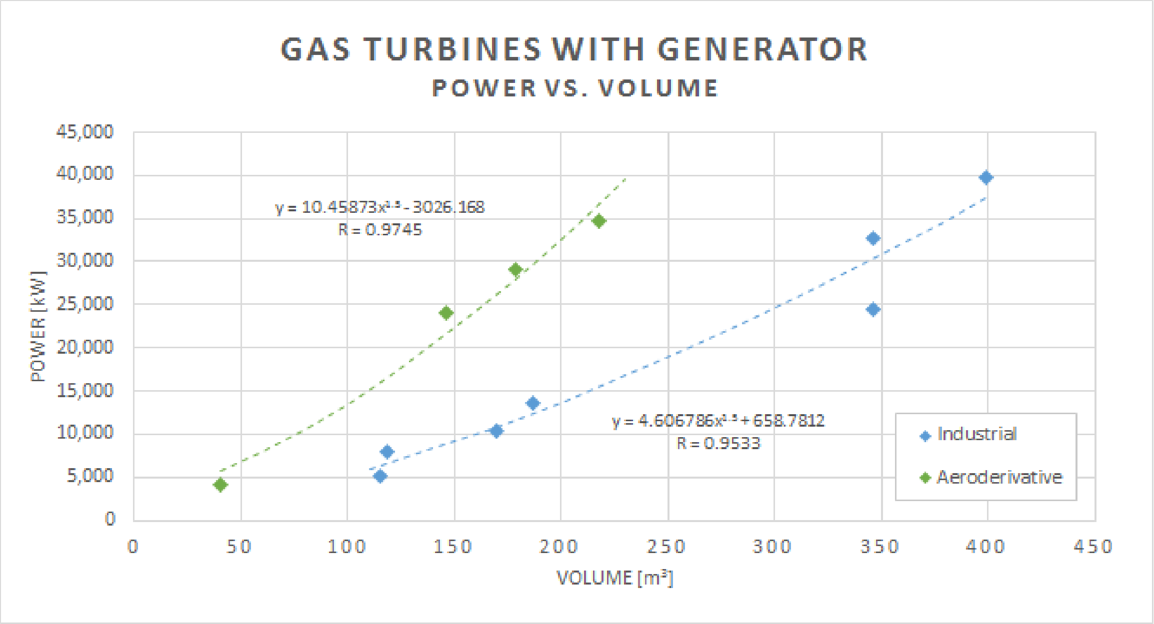

Figure 5.11: Gas Turbine with Generator Power vs. Volume Data

Trendlines between Power vs Mass and Power vs Volume for were made. Figure D.8 and D.9 shows these trendlines respectively. These are not used in this work and left for future work.

In addition to the scaling, there's another explanation for the high R^2 values for each of the turbine categories. For each of the category of turbines, turbine data is acquired specifically from a single manufacturer. Turbine manufacturers tend to use the same design characteristics, materials for upscaling or downscaling their turbines. So, comparing a GE turbine to Siemens turbine does not give a fair idea.

5.4.3. Heat Exchanger

The PHX and IHX were sized for a nuclear reactor with thermal power of 100 MW. The inlet and outlet temperatures of HXs were found by iterating such that the constraint of 10 K approach temperature is satisfied. The LMTD and Heat Transfer Area is given in Table 5.2. Forthwith, the same U and LMTD is assumed for scaling up or scaling down of Heat Exchangers (PHX and IHX).

Table 5.2: Parameters for PHX and IHX

Heat Exchanger	**Area** (m^2)	**LMTD**	**U (kW-**m^2**-K)**
PHX	12232.5	10.0567	0.849431
IHX	4767.89	25.8632	0.849431

The area of the IHX is found by

$$A_{IHX} = 12232.5 \times \frac{P_{thermal}}{100000} \tag{5.17}$$

The area of the PHX is related by the equation

$$A_{PHX} = 4767.89 \times \frac{P_{thermal}}{100000} \tag{5.18}$$

To compute the mass of the heat exchanger, the metric area density of a heat exchanger is defined. Area density is defined as :

$$\beta = \frac{Heat\ transfer\ surface\ area}{Volume\ of\ Heat\ Exchanger} \tag{5.19}$$

The area density of Shell & Tube Heat Exchangers vary between 50-500 $\frac{m^2}{m^3}$ (see Appendix C.12.1). In this work, an area density of 50 is used for physical dimensioning of the heat exchangers (a conservative estimate). The use of a S&T HX or any other compatible HX with higher area density would reduce the volume requirements.

Hence, the volume of the heat exchangers is given by

$$V_{PHX} = \frac{A_{PHX}}{50} \tag{5.20}$$

$$V_{IHX} = \frac{A_{IHX}}{50} \tag{5.21}$$

For calculation of the mass, a generic metric for mass per area of heat exchangers is employed. For S&T heat exchangers, such a factor was pegged at 39.05 $\frac{kg}{m^2}$ [9]. A factor of 32 $\frac{kg}{m^2}$ was confirmed with specifications from a manufacturer (see Appendix F.5.1) and a similar factor was suggested by various designs in Aspen Heat Exchanger Module. Hence, a factor of 32 $\frac{kg}{m^2}$ would be used in this work and the mass of the HXs would be calculated as per Equation 5.22.

$$W_{PHX} = A_{PHX} \times 32 \tag{5.22}$$

$$W_{IHX} = A_{PHX} \times 32 \tag{5.23}$$

5.4.4. Emergency Generator, Load Bank and Clearances

Because of the passive cooling feature of HTGRs, there is no requirement for emergency supply system for the nuclear reactor cooling. However, some emergency supply in this concept is provided via battery packs. The energy storage capacity of these batteries is taken as 6 times the energy storage required for the operation of the dredger with the assumption that there is no regulation in this regards. This is enough to supply propulsion power demand for more than 2.5 hours. Load bank is added to the system. The rating of the load bank is such that it is about 30% of the nuclear generation. The data on load bank used in this work is given in B.11. Due to this addition, there is an additional barrier in avoiding the Iodine pit.

Since, most of the equipment is static in nature except for the compressor-turbine-generator and the volume is increased ~ 3 times of the total volume.

5.4.5. Biological Shielding and Confinement

Radiation shielding represents a substantial percentage of the total mass of a vessel [159]. For land based reactors, the choice of shielding design and material is governed by the costs, however, for marine applications , there is a second factor of mass. In this work, on top of this second factor is the factor of volume (due to retrofitting).

The primary shield reduces the dose rate of neutrons and gamma rays. For the HTTR, the upper shield consists of 90 cm thick concrete and 30 cm thick carbon steel [325]. The lateral core shields are made of borated graphite and stainless steel and RPV steel and ordinary concrete [326]. The secondary shield is made up of 60 cm thick steel [271]. The reflector thickness at the top and bottom is more than at the sides 1.16m vs 0.99 m. This is because the top and bottom reflector regions serve as plenum chambers [10] and the thickness requirements are greater than just due to nuclear considerations [327].

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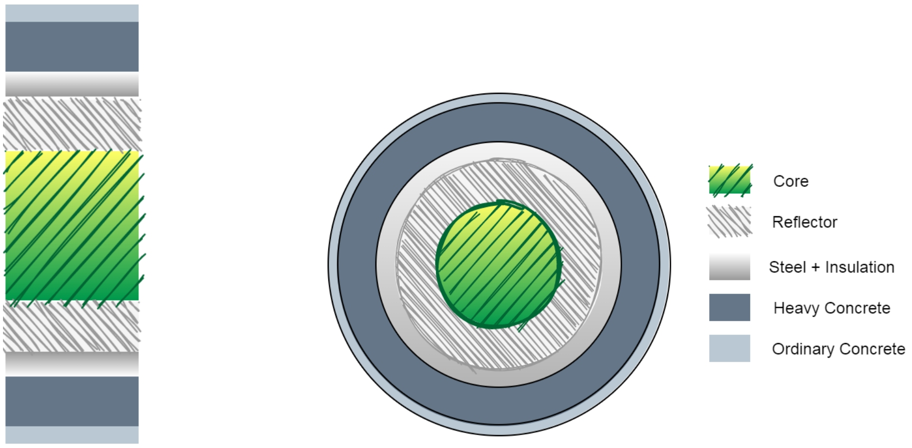
[9] 8 $\frac{lb}{ft^2}$ of total surface area [324].

[10] The plenum is the pressurised housing containing the fluid which functions to equalise the pressure. Typically a plenum is relatively large in volume.



(a) Side View (b) Top View

Figure 5.12: Cross section of nuclear reactor & shielding

2 m ordinary concrete [11] as biological shielding [328] is enough for HTGR-10, a 10 MW_{th} reactor using fuel enrichment of 17 % with $\frac{H}{D}$ = 1.10. Jacobs's [10] design for the shield of 30 MW_{th} HTTR consisted of heavy concrete [12] (1 m thickness) and normal concrete [13] (0.35 m thickness). The total mass of the reactor (with shielding and auxiliaries) was reported as 1370 tons (height of 11.55 m and 8.7 m as flange-to-flange width). This shielding design would be used in this work.

The physical dimensions of the shielding are calculated based on the core size. Since, the materials used is known, the density of the material is used to calculate the mass of the shielding from the volume of the shield. The cross section of the top and side view of the nuclear core along with the reflector and shielding used in this work is given in Figure 5.12.
The containment designs vary within the same type and even, the design of reactors. The exact design of the containment building depends on the manufacturer and also the technology. It can either be inner steel containment with outer concrete or double concrete layers [329]. A sealed containment might not be required and a vented confinement like the PBMR concept might be justified. It has been argued that a vented containment [14] is more suited to a HTGR than a leak tight containment [15]. The confinement volume 20% less volume than containment.

5.5. Nuclear System : Indirect Usage

In a scenario of increased penetration of the renewables which appears to be a more and more plausible situation in the future, the excess energy from nuclear power plant could be used to produce H_2 or store it in form of batteries. It was interesting to see if coastal nuclear power plants or floating power plants can be utilised to power dredgers in some way. Two possible system options were battery based dredging vessel and PEMFC based dredging vessel. For the evaluation of this, the energy and power requirements of the dredgers was used to find the number of units and the physical dimensions of the system. Minnehan et al. [317] conducted a study on applicability and limits of PEMFC and battery based systems for a number of vessels. However, a look at the data source revealed that some of the components used for making the analysis have been taken out of production or upgraded (For example : FCe-150, 4xHyPM HD 30 Power rack fuel cells and most of the battery packs offered by SPEAR, HARPOON Series). Further, none of the vessels that was considered was a dredging vessel. Considering that power and energy is required in a dredging vessel for propulsion and work, a separate analysis is mandated.

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[11] density of 2.3 $\frac{g}{cc}$

[12] density of 4.65 $\frac{ton}{m^3}$

[13] density of 2.39 $\frac{ton}{m^3}$

[14] Confinement is a vented low pressure containment.

[15] For power reactors, a leak tight containment is required as per CFR 50.

Similar to case of the nuclear (HTGR-NABC) system, it is imperative to have maximum specific power and maximum power density (due to the mass and volume limitations on a dredger). In certain cases, either one can be achieved.

$$Specific\ Power = \frac{Output\ Power\ (kW)}{Fuel\ Cell\ Mass\ (kg)} \tag{5.24}$$

$$Power\ Density = \frac{Output\ Power\ (kW)}{Fuel\ Cell\ Volume\ (m^3)} \tag{5.25}$$

5.5.1. Fuel Cell Systems

Most of the H_2 production in the world is based on Steam Methane Reforming (SMR). High temperature PEMFC are a better option when H_2 is sourced from SMR. This is because high temperature PEMFCs can tolerate far more amount of CO in the fuel but is not possible of a cold start [330]. However, since, the idea is to use nuclear hydrogen the issues of fuel purity (CO incursion) would allow the use of low temperature PEMFC.

The data for Fuel cell (system and module) is given in Appendix (Table B.3). The fuel cell module along with subsystems like the air delivery [16], coolant subsystem [17] etc.) form the system. Trendlines between Power vs Mass and Power vs Volume for Fuel Cell (systems and modules) were made. These trendlines are given in Appendix Figure D.7 and Appendix Figure D.6 respectively.

The Equations linking Power to Volume and Power to Mass for Fuel cell systems are given as :

$$Power[kW] = 133.23 \times Volume[m^3] + 24.063 \tag{5.26}$$
$$R^2 = 0.7859$$
$$Power[kW] = 0.2243 \times Mass[kg] + 26.332 \tag{5.27}$$
$$R^2 = 0.7909$$

The Equations linking Power to Volume and Power to Mass for FC modules are given as :

$$Power_{module}[kW] = 665.85 \times Volume[m^3] - 18.329 \tag{5.28}$$
$$R^2 = 0.9982$$
$$Power_{module}[kW] = 0.6769 \times Mass[kg] - 21.99 \tag{5.29}$$
$$R^2 = 0.9646$$

It can be realised that the R^2 values for modules is much higher than the R^2 values of the mentioned systems. This is because, the description of modules is clearer while the description of the system tend to have certain amount of variation across manufacturers.

The system level Fuel cell data is a better representative of the physical dimensions and the mass of the Fuel cell based powerplant. Hence, this is used in the analysis. The system trendlines developed from data of this work are compared with the trendlines of the data from Minnehan et al. [317]. The Power vs Mass and Power vs Volume are given in 5.14 and 5.13 respectively. The Equations developed in this work corresponds with Minnehan et al. [317] if the removed entries (being out of production) are re-considered. Because of how linear regression works[18], the data point(s) were weighing heavily on all the other entries. Figure D.5 and Figure D.5 provide the visual representation of the same.

The power that can be produced by each module of Fuel Cell has a maximum limit. The energy on the other hand is decoupled from the peak power produced and dependent on the amount of H_2 that is available or can be supplied.

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[16] composed of air compressor, motor, controller and mass flow sensor is responsible for delivering right amount of air for the reaction.

[17] composed of coolant pump, piping, valves and freeze protection. Coolant is a mixture of ethylene glycol and water. The subsystem is responsible for delivering coolant to the cell stack of

[18] Linear Regression is the weighted average of the data

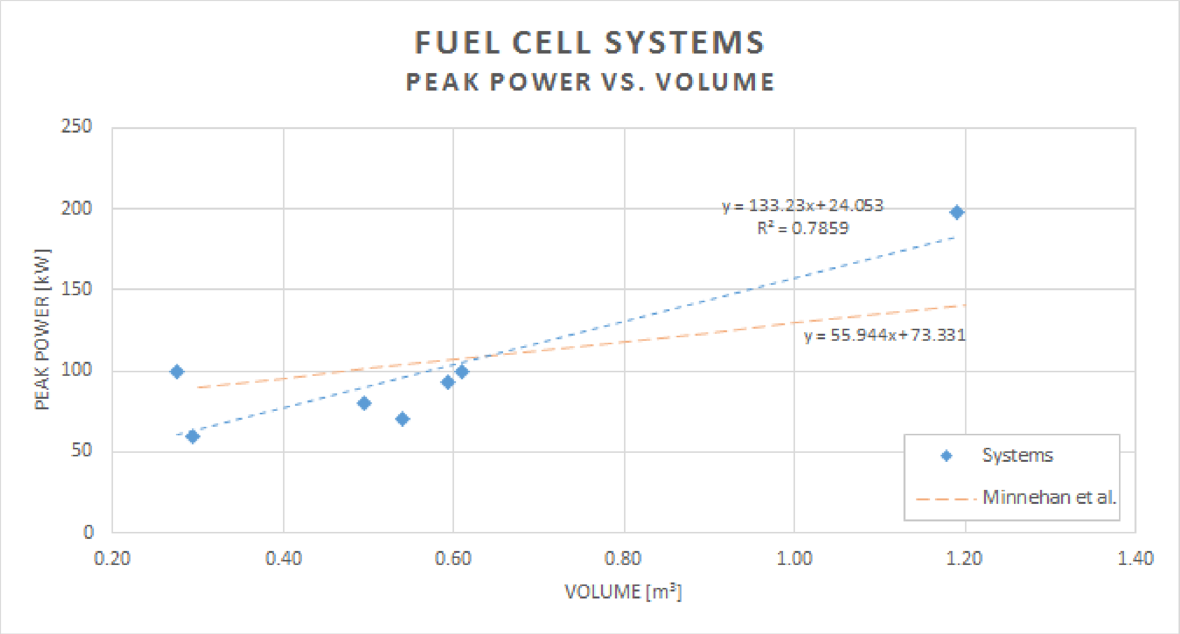

Figure 5.13: Fuel Cell Systems compared to Minnehan et al. (Peak Power vs. Volume)

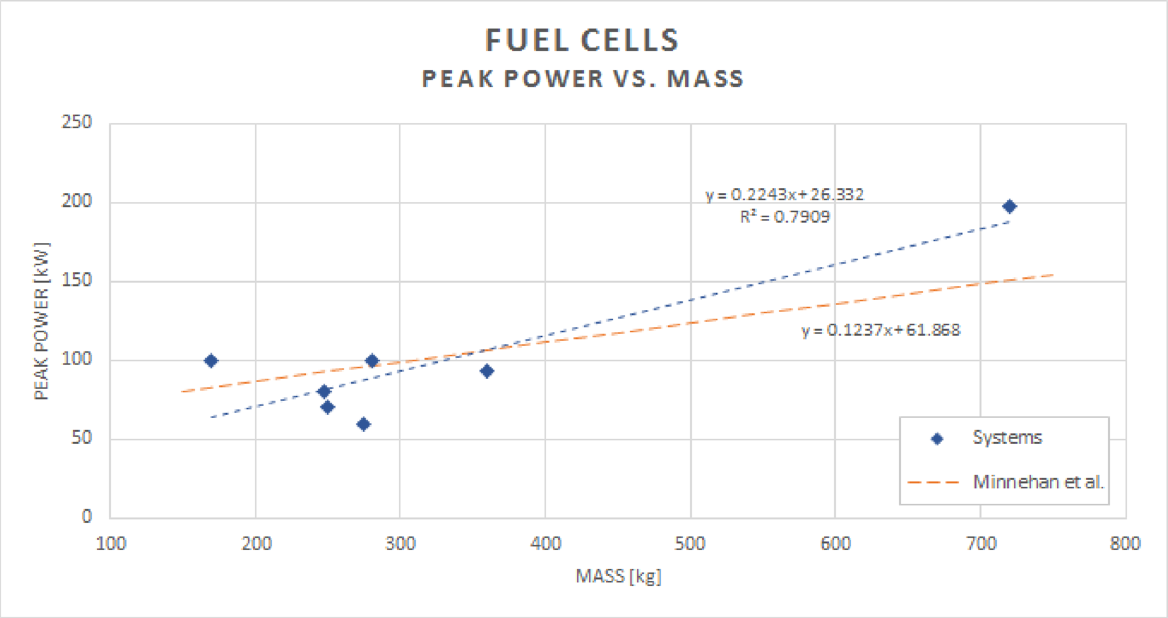

Figure 5.14: Fuel Cell Systems compared to Minnehan et al. (Peak Power vs. Mass)

Hydrogen Storage

At 1 atm and 21°C, 1 kg of H_2 needs almost 12 m^3 of volume. Hence, hydrogen storage for any useful purpose requires either compression, cryogenic temperatures or conversion into hydrides. Different commercial H_2 storage media i.e. compressed tanks, hydride storage and liquid hydrogen storage tanks are considered in this work.

Compressed hydrogen storage tanks are easier to manufacture and maintain. These are also more readily available than liquid hydrogen (LH2). However, the use of LH_2 provides with the added benefit of a smaller and lighter system for comparable amount of H_2. Metal hydride storage can be used to store hydrogen at near atmospheric pressures and temperatures. Space launch vehicles use liquid hydrogen and liquid oxygen as propellants. The Ariane launch vehicle (provided by AirLiquide) contains 28 tons of liquid hydrogen at -252,87°C. The tank itself weighs 5.5 tons empty and the casing is < 1.3 mm thick [331]. At 700 bar 5 kg of hydrogen can be stored in a 75-liter tank.

In this work, the compressed storage tanks at pressures of 60 bar, 350 bar and 500 bar are considered. Hydride storage with and without heat exchangers and Liquid storage with H_2 at -252°C based on is considered. The specification of compressed storage tanks is obtained from MAHYTEC (60 bar and 500 bar) and Luxfer (350 bar). The specification of the hydride storage are from Pragma Industries. For the liquid storage, the specifications [19] of the LLNL Gen-3 cryo-compressed tank system [332] is used in this work. The details of these tanks are given in Table B.5 of Appendix B.

For all types of storages, it is required to know the volume and mass requirements per kg of H_2 stored. This value differ slightly from manufacturer to manufacturer due to the difference in the material that is used. While the arrangement can vary widely, the selected storage tanks are a good representation on what to expect. Because an individual tank does not hold enough quantity of H_2, an array of tanks is considered. An array of smaller tanks would have additional volume and mass requirements due to the need of clearances and frame. The use of larger tank sizes is possible and this has the possibility to improve the amount of H_2 that can be stored, hence, utilising tanks of these commercially available sizes is conservative. However, the sizing of the individual tank (in volume) with the size (in terms of number) of the array is an optimisation problem and would not be taken up in this study.

5.5.2. Battery System

A number of battery models from different manufacturers was considered by Minnehan et al. [317]. As mentioned earlier, a closer look of the data revealed that some of the manufacturers have either changed their product offering, iterated to better versions. Bigger systems are also available as some companies are already offering containerised battery storage [333]. The largest of such is the 53 ft container [20]. This offers significant reduction of costs by the use of standard ISO packaging in comparison to individual system or modules. This necessitated a re-look of the data and data collection was carried out to better reflect the change in the models and technology, new data was collected for this work instead of using the battery models from the work.

The data for battery systems (system and module) is given in Appendix A (Table B.2). This data consists of high C-rate batteries and Tesla Power pack [21]. If there is a need of conversion from Direct Current to Alternating Current because of the electrical system requirements, bi-directional inverter(s) would be needed to carry out this job. For such a case, the data for Tesla Power pack with its inverter is also considered.

Trendlines between Energy capacity vs Mass and Energy Capacity vs Volume for systems and modules for high C-rate batteries were made. Since, many modules make up a system and the mass and volume penalties of array arrangement and auxiliary equipment is taken into consideration. Hence, similar to the Fuel cells, the system level battery trendline(s) will be used for calculating physical dimensions and mass of the battery system required for the dredger.

Figure 5.15 and 5.16 presents the plots of data and the trend lines for the Energy Capacity vs Volume and Energy Capacity vs Mass for the batteries respectively.
The Equations linking Energy Capacity to Volume and Energy Capacity to Mass are given as :

$$Energy\ Capacity[kWh] = 64.378 \times Volume[m^3] + 9.9429 \qquad (5.30)$$
$$R^2 = 0.7726$$

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[19] The specifications includes significant balance-of-plant (BOP) components like a pressure regulator, fill tube/port, valves (control and pressure relief), rupture discs, level/pressure sensors, transducers, and thermocouples.
[20] With an internal volume of 121 m^3 and floor space of 41.82 m^2.
[21] Arguably, as the most recognisable solution for battery storage is the Tesla Powerpack

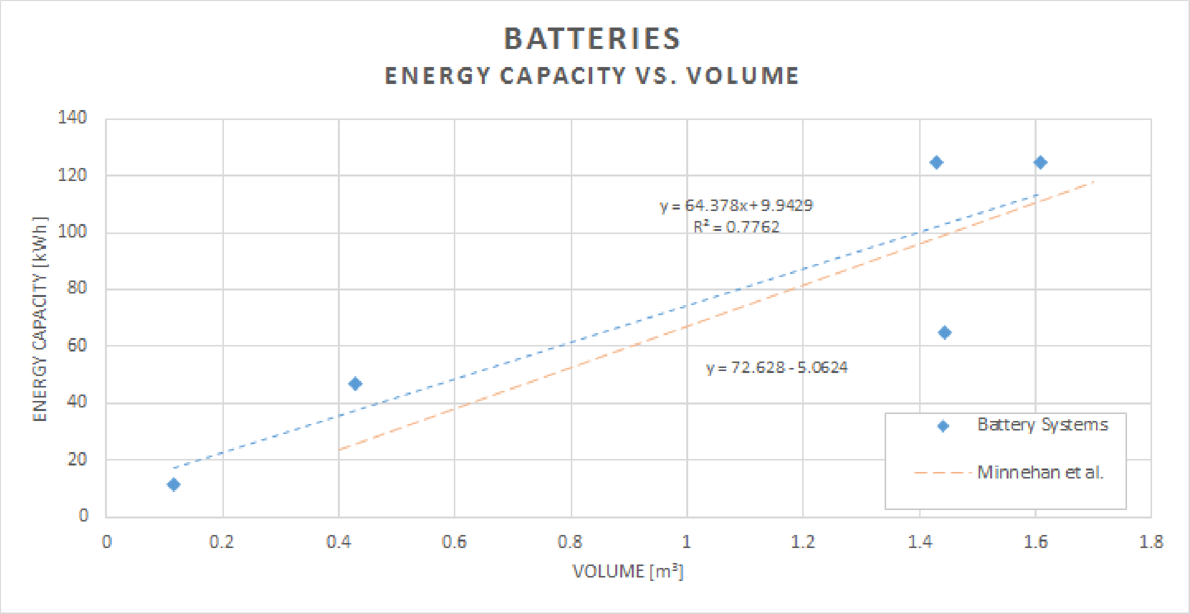

Figure 5.15: Batteries Data (Energy capacity vs. Volume)

$$Energy\ Capacity[kWh] = 0.0718 \times Mass[kg] + 6.8892 \tag{5.31}$$
$$R^2 = 0.9673$$

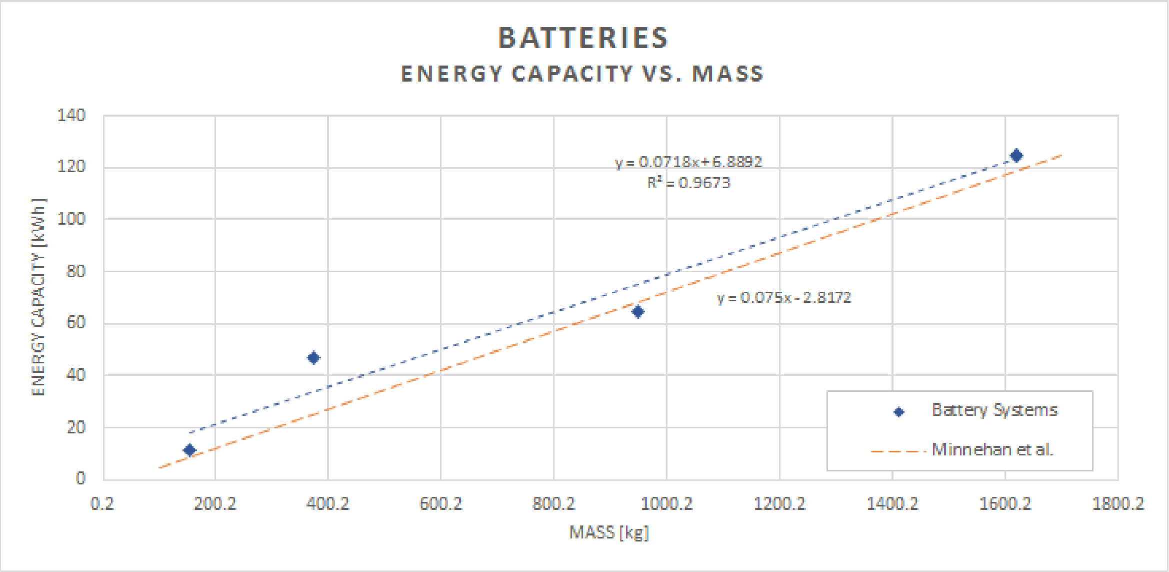

Figure 5.16: Batteries Data (Energy Capacity vs. Mass)

In an optimal scenario, there would be a mix of the two types of batteries as the high C-rate batteries would be required to cope with the sudden changes in power requirements while the low C-rate batteries would supply energy for less intensive demands. Hence, the trendline over-predicts the size and volume of such an optimal system as only power-type batteries are considered.

Unlike a Fuel Cell, the power and energy in a battery is coupled. The Energy capacity required by the battery packs is dependent on the energy requirements and the DoD and is given in Equation D.40.

$$Required\ Energy\ Capacity\ (kWh) = \frac{Energy\ Requirements}{Depth\ of\ Discharge} \tag{5.32}$$

The capacity loss of the Li-ion batteries based on the charge-discharge cycles has been studied earlier [334]. In a practicably useful manner, the 85-25% SoC and 85-25% SoC provide longer life of the batteries. Hence, 50-70% DoD values are considered in the calculations as this depth of discharge does not have ramifications on the life of the battery. Hence, in this work the energy capacity requirements for the battery pack have been sized for different Depth of Discharge values (50% and 90%).

5.6. Total Mass and Volume

5.6.1. Onboard Nuclear System

The total mass of the power conversion system is based on the following equation

$$w_{PCS} = w_{COMPRESSOR} + w_{GT} + w_{GENERATOR} + w_{BATTERY} + w_{EMERGENCY} \tag{5.33}$$

where, w represents the mass and the subscript refers to the component.

The buoyancy of the ship is maintained by limiting the ship's density. The energy required for propelling a ship increases with mass of the ship. The total mass of the system is given by the following equation

$$w_{total} = w_{PCS} + w_{MMR} + w_{Containment} + w_{PHX} + w_{IHX} \tag{5.34}$$

Similarly, the total volume of the power conversion system is based on the following equation

$$V_{PCS} = V_{GT} + V_{COMPRESSOR} + V_{GENERATOR} + V_{BATTERY} + V_{EMERGENCY} \tag{5.35}$$

The total volume of the system is given by the following equation

$$V_{total} = V_{PCS} + V_{MMR} + V_{Containment} + V_{PHX} + V_{IHX} \tag{5.36}$$

The volume of the IHX and PHX have been computed by using the area density values appropriate for air to air heat exchangers.

Note : The Equations for total mass (Equation 5.34) and total volume (Equation 5.36) are without clearances and additional factors [22] that are considered in this work.

5.6.2. Indirect Nuclear Systems

Fuel Cell Systems

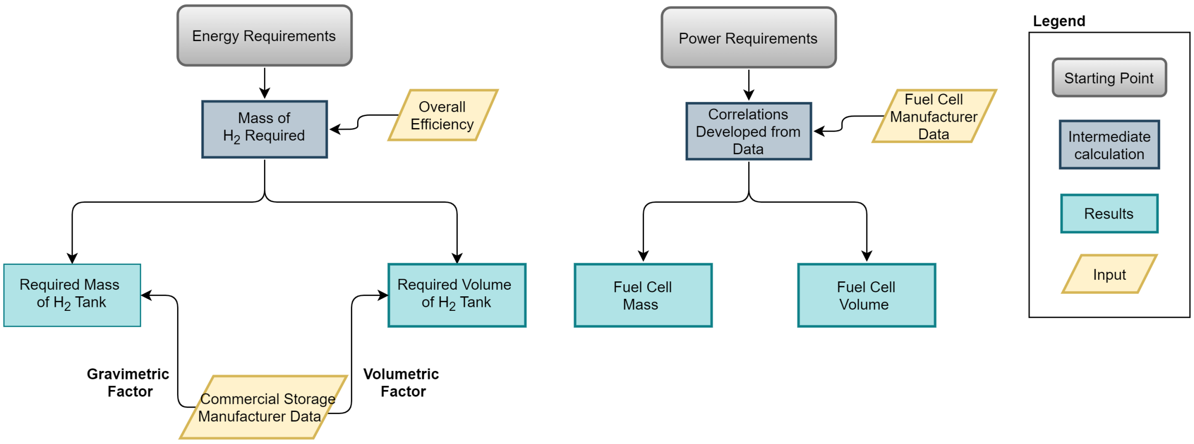

Figure 5.17: Workflow for Determination of Mass and Volume Requirements of Fuel Cell System

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[22] See 5.4.4.

The mass and volume of the hydrogen gas along with the storage tanks needs to be determined.

The requirement of H_2 is dictated by the energy requirements and the system efficiency. The required mass of H_2 is given as :

$$Required\ Mass\ of\ \mathrm{H_2}\ (kg) = \frac{Energy\ Requirements\ (kWh)}{Overall\ System\ Efficiency} \times \frac{3.6}{LHV\ of\ \mathrm{H_2}} \tag{5.37}$$

The Lower Heating Value (LHV) of H_2 is taken as 120 $\frac{MJ}{kg}$. The system efficiency of the Fuel Cell system varies anywhere between 40% and 60%.

After the determination of the mass of H_2 required, the mass and Volume of the tank was found by the following equations.

$$Required\ Mass\ of\ Tank\ (kg) = Required\ Mass\ of\ \mathrm{H_2}\ (kg) \times \frac{Empty\ Mass\ of\ Tank\ (kg)}{Mass\ of\ \mathrm{H_2}\ stored\ (kg)} \tag{5.38}$$

$$Required\ Volume\ of\ Tank\ (m^3) = Required\ Mass\ of\ \mathrm{H_2}\ (kg) \times \frac{Volume\ of\ Tank}{Mass\ of\ \mathrm{H_2}\ stored\ (kg)} \tag{5.39}$$

The total mass and volume of the system is combination of the H_2 storage tanks and the Fuel cell system. This is given by :

$$Volume\ of\ FC\ System\ (m^3) = Volume\ of\ \mathrm{H_2}\ tank\ + Volume\ of\ Fuel\ Cell \tag{5.40}$$

$$Mass\ of\ FC\ System\ (kg) = Mass\ of\ \mathrm{H_2}\ tank + mass\ of\ Fuel\ Cell \tag{5.41}$$

The extent of system equipment included (air delivery subsystem, coolant subsystem etc.) in the specification is sometimes vague. This may result in variation in the the data and the actual installation size. This has the possibility of underpredicting the actual installation size.

Fuel cells with different powers can share the same specifications for the coolant and air delivery subsystem. Hence, depending on the size of the fuel cell system these subsystems have additional volume and mass. It was found that the values can be anywhere between 20-50% higher in terms of mass and in terms of volume between 25-40% higher in comparison to the volume and mass values given in a particular data sheet.

Battery Systems

After the determination of the energy capacity requirements, Equation 5.30 and Equation 5.31 are used to find the Volume and Mass of battery packs respectively.

Then, the mass of the battery system is given as

$$Mass\ of\ Battery\ System = Battery\ Mass + Mass\ of\ Inverter/Rectifier \tag{5.42}$$

The volume of the battery system is given as

$$Volume\ of\ Battery\ System = Battery\ Volume + Volume\ of\ Inverter/Rectifier \tag{5.43}$$

5.7. Simulation and Modelling Flowchart

Figure 5.18 represents the flowchart for the simulation and modelling that is carried out in this work. The green colored hexagon represents the reading of data from Excel worksheets, the purple colored hexagon represents the simulation carried out in AspenPlus.

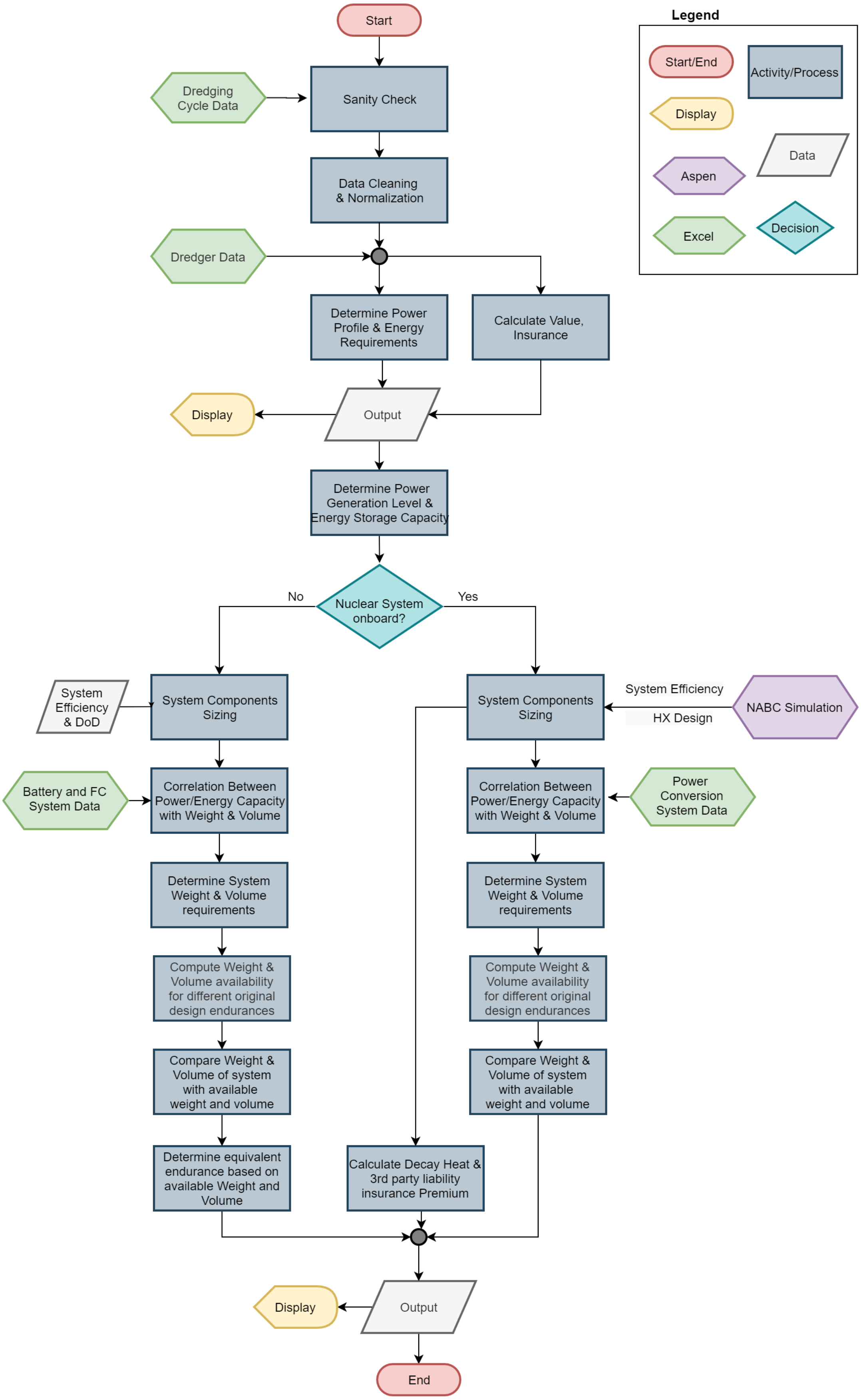

Figure 5.18: Flowchart for MATLAB® code

6

Results and Discussions

Section 6.1 covers the analysis and descriptive statistics of the dredging cycles. Section 6.2 covers the modelling of NABC turbomachinery, effect of inlet air temperature and the comparison of exhaust flow rate between NABC based systems and marine diesel engines. Section 6.3 discusses the volume and mass requirements for the High Temperature Gas-Cooled Reactor-Nuclear Air-Brayton Cycle system. direct and indirect nuclear based systems. Section 6.4 discusses the volume and mass requirements for the indirect system composed of PEMFC with H_2 storage (compressed, solid and liquid) and batteries. Section 6.5 comprises of the the development of retrofit maps out to avoid the repeated computation of expected endurance for different system efficiencies and original design endurance.

6.1. Dredging Cycle Data : Descriptive Statistics and Analysis

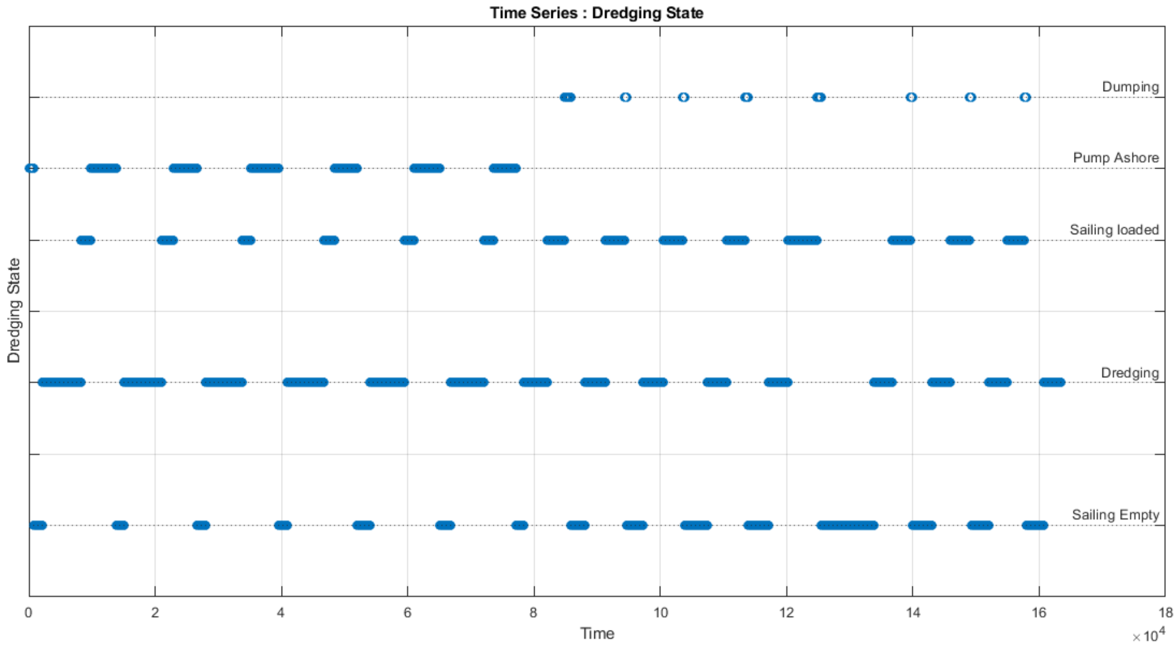

Figure 6.1: Dredging Times Series

In this section, the analysis of the dredging cycle data was carried out to check if the data values for the dredging cycle are correct. If the reader wishes, this section can be skipped. This section reinforces that there is no typical dredging cycle and the takeaway from this section is that the analysis on only

Dredging Cycle I will be carried out due to its broader applicability.

For the entire data, Figure 6.1 gives the different dredging states with time on x-axis. The first half of the data represents the Dredge Cycle I while the second half (where ”dumping” has data points but ”pump ashore” does not) is Dredge Cycle II. The approximate cycle time for Dredge Cycle I is 12750 time units (13415.5 s ~ 3.7 hours) while the cycle time for Dredge Cycle II is 9200 time units (9776.8 s ~ 2.7 hours).

The time spent in each phase of the dredging cycle is given in Figure 6.2. The time for discharging in Dredge Cycle I (pump ashore) is far more than time for discharging in Dredge Cycle II (dumping). This essentially is because in dumping, the operation requires opening up of bottom doors while pump ashore requires the pumping. The time spent ”sailing empty” in Dredge Cycle I is very small in comparison to Dredge Cycle II. In general, in Dredge Cycle I, the distance between the borrow site and discharge site is closer than in Dredge Cycle II [1].

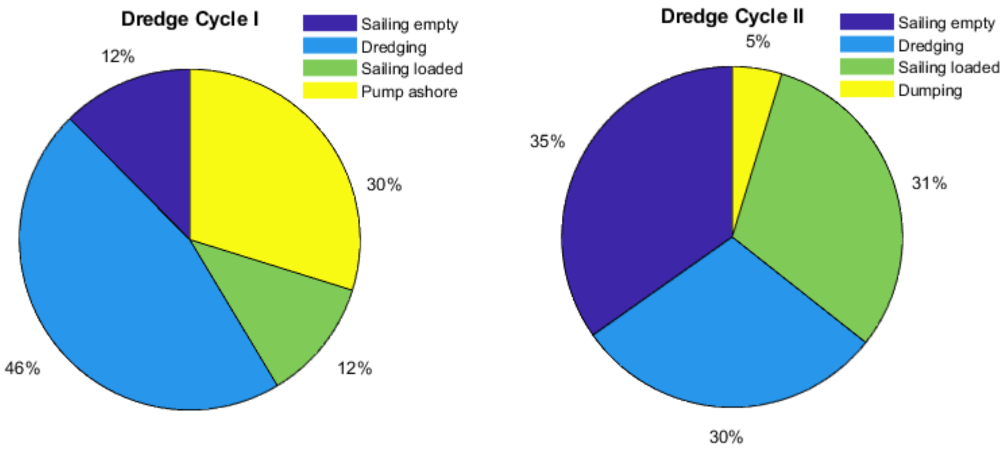

Figure 6.2: Temporal Distribution of Dredging Cycle Phases

Thus, the vessel spends more time in mobilising to the discharge site than in a pump ashore dredge cycle. In general, for the same dredged material, more dredging can be carried out in a pump ashore discharge cycle than in a dumping discharge cycle. Pumping ashore gives the flexibility to transfer dredged material in places where dumping is not possible or the discharge site is far off to make an economical sense in mobilising to the site.

The temporal distribution at various power levels is given in Figure 6.3. In Dredge Cycle I, more than 70% of the time is spent above 60% of the power levels. While, in the Dredge Cycle II, ~ 43% of the time is spent at power levels above 60% of the total installed power. There is never a moment in any of the dredging cycles where the power demand falls to less than 10% of the total installed power. While, the load over 90% forms a minuscule portion (<1%) of the installed power.

It was found that in the dumping cycle the TSHD is doing maintenance dredging (very fine material or soft clay) while in the pump ashore cycle the TSHD is dredging sand.

On a deeper dive, it was realised that the average power demand in the states ”sailing loaded” /”sailing empty” of ”pump ashore discharge cycle” (first half of the data) are both about 50% lower than the respective power in the ”dumping cycle” (second half of the data) (See Figure 6.4 (a)).

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[1] The discharge site in Dredge Cycle I is a pump ashore site (from where the dredged material is transported to discharge site) while in Dredge Cycle II, the vessel has to physically move to the discharge site.

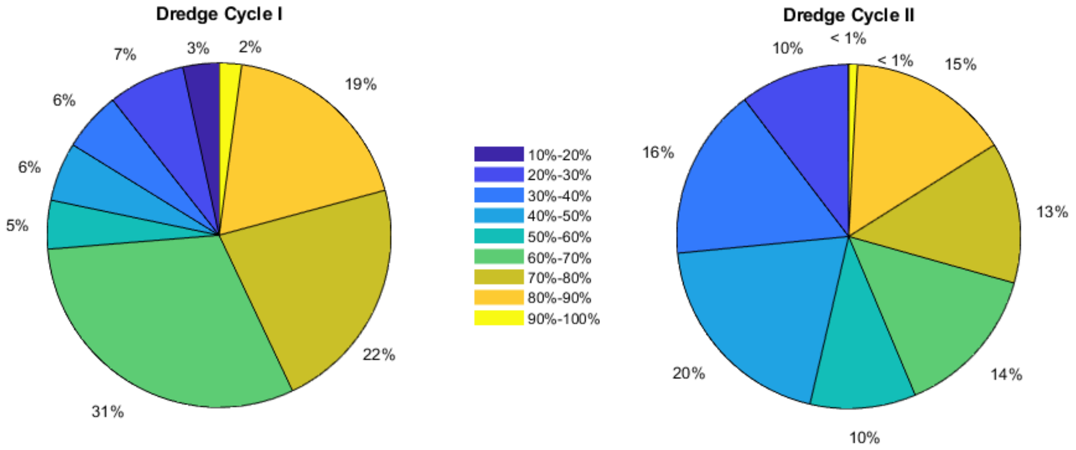
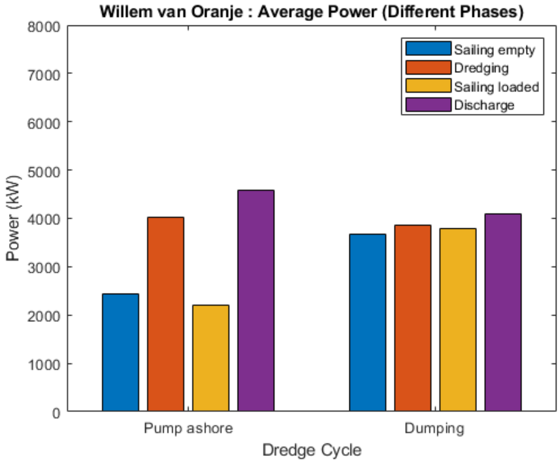
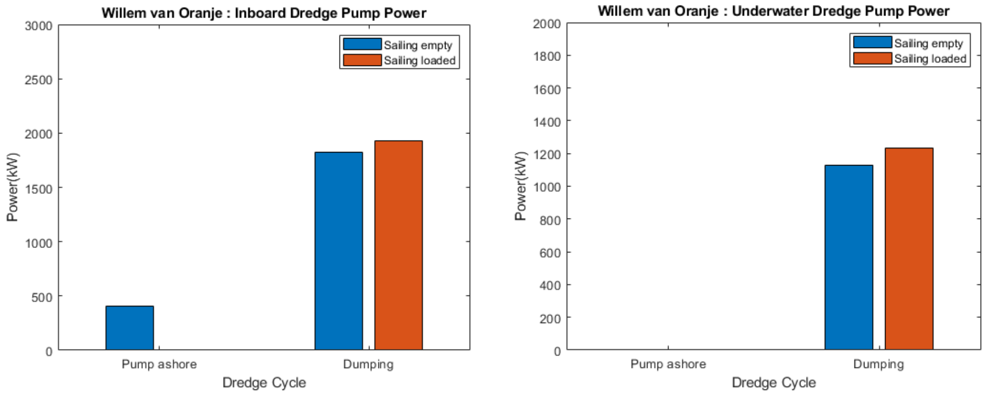


Figure 6.3: Temporal Distribution at different power levels

The speed/depth restriction could be responsible for this. The sailing speed was found to be higher, however, it was realised that the powers consumed by the pumps is much higher. In the dumping cycle the inboard dredge pump is used to empty the hopper and fluidise the load.



(a) Average Power Demand in different states of the dredging cycle



(b) Power Demand of the Inboard Dredge Pump Power in dredging cycle state : "Sailing empty" and "Sailing loaded"

(c) Power Demand of the Underwater Dredge Pump in dredging cycle state : "Sailing empty" and "Sailing loaded"

Figure 6.4: Average power consumption in different dredging states

The average power consumed during "sailing loaded" state in the "pump ashore discharge cycle" is 10% lower than average power consumed while in "sailing empty" state of "pump ashore discharge cycle". This was a counter-intuitive result as the sailing loaded state should be consuming more power on average than sailing empty state. During sailing loaded, due to draught restrictions, sailing loaded will be slower than sailing empty. In general, when sailing loaded the total mass is much more so, in order to save some fuel or because of speed restriction in the pump ashore area the speed is reduced. Also, the speed and power will be low because the vessel approaches the point where it stops completely.

The average power consumed in both the cycles is almost similar for the discharge part. This was counterintiutive as running pumps for pump ashore transport would consume more power than dumping (which involves opening up bottom doors). It was checked if the pumps were being used. The Dredge Pump and Underwater Dredge Pump were both found to be in use in the dumping part of the dredge cycle. The reasoning for this was that for dumping the load as quickly as possible, the load sometimes needs to be fluidised. This fluidisation operation is carried out by pumping water into the hopper.

Table 6.1: Comparison between Dredging Cycles

Rack Setting Parameters	**Minimum**	**Maximum**	**Standard Deviation**	**Average**
Dredging Cycle I	1.99	0.24	0.39	1.28
Dredging Cycle II	2	0.33	0.39	1.12

Descriptive statistical metrics for the two cycles are given in Table 6.1. It is clear that the variation in power demand in the the two cycles is equal (0.39) but the average power demand in Dredging Cycle I is 15% higher than Dredging Cycle II. This equivalently also implies increased energy requirements/need for bigger systems. Since, one of the defining features of a TSHD is its flexibility, the dredger should be capable of operating with all discharge types and not be restricted to dumping. Hence, for further analysis only Dredging Cycle I is considered.

6.2. HTGR-NABC Aspen Plus Modelling

A pressure ratio of 2.75 per stage was found to be near the optimal (in terms of W_{NET}).
The entry and exit temperatures of the IHX and PHX are given in Figure 6.5. The stream in color blue is the cold stream while the stream in the color red is the hot stream of the heat exchangers respectively.

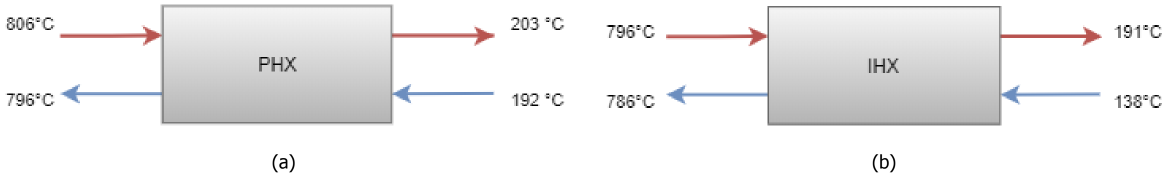


Figure 6.5: Heat Exchanger Outlet and Inlet temperatures from Aspen Plus Simulation

With the parameters considered for modelling the cycle in Aspen Plus, the achievable efficiency is 29%. The reported efficiency in an earlier work is 21% [10]. However, the work did not consider the application of multistage intercooled compressors and relies on single stage compression. The turbine exhaust temperature is around 300°C. Assuming a 60% efficiency in a bottoming cycle, there's a possibility of a Rankine bottoming cycle of improving the efficiency by 5-10 %.

6.2.1. Air Inlet Temperature

The inlet temperature at the compressor inlet was varied from -20°C to 45°C. Figure 6.6 shows the effect of the inlet air temperature on the overall efficiency of the Nuclear Air Brayton system. there is about 3.5 % increase in the overall system efficiency if the temperature decreases to -20°C from 35°C.

At inlet air temperature of 25°C, the efficiency is 23.46 %. It is to be noted here that the system is modelled with 80 % compressor polytropic efficiency.

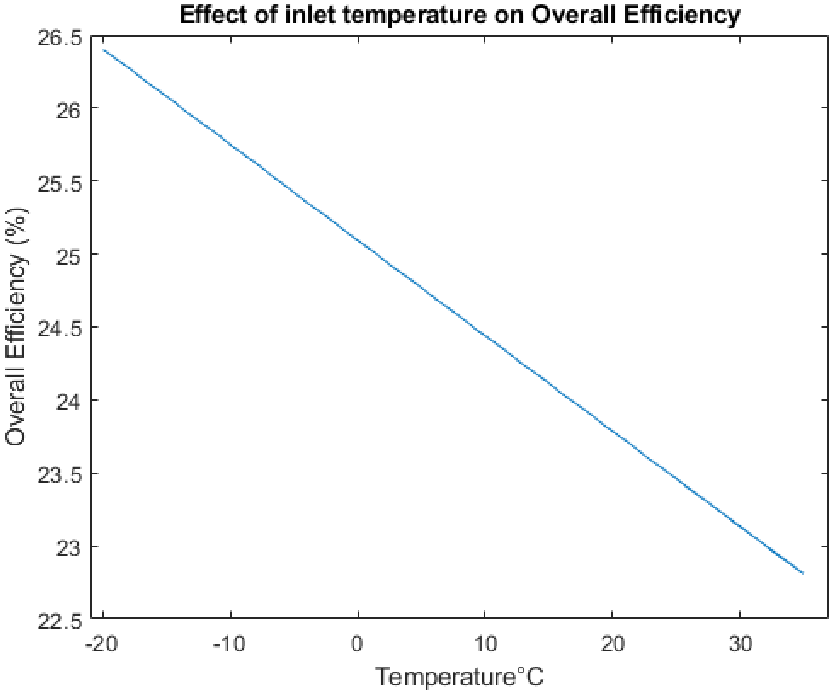


Figure 6.6: Overall Efficiency vs. Inlet Air Temperature

6.2.2. Turbomachinery Efficiency

It is obvious a decrease/increase in the efficiency of turbomachinery equipment, the overall system efficiency decreases/increases and vice-versa. For example, if 80% polytropic efficiency for compressor stages is assumed, the overall efficiency drops to 23.46%. This is attributable to the increase in the work required for the air compressor and the Helium blowers (due to higher inlet temperatures). While when the isentropic efficiency of the turbine is reduced to 80%, the overall system efficiency reduces to 20.27 %. The turbine outlet temperature in this case is 324°C.

6.2.3. Heat Exchangers

For PHX design with hot fluid on the shell side, the cost of INCONEL® 600 HX is lower than cost of INCONEL® 625 (about 19%) and marginally lower (about 4%) than INCOLOY® 800 HX. However, the mass of the INCOLOY® 800 increases by about 47% in comparison to INCONEL® 600 while the mass of INCONEL® 625 is 10% lower than INCONEL® 600 Shell & Tube Heat Exchanger. See Appendix Table F.2.

The difference between the pressure drop between horizontal and vertical baffle cut on the shellside can be as high as 2.75 times (see Appendix Table F.3 for some of the design characteristics). While, the cost premium for a vertical baffle cut is only marginally higher.

Shell & Tube Heat Exchanger designs were used as PHX and IHX. But the use of compatible compact heat exchangers would give a better result (in terms of requirements of mass and volume).

6.2.4. Exhaust Gas Flow Rate

In Nuclear Air Brayton cycle, there is a need for inlet/out air port and ducts. In comparison, a PWR does not need air ports as it is based on the steam generation system. Table 6.2 gives the Exhaust Flow Rate of the diesel engines. The exhaust gas flow rate was not readily available for all the engines and was estimated based on D.4.

Table 6.2: TSHDs Diesel Engine's Exhaust Gas Flow Rate

	Exhaust Flow Rate (kg/s)
Literature	
WILLEM VAN ORANJE	12.6
Estimated	
OPTIMUS	6.3
HAM 318	25.17
CRISTÓBAL COLÓN	31.5

The air flow requirements for NABC is about 3 times more than the exhaust gas flow rate of the marine diesel engines. Because of this factorial increase in the gas flow rate, much bigger air ducts (intake and exhaust), expansion joints and filters than diesel engine of comparable output would be required for NABC power conversion system.

6.3. HTGR-NABC System Mass and Volume Requirements

6.3.1. Mass Requirements

Figure 6.7: Total Mass Requirements & Mass Availability

The total mass requirements along with the mass availability for different design endurances (15 days, 20 days and 30 days) for a nuclear based system different dredgers is given in Figure 6.7. HAM 318 is modelled with two different nuclear reactor (2×30 MW and 60 MW) and CRISTÓBAL COLÓN is modelled with different options (3×30 MW, 2×45 MW and 90 MW). The 90 MW CRISTÓBAL COLÓN and 60 MW HAM 318 design require lesser mass than 15 day endurance on the HFO-based design.

The bigger the dredger, the lesser mass requirements in comparison to the available mass. For example, WILLEM VAN ORANJE requires mass available to a little more than 20 days design endurance. But CRISTÓBAL COLÓN and HAM 318 both require less mass than 20 days design endurance (HFO-based).

The distribution of mass across different equipment and components is shown in Figure 6.8. The mass fraction [2] of components differs for different dredgers. However, the mass of the nuclear reactor and shielding forms the biggest fraction of the total mass (> 60%). The IHX and Emergency Power are the next biggest contributors to the mass of the dredger.

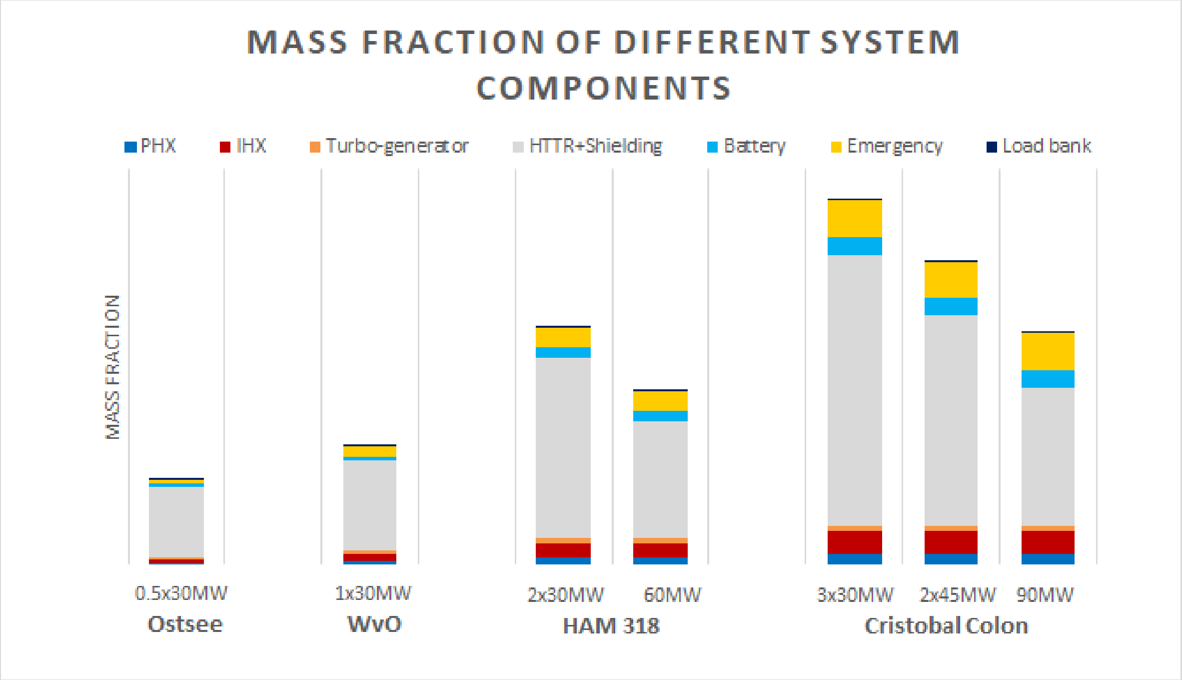


Figure 6.8: Mass Fraction of System Components

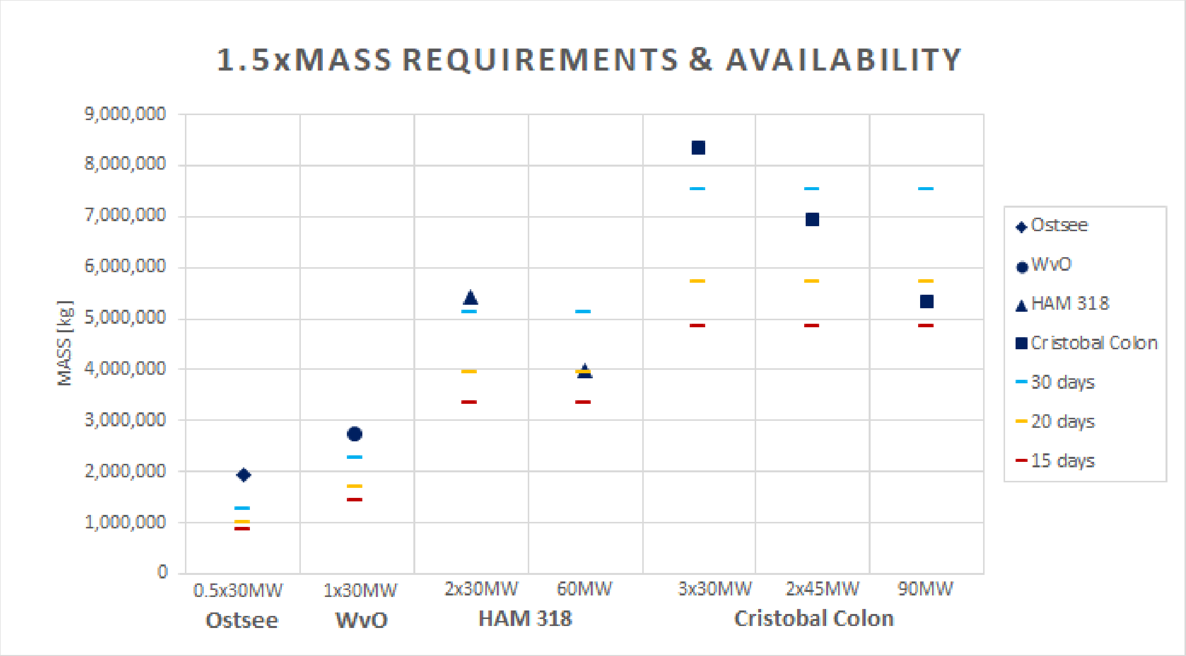


Figure 6.9: Mass Availability and effect of 50% increase in Mass requirements

The general trend is the decrease of mass fraction of the nuclear reactor and shielding as the hopper

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[2] $\frac{\textit{Mass of the component}}{\textit{Total Mass}}$

volume/ displacement of the vessel increases. For the same hopper volume/displacement (from 82% aboard OSTSEE to 74% for CRISTÓBAL COLÓN based on the 30 MW$_{th}$ different sized multiples of HTTR module). A design with a single reactor supplying the entire required power is better in this regards than a design with smaller modules.

To understand the sensitivity of the mass on the retrofittability, the mass was increased by 50%. The effect of this is shown in Figure 6.9. None of the 1 reactor system satisfy the mass availability constraints (for HFO-based design endurances till 30 days). However, the 2 reactor system design for HAM 318 and CRISTÓBAL COLÓN and the 3 reactor system design for CRISTÓBAL COLÓN satisfy the mass availability constraints.

6.3.2. Volume Requirements

Similar to the mass fraction, the volume fraction [3] is largest for the nuclear reactor and shielding. However, unlike the mass fraction, the nuclear reactor and shielding is not as dominant in terms of the volume fraction.

Volume requirements of nuclear-powered OSTSEE and WILLEM VAN ORANJE are more than the volume requirements for a HFO-based design of the dredgers with 30 days design endurance. However, nuclear-powered HAM 318 and CRISTÓBAL COLÓN have volume requirements which are a little less than the volume requirements for a HFO-based design with 30 days design endurance.

The volume requirements of the nuclear system are a bigger constraint than the mass of the system. For example, the mass requirements for three reactor system design of CRISTÓBAL COLÓN is lesser than the mass requirements for a 20 day endurance design (HFO-based), however, the volume requirements of the same nuclear design requires volume that is a little more than 30 day endurance design (HFO-based). This is also the case when 50% increase in mass requirements is considered (Figure 6.9).

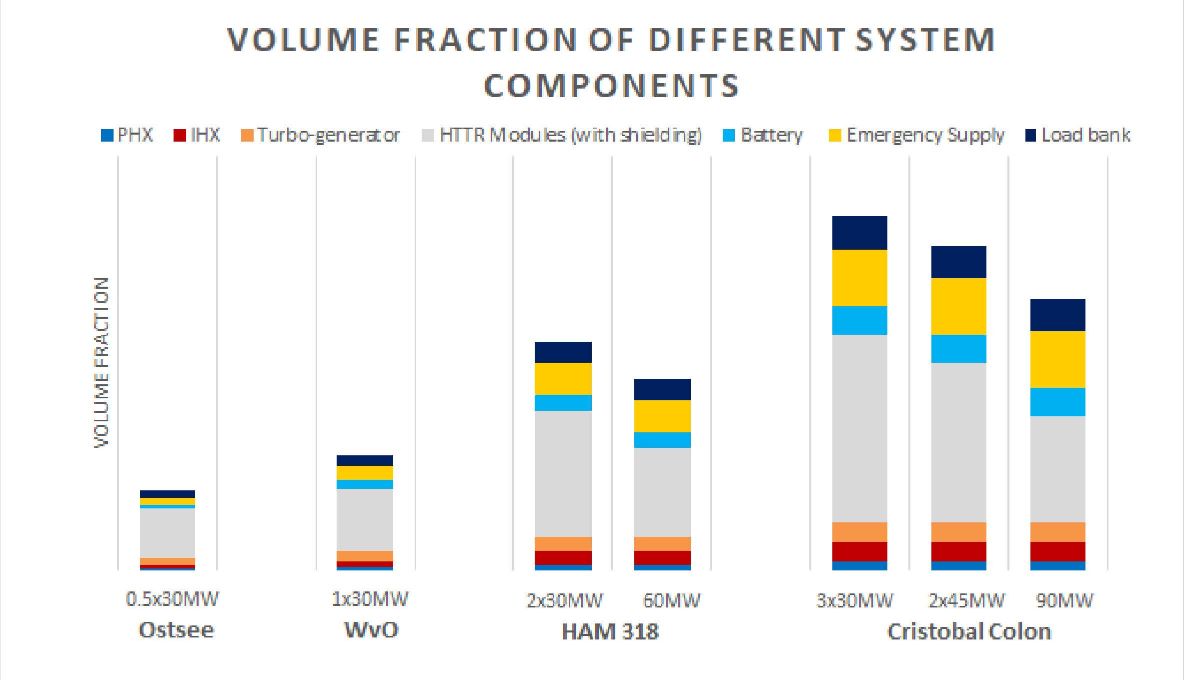

Figure 6.10: Volume Fraction of System Components

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[3] 4

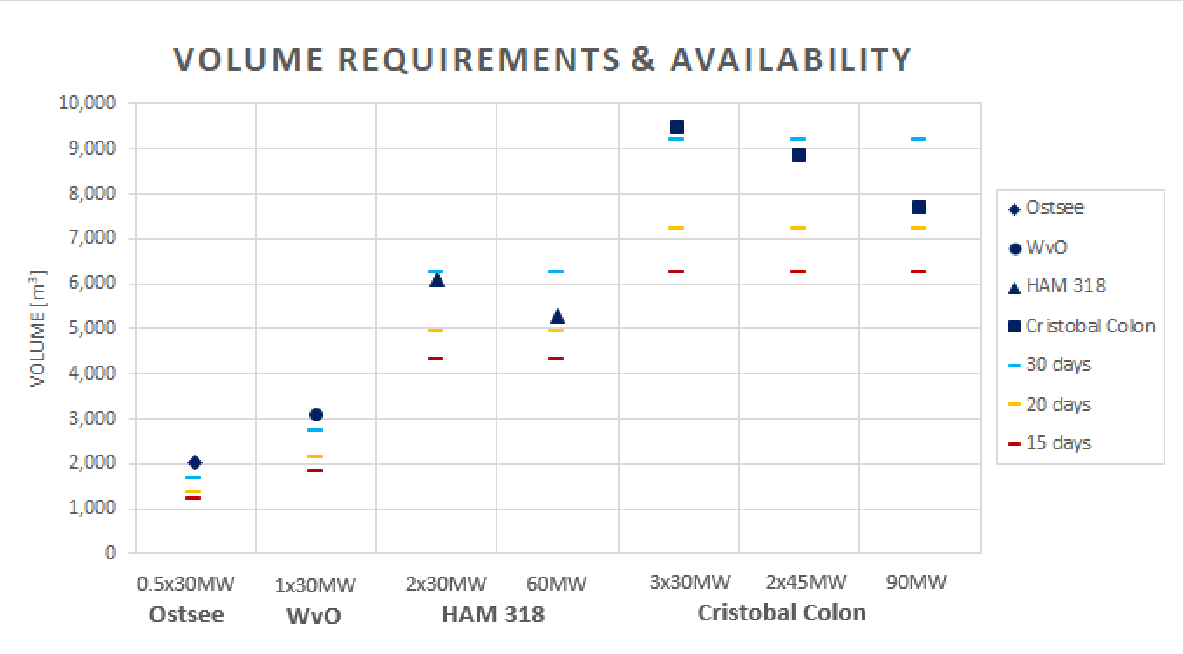

Figure 6.11: Total Volume Requirements & Volume Availability

For a HAM 318 sized dredger with an original endurance of about 22 days (HFO-based) has enough available volume and mass to be retrofitted with a nuclear system based on a 60 MW$_{th}$ scaled up version of HTTR. While for CRISTÓBAL COLÓN the same can be achieved for an endurance of 20.5 days with a single nuclear reactor design. The single reactor design is more efficient [5] when it comes to volume and mass requirements. For example, the volume requirements of HAM 318 with a 60 MW$_{th}$ nuclear reactor design are about 13% lower when compared with 2×30 MW nuclear reactor design. And for CRISTÓBAL COLÓN, a design with 90 MW$_{th}$ reactor when compared with 3×30 MW reactors, the volume requirements are about 24.5% lower.

6.4. Indirect Nuclear-based Systems : PEMFC and Batteries

It was realised that the use of PEMFC and Batteries as energy sources for the dredging vessels was sub-optimal for the performance and productivity in most cases. To understand the niche that Batteries or PEMFC systems could serve, if any, a deeper analysis was carried out.

6.4.1. 1 Day Operations (PEMFC)

Based on the energy requirements for 24 hours of operation (1 day), the mass and volume requirements of the PEMFC as energy sources for the dredging vessels was computed.

If the dredger WILLEM VAN ORANJE is fitted with a PEMFC-only system, the volume and mass requirements for 1 day of operations is given in Figure 6.12 and Figure 6.13 respectively. The volume and mass requirements for 1 day of operation of other dredgers (pure PEMFC-based) are given in Appendix Figures F.5 F.6 (HAM 318), Appendix Figures F.1 F.2 (OPTIMUS) and Appendix Figures F.9 F.10 (CRISTÓBAL COLÓN).

All the dredgers have similar trends and the instead of discussing them individually, a general explanation of the trends follows.

Volume Trends

The Fuel Cell volume w.r.t. the storage volume is maximum for liquid storage while this ratio is minimum for the Fuel Cell system with 60 bar compressed storage. The volume requirements of compressed

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[5] Although, provides redundancy.

storage based system decreases as the pressure of the stored hydrogen increases. There are no surprises there as the increase in the pressure increases the volumetric energy density. An interesting thing to note here is that the volume occupied by the 1000 standard litre (sl) hydride storage system is marginally lesser than the hydride storage system with bigger tank volumes. One of the possible reasons for this is the addition of the heat exchanger to the system [6].

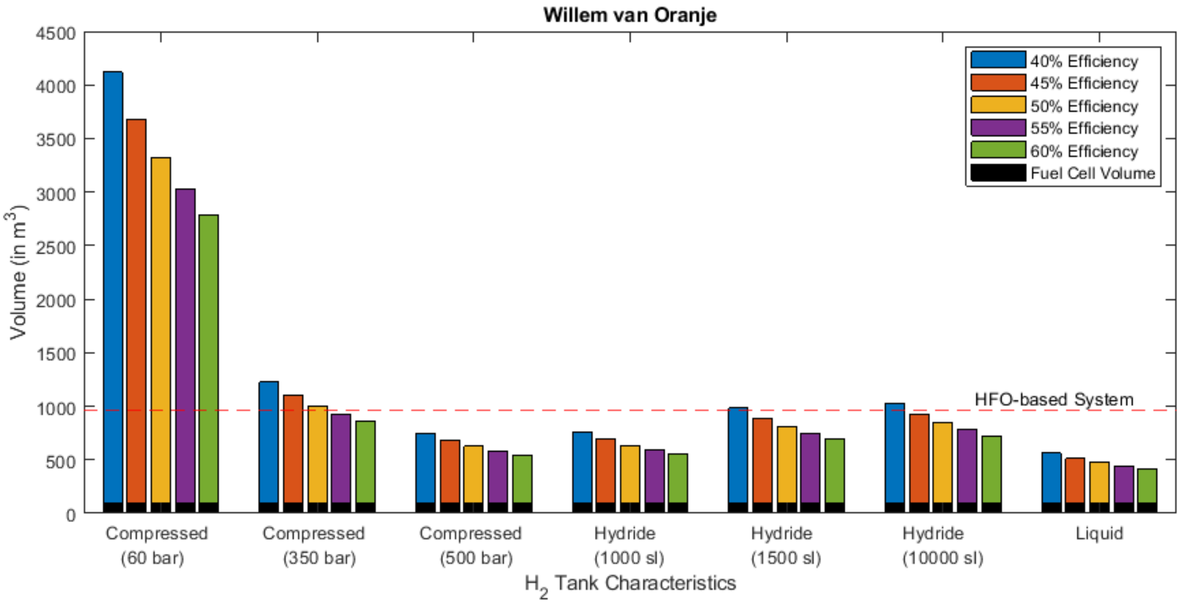

Figure 6.12: Volume requirements for various PEMFC systems for 1 day operations of WILLEM VAN ORANJE

Mass Trends

The mass of the 350 bar compressed storage based system is lower than mass of the 500 bar compressed storage based system. One possible reason for this is the vessel type. The 350 bar storage tank is a Type III vessel while the 500 bar storage tank is a Type IV vessel. Type IV vessels are manufactured to handle higher pressures of up to 700 bar while 350 bar is the maximum pressure limit for Type III storage vessels.

The mass requirements of the 10000 sl system is higher than 1000 sl system because of the added mass of the heat exchanger. The difference in the mass requirements of the 1500 sl and 10000 sl can be attributed to the size of the heat exchanger required for 10000 sl. The time required for the emptying/filling of 10000 sl is ~ 66 minutes while for the 1500 sl tank it takes 60 minutes. There's a 10% difference in the time for emptying/refilling between the 10000 sl and 1500 sl tanks but the difference in the volume is ~ 6.67 times. Therefore, the rate of heat rejection required for the 10000 sl is much higher and would require a higher heat exchanger area than a direct scaling up based on their volumes. This leads to the higher mass of the 10000 sl based hydride storage system.

The mass of the 1500 sl is lower than that of 1000 sl. The additional mass due to the heat exchanger seems to be compensated by the increase in the stored H_2 mass.

In terms of mass, compressed storage has at least twice lower mass than hydride storage.

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[6] Volumes equal to or above 1500 sl are provided with heat exchangers.

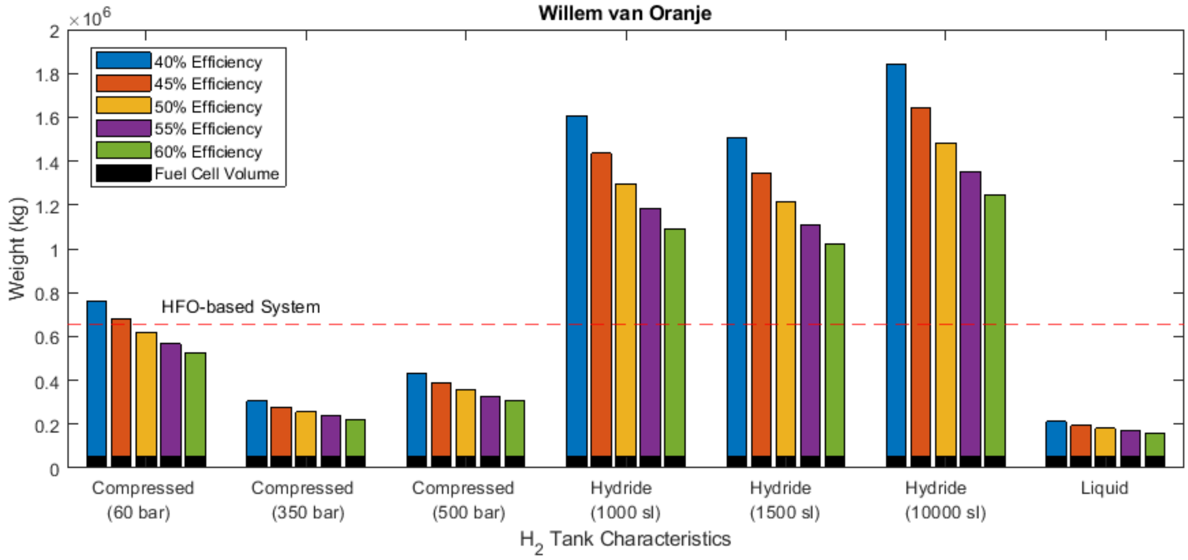

Figure 6.13: Mass requirements for various PEMFC systems for 1 day operations of WILLEM VAN ORANJE

Takeaway
Liquid storage based PEMFC system is by far the best choice (least value) in terms of the mass and volume requirements.

In terms of both the volume and mass requirements, the 500 bar H_2 storage is better than all the hydride storage that have been considered in this work.

In a vessel, having numerous arrays of small tanks would be undesirable because of the sheer amount of time and labour required while refueling. The bigger hydride tanks have bigger orifice sizes (in comparison to their volumes). This implies faster refilling/discharging. Hence, even though 1000 sl hydride storage is competitive to the 10000 sl storage, the bigger size tank is a better choice.

Similarly, having low energy density (volumetric or gravimetric) is an undesirable trait as it either increases the number of tank array required or constrains the performance of the dredger (due to the limited volume and space requirements). Therefore, the 500 bar compressed storage system is a better choice if PEMFC-based on compressed storage system is opted.

6.4.2. 1 Day Operations (Battery)

Based on the energy requirements for 24 hours of operation (1 day), the mass and volume requirements of the Batteries as energy sources for the dredging vessels was computed. If the dredger WILLEM VAN ORANJE is fitted with a battery-only system, the volume and mass requirements for 1 day of operations is given in Figure 6.14 and Figure 6.15 respectively. The volume and mass requirements for 1 day of operation of other dredgers (pure battery based) are given in Appendix Figures F.7 F.8 (HAM 318), Appendix Figures F.4 F.3 (OPTIMUS) and Appendix Figures F.11 F.12 (CRISTÓBAL COLÓN). All the dredgers have similar trends and instead of discussing them individually, a general explanation of the trends follows.

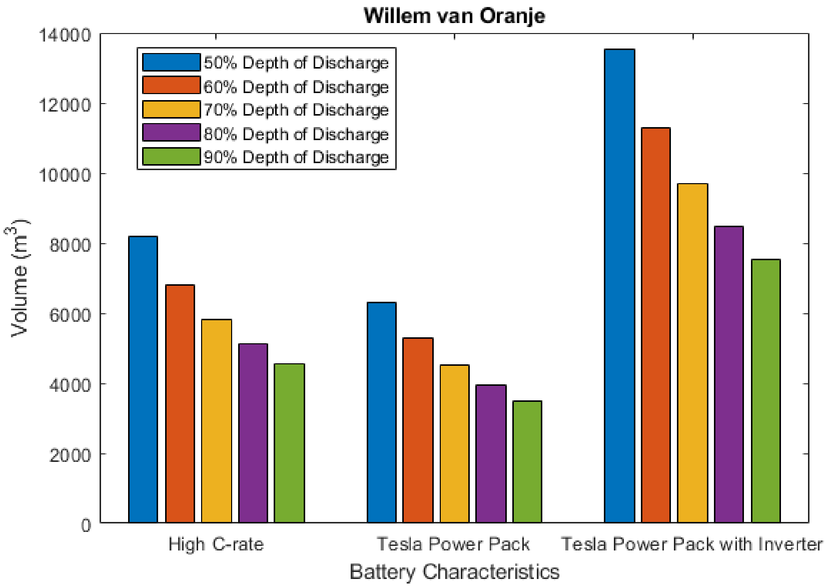

Figure 6.14: Volume requirements for battery based system for 1 day operations of WILLEM VAN ORANJE

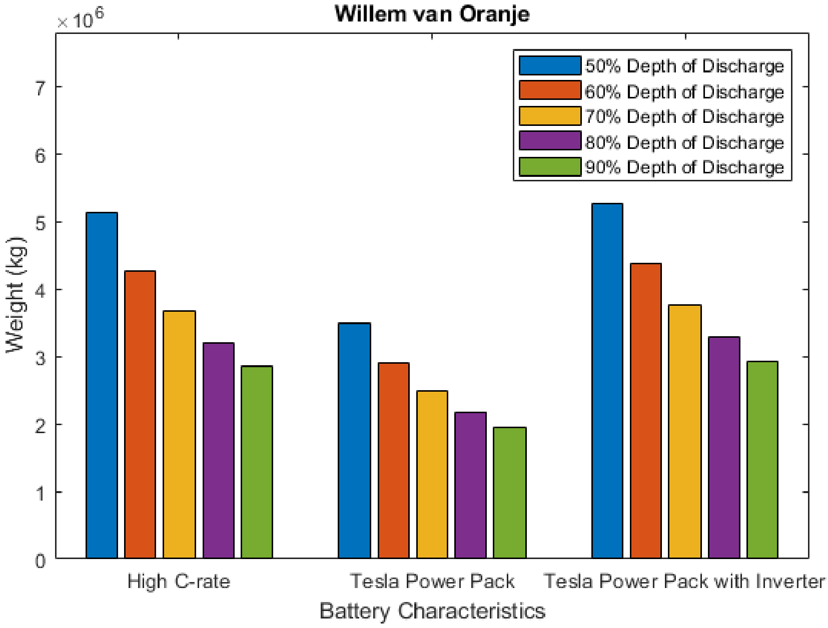

Figure 6.15: Mass requirements for battery based system for 1 day operations of WILLEM VAN ORANJE

Volume Trends

As the Depth of Discharge increases, more energy is available for disposal by each battery [7]. Hence, the volume and mass requirements decrease. The high C-rate batteries occupy more volume than the Tesla Power pack. This is because the Tesla batteries are 0.5 C-rated batteries and can be classified as ”low C-rate batteries”. Low C-rate batteries have higher energy densities in comparison to high C-rate batteries. In case, a DC grid cannot be used aboard the vessel (possible reason could be the non-availability of compatible motors), the third group of column shows the volume requirements of the compatible bidirectional inverter of Tesla Power pack. For the same discharge of depth, the addition of an inverter approximately doubles the volume requirements of the system. Such a system is about 50% bigger than a system made of only high C-rate batteries. Each Tesla Powerpack comes

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[7] However, this also reduces the life of the batteries.

with its own bidirectional inverter. An array of such units (battery+bidirectional inverter) would make a battery-based system that can operate on AC grid. A large bidirectional inverter can also be considered and would possibly have lower mass and volume requirements.

Mass Trends
Similar to the trend for volume, the mass decreases as the depth of discharge increases. Mass-wise, the addition of a bidirectional inverter is not very prominent. The mass of the high C-rate batteries is about 12% higher than Tesla Powerpack with bidirectional inverter.

Takeaway
Low C-rate batteries are better in terms of the volume and mass requirements (~30% lower). However, the ability of these batteries to be able to cater the surge in the power requirements (common in TSHDs) is not clear.

6.4.3. Volume Requirements (10-day operation)

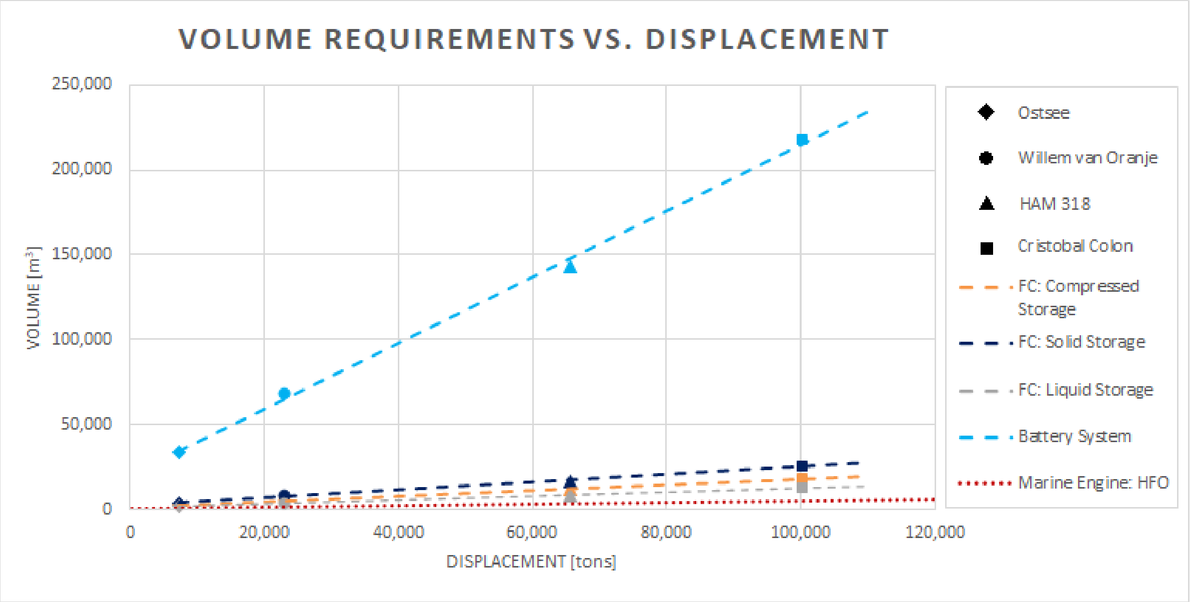

Figure 6.16: Required Volume (10 day Endurance) vs. Displacement for different energy sources

The endurance of a dredging vessel can vary from a day to 30+ days. The volume requirements for a purely Fuel Cell or Battery-based system for an endurance of 10 day operation was determined for all the vessels. For the determination of the volume requirements, the Fuel Cell has been taken as 45% efficient and the batteries have 60% DoD.

The net tonnage is related to the hopper volume of a dredging ship. Further, the net tonnage of the dredging vessels shows a good correlation with the displacement of the vessels as shown in Appendix Figure D.10 and Appendix Figure D.11. Since, Displacement of a vessel is more relatable metric in marine engineering, the displacements of the four dredgers were calculated (See Appendix D.7). A scatter plot with the vessel displacement and the volume requirements for 10 days operation along with the available volume (HFO-based operation) is shown in Figure 6.16.

In Appendix F.15, the volume requirements w.r.t. displacement are represented as a log-linear plot and the various trendlines resemble a logarithmic growth curve.

None of the technologies (PEMFC with liquid/compressed/solid storage and battery based system) has volume requirements comparable to the HFO-based system for an equivalent endurance of 10 days. PEMFC based on Liquid storage of OSTSEE comes closest to the volume constraints of a HFO-based system. There is almost a 100x factor difference in the volume requirements of the HFO-based system and battery based system for an endurance of 10 days. Hence, all the systems with the four dredgers require more volume than an HFO-based system with a capability of 10 day endurance.

Similar to the volume constraints, another constraint is the on board availability of mass. A scatter plot with the vessel displacement and the mass requirements for 10-day operation along with the available volume (HFO-based operation) is shown in Figure 6.17.

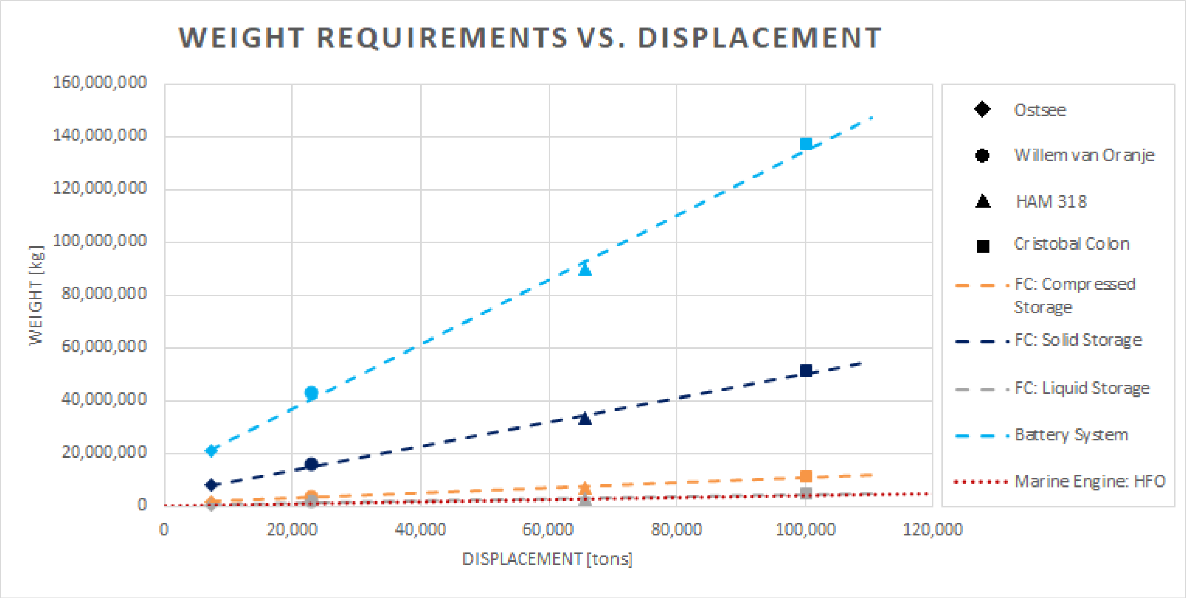

Figure 6.17: Mass Requirements (10 day endurance) vs. Displacement for different energy sources

There are four instances (PEMFC system with compressed storage and liquid storage for OPTIMUS and PEMFC system with liquid storage for WILLEM VAN ORANJE and HAM 318) where the retrofitted system does better than the original dredger in terms of mass requirements to the mass requirements of the HFO-based system. While at two other instances (PEMFC system with compressed storage for WILLEM VAN ORANJE and PEMFC system with liquid storage for CRISTÓBAL COLÓN), the retrofitted system performs very close to the HFO-based system.

It is clear from the above discussion that the volume requirements are a bigger constraint than mass requirements for all the systems except for solid hydride storage where mass is a bigger constraint than volume. With the exception of solid hydride storage system, the endurance of the vessel is affected by the maximum available volume for the retrofitting of the PEMFC or battery systems and not the mass.

6.4.4. Probable Endurance (Volume-constrained)

Now, the next task was to understand how much of endurance can be expected from a dredger operating within the constraints of the available volume. For this, the volume was limited to the volume available from designs with 15 days of endurance (HFO-based operation) and the PEMFC (different storages) and Battery system are fitted into the space. Then, the endurance of the vessels was calculated based on the volume-constrained system [8]. The approximate endurance that the vessels are capable of achieving as a function of different displacements is given in Figure 6.18. Like the case with the volume requirements for 15 days of endurance, the Fuel Cell have been taken as 45% efficient and the batteries have a 60% DoD.

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[8] This is essentially reverse of what is explained in 5.6.2 and 5.6.2. See D.10 for more.

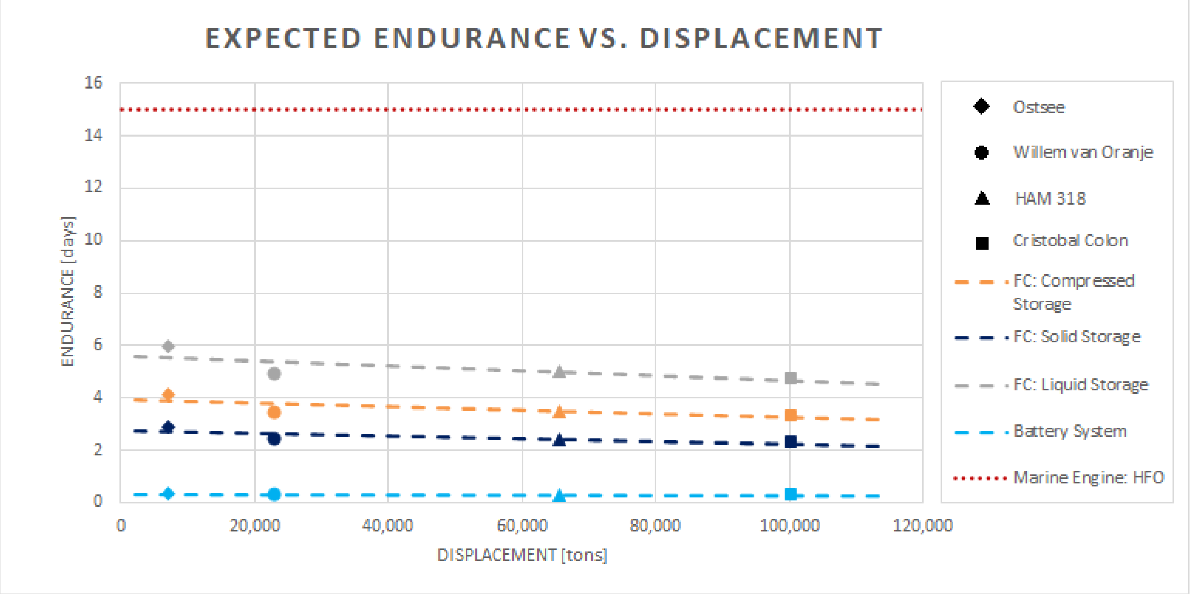


Figure 6.18: Endurance vs. Displacement (Available Volume constrained at 15 day endurance of HFO-based system

For a retrofit based on 15 day original endurance design, the expected endurance decreases slightly as a function of increasing displacement. Inline with the volume requirements (Figure 6.16), the endurance is highest for liquid storage based system (~ 5.5 days) and the lowest expected endurance is for battery based system (~ 6 hours).

6.5. Retrofit Maps

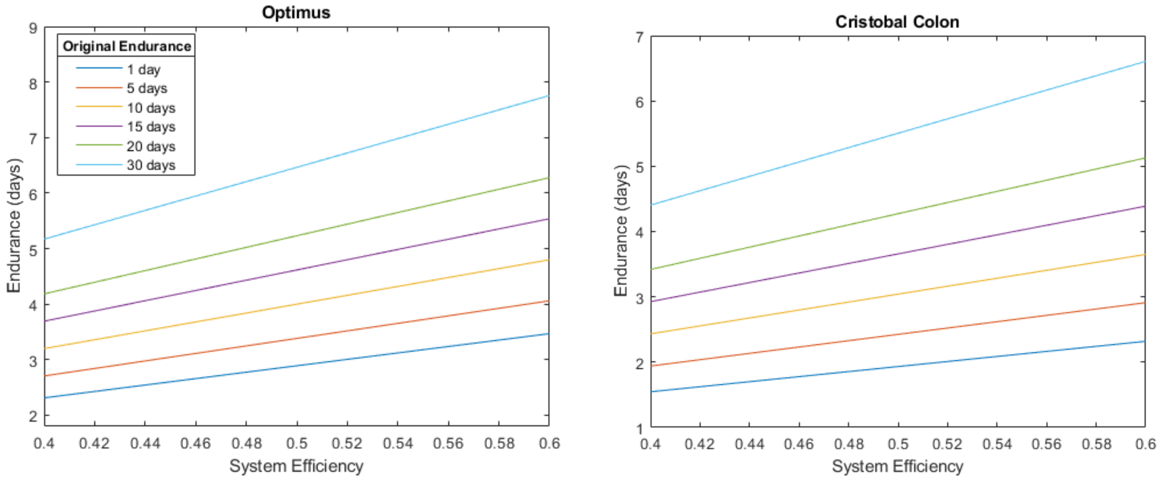
The expected endurance of the PEMFC system or battery system of Figure 6.18 and Figure 6.17 were based on some parameters (volume/mass availability based on 15-day endurance of a HFO-based system, 60% DoD for batteries and 45% system efficiency for the Fuel cell system). This exercise would have to be repeated a number of times to produce such graphs for knowing the approximate endurance of the retrofitted system at different parameters (different DoD, different system efficiency and volume availability based on n days endurance of a HFO-based system).

It was realised that it is interesting as a TSHD designer/decision maker to know what would be the approximate endurance of a dredger vessel when it is retrofitted with particular power generation technology and storage type. For PEMFC, the H_2 storages that were considered are the 500 bar compressed storage, 10000 sl hydride storage and liquid storage. The selection of these three specific storage technologies was based on their superior performance (Figure 6.12 and Figure 6.13). The utility of these maps is in having a quick reference to the expected endurance of a retrofitted vessel based on the retrofit technology used, system efficiency and the original design endurance.

For a Fuel Cell/Battery-based system, the volume and mass constraints/requirements are decided by two factors : endurance and the peak power requirements. After a retrofit, the power requirements would remain unchanged irrespective of the original endurance of the vessel. Therefore, the volume and mass constraints of the dredger vessel are decided by the original endurance only. Using these constraints, the volume and mass of the fuel cell and battery system were ascertained. This would be essentially reverse of what was carried out in 5.6.2 and the methodology is presented in Appendix D.10.

Maps were made where the new endurances for a dredger vessel can be determined as a function of system efficiency and the original design endurance (HFO-based) of the vessel. The x-axis represents the system efficiency or DoD (in case of battery based systems) and the y-axis represents the endurance of the system. Six original design endurances (in different colors) are considered for each vessel. 'sky blue' color indicates a vessel with an originally designed endurance of 30 days, 'red' color indicates a vessel originally designed for endurance of 20 days and so on. The retrofit maps for the four dredgers (combined) powered by PEMFC system and compressed. hydride & liquid H_2 storage is given in Appendix Figures F.20, F.21, F.22 respectively. The qualitative trends are very similar and the expected endurance of the vessel decreases as the vessel displacement increases. Trends for retrofit maps are discussed for two dredgers : OSTSEE (smallest TSHD considered in this work) and CRISTÓBAL COLÓN (currently the largest TSHD in the world) in the following discussions covering systems based on PEMFC (compressed, solid and liquid storage) and Battery-based system.

System : PEMFC with compressed H_2 storage



(a) (b)

Figure 6.19: Retrofit Map for PEMFC System with Compressed Storage

The retrofit maps for the dredgers powered by PEMFC system and 500 bar compressed H_2 storage is given in Figure 6.19. Discussion on the trends for each of the dredger follows.

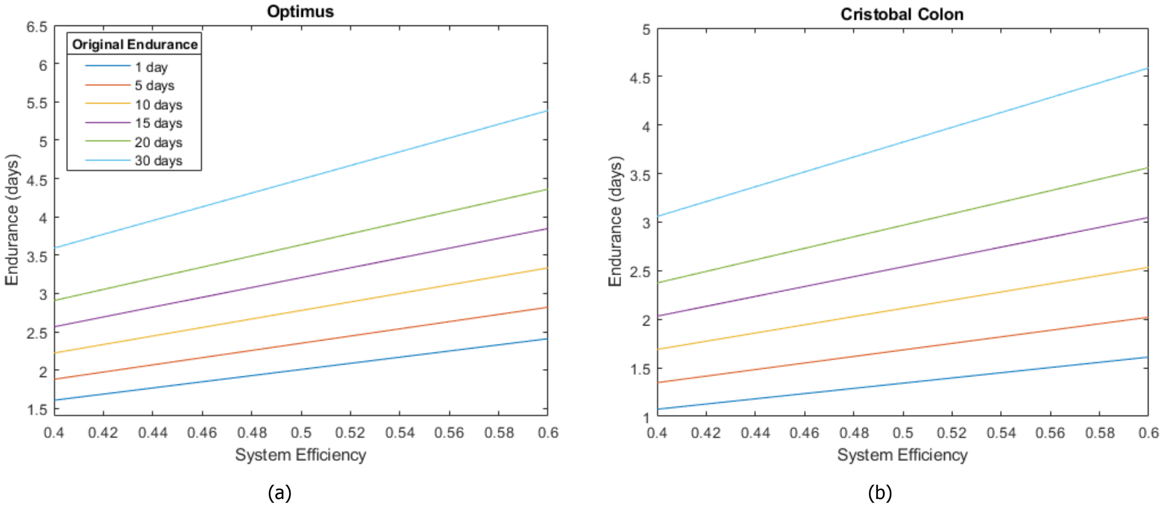
OPTIMUS

For a dredger the size of OPTIMUS (original endurance of up to 1 day), the PEMFC with compressed storage system delivers far better results than a fossil fuel based system. In general, dredgers the size of OSTSEE are used for works that require endurances of less than 5 days. The red colored line reaches a maximum of 5 days at 60% efficiency the system with compressed storage. The PEMFC system with compressed storage for an OPTIMUS sized dredger with an original endurance of 5 days or more cannot deliver the same performance as a fossil fuel based system (for any efficiency).

CRISTÓBAL CÓLON

A retrofitted dredger the size of CRISTÓBAL CÓLON is generally designed for 15+ days of endurance. If the original design endurance is 5 days, the maximum endurance (even at 60% system efficiency) is around 4 days. Only if the dredgers had been designed for 1 day endurance, the PEMFC system with compressed storage performs better volumetrically than a fossil fuel based system.

System : PEMFC with Hydride Storage



(a) (b)

Figure 6.20: Retrofit Map for PEMFC system with Solid Storage

The retrofit maps for the OSTSEE and CRISTÓBAL COLÓN powered by PEMFC system and 10000 sl hydride based H_2 storage is given in Figure 6.20. Inline with the insights from 6.4.1, the performance of the hydride storage based system is marginally worse than the 500 bar compressed storage system. Discussion on the trends for each of the dredger follows.

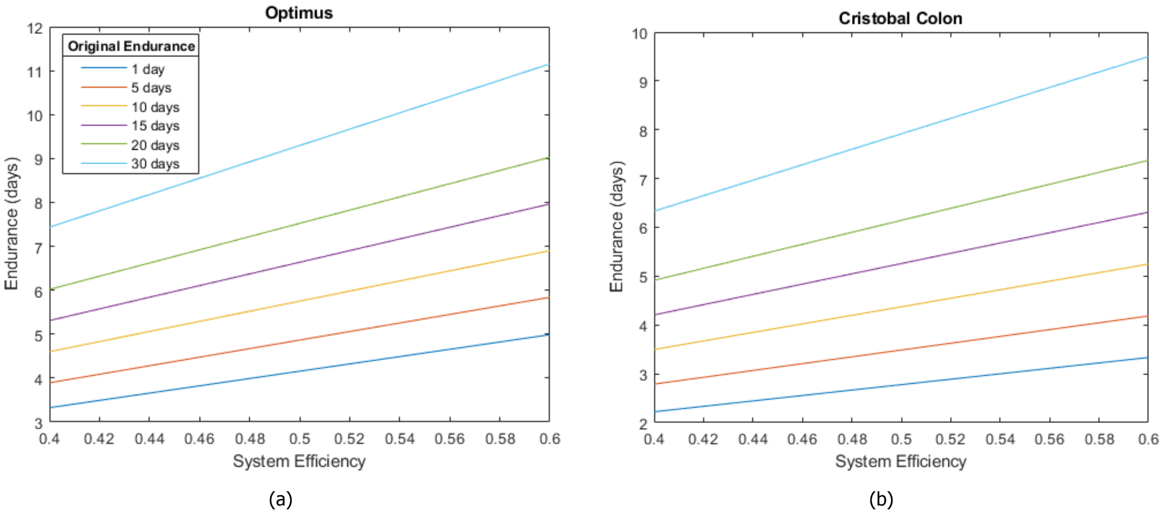
OPTIMUS

For a dredger the size of OPTIMUS (original endurance of up to 1 days), the PEMFC with hydride storage system delivers better results than a fossil fuel based system (at all system efficiencies). If the original design endurance is 10 days, PEMFC with hydride storage reaches an endurance of around 3.5 days. In a best case criteria, an endurance above 5.5 days is not reachable even if the original design endurance is 30 days.

CRISTÓBAL CÓLON

For a retrofitted dredger the size of CRISTÓBAL CÓLON, the maximum endurance of such a vessel designed for 30 days as original endurance is a little above 4.5 days. Only if the dredgers had been originally designed for 1 day endurance, the PEMFC system with compressed storage performs equally (at 40% system efficiencies) or better (at higher system efficiencies) volumetrically when compared to fossil fuel based system.

System : PEMFC with LH_2 Storage



(a) (b)

Figure 6.21: Retrofit Map for PEMFC system with Liquid Storage Fuel Cell

The retrofit maps for the OSTSEE and CRISTÓBAL COLÓN powered by PEMFC system and liquid H_2 storage is given in Figure 6.21. Inline with the insights from 6.4.1, the performance of the liquid storage based system is far superior than the 500 bar compressed storage or hydride storage system. Discussion on the trends for each of the dredger follows.

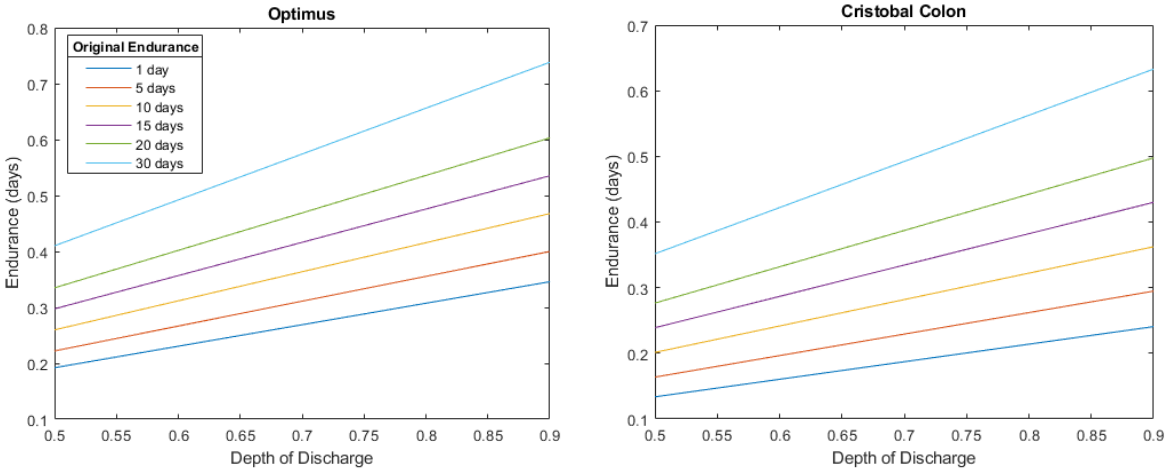
OPTIMUS

For a dredger the size of OPTIMUS (original endurance of up to 5 days), the PEMFC with liquid storage system delivers equal or superior endurance. But if the original design endurance is 10 days, the available space falls short and a maximum endurance of around 7 days is possible . While if the original design endurance is 30 days, the maximum endurance is around 11 day.

CRISTÓBAL CÓLON

For a retrofitted dredger the size of CRISTÓBAL CÓLON (designed for an original endurance of 30 days, volumetrically there's space to fit only a system that has an endurance of a little above 9 days. However, if the dredger had been designed for 1 day endurance, the PEMFC system with liquid storage can last at least for 2 days.

System : Battery-based



(a) (b)

Figure 6.22: Retrofit Map for Battery Systems

The retrofit maps for OSTSEE and CRISTÓBAL COLÓN powered by battery systems is given in Figure 6.22. It is assumed here that there are no constraints in the implementation of a DC grid. Therefore, there is no need of a bidirectional inverter and only high C-rate battery systems are considered.

OPTIMUS

For a dredger the size of OPTIMUS, a Depth of Discharge of around 90% still does not achieve one day of endurance if the original design endurance was 30 days. However, if the original design endurance was 1 day and the Depth of Discharge is 50%, the dredger has an expected endurance of ~ 4.5 hours. The expected endurance is 50% of the expected endurance when original design endurance is more than 30 times!

CRISTÓBAL CÓLON

For a retrofitted dredger the size of CRISTÓBAL CÓLON, the expected endurance is slightly lower and is inline with other previously discussed powering options. For an original design endurance of 20 days with batteries operating at 90% DoD, the maximum achievable endurance is around 13 hours.

7

Safety, Sustainability, & Economics

Section 7.1 collates data on accidents relating to dredgers, possible events and some of the safety features of nuclear-powered vessels. Water and air ingress in a HTGR and the threshold temperature to prevent runaway is discussed. Decay heat from the reactor is covered next. Section 7.2 covers in brief the public acceptance, fuel related aspects (requirements and availability), decommissioning, nuclear wastes and emissions (thermal NO formation and decomposition of CO_2). Section 7.3 discusses on some necessary infrastructural requirements like home port, service vessel, permanent repository etc. Section 7.4 examines the calculation of value of conventional TSHD vessel (CIRIA 2005 Methodology), insurance premiums including nuclear third-party liability, heat exchanger and decommissioning costs.

7.1. Safety

With 0.01 deaths per TWh [335] [1], nuclear energy source is better than other low-carbon energy sources (including wind, solar, hydropower and biomass). Dredging is an essential maritime activity but it brings with it, its own set of risks and hazards. Accidents generally tend to occur near shore or in shallow waters due to the type of activity dredging entails. For public acceptance, this nuclear-powered dredging dredger must be safer than a conventional powered dredger.
To understand the possible events that can cause damage to the reactor, the starting point would be to look at the accidents and incidents that have endangered the safety of dredgers in the past. Shipping accidents are supplied by IHS Markit's data [336]. The accidents specific to dredgers for year 2018 are tabulated in Table 7.1

Table 7.1: Shipping accidents involving Dredgers

	Capsizing	**Collision***	**Stranding**	**Foundering/Sinking**
Suction Dredger	1	1	2	1
Suction Hopper Dredger	1	-	1	-
Trailing Suction Hopper Dredger	-	1	1	-

*Includes with another vessel or another object for example pillar

Capsizing, collision, stranding, foundering are all possibilities. In the year 2018, specific to TSHD, only collision and stranding were reported. Minor damage was reported in all the accidents involving TSHDs. Some other dredgers reported partial sinking. However, drawing conclusions from a single year might not be apt. More in-depth analysis is needed and required data can be found on IMO [337] Lloyd's Register [338] [339]. The accidents over a longer time period (50 years) involving dredgers can be filtered out and analysed. A better judgement can be made with such an analysis. However, such an exercise is beyond the scope of this work and left for a future work.

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[1] Number is based on deaths from accidents between 1950-2014 for land-based nuclear power plants (inclusive of the fuel cycle). No updated numbers for nuclear naval propulsion could be found.

7.1.1. Possible Events

The safety requirements depends on the possible events and the risk [2] these events pose. Some possible safety issues and their solutions for cargo ships have been discussed earlier [10]. Some of the possible events that can occur during the life of the nuclear dredger are discussed briefly.

Stranding

Stranding can lead of hull deformation and expose the reactor esp. in case, of reactor integration to the hull. One possible solution could be reactor placement onto some sort of pedestal [10].

Hull penetration

Engine room flooding is a possibility and the presence of another electric supply would be handy [3]. It is to be noted here that the chances of an incident with another ship are low due to restriction to special access lanes via transit. Further, the speed of the vessel in and around harbours is slow to cause much damage.

Capsizing and Sinking

Uneven load distribution in the hopper or damaged compartments can result in the vessel to heel to one side and possible flooding or sinking. A flooded reactor compartment can cause water to puncture into the primary loop and cause water ingress.

Fire

Fire outside of the reactor can cause thermal stress and lead to material failure. Appropriate fire retardant coatings and fire suppressant systems (for example automatic N_2 or CO_2 extinguisher systems) should be available in the reactor compartment. Water sprinklers should be avoided in the reactor compartment as far as possible.

Security threats

The act of sabotage or attack would be symbolic in nature. The inherent safety of the HTGR on loss of coolant and other incidents, substantially reduces the chance of release of even a small amount of radioactive material. Nonetheless, the ingenuity of some humans to find ways of causing destruction cannot be discarded. Hence, analysis of various accidents in detail should be carried out. Human-initiated events that are important in context of nuclear-powered dredger are terrorism attack, sabotage and deliberate accidents. A nuclear engineering trained sabotager/terrorist might be able to bypass the safety measures and cause an excess reactivity in the nuclear reactor. The possibility of bypassing safety measures should be eliminated (without ramifications on the safety itself) .

Salvageability

If the vessel is lost, it should be possible to salvage the reactor safely without causing any pollution to the environment. There are two possibilities :

- Salvaging a floating reactor
- Salvaging from wreck

Salvaging a floating reactor would require a way to keep the reactor afloat and dislodging of the reactor from the interior of the vessel. Jacobs [10] proposed the development of fast inflating cushions (like airbags in cars) and creation of overpressure for ejection of the reactor from the ship structure to achieve the same. However, to ensure the possibility of the solution working in all conditions and the effect of the radiation on the cushion material needs to be ascertained before such a solution is applied.

The salvagibility from the wreck can be further ensured if the structure can handle the compressive stress and not fail. This can be compared to a submarine in dived condition. For every 10 metres, the external pressure rises by 1 bar. Depending on the location of the operation (which decides the depth), the vessel can be manufactured to resist the external pressure. In such a condition, the longitudinal compressive stress on the submarine hull is given as per Equation 7.1 [340].

$$Longitudinal\ Compressive\ Stress = \frac{External\ pressure \times Radius\ of\ pressure\ hull}{2 \times Thickness\ of\ pressure\ hull\ plate} \tag{7.1}$$

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[2] Quantified by probability of an events occurring and the damage of the outcome

[3] A mandatory requirement as per regulations

Wrap up

The intensity of intentional/unintentional harm that can be caused due to SMRs/MMRs based on HTGR technology is low. Mainly, the deliberate ingress of large quantities of air and water has the potential to cause damage to the reactor and vessel. In addition to nuclear reactor specific SCRAM measures, automatic SCRAM and activation of auxiliary cooling system should be considered for excess heel angles, abnormal accelerations (indicating being hit) etc.

7.1.2. Safety Features of Nuclear-powered Vessels : Past and Present

Because of the shared nature of the possible events, some of the safety features that had been part of the Merchant Nuclear Vessels/are part of the naval nuclear vessels can be extended to Nuclear Dredging vessel.

Pacific Nuclear Transport Ltd. is the largest transporter of spent fuel, vitrified high level waste nuclear material[4] and MOX fuel assemblies [341]. They regularly undertake transport between Europe and Japan. Established in 1975, they have a fleet of three vessels that are specifically built for handling nuclear cargo. The vessels have 2 collision bulkheads [341]. The double hulls are further reinforced with 20 mm steel plates to withstand collision damage [342]. The vessels are fitted with naval cannon and in some cases also have armed officers on-board [343].

Some of the safety features that were incorporated in NS SAVANNAH are in public domain [344]. Summarised, these safety features are :

- Two compartment standard of subdivision [5].
- Diesel power generator and forced circulation steam boilers for emergency propulsion.
- Steel containment shell capable of withstanding rupture of main coolant pipe.
- Ability to withstand collision without damage to nuclear reactor compartment to > 98% of the world's merchant fleet [6].
- Stiffened and heavier than required ship structure.
- In case of sinking, automatic flooding of containment and valves that close upon pressure equalisation.
- Connections were provided to allow for purging of containment or filling with concrete (in case of non-salvageability).

Other safety features that were considered in other vessels are :

- For SEVMORPUT, the possibility of a passenger aircraft crashing or collision with the reinforced bow of an icebreaker or running aground were considered in the design [144].
- NS OTTO HAHN had two oil fired water tube boilers as backup. To prevent penetration into the structure, NS OTTO HAHN had "cutting decks" [7].
- AKADEMIK LOMONOSOV has crumple zones for withstanding hit from a laden cargo vessel. The FPU has been built to survive a 10,000 year storm [346]. The barge's bows are built for cutting through the waves, anchors are attached to swivelling "mooring turrets" and always point to the wind or remain bow-on to the waves.

Watertight doors and valves (flapper type in ventilation lines and stop valves in piping) can ensure the integrity of watertight internal compartments. Further, the concrete outer shell of the nuclear power plants is strong enough to resist anti-tank rockets. This has been proven during attacks on Superphoenix breeder reactor [347].

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[4] liquor for reprocessing of spent nuclear fuel is converted into borosilicate glass in UK

[5] Even with two main compartments flooded, the ship remains afloat.

[6] A ship moving at a speed of 15 knots does not penetrate the containment [161].

[7] ridged decks would cut an incoming object into pieces, creating a larger surface resulting in less penetration [345]

7.1.3. Water and Air Ingress

The HTGRs use graphite and are in general, undermoderated. The ingress of air and water is a red flag for such a reactor.

Air ingress can become a major issue and lead to graphite corrosion. Below 400°C, there's negligible oxidation of the graphite. However, graphite fire is self-sustaining at 550°C [348]. The oxidation can lead to formation of CO and CO_2 as per the Equation 7.2 and Equation 7.3 respectively.

$$\mathrm{C} + \mathrm{O_2} \longrightarrow \mathrm{CO_2} \quad \Delta\mathrm{H} = -393.5\,\mathrm{kJ/mol} \tag{7.2}$$

$$2\,\mathrm{C} + \mathrm{O_2} \longrightarrow 2\,\mathrm{CO} \quad \Delta\mathrm{H} = -110.5\,\mathrm{kJ/mol} \tag{7.3}$$

Water ingress is a possible eventuality and presents a more complicated scenario than air ingress. There are two effects related to water ingress, graphite corrosion and positive reactivity insertion [8]. Depending on the rate of water ingress, the positive reactivity insertion can be compensated by the negative temperature reactivity feedback. However, the graphite can overheat and fuel damage can occur if water vapour density increases above a certain limit and control rods are not operated [349]. When exposed to water, graphite exhibits an endothermic and an exothermic reaction (Equation 7.4 and Equation 7.5). Both of these reactions are negligible below 800°C.

$$\mathrm{C} + \mathrm{H_2O} \rightleftharpoons \mathrm{CO} + \mathrm{H_2} \quad \Delta\mathrm{H} = 131.5\,\mathrm{kJ/mol} \tag{7.4}$$

$$\mathrm{C} + 2\,\mathrm{H_2O} \rightleftharpoons \mathrm{CO_2} + 2\,\mathrm{H_2} \quad \Delta\mathrm{H} = -82.4\,\mathrm{kJ/mol} \tag{7.5}$$

However, there are two other reactions that are also possible and this makes HTGR-water ingress into at least four simultaneous reactions affecting each other [350].

$$\mathrm{CO} + \mathrm{H_2O} \rightleftharpoons \mathrm{CO_2} + \mathrm{H_2} \tag{7.6}$$

$$\mathrm{C} + \mathrm{CO_2} \longrightarrow 2\,\mathrm{CO} \tag{7.7}$$

The exact kinetics and the values depend on the type of graphite and its microstructures. The corrosion rate becomes constant after 180 s and decreases eventually. In the reactions from Equation 7.4-7.6, an inflection point exists at 1300°C (corrosion controlled entirely on temperature), for the corrosion rate [351] after which corrosion rate increases. CO_2 is bled into the RPV upon a depressurisation accident in AGRs to prevent air ingress [348]. To prevent chimney affect, the ducts (inlet/outlet) are placed at the bottom of the RPV.

7.1.4. Decay Heat

Even after a complete shutdown of the nuclear reactor, heat still gets produced due to the decay of the new nuclides that are produced in the fission process [9]. Most of the heat in this decay can be attributed to the beta and gamma radiation. SCALE/ORIGEN-ARP code can be used to calculate the decay heat rates for specific fuel composition and burnup. However, a rough approximation attributing a single half-life for the overall decay is realisable by using the Way-Wigner formula [352]. This approximation is valid best 10 seconds to several months after shutdown [353]. The approximation is given by Equation 7.8.

$$P_D(t) = 0.0622 \times P_0 \times [t^{-0.2} - (t_0 + t)^{-0.2}] \tag{7.8}$$

where,

$P_D(t)$ = Thermal power due to beta and gamma rays
P_0 = Thermal power before shutdown
t_0 = Time at the thermal power level before shutdown (s)
t = Time since shutdown (s)

The decay heat is a function of the thermal power, time elapsed after shutdown and time period at the thermal power level before shutdown. For a nuclear reactor running for an infinite time at a specific

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[8] For more, see Appendix C.15.

[9] Neutronic power is not considered as after the first 100 s it reduces to a negligible value.

thermal power level, the production of decay heat over time is presented in Figure 7.1. In the first 500 seconds, there is a steep decrease in the heat (~3.5x) decay heat falls by more than 4 times and in 2000 seconds, the decay heat falls by almost 9 times.

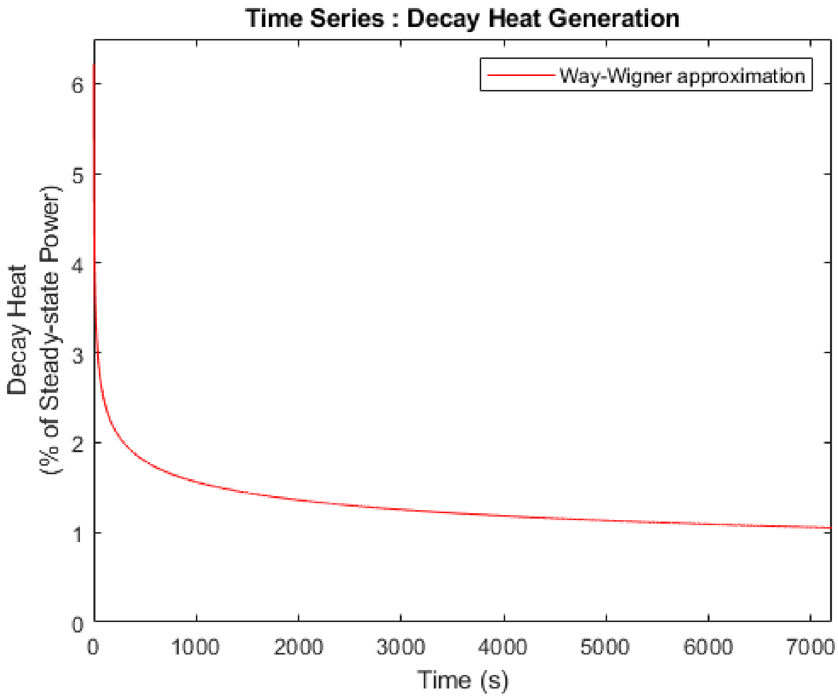

Figure 7.1: Decay heat generation 2 hours post shutdown

It is clear that the need for heat removal is especially important in the first few minutes. The modular HTGR core has high surface area to volume ratio. This allows for a design such that natural circulation enabled cooling is enough to remove the decay heat and cool the RPV. A Reactor Cavity Cooling system achieving passive cooling of the reactor vessel by naturally circulated air through cooling panels on the reactor walls has been proposed and designed earlier [354].

A reduced core temperature substantially reduces the reaction between seawater and graphite (in case of water ingress after sinking). Hence, the removal of decay heat becomes very important in case the ship starts to sink. An arrangement where Emergency cooling pumps (utilising seawater) can be connected to the cold side of the intermediate/primary heat exchangers can set natural circulation inside the heat primary pressure boundary. The reactor pressure vessel and components of primary pressure boundary must be designed to not rupture under external compression. If that is the case, then even after sinking, the removal of the decay heat would continue through seawater acting as the ultimate heat sink. Possible buildup of pressure due to steam generation should be taken into consideration in the design.

7.2. Sustainability

Few things polarise the opinion as much as the sustainability (or un-sustainability) of nuclear energy. While some believe that it is sustainable and should be part of the energy mix [355] [356], some are completely against it [357]. The truth possibly lies somewhere in between. Nuclear technology cannot guarantee unlimited energy like the sun or the wind but offers a medium-term solution for the resolution of the climate crisis, possibly the biggest adversity humanity has ever faced.

Sustainability as per Oxford Dictionary is defined as the ”the quality of being able to continue over a period of time.” It is a complex concept. The most often quoted definition of sustainable development is from the World Commission of Environment and Development’s report titled ”Our Common Future”

[358] [10] that was released in 1987 :

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

There are three pillars of sustainability. These are economic, environmental and social. True sustainability is achieved only when all of these three pillars are balanced. In general, the environment is the most focused upon pillar. Emissions, waste reduction, wastewater or other actions directed at reduction of the environmental impact form the core of activities that form this pillar. The social pillar is related to the support of the stakeholders and society. Economic sustainability is the strategy to utilise the resources in their most efficient and responsible way to provide long-term benefits and sustained profits. This is the premise of economic pillar. To analyse all of the pillars and their subdivisions is a huge undertaking. With this work, a small step in the direction of the understanding the environmental and economic pillars of sustainability (in relation to a nuclear-powered TSHD) is taken.

7.2.1. Public View

Public acceptance of nuclear power is a tricky issue. Public perception and acceptance are significant barriers [129]. The support for nuclear correlates with experience level and the knowledge of nuclear power [359]. As per the survey results of Kim et al. [360] India, China, US have high acceptance level with strong acceptance of high level. While Russia, France, UK have high acceptance levels but strong acceptance is comparatively lower.

7.2.2. Uranium & Fuel Availability

The geological distribution (in countries like Australia, Canada etc.) of uranium reduces the risk of market disruptions [356]. At US130$, 6.14 million tons of uranium is recoverable [361]. At the current requirements, this can last 130 years. However, with Thorium, which is three times as abundant as Uranium, there is enough to last for a few centuries [11].

Uranium Oxycarbide (UCO) is an acceptable fuel for both pebble and prismatic design and higher burnups are possible. UCO TRISO fuel is also less costly than UO2 TRISO [362]. Burnups of upto 120 MWd/kg are achievable and the fuel costs are comparable to LWR [363]. There are some concerns about the lack of HALEU fuel. However, downblending of HEU feedstocks to HALEU is an option that is being considered [364]. In 2018, it was noted that the development of the HALEU fuel cycle infrastructure would require minimum 5 years and sufficient demand [365]. However, UCO TRISO fuel have been started to be produced commercially and capacity upgrades are also being carried out in some facilities [366].

The TRISO fuel manufacturers [367] [368] [369] (current and potential) are tabulated in Table 7.2.

Table 7.2: Status and location of TRISO fuel facilities

Company	**Country**	**Status**
Tokai Works, Nuclear Fuel Industries Ltd.	Japan	Commercial
Northern Branch of China Nuclear Fuel Element Co Ltd.	China	Commercial
BWX Technologies Inc.	United States	Commercial
X-energy hosted at ORNL	United States	Pilot Facility
Institute for Nuclear and New Energy Technology	China	Pilot Facility
TRISO-X Commercial Fuel Fabrication Facility Co. X-energy	United States	Under Development

Global Nuclear Energy Partnership (GNEP) was an US initiative with the vision to establish a global network of nuclear fuel cycle facilities under IAEA control/supervision. This evolved into International Framework for Nuclear Energy Cooperation [370] (IFNEC) with 34 participating countries and 31 observer countries (of the major nuclear power generating nations, only India missing in the list). IFNEC

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[10] The Brundtland Commission classifies breeder reactors as a conventional renewable energy source.

[11] The majorly Th based AVR Pebble bed Gas Cooled Reactor (PBR) achieved burn-up of 150 MWd/kg.

among other things ”envisages the development of comprehensive fuel services, including such options as fuel leasing, to begin addressing the challenges of reliable fuel supply while maximizing nonproliferation benefits” [371]. The establishment of the comprehensive and reliable fuel services is expected to create a more practical approach to nuclear power without the need for every nation pursuing nuclear power to establish their own fuel cycle facilities.

7.2.3. Decommissioning

3.1.7 discussed different decommissioning strategies and demonstrated that the specific requirements for decommissioning depends on the country and the terms of the license. Further, license termination occurs only after successful decommissioning has been carried out.

In general, the social, political and land scarcity concerns have led the national policies to not support entombment as an option. Only 4 major nuclear reactors have been entombed (see C.14.1.).
Table 7.3 provides a qualitative comparison (non-exhaustive) between expected costs for the deferred and immediate decommissioning options. Immediate dismantling is assigned a value of ”0” (datum for comparison). A ”+” indicates a better situation while ”-” indicates a worse off result.

Table 7.3: Qualitative Cost Comparison between Decommissioning Methods

	Decommissioning Method	
	Deferred Dismantling	**Immediate Dismantling**
Expected Costs		
Waste Disposal	+	0
Waste transport and processing	+	0
Maintenance	-	0
Insurance and Regulatory	-	0
Property Taxes	-	0
Overall	-	0

Specific to marine nuclear reactors, the experience is concentrated mainly in decommissioning of nuclear submarines (PWRs and LFRs). Russia has decommissioned over 190 nuclear submarines while US has decommissioned 125 nuclear submarines [372]. Russian submarines are decommissioned using the three compartment unit method, where two neighbouring compartments of the reactor act as buoyancy compartments [373]. Whereas the reactor compartments of the American nuclear submarines is cut and sent to the US Department of Energy’s Hanford Facility for storage [374]. Most of the material is reused or recycled.

With respect of civilian nuclear-powered vessels, NS SAVANNAH had been defueled and put in protective storage. As per the MARAD document [375], the industrial dismantling of remaining components was to be started at the end of 2019 and the decommissioning is expected to end by September 2024. NS OTTO HAHN and NS MUTSU have been decommissioned. The nuclear powerplants of both the vessels were replaced with a diesel powerplant and the vessels continued to operate. NS OTTO HAHN’s decontamination was the first instance of a nuclear powerplant decommissioning that readied a vessel for commercial reuse [376]. NS MUTSU used a one-piece removal method where the reactor compartment was removed in one piece and transported to a long term storage facility [377]. 5250 tonne of steel and lead was recycled from the 10MW$_e$ STURGIS [378]. Similarly, most of the dredging ship could be recycled and/or reused.
The extent of decommissioning that would be required would be lesser for a reactor with the Nuclear Air-Brayton Cycle configuration. In terms of decommissioning, Nuclear Air-Brayton cycle does away with the requirement for the decommissioning of cooling towers/cooling ponds, dismantling of turbines, pumps and valves.

Design for Decommissioning

One of the first instances of use of this phrase was in the work of Hicks et al. [379]. This work was focused on decommissioning of chemical plants and discussed how the implementation of design focusing on end-of-life of a chemical plant can have the potential to reduce the lifetime costs.

This design philosophy has also found its way in the offshore industry, especially in the oil and gas sector due to the decommissioning of North Sea oil and gas fields. The starting point is the creation of a database for providing guidance to new installations and modification of current installations to make them decommissioning-friendly. The initiative to create a database in Oil & Gas industry was taken in 2016 with the Joint Industry Programme (JIP) on ”Design for Decommissioning” [380]. In the nuclear industry, steps in this direction have already been taken [381] [382] [383]. As per OECD document [383], decommissioning aspects should be undertaken in the design stage and operation of the plant. Such steps also have implications of reducing costs and worker doses. The development of sequential dismantling and adequate empty spaces could help achieve a faster and cheaper decommissioning process.

7.2.4. Nuclear Waste

Nuclear waste is a bigger concern of public than the safety of operations [359]. This is possibly because the public is aware that there are strong safeguards and very strict rules around the operations of a nuclear power plant. But this also suggests that nuclear waste treatment and its storage is of prime importance when considering a nuclear propulsion concept.

Compared to fossil fuels, the nuclear wastes are small in weight and volume. Major portion of the waste is easy to handle, nonetheless, there is some waste which is radioactive for hundreds of years. This waste needs a long term storage repository. Unlike, PWR spent fuel, TRISO fuel wastes requires no safety graded cooling system to prevent fuel failure [384]. This saves costs, space and makes the storage easier. However, unlike other forms of nuclear fuel, TRISO fuel has more material usage (generally, more than twice the relative to the amount of fuel).

Reprocessing and Reduction

96% of the fuel of Light-water reactor (LWR) can be recycled. Utilising just the Pu part to make MOX (mixed oxide fuel) the recycled fuel the natural Uranium consumption can be reduced by 25% while the uranium portion can be re-enriched [385]. The method for reprocessing of TRISO fuel are being developed, some of them are mentioned in C.14.2. The development of the fuel processing plant for such a venture is unnecessary and it could be treated in the Le Hague [12] like the rest of the nuclear waste from Netherlands, France, Belgium, Germany, Switzerland, China and Japan. Molten Salt Reactors have been proposed for using all trans-uranium elements (from reprocessing of spent nuclear fuel) and part of the regenerated Pu. This has the possibility of closing actinide nuclear fuel cycle and reduction of wastes and costs associated with storage/disposal [386].

Proliferation Concerns

The processing of spent nuclear fuel for proliferation requires substantial technical and safety issues, requirement of sophisticated equipment and expertise; all of which entail substantial costs [387]. Additionally, TRISO fuel is chemically stable and hence, extreme methods are required for reprocessing. Hence, the chances of proliferation is very very low.

Decommissioning related

At the start of decommissioning process, spent fuel is removed. This removes ~99% of total radioactivity. With regards to decommissioning, 97% of waste by volume is low and intermediate level waste [388], this can be disposed in near-surface repositories. The nuclear reactor and the primary pressure boundary would be the most radioactive and might be treated as low radioactive waste. While the graphite moderator blocks can be recycled, buried or pre-processed and oxidised into CO_2.

7.2.5. NO Formation

NO formation happens due to the oxidation of N_2. There are three types of NO formation based on the pathway (Thermal, Prompt and Fuel). Thermal NO is formed due to oxidation of N_2 at high temperatures. Prompt NO is formed by reaction of N_2 with hydrocarbon radicals. The contribution is

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[12] It is to be noted that as per the French law, the spent fuel after recycling is returned to country of origin.

insignificant if lean burning of fuel occurs or operation is with high dilution (for example in exhaust gas recirculation). In stoichiometric laminar flames, the contribution of this mechanism to the total NO production is estimated to be about 5-10%. The formation of Fuel NO is due to N_2 in the fuel. In fossil fuel based (diesel, gas, gasoline, alcohol etc.) engines, the contribution from this mechanism is minimal [389]. In case of Nuclear Air Brayton cycle, the NO formation would be only thermal NO. Other mechanisms of NO formation like Prompt and Fuel NO would not occur.

Thermal NO Formation

The following reactions are part of the original Zeldovich reaction and relevant to the case of NO formation in Nuclear Air Brayton cycle. The mechanism and kinetics of NO generation in hydrocarbon based flame has been discussed by Westenberg [390]. Here, the same work was modified to reflect on the NO generation from a Nuclear Air Brayton Cycle.

$$\mathrm{O} + \mathrm{N_2} \underset{\mathrm{k_{-1}}}{\overset{\mathrm{k_1}}{\rightleftharpoons}} \mathrm{NO} + \mathrm{N} \tag{7.9}$$

$$\mathrm{O_2} + \mathrm{N} \underset{\mathrm{k_{-2}}}{\overset{\mathrm{k_2}}{\rightleftharpoons}} \mathrm{NO} + \mathrm{O} \tag{7.10}$$

Equation 7.9 is highly endothermic and is the rate determining reaction for NO formation.

Now, the rate of formation of NO is given by

$$\frac{\mathrm{d}}{\mathrm{dt}}[\mathrm{NO}] = \mathrm{k_1}\,[\mathrm{O}][\mathrm{N_2}] - \mathrm{k_{-1}}\,[\mathrm{NO}][\mathrm{N}] + \mathrm{k_2}\,[\mathrm{N}][\mathrm{O_2}] - \mathrm{k_{-2}}[\mathrm{O}][\mathrm{NO}] \tag{7.11}$$

where, [] is the concentration in mol/cm^3.

The mole fraction of N is in the order of 10^{-8} [389]. Further, under the steady state approximation, the rate of formation/destruction of N is small relative to its concentration.

So, in steady state

$$\frac{\mathrm{d}}{\mathrm{dt}}[\mathrm{N}] = \mathrm{k_1}\,[\mathrm{O}][\mathrm{N_2}] - \mathrm{k_{-1}}\,[\mathrm{NO}][\mathrm{N}] - \mathrm{k_2}\,[\mathrm{N}][\mathrm{O_2}] + \mathrm{k_{-2}}[\mathrm{O}][\mathrm{NO}] = 0 \tag{7.12}$$

Then, the rate of formation of NO is given by

$$\frac{\mathrm{d}}{\mathrm{dt}}[\mathrm{NO}] = 2\,[\mathrm{k_1}\,[\mathrm{O}][\mathrm{N_2}] - \mathrm{k_{-1}}\,[\mathrm{NO}][\mathrm{N}]] \tag{7.13}$$

Now, the steady state concentration of N is given as :

$$[\mathrm{N}_{SS}] = \frac{k_1[\mathrm{O}][\mathrm{N_2}] + k_{-2}[\mathrm{NO}][\mathrm{O}]}{k_{-1}[\mathrm{NO}] + k_2[\mathrm{O_2}]} \tag{7.14}$$

Then in Equation 7.13, elimination of [N] gives

$$\frac{\mathrm{d}}{\mathrm{dt}}[\mathrm{NO}] = 2\,[\mathrm{k_1}\,[\mathrm{O}][\mathrm{N_2}] - \mathrm{k_{-1}}\,[\mathrm{NO}][\frac{\mathrm{k_1}\,[\mathrm{O}]\,[\mathrm{N_2}] + \mathrm{k_{-2}}[\mathrm{NO}][\mathrm{O}]}{\mathrm{k_{-1}}[\mathrm{NO}] + \mathrm{k_2}[\mathrm{O_2}]}]] \tag{7.15}$$

This is exactly similar to the equation arrived at by Bowman [391] when considering the extended Zeldovich Mechanism. This is because of some similar underlying assumptions between this work and Bowman's work and other assumptions considered by Bowman (like lean fuel air mixture). Therefore, the rate of NO formation can be approximated as derived by Bowman et al. [391] :

$$\frac{d[\mathrm{NO}]}{dt} = 6 \times 10^{16}\ T_{eq}^{-0.5}\ exp[\frac{-69090}{T_{eq}}] \times [\mathrm{O_2}]_{eq}^{0.5}[\mathrm{N_2}]_{eq}\ moles/cm^3 - s \tag{7.16}$$

The residence time of air would be a few seconds and maybe a maximum of 10 seconds. Based on the air requirements for 100 MW_{th} NABC system, Figure 7.2 gives the generation of NOx at 20 bar and temperatures of 900 K, 1100 K and 1300 K. At constant temperature of 1100 K, the emissions increase linearly with time and pressure (see Figure D.13). Unlike pressure variation, the NO emissions are very strongly dependent on the temperature (at constant pressure). An increase in the temperature by 200 K results in an increase in NO emissions of almost 10^5 g/kWh.

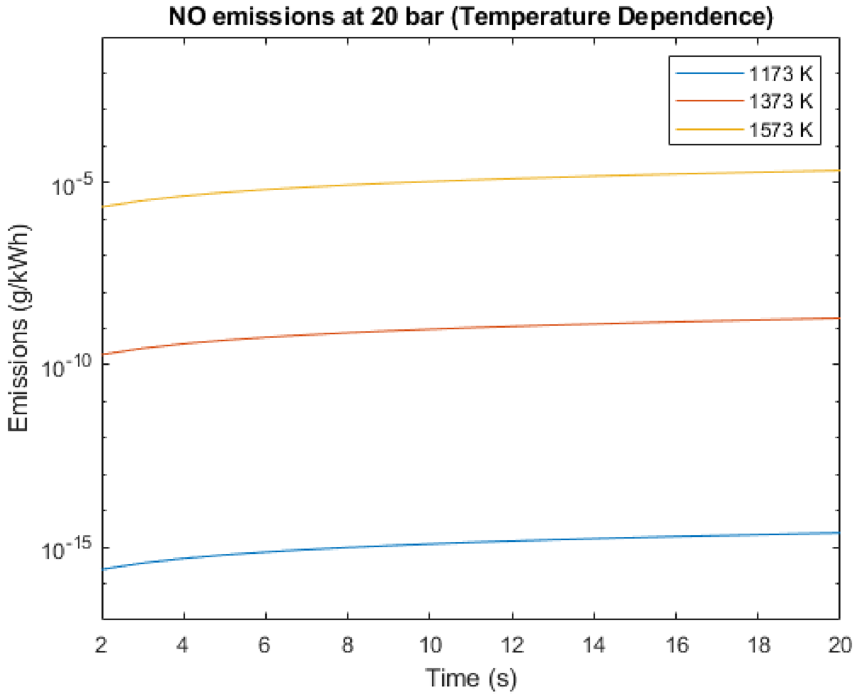

Figure 7.2: NO generation at 20 bar with varied temperature

Characteristic time is the time to reach equilibrium concentration of NO. The characteristic time is given by Equation 7.17 (from [389]).

$$t_{\mathrm{NO}} = \frac{3.38 \times 10^{-16} T exp(58635/T)}{P^{0.5}} \tag{7.17}$$

where,

t = time [s]
T = Temperature [K]
P = Pressure [atm]

At 20 atm and T = 1100 K [13], the characteristic time is ~ 2950 hours. Therefore, at 1100 K, NO emissions are not equilibrium limited but kinetically limited (temperature limited). Table 7.4 gives the characteristic time dependence on temperature and pressure.

Table 7.4: Dependence of NO Characteristic on Temperature and Pressure

Pressure [bar]	**Temperature [K]**	**Characteristic Time [hr]**
20	1100	2964.6
25	1100	2651.6
20	1300	0.8137
25	1300	0.728

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[13] the operating point of the HTGR-NABC system

The characteristic time is a very strong function of temperature. Increasing the temperature by 200 K from 1100 to 1300 K decreases the characteristic time by more than 3000 times. Hence, equilibrium concentration of NO is reached much much faster.

Higher generation at low temperature and high pressure?

Much higher NO_x are formed at lower combustion temperatures (<1500 K) as suggested by Zeldovich Mechanism. One of the prompt NO generation mechanisms, the formation of NO via N_2O has been reported as a possibility at low temperatures and high pressure in conditions of intense mixing and high air to fuel ratio [392]. Further, this mechanism is important when NO formation rate is relatively low [393] and at high pressures. This is a case that is similar to the Nuclear Air Brayton Cycle. Hence, this mechanism might play an important role in the NO formation.
The generation of N_2O from N_2 occurs through

$$\mathrm{N_2 + O + M \rightleftharpoons N_2O + M} \tag{7.18}$$

This N_2O can react with free O_2 radical to form NO via the reaction

$$\mathrm{N_2O + O \rightleftharpoons NO + NO} \tag{7.19}$$
$$\mathrm{N_2O + O \rightleftharpoons N_2 + O_2} \tag{7.20}$$

The NO formation eventually leads to formation of NO_2.

$$\mathrm{2\,NO + O_2 \longrightarrow 2\,NO_2} \tag{7.21}$$

However, NO_2 has been shown to be a transient species in the high temperature conditions [391]. The conversion reaction of NO_2 to NO is rapid in the temperature range of 240-1800 K [394]. This is given by the equation

$$\mathrm{NO_2 + O \longrightarrow NO + O_2} \tag{7.22}$$

The rate constant is given by Equation 7.23

$$k = 5.5 \times 10^{12} \frac{cm^3}{mol - s} \tag{7.23}$$

Quantification of NO emissions from this mechanism would not be taken up in this work and is left for a future work.

Possible production from N and CO_2

Atomic nitrogen produced in Equation 7.9 can combine with CO_2. Avramenko et al. [395] found that the rate constant was not dependent on pressure. The reaction mechanism is given by Equation 7.24-7.25.

$$\mathrm{N + CO_2 \xrightarrow{k_3} NO + CO} \tag{7.24}$$

This is followed by a very fast reaction :

$$\mathrm{N + NO \longrightarrow N_2 + O} \tag{7.25}$$

The rate constant k_3 is given as

$$k_3 = (1.93 \pm 0.24) \times 10^{11} \exp \frac{(-3400 \pm 300}{RT}) \frac{cm^3}{mol - s} \tag{7.26}$$

At 1150 K, this leads to a k_3 value of $4.36 \times 10^{10}\ cm^3 molecule^{-1} s^{-1}$.

Ever since this reaction was discovered by Avramenko, there have been a lot of works and makes it a bit controversial. At 550 K, the total reaction was found to be not significant [396]. The extrapolation of the equation from Lindackers et al. [397] yields $3.24 \times 10^{11} cm^3\ mol^{-1} s^{-1}$. While Fernandez et al. determined the upper limit for a temperature of 1142 K as $5 \times 10^{-16}\ cm^3 molecule^{-1} s^{-1}$ [398] or $3 \times 10^8 cm^3\ mol^{-1} s^{-1}$. However, these are comparatively small values to be of any importance. Further, the mole fraction of N in Equation 7.9 is order of 10^{-8} [389], which is very low. There are a lot of things going on and the exact mechanism or the precise values are beyond the scope of this work. Further, depending on the type of reaction control, the end product of a chain of reactions could be the Thermodynamic product (relative product stability) or the Kinetic (rate of formation) [14].

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[14] For more, check Appendix E.5.

7.2.6. Decomposition of CO_2

CO_2 as the fourth most abundant gas in the atmosphere and in the Nuclear Air-Brayton Cycle would find the way to high temperature zones. This high temperature has the possibility to lead to the decomposition of CO_2. The decomposition could lead to carbon deposition on the surface of the IHX over time can reduce the heat transfer between IHX and air. This would affect the system efficiency and emission of carbon black into the atmosphere is a possibility. Further, this can lead to temperature hotspots and material failure of the IHX. Lietzke et al. [399] looked into the dependence of the products of thermal decomposition of CO_2 by calculation of equilibrium concentrations at different temperatures and pressures. The products of such a decomposition include CO, O_2 and even C. The reactions are given in Equation 7.27-7.29.

$$\mathrm{CO_2} \rightleftharpoons \mathrm{CO} + \frac{1}{2}\mathrm{O_2} \tag{7.27}$$

$$2\,\mathrm{CO} \rightleftharpoons \mathrm{CO_2} + \mathrm{C} \tag{7.28}$$

$$\mathrm{C} + \mathrm{O_2} \rightleftharpoons \mathrm{CO_2} \tag{7.29}$$

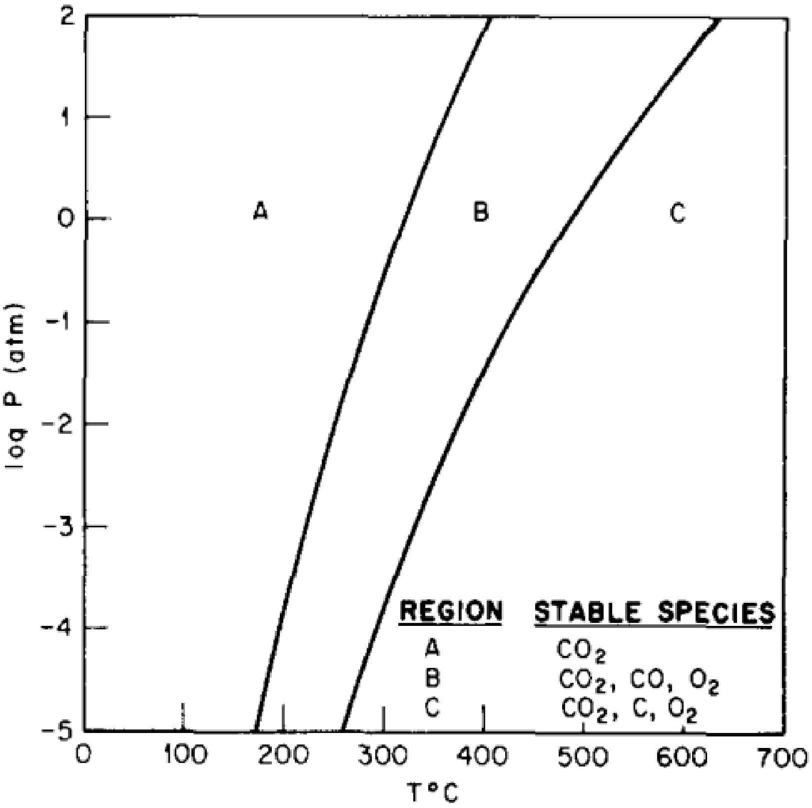

Figure 7.3: Phase boundary curve for CO_2 Dissociation

Source: [399]

The phase diagram for the dissociation of CO_2 is shown in Figure 7.3. Lietzke et al. [399] found no region where both CO and C coexist. For 1 mole of CO_2, 10^{-9} mole of CO was the largest amount formed. This was at 100 atm and 632°C while the carbon production was 10^{-23} mole at 633 °C and 100 atm. At 100 atm, the carbon production increased gradually with the increase in temperature to about 10^{-9} mole at 2000°C.

Since the work by Lietzke et al. does not provide continuous data for different pressure and temperature. So, an estimate for the carbon production at 10^{-15} mole per mole of CO_2 is made. Using this carbon production (10^{-15} mole per mole of CO_2), the yearly decomposition of CO_2 to C is calculated to be about 2.16 $\times 10^{-6}$ g/year for the HTGR-NABC system (See Appendix D.9 for calculation). Hence, the decomposition of CO_2 does not pose any issues related to carbon black formation or emissions.

7.3. Necessary Infrastructure

7.3.1. Ship Building

A ship yard which can build a conventional dredging ship can build the nuclear-powered dredging ship. The factory-built SMR module can be shipped to the shipping yard and secured inside the dredging ship. However, the fuelling of the reactor can be carried out only at specific locations in the world and would require specific licenses, specialised equipment, and trained personnel. This would not be a novel or radically different way to do things. For example, Russian icebreakers VAYGACH and TAYMYR were built in Finland and while the installation of nuclear reactor happened in Baltiysky Shipyard in St Petersburg [400].

Newer manufacturing techniques like 3D printing, powder metallurgy and electron beam welding have a great potential for reducing costs and time period. Aerospace industry already utilises these manufacturing techniques. In 2018, using some of the newer techniques 90% reduction in the the cost and production time of a submarine hull was achieved (in comparison to using conventional manufacturing.) [401].

7.3.2. Home Port

An ideal home port would have equipment for refueling and maintenance facilities. It is preferable to have a port with a low population density and where a possibility of future expansion exists.

Murmansk in one of the very few places in the world where radioactive waste can be handled, maintenance work (reactor related and non-reactor related) can happen and the fuel loading/unloading can take place [140]. New facilities like reactor reloading complex for repair and maintenance of reactors, additional docking facility, and dry dock are being built [402]. There are a couple of places in the world that are capable of providing facilities like refueling, maintenance and decommissioning of reactors. Nerpa and yard No. 10 Shkval are two such places. Severodvinsk is a similarly capable port but services Russian military vessels exclusively.

In Netherlands, a possibility that was identified by Jacobs [10] for nuclear coasters (130 metres long) was dock 2 of the Royal Schelde [403] in east Vlissingen. In addition to being big enough for the coasters to dock, it is covered by a hall and equipped with 2 x 75 ton cranes. Central Organisation For Radioactive Waste (COVRA)[15] is near the location and this would be ideal for low-level and intermediate-level waste storage.

Another possibility is to use floating dry docks to service the nuclear-powered dredger. There have been antecedents of this, for example the ARCO (ARDM 5) [404] is one of the many floating dry docks of US Navy that regularly handles nuclear submarines. Floating dry dock at yard No. 82 (PD-50) in Russia has serviced nuclear-powered navy ship and SEVMORPUT [146].

7.3.3. Refueling

In the current commercial nuclear reactors, one-third of the oldest fuel bundles are taken out of the reactor every 1.5-2 years, the new bundles reshuffled and new bundles are added. The extracted fuel bundles are transferred to a used fuel pool. The refueling takes about three weeks [405].

The current marine nuclear reactors aboard the vessels are not meant for regular refueling. Different vessels (submarines, aircraft carriers, destroyers) of the nuclear navies have been refuelled numerous times. Naval Submarines are refuelled every 15-20 years and the aircraft carriers last over 20 years. Under the Ohio-class replacement program, the new submarines that are being built would not need to be refueled for 50 years [406]. All the nuclear cargo merchant ships (NS SAVANNAH, NS OTTO

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[15] For more on COVRA, see Appendix E.3.5

HAHN and SEVMORPUT) have been refueled except for NS MUTSU. The nuclear icebreaker LENIN was refueled multiple times in its operating life.

Hence, there is experience in refuelling of PWR based marine reactors. however, experience is lacking in refuelling of marine based HTGR. The possible ways to carry such an exercise has been discussed earlier [10].

7.3.4. Service Vessel

Enlisting a nuclear service vessel to load and unload fuel at sea, carryout small repairs is a possibility. The Russian nuclear-powered icebreakers are serviced by SEREBRYANKA or IMANDRA. In the past, this role was carried out with LEPSE. LEPSE served to accommodate machine parts and radioactive waste between 1963-1981 and now serves as a permanent spent nuclear fuel storage ship [407]. NS SAVANNAH also had a nuclear servicing vessel, the ATOMIC SERVANT at its disposal [161].

7.3.5. Permanent Storage

The first disposal of radioactive waste into the sea took place in 1946. Dumping of radioactive waste/nuclear vessels into the sea was a common practise. However, at the 16th Consultative Meeting of London Convention in 1993, the member countries adopted a Resolution for prohibition of disposal of radioactive wastes at sea. This Resolution came into force on 20 February 1994 [408]. The last reported dump was liquid radioactive waste in 1993 in the Sea of Japan by Russian Federation [409].

In Europe, no repository exists for long-lived High-level waste (HLW). However, Finland is building a nuclear waste repository at Onkalo [410]. This would also be the world's first permanent nuclear-waste repository and is expected to start in 2024 [411]. Sweden and France are in advanced stages of putting up such facilities. Finland and Sweden have successfully navigated the Not In My Back Yard (NIMBY) phenomenon and sited their nuclear waste disposal sites accordingly [412]. Outside of Europe, a deep geological repository exists in salt beds in the United States since 1999. However, this repository is dedicated for military radioactive waste.

Like Finland, France and Sweden, The Netherlands also applies the "polluter pays" principle. In Netherlands, deep drillings of salt domes were proposed as the solution for underground nuclear waste storage. These salt layers and clay layers are self-healing [413]. Since 1993, consideration on the retrievability and public acceptance of the nuclear waste has been the central theme of government policy [414]. The main benefit of the retrievable nature of waste storage sites is the control of the nuclear waste. The nuclear waste can be retrieved, repaired and recontained. OPERA, the research program dedicated for the geological disposal of radioactive waste established that radioactive waste can be stored in deep clay layers [415]. These have been established to be stable for long term. However, such a repository needs to be made only after 2100 [416].
There is a possibility of countries possessing low amounts of HLW to join together to make a geological repository [417]. There is also research being undertaken in Partition and Transmutation (P&T), an experimental technique to shorten the life of the radioactive waste [413].

7.4. Economics

It is more cost-effective to operate a dredging plant for the longest uninterrupted timing so that the fixed cost elements can be spread over the maximum possible number of working hours [418]. This is because a considerable proportion of the costs of dredging are effectively fixed (bank interest rates, insurance premiums, repair reserves and salaries). Only the wearing costs, fuel and lubricant costs actually depend on the actual volume of material dredged. But fuel costs alone can represent 30 % of the cost of dredging [7].

In 2018, it was expected that the price of low sulphur bunker fuels would go up 30% due to the new IMO standard from 450 to 600$/tonne [419]. This occurred (qualitatively) while the quantitative effect seemed to have been underestimated, at least for the initial months of the 2020. With the increase in the fuel costs, the dredging project execution costs would be escalated by at least 5-10%. As the grip of novel Covid-19 virus tightened around the world, to contain the spread, countries started locking down. This affected the price of the bunker fuel as shown in Figure 7.4. It is still clear from the Figure that that there is a price differential of two times between the price of IFO 380 and MGO and about 30% between VLSFO and IFO 380.

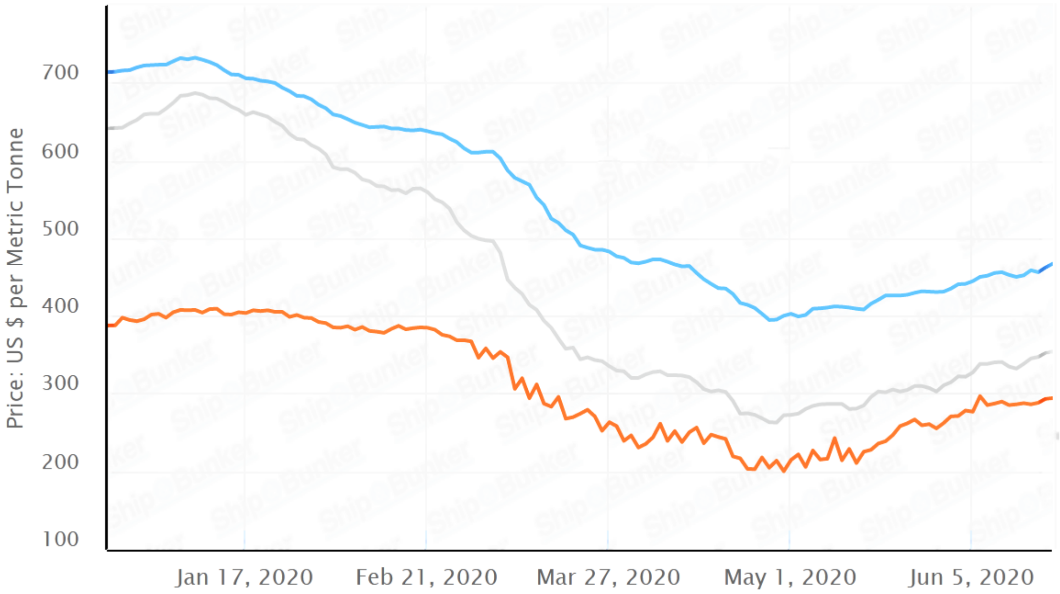

Figure 7.4: Effect of recent events on bunker fuel price [MGO : Blue VLSFO : Grey IFO 380 : Orange]

Source: Ship & Bunker [420]

The actual lifetime of dredging vessel is well above 30 years and even longer with thorough retrofitting [4]. With the requirements that the various nuclear safety code enforces, the lifetime of a nuclear dredger would be even longer.

None of the nuclear merchant ships were deemed economically viable. The hybrid passenger-cargo vessel design of NS SAVANNAH was a handicap to the nuclear vessel. The payload of NS OTTO HAHN (~ 10000 DWT) was too small to make it economically viable [130]. While the MUTSU was a oceanographic research vessel and was not made to test the economic viability. The economic benefit of a nuclear-powered dredger depends on the difference between the long-term operating costs and increase in productivity balancing out with capital costs of nuclear reactor. Additional factors could be the possible carbon taxation and revenues from ”power onshoring” which can serve as an additional source of revenue. A detailed economic analysis would not be covered in this work and can be undertaken in the future.

7.4.1. Conventional Vessel Value

The rough price estimation of a TSHD running on fossil fuels is provided by the methodology for vessel valuation from CIRIA 2005 [421].

Computation of Value (in €)

$$V = 4400 \times LW + 89400 \times LW^{0.35} - 4766000 + 1400 \times P_{dp} + 580 \times P_{jp} + 670S \tag{7.30}$$

where,

LW = Lightweight ship [tons]
P_{dp} = Power requirements during suction (dredgpumps) [kW]
P_{jp} = Power requirements during suction (jetpumps) [kW]
S = Free sailing power [kW]

Since, the values of Lightweight of the TSHDs considered in this work are not readily available. The lightweight is computed from equation of fit (Equation 7.31 [16]) for Lightweight vs. Deadweight (Figure 7.5).

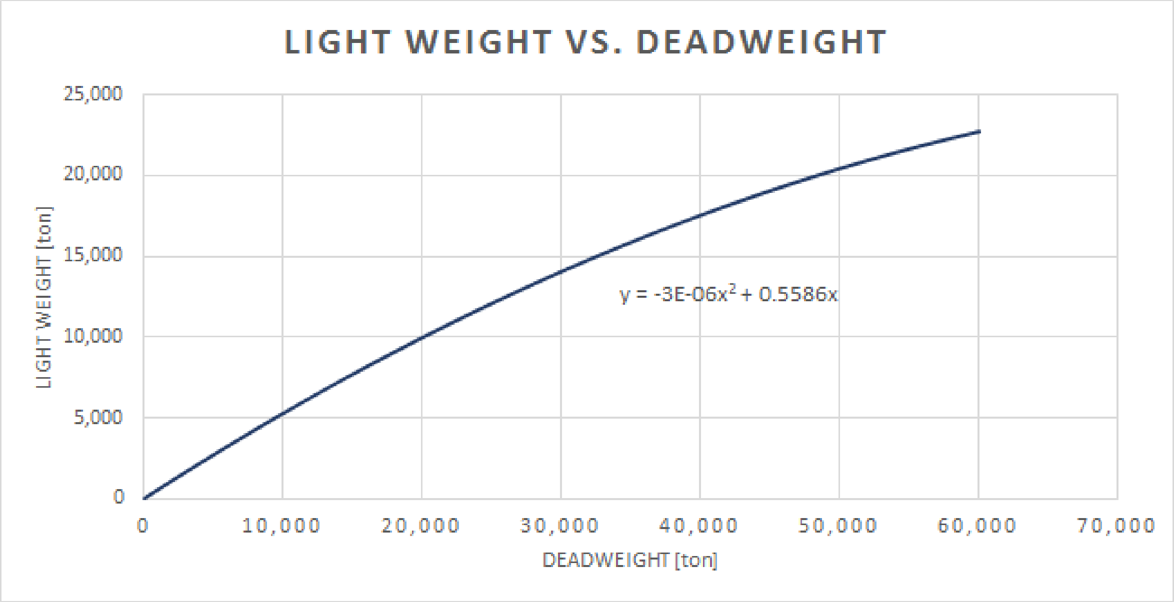

Figure 7.5: Light weight as function of dead weight

Source: [422]

$$Lightweight = -3 \times 10^{-6} \times Deadweight^2 + 0.5586 \times Deadweight \tag{7.31}$$

The weekly insurance cost for the TSHD is given as

$$Weekly\ Insurance\ Cost = \frac{0.03 \times V}{100} \tag{7.32}$$

7.4.2. Insurance

Premiums

The inflation adjusted value [17] of the dredgers and insurance for the four dredgers considered in this work is given in Table 7.5. AKADEMIK LOMONOSOV which costed to 232 million $ [423] is comparable to the value of the dredger CRISTÓBAL COLÓN.

Table 7.5: Vessel Value and Insurance costs

Dredger	**Inflation adjusted value (2019)** (USD)	**Insurance/year** (USD)
OSTSEE	38,398,140	736,783.5
WILLEM VAN ORANJE	111,813,150	2,145,470.7
HAM 318	197,292,000	3,785,638.9
CRISTÓBAL COLÓN	226,762,800	4,351,124.6

Third-party Liability Insurance

As discussed in the Chapter 3, the damage cost is capped (or sometimes, there's no cap on the liability amounts) by the international/national liability regimes and conventions. The actuarially fair premium

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[16] with a $R^2 = 0.9607$

[17] Multiplication factor of 1.23

does not exist in the nuclear industry due to the uncertainties and asymmetry of information that exists. Liability depends on the region and country. So, the insurance premium is a function of the perceived risk and flag country and/or work country.

The premium rate of liability insurance is generally set in the following basis

$$P = \frac{C \times F + M}{N} \tag{7.33}$$

where,

P = Rate of Liability Insurance
C = Damage Costs
F = Frequency
M = Insurance company's fees/other charges
N = Number of Insurers

For large damage costs, re-insurance is carried out to reduce the risks. In the nuclear industry, there is a difficulty in setting the premiums because the law of large numbers is not applicable as the number N is not large enough. In case, the damage costs have no limits (in case of unlimited liability), there's no way to ascertain the premium [424].

The nuclear third-party liability insurance premiums mainly depends on the liability cap regulations. These liability cap regulations vary from country to country. Analysing data from US, the multiplicative factor could be anywhere between 2.22 - 111.11 times depending on the accident frequency (10^{-3} to 2×10^{-5}) is assumed for the calculation of premiums [18]. For an accident frequency of 10^{-3}, the premium for one ship with the liability regime of Spain would amount to 66,660 € while as per the liability regimes for Belgium/UK this would amount to almost 160,000 € [19]. In case of unlimited third-party liability (no cap scenario), the premium would higher (possibly 1 million USD).

NS SAVANNAH was covered under the Price Anderson Act and there was ready availability of commercial P&I insurance for nuclear merchant vessels [130]. Report by Comptroller General of United States on NS SAVANNAH [425] gave the opinion that a nuclear-powered ship may be a better risk than other merchant ships. Particular to NS SAVANNAH, very small amount of claims were paid by the underwriter compared to the premiums paid for the protection and indemnity insurance carried on the NS SAVANNAH. Hence, it was suggested that it be more economical to adopt the policy of self-insurance.

It was reported in 2013 by Ostreng et al. [426] that in accordance with Russian regulations, the Russian nuclear icebreakers were not required to have third-party liability insurance. However, it was found that a requirement was set by Gosatomnadzor, the state nuclear inspection agency for obtaining a compulsory insurance for the nuclear icebreakers. Therefore, since the end of 1998, nuclear icebreakers were required to obtain insurance coverage to be able to operate. The Industrial Insurance Company insured against all possible damage and Russian nuclear pool re-insured the risk [427]. The 6 Russian icebreakers were insured for a premium of approximately 12.5 million \$ (2.1 million \$ each) for "all possible claims" (hinting towards an unlimited third-party liability cover). Accessing data from Russian Nuclear Insurance Pool [428], the insurance premiums for Russian nuclear power plants are about 20-30% lower than American Nuclear third-party liability premium. Sogaz [429], the largest Russian insurance company provided third-party insurance for AKADEMIK LOMONOSOV.

It has been mentioned that there is a possibility of expansion of nuclear mutual insurance in the future [204]. Hence, one of the possibilities is to go for co-insurance. A particular example already exists in the dredging industry : MUNIS. MUNIS is a mutual insurance company that works as an insurer in the co-insurance market. MUNIS provides the Hull & Machinery and Disbursement / Increased Value. It is owned by Boskalis, Van Oord, DEME and Jan de Nul [430].

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[18] Methodology and discussion in Appendix D.7

[19] Since it would be one of the first such ventures, these values could be higher.

7.4.3. Heat Exchanger Costs

Jacobs [10] for his Shell and Tube Heat exchanger (with 1 inch tubing), the cost of the Shell & Tube Heat Exchangers arrived at was 17.2 M€. While the cost of a plate heat exchanger rated for the same rating was quoted at 4.2 M€.

The optimal design of the heat exchanger depends on the objective function (economic, mass and volume). The type of heat exchanger, design and the material used affect the cost of the heat exchanger. In the investigation in this work, it was found that for the same material with different pressure drops, the cost of Shell & Tube Heat Exchanger increases substantially if the pressure drop is decreased. The cost of double segmented Shell & Tube Heat Exchanger is lower than the cost of a single segmented Shell & Tube Heat Exchanger. The bigger the diameter of tubes, the costlier the S& T heat exchanger is.

The cost of the shells for BEM with 1.905 cm tube OD, double segmental INCONEL®shell side hot fluid 290 million$. In no way, this should be taken as the optimised value but is just an indication on how expensive the HX could be. See Appendix Table F.3 for some of the design characteristics.

7.4.4. Retrofit Costs

There would be additional costs due to retrofitting of additional hull and other required safety measures. The cost per DWT depends on the DWT of the vessel.

The cost per DWT for double-hull vessels is higher by 9.9% for a vessel of 47,000 DWT and 11.1% for a 67,000 DWT vessel [431]. There is an increase in the Maintenance and Repairs cost due to the protective coating of the double hulls, War risk and H&M insurance premiums would also increase as they are related to the value of the vessel. All in all, taking the reference of the study by Ocean Studies Board et al., the increase in the operation costs is estimated to be 13%.

If a vented confinement is allowed to be used, it could be a better in terms of cost than a containment. The cost of the vented confinement should be lower but the exact values depend on the specifications [329].

8

Conclusions and Recommendations

"Dredging starts where the world ends"

This quote from the past might be even more applicable in future, when our hunger for resources and the need for energy transition makes us mine the deep seas. However, the emission regulations around dredging vessels is tightening. The dredging industry has been granted some respite but most of the emission regulations are still applicable. The industry had seen this coming and responded, albeit slowly until the last 3-5 years. In these last years, the response has gathered momentum towards finding and utilising technologies that are emission regulation compliant. This chapter rounds up on the conclusions of this work in the Section 8.1 and in Section 8.2 provides some recommendations for future work.

8.1. Conclusions

The scarcity of works on nuclear dredgers was highlighted in this report. This a definitive literature gap. In this work, the applicability of nuclear energy source to the Trailing Suction Hopper Dredgers (TSHDs) has been considered. The analysis of energy and power requirements was based on only Dredging Cycle II (pump ashore discharge type) as this ensured the flexibility in the operations of TSHD. Overall, here it was tried to lay the groundwork and help inform on some of the larger questions around nuclear-powered TSHDs. Additionally, the energy and power requirements based on Dredging Cycle II were used to determine the extent and best role for TSHDs powered with Proton Exchange Membrane Fuel Cell (PEMFC) and batteries. The conclusions from this work are discussed in the following subsections.

8.1.1. HTGR-Nuclear Air-Brayton Cycle

High Temperature Gas-cooled reactor (HTGR) and the Nuclear Air-Brayton Cycle (NABC) were evaluated as the nuclear reactor and the power conversion system of choice. The propulsion arrangement is based on Integrated electric propulsion (IEP). Because of the large and rapid fluctuations, an energy system based only on nuclear reactor(s) is not ideal. The nuclear reactor's ramping rates are slower than the required response time. Hence, another quick response energy source or energy storage system was required. For this purpose, due to their maturity, higher energy density and lower costs, Li-ion batteries were chosen in this work.

The efficiency of the NABC coupled with HTGR depends on the turbomachinery efficiency, primary/secondary coolant temperature, heat exchanger effectiveness, inlet air temperature. The overall efficiency of the HTGR-NABC is strong function of the efficiency of the turbomachines (air compressor, expansion turbine, He blowers). There is a small increase/decrease in efficiency when the inlet air temperature is decreased/increased respectively.

It was established that the emissions of NO_x (from different oxidation mechanisms of N_2) and carbon black formation (due to decomposition of CO_2) in a high temperature NABC is negligible.

In the NABC based systems, the component footprint of the turbomachinery is small. It was realised that the use of Shell and Tube Heat Exchangers as PHX and IHX might not be the best choice. The volume and mass requirements for these HX is not a big issue but the costs were found to be prohibitive. Hence, for the realisation of a NABC, a cheaper suitable option for HX needs to be found.

A NABC powerplant has high inlet air and exhaust requirements (in comparison to conventional diesel engines). This would require much bigger air ducts (intake and exhaust), expansion joints and filters than diesel engine of comparable output. Hence, a nuclear system based on Nuclear Air-Brayton Cycle may not be the best choice as a powerplant for retrofitting in a nuclear-powered vessel or in general, for new build vessels.

8.1.2. Direct Nuclear-based Systems

The nuclear reactor and biological shielding forms the biggest fraction of total mass and volume requirements. For mass requirements, this is followed by the IHX and Emergency Battery system. However, for volume requirements, this is followed by the Operational Battery and Emergency Battery system.

It was found that the bigger TSHDs are better suited at being retrofitted by a NABC-based nuclear system. For example, a dredger with a hopper volume of 12000 m^3 would have to undergo extension or should have been originally designed for more than 30 days of endurance while a dredger like HAM 318 would not have to undergo any extensions. Although having multiple reactors provides system redundancy, a single reactor design is more efficient when it comes to volume and mass requirements. In such a case, there is a possibility to have even lower requirements than current fossil fuel based powerplant. The TSHDs, HAM 318 and CRISTÓBAL COLÓN are retrofittable within the constraints of both, volume and mass. With the exception of 3-reactor system (CRISTÓBAL COLÓN) and the 2-reactor system (HAM 318), this is true even when the mass requirements are increased by 50%.

In the current designs of TSHDs, the hopper forms the middle portion of the dredger and the fuel is stored on the port and starboard side of the vessel (across the length of the hopper). The main engines are situated at the back of the dredger and depending on the design auxiliary engines can exist (generally towards the bow). A HTGR-NABC nuclear-powered vessel has the mass concentrated only across a few components. Therefore, the distribution of mass like the conventional fuel powered dredger vessels would not be possible in a nuclear powered dredger. Consequently, even with the satisfaction of other constraints, a redesign of the dredger would be necessitated because of this.

8.1.3. Regulations & Third-party Liability Insurance

Some of the regulatory requirements while pursuing a nuclear-powered dredger were discussed in this work. The terminology of referring to a nuclear-powered vessel is referred to in the codes is itself not straightforward. A nuclear-powered vessel could be referred to as ”nuclear propulsion ship”, ”nuclear ship”, ”atomic powered”.

Specific to nuclear-powered dredgers, there are at least a dozen internationally applicable regulations and on top of that there are regional and national regulations that need to be complied with. Some of these are listed in Table 3.2. In this work, UNCLOS and SOLAS are identified as the most important international regulations for access to territorial waters and port access by nuclear vessels. For the safety of nuclear-powered vessels, Code of Safety for Nuclear Merchant Ships - Res. A.491(XII) was adopted internationally in 1981. This was based on the use of Pressurised Water Reactors (PWRs) only and, obsolete now. While for the physical security of nuclear facilities, the Convention on the Physical Protection of Nuclear Material and its Amendment are legally binding. Additionally, country-specific regulations might also exist and need to be complied with. Some of the relevant Chapters, Sections, Clauses etc. of the regulations are covered in Chapter 3.

The nuclear third-party liability premiums are dependent on the country, the risk category and the size of the nuclear reactor. The various probabilities and factors for calculation of insurance premium are not available in the public domain but even the use of accident frequency of 10^{-3} still yields an actuarially unfair premium value (for reactors in US). As per the current regulations, in some countries at least (US, Spain, Belgium and UK), the premiums for third-party liability should be constant for TSHDs ranging in size from WILLEM VAN ORANJE to CRISTÓBAL COLÓN. Even if the power requirements for the future TSHDs is about twice the power requirements of the biggest TSHD in existence today, the nuclear third-party liability premium would not change much.

Overall, there is a lack of uniformity and clarity in the insurance and regulatory regime. The realisation of at least the first nuclear-powered dredger would require some kind of state sponsorship or endorsement. So as to maximise the uptime and reap most benefits of the nuclear energy source, such a dredger would be more suited to capital works and not the routine maintenance dredging. In the future, the use of nuclear-powered TSHDs to carry out deep-sea mining presents a prospective opportunity because of the no-to-very low operational and overall emissions, capability to work without the need to bunker and low downtime.

8.1.4. Indirect Nuclear-based Systems : PEMFC and Batteries

The liquid storage based PEMFC systems is the most efficient choice (volume and mass requirements wise), followed by 500 bar compressed H_2 storage. It was found that volume availability is a bigger constraint than mass availability for compressed and liquid H_2 storage based system. An interesting thing is that for solid hydride storage, mass is a bigger constraint than volume. The Available volume was shown to be correlated with the net tonnage, hopper volume and displacement of the dredger.

When volume requirements are treated as a constraint, across all the considered systems (PEMFC with all types of H_2 storage and Battery-based systems) the smaller TSHDs perform better than larger TSHDs.

It is realised that if the original design endurance is 1 day, the endurance of the retrofitted dredger matches or is even better than the original design endurance (i.e. 1 day). However, mega and jumbo trailers are not designed for 1 day endurance. As the size and endurance of the dredger increases, PEMFC were found to have increased suitability than batteries.

With the current limitations in commercial technologies, dredgers that are powered by Fuel Cells or batteries are suitable only for maintenance dredging or projects where continuous dredging is not desired or required. Specifically, the retrofitted TSHDs powered by Fuel Cells with liquid H_2 storage or 500 bar compressed H_2 storage are suitable for maintenance dredging or capital dredging for short duration (couple of days). While retrofitted TSHDs powered by batteries are suitable only for very short maintenance dredging operations (less than half a day of operations).

At this juncture, it must be realised that not all dredger vessels are or have to be equipped for pumping ashore, rainbowing and dumping. If a dredger that can be made for dumping purposes only, then the viability of using Fuel Cells and Batteries for the dredger increases.

Retrofit map is a new visualisation tool that was developed in this work. These maps do away with the need to have repeat calculations for finding the approximate endurance of the retrofitted system at different parameters (different DoD, different system efficiency and volume availability based on n days endurance of original system). In Section 6.5, such maps were made for batteries and PEMFC systems based on available volume of a HFO system (n-days endurance). These maps can act as predictors of vessel endurance if a particular power source is retrofitted into the vessel. Further, these maps can be also used to predict the suitability of different power sources based on their size of the vessels and their original design endurance.

This study also exemplifies on the need for multi-fold improvement in the energy density of H_2 storage and batteries for achievement of the same endurance level. Additionally, a change in the operational style of the TSHDs could be required if fuel cell or battery-based systems are to be employed.

8.2. Recommendations

Future research can be undertaken to improve this work. Some examples of the possible studies that can be undertaken are :

- In this work, the volume and mass requirements were computed and compared with the constraints. Some of the TSHDs were found to have enough availability of volume and mass to accommodate for the requirements of a HTGR-NABC based nuclear system aboard. However, equipment placement was not the scope of this work. A HTGR-NABC nuclear powered vessel would have the concentration of the mass across only a few components, hence, the distribution of mass like the conventional fuel powered dredger vessels would not be possible in a nuclear powered dredger. Consequently, a redesign of the dredger will be required. This could be a possible direction for the future work. This work can also consider the changes that need to be done in the vessel due to nuclear vessel regulations noted in Chapter 3.
- For making the assessment in this work more accurate, information on the actual fuel capacity, endurances, block coefficient of the vessels would be vital. The information on the exact specification of the fuel cell and battery systems, volume and mass availability, amount of space used for maintenance and possible sizes of large sized deployment of batteries and fuel cells should be part of future design studies for refining the limits.
- To find exact limits, accurate definition of the mission can refine the system characteristics. Simulations that use data with different parameters of dredging cycles (longer/shorter dredging time, longer/shorter sailing time) than considered in this study would help in better ascertaining the requirements of the system and eventually the mass and volume requirements.
- In this work, it was assumed that the nuclear reactor has no capability for load following. However, that is not entirely true and a nuclear reactor can follow load, the extent of which is dependent on the amount of cycles over the entire life. A study that carries out the dynamic analysis of the system ensuring that the effect of load-following on life of the nuclear reactor is negligible would give better estimate of the actual size and physical dimensions of the nuclear system.
- If HTGR reactors are to be commercially deployed in vessels, heat exchanger designs (other than S&T heat exchangers) need to be evaluated for technical and economic viability.

This work also serves as a starting point for other works such as :

- A hybrid vessel concept can be considered. Some of the possibilities are Nuclear-FC, Nuclear-Diesel, Diesel-FC, FC-Battery, Diesel-battery etc. In such a concept the utilisation of battery pack or Fuel cell or diesel [1] can be considered for a part of job, for example : powering dredge pumps or for supplying/supporting during ramping up operation.
- The use of specific reactors that are exact fit (in their ability to supply power) for development of the nuclear-powered TSHD concepts should be carried out. For example HTR50S, a 50 MW_{th} reactor that is being developed for commercial deployment in the 2020s [432] might be better suited for some of the Jumbo sized dredgers instead of HTTR-like modules.
- In this work, the bottoming cycle or recuperative cycle were not considered. Additionally, the co-firing of hydrogen in the bottoming cycle of NACC to act as a replacement for Fuel Cell or batteries to cater to the power ramp-up needs can be investigated.
- H_2 production from HTGR was not considered in this work. A concept can be explored where H_2 produced by HTGR is used to run the the auxiliary system or provide power during ramp-up. This concept can potentially have the advantage of reduced volume and mass requirements in comparison to battery based ESS/Emergency system for the nuclear system that was modelled in this work.
- This work can be extended to include other common dredger vessel types like grab dredgers and cutter suction dredger.

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[1] In case of nuclear system, the diesel generator can also act as a backup generator.

- Due to their higher density, H_2 carriers like natural gas and ammonia can also be used a energy source for fuel cells. The mass and volume requirements of TSHDs powered with fuel cells using such H_2 carriers can be studied.
- The sCO_2 Brayton can be a better power cycle than the Nuclear-Air Brayton Cycle. Hence, a concept with an improved thermodynamic cycle utilising with sCO_2 can be studied. In the recent years, a lot of research thrust has been put onto the sCO_2 cycle (especially for the solar power towers and solar concentration towers). However, some research has also been carried out on the sCO_2 cycle for nuclear reactors [433].
- This study did not carry out a full economic analysis of the concepts. A future study could be geared towards carrying out an economic analysis based on the upfront costs for the vessels, infrastructure development costs, effect on productivity due to reduced bunker calls and full operational costs. This could help further establish the cost benefit relationship.
- The retrofit maps developed in this work can be extended to other technologies, dredgers and vessel types. For example, the retrofit maps could be created when other marine fuels (LNG, MDO etc.) are used.
- For the salvagibility of a HTGR used for marine applications, the possibility of damage by water and air ingress needs to be kept minimum. Designing of an auxiliary cooling system could be undertaken that achieves the reduction of temperature below 800°C (for preventing damage due to water ingress) and below 550°C (for preventing damage due to air ingress) in case of air/water ingress incidents.
- The embodied energy for the development of nuclear-powered/FC-only/Battery-only TSHDs can be calculated to understand the overall impact of such vessels.
- Statistical analysis of accidents involving dredgers could be carried out to determine the most common damage location on the dredger vessel. This location can be potentially provided with higher reinforcement. The implications of this on the mass/volume requirements and economics can be studied. Work based on ship-ship collisions and tankers vs other ships has been undertaken earlier by Lutzen [434]. Additionally, there's a need to understand the reasons and risk of accidents. Such a analysis was part of one work [435]. However, no dredger vessel specific work has been done, the dredging ships are often clubbed with "other vessel types" [436].

A

Report : Entrepreneurship related

This was carried out in partial fulfillment of the requirements for the Master Annotation in Health Innovation and Entrepreneurship at TU Delft.

A.1. Abstract

A preliminary case for the commercialisation of the concept developed in the main master thesis titled: ”An Exploratory Study of powering Trailing Suction Hopper Dredgers with an emphasis on Nuclear power” was carried out through this work. The master thesis evaluated the possibility of retrofitting Trailing Suction Hopper Dredgers with nuclear reactor based systems (direct and indirect) by comparing the available and requirements for volume and weight. The direct retrofit meant placing small modular nuclear reactor inside the vessel, while in the indirect retrofit case technologies that can use land based nuclear energy sources were considered. In particular, two powering options : batteries and H_2 fuel cells were evaluated.

This work tried to understand the value of a nuclear-powered TSHD to dredge operators, the market potential, the possible geographical beachhead market and identified the stakeholders for such a concept. The main activities undertaken to grasp the above mentioned objectives was among others by the development of a value proposition canvas, carrying out an industry analysis, PEST analysis and mapping stakeholder.

A.2. Introduction

Dredging is the activity carried out to remove the material underwater. The objective of dredging are many. Dredging can be carried out for creation of deeper waters, coastal protection, land reclamation, extraction of construction materials (sand and gravel), wreck clearance, offshore renewables, undersea cable laying, and even picking up shellfish from the sea floor. All in all, infrastructure that is constructed or maintained in connection with water almost always requires dredging. The global dredging market value is expected to be 21.1 billion $ in 2029 (CAGR of 3.3% between 2019-2020) [437]. Trailing Suction Hopper Dredgers are regarded as the workhorse of the dredging industry and the most common dredger type. These vessels act as giant vacuum cleaners and remove the material from the ocean floor. The carrying capacities of Trailing Suction Hopper Dredgers have been rising and there’s a industry wide move towards larger sized vessels.

Dredging vessels have been traditionally driven by HFO and very rarely, with distillate fuels. With the signing of the Paris Agreement and implementation of IMO 2020/ECAs to control different emissions (CO_2, SOx, PM, and/or NOx), the external pressures for reduction of emissions in dredging are rising. Additional motivation factors are the rise in the fuel costs which forms a major component of dredging project costs and the incentives from regulatory authorities like the Dutch Directorate-General for Public Works and Water Management to reduce the carbon intensity in dredging operations. Often, the achievement of one objective leads to deterioration of another, for example, the use of IMO compliant fuel can increase the overall carbon emissions. In recent years, alternative fuels have been explored. These include : LNG, biofuels, methanol, ammonia among others. Vessels utilising LNG and biofuels are already started to ply the oceans and working on the seabed. However, the alternative fuel and power technologies suffer from their own set of issues (supply, energy density, volumetric density, captive and life cycle emissions etc.). Further, with the predicted increase of distances between the loading and dumping sites and increased frequency of bunkering calls, the usage of these alternative fuels would imply lower production and consequently, lower earnings (especially in large dredging projects).

In the main masters thesis work, a marine power plant concept that has been rarely discussed in the context of dredging was explored and forwarded: a nuclear-powered dredging vessel. The feasibility of retrofitting existing TSHDs with a nuclear power plant was studied by comparison of weight and volume requirements of the nuclear power plant, with the mass and volume of the engine and fuel storage system of current TSHDs. Fundamentally, such a power plant addresses the issues related to the emissions and essentially eliminates bunkering stops. A part was also dedicated to the pertinent question of the third party liability insurance premiums for a nuclear powered ship and the regulations that such a ship would be subjected to. Further, the technological forces and trends like the development of Small Modular Reactors, deep-sea mining and autonomous ships, could favour the development of a fleet of nuclear-powered dredging ships in the future.

A.2.1. Approach

There is a potential market opportunity for powering of TSHDs with nuclear energy. In this work, only direct powering of the TSHDs (nuclear power system onboard) is considered. For the evaluation of the market opportunity of a nuclear powered Trailing Suction Hopper Dredger, an intrapreneurial approach[1] was applied. The company in question could be any dredging vessel manufacturer (like Royal IHC, one of the largest dredge manufacturing companies) and this would be a new entrepreneurial venture project within the established organisation. In this work, it is assumed that Royal IHC is the organisation that is looking forward to test the business case of the idea before more investment is poured into the development of the concept.

A.2.2. Research Objectives and Activities

The research objectives of this specific work were :

1. What could be the value of a nuclear powered dredger for a dredge operator?
   Dredging vessels have an average life of over 30 years. A long term outlook is necessary when investing in a new dredging vessel. In the current regulatory atmosphere, oil powered dredging vessels have significant unpredictability around them. Most potential alternative powering options limit the extent of operations and the way business is conducted. Nuclear reactor powering comes with significant upfront costs. However, these costs are somewhat balanced by a significant increase in the productivity, no taxation on emissions, substantially lower fuel costs among other things.

2. What could be the market potential for a nuclear powered vessel?
   It is to be understood that dredging vessels of any size are interesting or make a convincing case for being outfitted with a nuclear reactor. Hence, what is the possible market size of the specific segment/dredging activities for which a nuclear powered vessel can be expected to be bought by dredge operators.

3. What could be a possible beachhead market (geographical) for (First of a Kind) FOAK nuclear powered vessel and who could the end user be?
   Not all the places on earth have conducive regulatory atmosphere, facilities, experience or a market need/size to be economical or interesting for a nuclear powered dredging ship.

4. Who are the stakeholders?
   Identification of the stakeholders is the first step in understanding the role that each stakeholder

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[1] thinking as an entrepreneur inside a company

plays in furthering and realising such a concept vessel.

Secondary research forms were mostly relied upon. However, primary research in form of interviewing was conducted with officials of two dredging companies. The following activities were undertaken to answer the research questions:

1. Development of a Value Proposition Canvas for understanding the value created.
2. An Industry Analysis focused on global turnover and industry growth drivers.
3. Estimation of the Market Potential.
4. An initial market screening based on the nuclear handling capabilities/experience is used to identify countries. Further, for the identification of the the beachhead, a PESTLE (Political, Economic, Social, Technological, Legal Environmental) Analysis was carried out for the select countries.
5. Stakeholder Identification and preliminary Porter's Five Forces Analysis for the concept.

Because of the extensive scope of the problem, the focus of this work is mainly on the qualitative research, as a first step. Further, the nascency of the concept does not support the quantification which can be a subject of a later research once the concept is a bit further.

A.3. Global Turnover and Growth Drivers

Global dredging turnover more than doubled between 2000 and 2011. For the global dredging industry, the last estimate for the total turnover was 10.68 billion € [438] [2] and is from the year 2011. An estimate of the global dredging market for 2029 is 21.1 billion $ [437]. In 2018, the net turnover for IADC members from open markets [3] was 5.1 billion € [439] [4].

Dredging industry's growth is dependent on six drivers :

- world trade
- urban development
- coastal protection
- energy
- tourism

As per the data from Dredging in Figures 2017 [51] trade related dredging has been the biggest driver since late 1990s. Further, capital dredging (on average more than 40 % of the total turnover) related to trade has been the biggest driver since 2005.

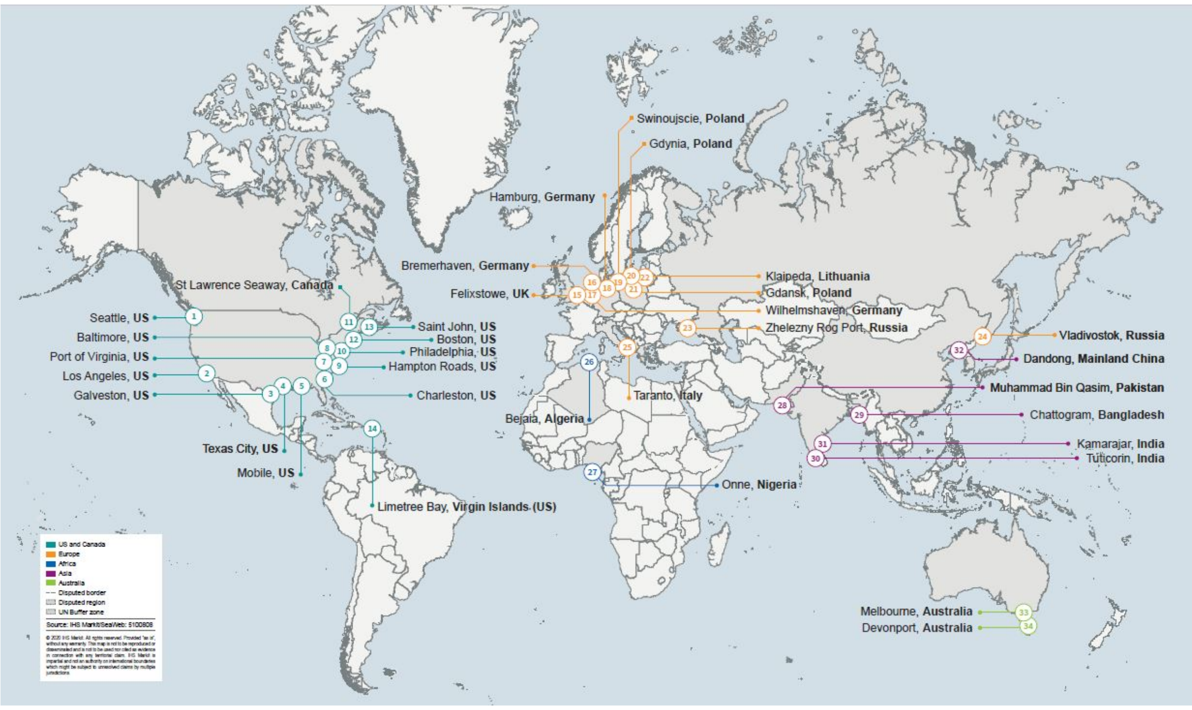

Figure A.1: Ports [5] with announced plans for future dredging work

Source: IHS Markit Ports and Terminals Data

The map (Figure A.1) shows the ports (already in existence and operational) that have announced future dredging work (as of May 2020). The US East coast and Eastern European ports are the hotbeds of activity.

The urban population has grown from 751 million to 4.2 billion between 1950 and 2018. By 2050, more 2.5 billion people would live in urban centres of the world [17]. The construction needs of the

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[2] construction of breakwaters, offshore installations, harbour infrastructure, dams, dikes are not included

[3] Two major dredging markets that are closed are United States of America and China

[4] Total value of work which was performed in the year. Dredging in inland waterways, rock installations (through side-stone dumpers and flexible fall pipe vessels are excluded.

world would continue to grow. Presently, this need for construction material is fulfilled by river aggregates and in general, unsustainable. It is expected that there would be a move from the river aggregates to sea sand [18].

Currently, coastal protection activities form about 10% of the dredgers activities. As per the Ocean Conference Factsheet [440] : coastal areas account for 50% of international tourists travel, about 40% of world's population lives within 100 km of the coast. Almost 2/3rd of cities (with population > 5 million) are at a risk of sea level rise and by the year 2100, 500 million people will live in coastal areas which are less than 5 metres above Mean Sea Level. With climate change leading to more intense storms and rise of sea levels, more money (than current) would be put into climate change mitigation techniques like coastal protection. Hence, it can be concluded that dredging would play an important climate change mitigation strategy and coastal protection would required increased dredging needs.

Climate change has and would bring about not just the need for coastal protection. Closely related to the need of coastal protection (climate change induced) is the impetus from governments all around the world to shift to renewable energy. Renewable energy in the form of ocean energy and offshore wind energy sources are not realisable without dredging.

Until now, 6 factors have been mentioned as drivers of growth for the dredging industry. However, there is a possibility of a 7th factor coming up in the near future : Deep Sea Mining. Deep Sea mining is the process of mineral retrieval from the ocean floor. Deep Sea mining may be a lucrative market for dredging vessels and near a breakthrough [14]. Deep Sea mining can be a crucial field to satisfy the thirst for critical raw materials especially those that have the possibility of powering the energy transition. The global market value for deep sea mining [6] is expected to be 15.3 billion $ in the year 2030 [441]. This is an implied Compounded Annual Growth Rate (CAGR) of 37.1 % between 2020 and 2030. In particular [7], rock phosphates (for example, in Chatham Rise - New Zealand), iron sands and diamonds (for example, in New Zealand, Papua New Guinea and Namibia) can be mined with the capabilities of current TSHDs.

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[6] sea floor at a depth of more than 500 metres

[7] due to the depths they are found at and the state they are found in.

A.4. Market Need and Value Creation

The new product to be introduced is a Nuclear powered Trailing Suction Hopper Dredger. The dredger is designed to operate with the nuclear fuel as its energy source.

This guarantees :

- Compliance with the current and any future emissions regulations
- Stable fuel price
- Increased bunker call period (even up to 20 years)
- Reduced fuel costs
- A realisable concept without much development effort.

Discussions with representatives of one of the world's biggest dredger maker and world's biggest dredging company confirmed that nuclear option is ”a blind-spot” and has not/is not being considered by the industry.

To visualise the value created for the dredge operators when utilising a nuclear powered TSHD a Value Proposition Canvas was developed. This is presented in Figure A.2. Value Proposition Canvas is a tool to visualise, design and test the value created for the customer is the Value Proposition Canvas. Invented by Dr Alex Osterwalder it is used to find a fit between the customer needs/values (market) and the product [442]. Broadly, the Value Proposition Canvas helps in characterising the customer profile and to understand the creation of value.

As is clear from the Value Proposition Canvas, a nuclear- powered Trailing Suction Hopper Dredger is a clear pain reliever and gain creator for dredging operators.

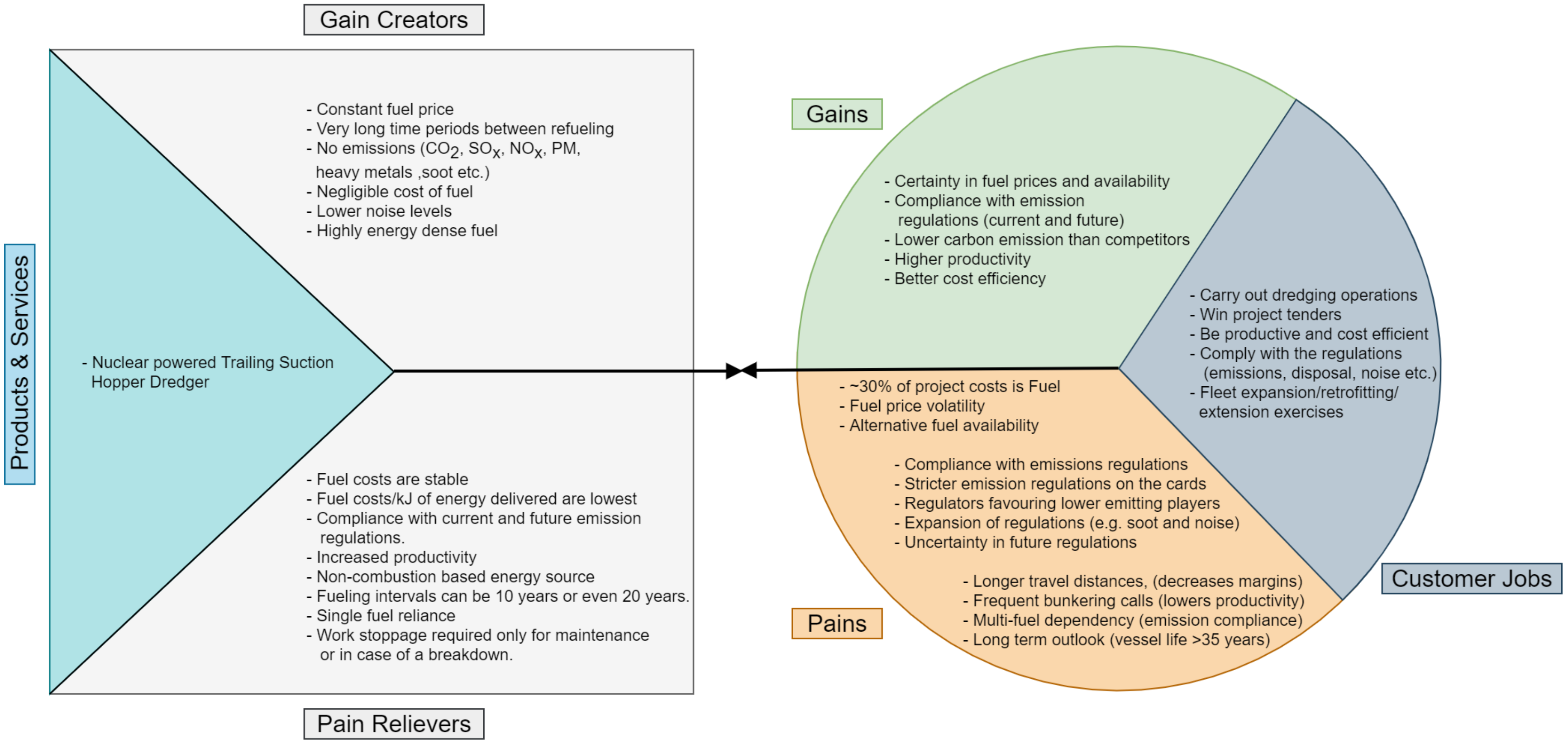

Figure A.2: Value Proposition Canvas

A.5. Market Potential

The estimation of market potential is not straightforward. Nuclear powered dredgers could replace the current dredgers or the current dredgers could be retrofitted or new orders for nuclear powered dredgers could be placed.

There are 26 dredgers that are bigger or comparable in size to WILLEM VAN ORANJE [8]. The cost of these dredgers is in the range of 110-220 million € (As per CIRIA methodology for estimation of dredger price). The estimated price for nuclear powered dredgers would be twice as much. The replacement of these alone presents an opportunity of 4 billion €.

Almost all of the larger dredgers (which are of viable size for the retrofit) were built in the last 25 years. The average age of TSHDs is almost 41 years [443], hence, this replacement exercise is going to happen over time and not overnight.

Nuclear powered TSHDs offer superior performance and are suitable over other dredgers in capital dredging. Hence, such larger nuclear powered TSHD could also displace some of the smaller TSHDs that are involved in capital dredging works. This could happen by the retrofitting of existing dredgers or new orders. An estimate for the retrofitting would be around 100 M€ per dredger. If all the dredgers were to be retrofitted, the possible revenues from the exercise would be around 2.6 billion €.

From the PEST Analysis, it can be estimated that atleast one dredger could be interesting for US, Russia and China (reasons for this is obvious from the discussion in Section A.6). The estimation of the total addressable market at this preliminary stage is not apt. However, if the first concept is successful and the benefits are realised, a snowballing effect can occur. In such a scenario, a conservative estimate of atleast 1 billion € can be made.

A.6. Possible Beachhead Market

Bill Aulet in Disciplined Entrepreneurship [444] refers to the beachhead market as "..the place where, once you gain a dominant market share, you will have the strength to attack adjacent markets with different offerings, building a larger company with each new following.". Hence, identification of beach head market is of prime importance. A good choice can make the product while a bad choice can break the product. In this work, the possible geographical beachhead market for a nuclear-powered TSHD is narrowed and identified.

The initial vetting of the country was based on experience with nuclear power capability and nuclear powered vessels. This gives a list of the following countries :

1. United States
2. Russia
3. China
4. India
5. France
6. UK
7. Germany
8. Japan

Out of these, Germany and Japan have operated only one nuclear powered vessel. Further, these vessels stopped operation over 25 years ago. There is no intention to run or thrust to run any more nuclear powered vessels in both of the countries. While, the size of the dredging markets of France

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[8] TSHDs bigger than the size of WILLEM VAN ORANJE ($\sim$ 20,000 m^3) hopper capacity are interesting for carrying out the retrofit

and UK are too small individually to justify the use of a nuclear powered vessel. However, EU as a region could present a big opportunity.

From this initial vetting, the following are identified as countries/region of interest :

1. United States
2. Russia
3. China
4. India
5. EU

It is to be noted that each of these country has the capability to run nuclear based systems and some sort of nuclear fuel cycle related facilities. Each of these have local shipbuilding facilities where such a concept could be built. Further, each of these options have long coast lines (within top 15 in the world [9]).

To provide a more objective view of the business environment for a nuclear powered TSHD concept, PEST Analysis was used. PEST Analysis is a tool for analysing changes in the business environment to understand the forces of change that a business is exposed to. It provides a framework for macro environmental factors. Professor Francis Aguilar is credited as being the creator of PEST Analysis. In his 1967 book ”Scanning the Business Environment” [446], he referred to four factors as having a major influence on business. These factors were economic, technical, political, and social factors. The purview of these factors vary across the business segment, market etc. PEST Analysis is a dynamic tool and new components can be added/have been added to enforce other factors. Hence, the exact description and scope of the different factors of PESTLE depends on the type of use. For the evaluation of a beach head market for the nuclear TSHD concept, the analysis was adjusted to fit the criteria that are important in this particular case. The following factors are considered :

1. **Political factors** includes coverage of any government policy, regulation that currently exists/is pending and how does it affect the business. What is the government intervention and influence on the sector? What are the regulations? In this particular case, nuclear third party liability regulations, availability of insurance, any special regulations for the sector (nuclear/dredging).
2. **Economic factors** in this case include the GDP growth, Ease of doing Business Rankings from World Bank [447], market size, and the nature of the market.
3. **Socio-geographical factor** covers the public acceptance of nuclear power in the country and the size of the country/region.
4. **Technological factor** includes the experience in operation of nuclear powered vessels (naval and civilian) and infrastructural availability for servicing of nuclear capable vessels.

The template for visual representation of PEST analysis is given in Figure A.3. The various factors and what they entail in this particular case are mentioned. Henceforth, each of the countries/regions of interest are discussed. The PEST analysis that was carried out is tabulated in A.1.

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[9] Data accessed from CIA World Factbook [445]

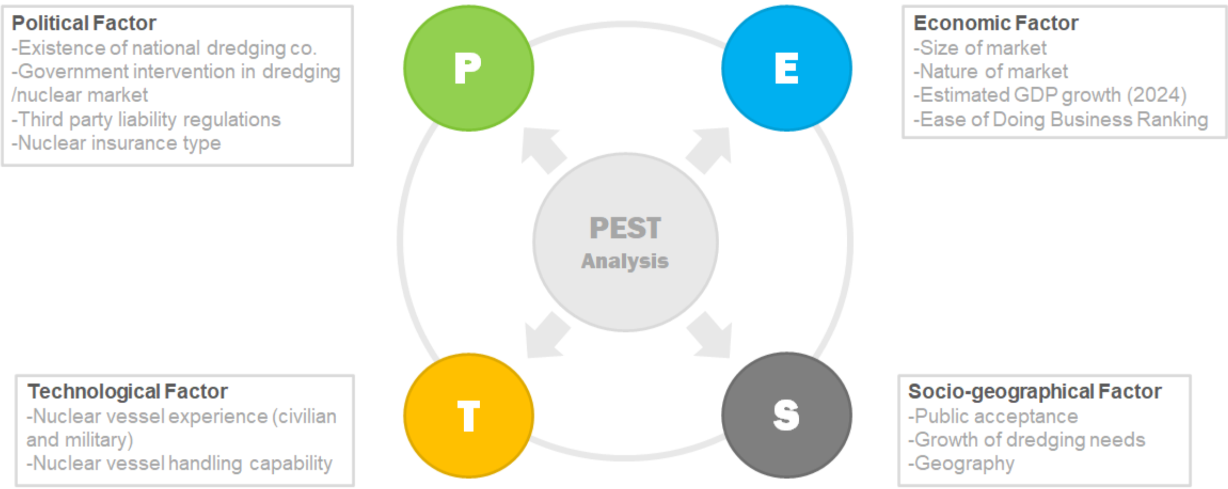

Figure A.3: Visual Representation : PEST analysis

United States

The US dredging market is valued around 4 billion $ [448]. However, only US companies are allowed to participate in US dredging market due to the restrictions enacted by two separate acts : Dredging Act and Jones Act. Some of the protective measures are [449] :

- Vessels should be US built, owned, flagged and crewed.
- 75% of the equity ownership should be owned by US citizen.

Forming and structuring joint ventures that satisfy the regulation and can bring in the European expertise [10] has been suggested for wind offshore [450]. There is a possibility that similar measures/workarounds might be possible for the dredging industry.

The US Navy has accumulated over 162 million miles and 6900 reactor years [11] of operating years without a reactor accident [451]. A nuclear merchant ship, NS Savannah was operated. The ship had visited 45 foreign ports and bilateral agreements were made between US and the countries where NS Savannah visited. Hence, the US has the diplomatic will and strength to drive get a nuclear TSHD to its location (if work site is not inside the US).

The US has a long coastline and both, the East/West coast has a number of large ports (5 in the top 50 largest container ports). As per data from World Shipping Council [452], there are 5 American ports in the top 50 largest container ports. US has high acceptance level with strong acceptance of nuclear at a high level [360].

Russia

The Russian dredging fleet is expanding and there are plans for further expansion [12]. 26 million m^3 needs to be removed to handle the expected increase in the capacity of North Sea Route. In Sabetta sea port alone, it is estimated that 200 million US $ of dredging work is required [454]. Recently, Russian government considered the establishment of national dredging company (NDC). Non-Russian dredging companies have contracts of nearly 1.5 billion USD in the past 2-3 years due to lack of dredging capacity internally [455].

The Russian Navy with its comparable size to the US Navy would has a similar number of reactor years as US Navy. Currently, only Russia owns nuclear icebreakers. Cumulatively, it has 400 reactor-years of experience with them [135]. Russia also operates the only floating power unit AKADEMIK LOMONOSOV [150].

There is an anticipated rise in traffic on the North Sea Route (NSR) and Arctic region. Russia have high acceptance levels but strong acceptance is comparatively lower [360].

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[10] Similar to European expertise in the dredging industry

[11] One reactor year is defined as one reactor operating for one year. Equivalently, ten reactor years could be 10 reactors operating for one year or one reactor operating for 10 years or or 5 reactors operating for 2 years each

[12] In March 2020, the most advanced dredger in the past 30 years was built. The average age of Russian dredging fleet 36 years and is in an "urgent need" of new dredgers into operation [453].

India

Indian dredging market is about 7% of the world's market share [456].
Out of the options for consideration here, India has the least amount of experience with nuclear powered vessels. Although, 6 Nuclear submarines are planned and nuclear aircraft carrier is planned by 2035 [457].
Under Sagarmala Project [458], the Government of India wants to develop existing ports and create new ports. Extensive dredging activities are expected as part of this. About 203.21 million m^3 of material needs to be dredged in the near future [459]. This opportunity can be valued at around 3-5 billion €.
The tenders are awarded on the basis of lowest valid offer. However, Indian flagged dredgers (owned by a domestic company) within 10% of their foreign flagged vessels are preferred. Further, the national dredging company, Dredging Corporation of India can be awarded capital dredging works on a nomination basis (without a competitive tender process) [458].
India has the shortest coast line of the group. As per data from World Shipping Council [452], there are 2 ports in the top 50 biggest ports in the world. India has high acceptance level with strong acceptance of high level [360].

China

China is the world's largest dredging market [14].
Since 2004 no access to the dredging market is possible (in practice). However, access is possible through a Wholly Foreign Owned Enterprise or Equity Joint Venture [460]. There is a charter tax system for building equipment (WTO, decree 113). Additionally, if foreign dredging companies are employed for work, 30% higher taxes are enforced. CCCC Dredging is the state owned dredging company and is the biggest dredging company in the world.
China has a nuclear navy and in 2018, China National Nuclear Corporation called for bids to make the first Chinese nuclear powered icebreaker [141]. In 2019, China General Nuclear Power Group (CGN) invited bids for an "experimental ship platform" which would feature two 25 MWe PWR, 152 metres long and displacement 30,000 tonnes [142]. China is engaged in designing and developing floating vessel to be equipped with SMRs for supplying electricity [151]. There are plans to eventually build 20 floating nuclear plants in South China Sea [152].
As per data from World Shipping Council [452], there are atleast 16 ports in the top 50 biggest ports in the world. China has high acceptance level with strong acceptance of high level [360].

European Union

There are no national dredging companies in EU member states. However, the world's biggest dredging companies are based out of Benelux. Nuclear is not seen as possible option for the future [13]. Each member state has its own nuclear third party liability regulations. The nuclear liability can also be unlimited (in some member states). The nuclear third party insurance if pool based (not all countries have a nuclear insurance pool). The dredging market is big and unlike the US or China, the market is open for competitive bidding. However, regulators in some countries (Belgium, Netherlands etc.) give preferential treatment if the carbon emissions of operations are low. In terms of nuclear-powered vessel experience, UK and France have nuclear navies while NS OTTO HAHN was a German nuclear-powered civilian vessel. The public acceptance differs between member state to member state. France, UK have high acceptance levels but strong acceptance is comparatively lower [360].

There is no clear winner from the analysis. However, there are certain 'red flags' and further elimination is possible based on the 'red flags'. EU due to its staggered market, complex regulatory structure (crossing member country borders) and non supportive view of nuclear power is certainly not a good choice. India has promising aspects, however, it is comparatively still nascent when it comes to nuclear powered vessels. China and United States are effectively closed markets. However, there are workarounds to evade and form a customer base. Russia appears to be a good choice overall and has no red flags as per the factors considered and the evaluation.

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[13] For example in financing of 1 trillion € low carbon technologies under the European Green Deal Investment Plan (EGDIP) the financing of construction of nuclear power plants was excluded [461].

Table A.1: PEST Analysis of the 5 different regions

		United States	Russia	China	India	EU
Political	**Government Intervention**	No national dredging company	Rosmorport (state owned dredging company)	CCCC Dredging is (state owned dredging company)	DCI can be awarded work on nomination basis	No national dredging company
		Only American owned companies allowed	Possible formation of National Dredging company	High excess taxes (foreign companies)	Indian flagged vessels preferred if bid +10%	Nuclear not seen as a preferred option
		Dredging Act and Jones Act				EU rules, national and international rules
	Third Party Liability	Price Anderson Act	Insurance agencies and pool	Pool based	Pool based	Pool based
			If nationally owned not required	45,000,000 $	200,000,000 $	Amount variable. Unlimited Nuclear liability (some)
Economic	**Market size**	Large	Smallest	Largest	Large	Large
	Nature	Closed market	Open	Closed	Semi-closed	Open
	Estimated GDP growth (2024)	2.10%	1.60%	5.50%	7.70%	2%
	Ease of Doing Business Rank	8	28	31	63	Depends
Socio-geographic	**Public Acceptance**	High	High	High	High	Depends
	Growth of Dredging	High	High	Medium	High	Medium
	Geography	Large	Large	Large	Smallest	Largest
		Largely navigable without any foreign involvement	Largely navigable without any foreign involvement	Some navigation subject to grant of rights	Largely navigable without any foreign involvement	Most navigation subject to grant of rights
Technological	**Experience**	6900 reactor years (US Navy)	6900 reactor years (US Navy)	Some experience	Least experience	Some experience
		NS Savannah (cargo)	Icebreakers and cargo carrier		7 new nuclear vessels planned	NS OTTO HAHN (Germany)
	Infrastructure	High	High	Medium	Low	Low (only UK and France)

A.7. Stakeholder Analysis and Porter's Five Forces

According to Frooman [462], the stakeholders can influence a firm by ”withholding strategies” and/or ”usage strategies”. The first is related to the suppression of resources and the second relates to the control of how the resource is used. Because stakeholders can influence the development of a nuclear TSHD concept directly or indirectly, hence, understanding who the stakeholders is of prime importance. Stakeholder model for an organisation was visualised by Mendelow [463]. Similarly, a concept's stakeholders may be categorised into government, company shareholders, customers, suppliers, lenders, employees, competition, media, public, regulators. At this juncture, it is also important to remember that the government is the most important customer for dredging companies [14]. Figure A.4 gives a visual representation of the the stakeholders.

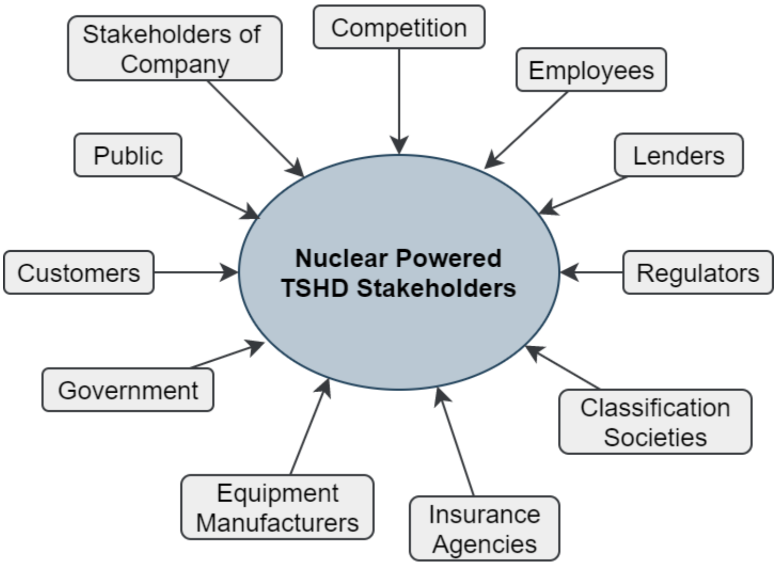

Figure A.4: Identified Stakeholders for the Nuclear powered TSHD concept

Now, for analysing the competitive environment, we would be using Porter's Five Forces. Porter's Five Forces were made for evaluating the competition, the standing in the industry and the factors that influence the profitability of an organisation [464]. In case of this work, Porter's Five Forces concept is extended to Nuclear powered TSHD. The factors along with their applicability are described as follows :

1. Industry Rivalry : Royal IHC is the world leader in development of large Trailing Suction Hopper Dredgers. The competitive rivalry in the space of large TSHDs is very low.
2. Threat of New Entrants : Due to the requirement of highly specialised knowledge and skills, the barriers to entry into the industry are very high. Hence, the threat of new entrants is very low.
3. Bargaining power of buyers : The bargaining power of customers is low as very special expertise is required for development of a TSHD. The addition of nuclear power and components to the vessels adds further complexity. Hence, for a prospective buyer, there are not many avenues left.
4. Bargaining power of suppliers : The supplier side in this particular case would be mainly related to the nuclear reactor and related machinery. There are more than two dozen such Small Modular Reactor concepts that are being developed and about a dozen companies that are vying for a piece of the business. The bargaining power of the suppliers is low due to the sheer number of available choices.
5. Threat of substitutes : The substitutes are the concepts powered with alternative fuel. Alternative fuel is competitive and a better solution in certain segments and sectors. But there are niches where the nuclear concept out competes all the possible substitutes.

Such an analysis of the Five Forces is generally followed by strategy to expand the competitive advantage. However, this is beyond the scope of this work.

A.8. Conclusions and Future Work

This work tried to build a preliminary case for the commercialisation of the nuclear-powered TSHD concept developed in the main master thesis titled: ”An Exploratory Study of powering Trailing Suction Hopper Dredgers with an emphasis on Nuclear power”.

- With features like compliance with the current and any future emissions regulations, stable fuel price, increased bunker call period (even up to 20 years), reduction of fuel costs and realisable concept without much development effort. It is clear from the Value Proposition Canvas that a nuclear-powered Trailing Suction Hopper Dredger is a clear pain reliever and gain creator for dredging operators.
- The replacement of 26 dredgers poses an opportunity of about 4 billion € while the retrofitting opportunity is estimated to be about 2.5 billion €. The estimation of the total addressable market at this preliminary stage is not apt. However, if the first concept is successful and the benefits are realised, a snowballing effect can occur. In such a scenario, a conservative estimate of at least 1 billion € can be made.
- The possible geographic beachhead market was narrowed and identified through an initial screening and then using PEST Analysis. There is no clear winner from the PEST analysis and further elimination was carried out based on possible ’red flags’. India is comparatively nascent, China and US are effectively closed markets but Russia appears to be a good choice overall and has no red flags as per the factors considered and the evaluation.
- Various stakeholders were identified. As the most important customer, regulator and endorses, the government is the most important stakeholder. As per the Porter’s Five Forces analysis, the threat of the substitutes is the biggest factor that would influence the concept. Although, there are niches where the nuclear concept out competes all the other possible alternatives.

The overall treatment of the entire concept was preliminary in this work. Because of the extensive scope of the problem, the focus of this work was mainly on the qualitative research, as a first step. Further, the nascency of the concept does not support the quantification which can be a subject of a later research once the concept is a bit further.

1. Each of the frameworks in this work would have to be updated as and when the more information is developed/available.
2. A more extensive analysis for selection of the beach head can be carried out.
3. The business case with the economics should be developed.
4. A SWOT Analysis was not carried as part of this work. Such a SWOT Analysis will help in better understanding how the business of a nuclear powered TSHD can fit in the company.
5. The three generic strategies (cost leadership, differentiation and focus) of Porter have not been dealt with in this work. They can be part of a future work to help expand the competitive advantage.
6. Influence matrix was introduced by Moreno et al. [465] to indicate how stakeholders influence each other, However, it was realised that it gets complicated fast.

A.9. Personal Reflection

All my life, I had always talked about ideas that are interesting and have a possibility to be converted into money-making machines. But these never made anywhere except for the neurons they occupied. Inevitably, I was a thinker and not a doer.

Various courses in Entrepreneurship hosted by Delft Center for Entrepreneurship made me notice that to be an entrepreneur is to be a doer. It made me realise that a problem that exists in one's mind, a world changing idea or that idea which would make billions; might really not have any takers. This is where the philosophy of the "Get out of the Building (GOOB)" where one is pushed into talking to experts and customers to understand and validate the problem is of prime essence. An entrepreneurial opportunity exists only if there is problem to be solved AND if there is someone who is not just willing but ready to pay for it. Hence, an early market validation of the idea in the most crucial step in an entrepreneurial venture and this prevents the unnecessary deployment of resources and time where none should have been.

The courses offered as part of the Annotation, provided the learning on a plethora of aspects (from how to use IP to devising a go-to-market strategy to marketing) but also numerous chances to meet the alumni. My own entrepreneurship journey has been as a member of Rocknroo, a student project that started as part of the course Health Business Development Lab. Over the past 1.5 years this has brought in enormous learning and opportunities. Personally, being an entrepreneur has been about solving problems that exist today but also preparing for what lies ahead in the future. It is about making a solution into a sustainable venture. It would not be wrong to say that the present work and my main thesis has been affected from my entrepreneurship leanings and learnings. At each step, I was not only thinking as an engineer but also as an entrepreneur and trying to be realistic and practical about things. At last, the entrepreneurial journey that started in November 2018 with the Health Business Development Lab is still going strong and would continue.

B

Data

This Appendix contains data tables that have been used in the report (in one form or another).

Table B.1: NOx Emission limits (tierwise)

Tier	**Ship construction date (on or after)**	**Total weighted cycle emission limit** (g/kWh)		
		n <130	**n = 130 - 1999**	**n ≥ 2000**
I	1 January 2000	17	45·n(-0.2) e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	44·n(-0.23) e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	9·n(-0.2) e.g., 720 rpm – 2.4	2

Source:[75]

Table B.2: Battery Data

Battery	**Company**	**Energy Capacity** (kWh)	**Volume** (m^3)	**Weight** (kg)	**Energy Density** (kWh/m^3)	**Specific Energy** (kWh/kg)	**Type**
Tesla Powerpack	Tesla	232	2.788	2199	83.21	0.11	AC
Corvus Dolphin Power vert. arr.	Corvus	47	0.428	375	109.73	0.13	System, High C-rate
Power 65 Series String	SPBES	65	1.444	950	45.01	0.07	System, High C-rate
SMAR-11N	Spear	11.3	0.12	152.7	98.01	0.07	System, High C-rate
Orca Energy vert. arr.	Corvus	125	1.43	1620	87.41	0.08	System, High C-rate
Orca Energy hor. arr.	Corvus	125	1.61	1620	77.70	0.08	System, High C-rate
Large Systems							
Tesla Powerpack	Tesla	232	5.977	3319	21.28	0.03	System, AC values
Corvus Blue Whale	Corvus	2400	20.64	20300	116.28	0.12	Low C rate
Tesla Megapack	Tesla	2500		23133		0.11	
Inverter							
Powerpack Inverter	Tesla		3.19	1120	0.04	0.04	

Source: [466] [467] [468] [469]

Table B.3: Fuel cell Data

Fuel Cell	**Company**	**Peak Power** (kW)	**Volume** (m^3)	**Weight** (kg)	**Specific Power** (kW/kg)	**Volumetric Power** (kW/m^3)	**Notes**
HD 90	Hydrogenics	93	0.59	360	0.26	156.57	System
HD 180	Hydrogenics	198	1.19	720	0.28	166.39	System
CELERITY	Hydrogenics	60	0.29	275	0.22	204.08	System
POWERCELL MS-100	Powercell	100	0.28	170	0.59	362.32	System
Fcmove - HD	Ballard	70	0.54	250	0.28	129.63	System
FC veloCity HD100	Ballard	100	0.61	280	0.36	164.11	System
FCETM 80	US Hybrid	80	0.49	248			System
HD 8	Hydrogenics	9	0.04	52	0.16	212.50	Module
HD 10	Hydrogenics	11	0.04	47	0.22	244.19	Module
HD 15	Hydrogenics	17	0.05	55	0.30	317.31	Module
HD 30	Hydrogenics	31	0.08	72	0.43	407.89	Module
HD 50	Hydrogenics	51	0.10	110	0.46	494.67	Module
Sub-systems							
FC veloCity HD100	Ballard						System
Coolant Subsystem			0.15	44			System
Air Subsystem			0.10	61			System
Large system							
Megawatt Power Plant	Hydrogenic	1000	174	32000			System

Source: [470] [471] [472] [473] [474] [475] [476]

Table B.4: Flywheel Data

Flywheel	**Energy Capacity** (kWh)	**Power** (kW)	**Rotor Weight** (kg)	**RPM**
Beacon Power, LLC (BP400)	25	100	1133	8000–16000
LEVISYS	10	10–40		
Stornetic GmBH (EnWheel 22 and EnWheel 60)	3.6	21.5–75		<45000
Flywheel Energy Systems Inc.	0.75	50	135	15500–31000
Powerthru/ Pentadyne	0.528	190	590	30000–53000
Calnetix (VDS-XE)	1.11	300	821	24500–36750
Amber Kinetcis (M32)	32	8	2268	<8500
ActivePower	50	50–250	272	7700
Temporal Power	0.958	100–500	3500	<10000
PowerStore	4.155	1560	2900	1800-3600
Piller	6	2400		1500–3600
Energiestro	5.833	5	1700	
CleanSource Plus SMS	3.25	300	2000	10000
CleanSource HD675 UPS	5	675	5000	7700

Source: [248] [477] [478] [479] [480] [481]

Table B.5: Tank Data

Name	**H_2** (kg)	**Pressure** (bar)	**Tank** (kg)	**Tank Volume** (L)	**Gravimetric Ratio**	**Volumetric Ratio**	**Company**	**Notes**
Compressed								
QUADRHY 20ft	50.4	60	3096	33137	61.43	657.49	MAHYTEC	
TANK (60 bar, 850 L)	4.20	60	215	850	51.19	202.38	MAHYTEC	Type IV
G-STOR™ H_2	7.72	350	141	429	18.26	55.54	LUXFER	Type III
TANK (500 bar, 300L)	9.50	500	260	300	27.37	31.58	MAHYTEC	Type IV
Metal Hydride								
MH 1000	0.09	1-10	10	2.86	112.61	32.23	Pragma Industries	No HEX (max.)
MH 1500he	0.13	1-10	14	5.78	105.11	43.39	Pragma Industries	With HEX (min.)
MH 10Mhe	0.89	1-10	115	40.38	129.50	45.47	Pragma Industries	Biggest Volume
Liquid								
Gen-3 cryo-compressed tank	10.70	1	123	235	11.50	21.96	LLNL	

Source: [482] [483] [484] [485] [486] [487] [332]

Table B.6: Gas Turbines with Generator Data

Turbine	**Weight** (kg)	**Volume** (m^3)	**Power** (kW)	**Company**
Industrial Gas Turbine				
SGT-750	175000	399.50	39800	Siemens
SGT-700	169193	345.92	32800	Siemens
SGT-600	149688	345.92	24500	Siemens
SGT-400	83825	169.59	10400	Siemens
SGT400 (13 and 15 MW version)	83825	186.62	13600	Siemens
SGT-300	59349	118.76	7900	Siemens
SGT-100	34927	114.84	5225	Siemens
Aeroderivative				
35.3 MW	97045	218.06	34700	GE
30.2 MW	94545	178.57	29000	GE
25.1 MW	90000	146.47	24050	GE
4.6 MW	27273	40.27	4200	GE

Source: [488] [489] [490] [491]

Table B.7: Steam Turbines Data (Kawasaki)

Name	**Weight** (kg)	**Volume** (m^3)	**Power**(kW)
UA-120	150000	800.66	7300
UA-160	170000	809.09	10300
UA-200	220000	848.40	13250
UA-240	260000	1168.23	16150
UA-280	280000	1223.64	19100
UA-320	295000	1316.70	22050
UA-360	300000	1316.70	25000
UA-400	305000	1316.70	27950
UA-440	330000	1646.40	30900

Source: [492]

Table B.8: Nuclear Reactor Data

	Diameter (m)	**Length** (m)	**Weight** (kg)	**Volume** (m^3)	**Power** (MW_{th})
HTR-10	4.35	11.50	320000	170.82	10000
Ubattery	3.70	6.55	250000	70.39	20
HTTR	18.50	30.00		8059.99	30

Source: [270] [326]

Table B.9: Engine Data of 4 selected dredgers

Dredger	**Engine name**	**Weight** (kg)	**Volume** (m^3)	**Power** (kW_e)
OPTIMUS	MAN 6 L32/40		75	2,895
	with Generator	75,000	127.10	
WILLEM VAN ORANJE	Wärtsilä W12V32	56,900	90.58	6,000
	with Generator	100,100	135.22	
HAM318	Wärtsilä 12V46C	169,000	237.04	11,349
	with Generator	265,000	378.84	
CRISTÓBAL COLÓN	MAN 16 V48/60B	240,000	329.71	18,400
	with Generator	360,000	494.56	

Source: [493] [494] [495] [496]

Table B.10: Engine Data for Exhaust Gas Calculation

Dredgers	**Bore** (mm)	**Stroke** (mm)	**RPM**	**Cylinders**
OPTIMUS	320	400	750	6
HAM 318	460	580	500	12
CRISTÓBAL COLÓN	480	500	500	16

Source: [493] [494] [495] [496]

Table B.11: Load Bank : Weight and Volume Data

	Load (kW)	**Volume** (m^3)	**Weight** (kg)
ASCO Load Bank Model 9800	2500-3000	59.77	9298

Source:[497]

Table B.12: Dimensions Reactor Pressure Vessel

Parameter	**Radial Dimensions (m)**
Vessel thickness	0.1
Radial reflector thickness	0.99
insulation thickness	0.1
barrel and gap thickness	**0.7**
	Axial Dimensions (m)
Reflector top	1.16
Reflector bottom	1.16
Top Plenum	0.5
Bottom Plenum	0.5
Support Structure	0.6
Core Support Plate	0.15
Insulation thickness top	0.6
Insulation thickness	0.3

Table B.13: Density of Nuclear Reactor Materials

Material	**Density (kg/m3)**
Heavy Concrete	4650
Ordinary Concrete	2390
Graphite	2270
Inside RPV (Fuel, voids, control rods etc.)	1895

C

Supplementary Information

This Appendix contains supplementary information to the report.

C.1. Current Marine Fuels

Since 1987, ISO 8217 standard "Petroleum Products – Fuel (class F) – Specifications of marine fuels" specifies the requirements for petroleum-based fuels used in shipping industry's diesel engines and boilers. A thumb rule is that higher the fuel quality, the higher is the viscosity. As per ISO 8217 standard, marine fuels or bunker fuels, are generally divided into two different classes:

- Heavy fuel oil (HFO)
- Distillates

The heavy fuel oils, also includes Low Sulphur Fuel Oil (LSFO), Ultra Low Sulphur Fuel Oil (ULSFO) etc. The distillates are referred to as marine gasoil (MGO). While blends of HFO and MGO are described as marine diesel oil (MDO) or intermediate fuel oils (IFO). HFO or MGO can be used on large ships but smaller vessels are not designed to run on heavy fuel oil [498].

Heavy Fuel Oil (HFO)

Heavy Fuel Oil (HFO) is defined as a fuel oil with a density greater than 900 kg/m³ (15 °C) a kinematic viscosity of more than 180 centistokes [1] (at 50 °C). Almost all medium and low-speed marine engines are designed to run on HFO [499]. The sulphur content of HFO cannot be greater than 3.5 %.

Marine Diesel Oil (MDO)/Intermediate Fuel Oil (IFO)

Marine diesel is similar to diesel fuel, but has a higher density. Unlike heavy fuel oil (HFO), marine diesel oil does not have to be heated during storage. The term MDO is for blends that have a very small proportion of HFO while IFO has a higher proportion of HFO [500]. MDO has sulphur content lower than 2% [501]. Sometimes, marine fuels are referred as LS 380 or IFO 180. The number following indicates that the maximum viscosity is 380/180 centistokes at 50 °C) respectively.

Marine Gasoil (MGO)

MGO has varying degree of sulphur content, though the maximum permissible sulfur content is lower than HFO. As per ISO 8217, the maximum permissible value is 1.5%. Low sulfur marine gasoil (LS-MGO) less than 0.1% S, therefore, it can be used at ports in EU or Emission Control Areas (ECAs) [502]. Ultra Low Sulphur Fuel Oil (ULSFO) is marine fuel that has sulphur 0.1% S. It can be sourced by desulphurisation of IFO fuels, however, this exercise is very expensive. Hence, this terms refers to MGO [499]. Compared to other marine bunker fuels, there is significantly lesser emissions of PM and soot from MGO.

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[1] $\frac{mm^2}{s}$

C.2. Marine Diesel Engines

Dual fuel engines are classified either as Low Pressure Dual Fuel (LPDF) or High Pressure Dual Fuel (HPDF). HPDF engines operate on Diesel process. Gas injection is at around 300 bar (high pressure) gas injection close to top dead centre (at the end of compression stroke). Whereas the LPDF engines operates on Otto process. Gas injection is at mid-stroke and <10 bar (low pressure).

Table C.1 gives the engine speed with the type of engine. The information is sourced from the Wártsilá Encyclopedia [503].

The main propulsion units can be driven by direct coupling of propeller and shaft (low speed 2-stroke engines) or by connecting via a gearbox (medium speed 4-stroke engine). Medium speed four stroke engine is also used for driving the auxiliaries.
Trunk piston engine is an IC engine where connecting rod connects directly to the piston (with a piston/gudgeon pin). The crosshead is a slider crank linkage where the crosshead slides in the guides and is connected to piston on one side and connecting rod on the other side.

Table C.1: Engine Type and Speed

Engine Speed	**RPM**	**Type**
High Speed	>1400	Trunk piston
Medium-speed	400-1200	Trunk piston
Low-speed	<400	Crosshead

C.2.1. Engine Derating for dredgers

This is elucidated by an example of a Wärtsilä 6L32 engine is rated at 3460 kW the same engine used aboard a dredger has a specified rating of 3120 kW [494]. It is clear that for use at dredgers is significantly derated. The reason for this is that the mechanically driven dredging pumps require operation at full torque even at 80% of nominal engine speed.

C.3. Emissions

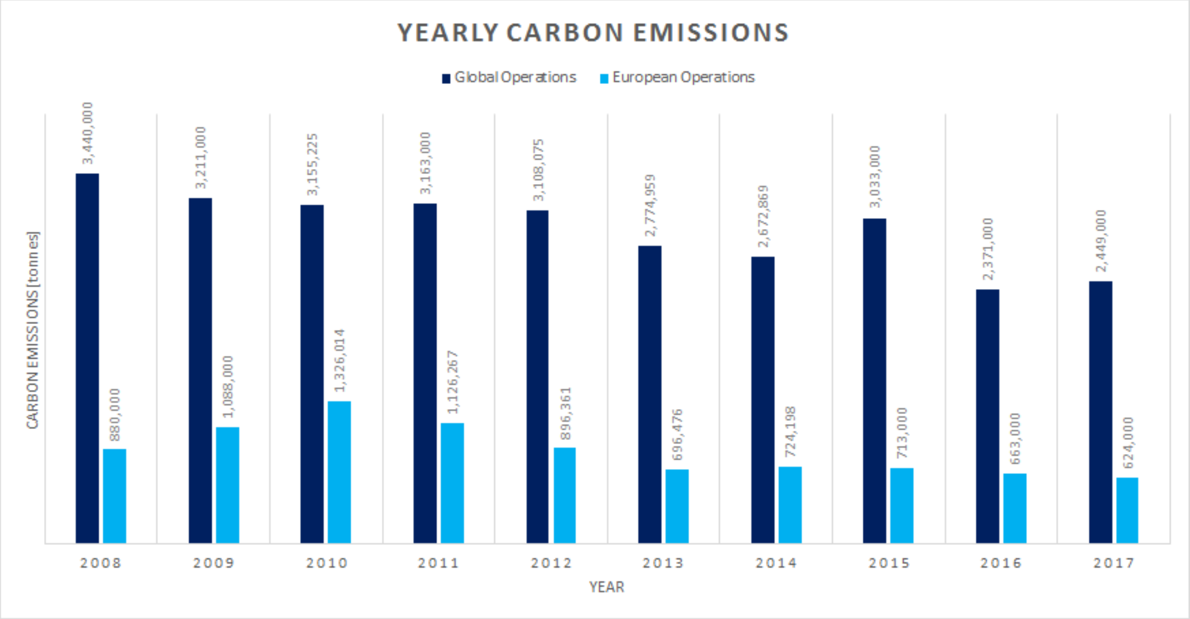

Figure C.1: Yearly Carbon emissions by EuDA members (in Europe and global)

Source: Data from EuDA Annual Report 2018 [439]

Figure C.1 gives CO_2 emissions of EuDA members (from their activities globally and in Europe). The variation in the emissions is linked to the global and sectoral activity. For example, European emissions are highest in 2010 because of dredging activity related to Maasvlakte 2 and the expansion of Suez Canal in 2015 led to higher emissions after a period of drop/constant emissions.

The emissions estimation for the year 2008 have been provided by EuDA [504]. This is based on 1171 vessels (sea and non-sea going). According to Clarksons [25], in February 2015, there were 1,911 dredgers already. The Dredger Register 2019 [505] lists more than 2000 dredging vessels and the calculation in the 2008 paper is done with only half that number. Hence, there's a lack of a more recent emissions data. This necessitates to make estimates for the current emissions for understanding the scale of the issue better. Further, heavy metals and SO_x emissions can be estimated from the fuel and the emission factor related to the fuel.

Emission Factors

When looking on a kg CO_2/tonne fuel basis the carbon content of each marine fuel is constant and not dependent on engine type, duty cycle or other parameters. These are unaffected by the sulphur content of the fuel burnt [506]. The carbon emission factors are same for main/auxiliary engines at slow, medium and high speeds [507].
The factors for the calculation of emissions of carbon dioxide, sulphur dioxide, Mercury (Hg) and Arsenic (As) per tonne of fuel are tabulated in Table C.2. These emission factors are taken from Statistics Norway [508] and IMO [509].

Table C.2: Emission Factors per tonne of fuel

	Emissions per tonne of fuel				
Fuel	**CO_2** $(tonnes)$	**SO_2** (kg)	**Hg** (g)	**Ar** (g)	**Pb** (g)
MGO/MDO	3.206	1.158	0.05	0.05	0.1
HFO	3.114	17.84	0.2	0.057	0.1
Methanol	1.375				
LNG	2.75				

Since, not all dredger vessels use HFO, the fuel requirements for any other fuel can be translated by dividing the calorific value of HFO with calorific value of the fuel. Table C.3 gives the lower calorific values of some common marine fuels.

Table C.3: Lower Calorific Value of various fuels

Fuel	**Lower Calorific Value** (kJ/kg)
HFO	40,200
MDO/MGO	42,700
LNG	48,000
Methanol	19,900

C.3.1. Carbon Reporting and Emissions : Company level

The majority of the carbon emissions attributable on dredging companies are due to the utilisation of their dredging equipment. 95% of the carbon emissions of Van Oord are due to equipment deployment [510]. For the DEME group, 93.5% of their carbon emissions are from Fuel Vessels and Floating equipment [511]. GHG emissions of Boskalis due to fleet operations account for around 99% of Scope 1 and Scope 2 CO_2 footprint [105].

The activity of the large TSHDs can affect the carbon footprint substantially. For example, the carbon footprint of Van Oord fell from 575.5 kilotons in 2018 from 676.6 kilotons in 2017. This was attributed to the fall in capacity utilisation rate to 22 weeks from 33 weeks for TSHDs [512]. However, capacity utilisation rate might not cover the entire picture. For instance, the FAIRWAY , a large hopper dredger operated by Boskalis recorded more operational days in 2018 compared to 2017, but less fuel use and consequently, lesser CO_2 emissions [105].

Jan de Nul publishes CO_2 emissions reports that are part of the CO_2 performance ladder certificate. However, this includes only the emissions from Netherlands and Belgium. Hence, the total extent of the carbon emissions can only be estimated/guessed. DCI, NDMC, CHEC/CCCC, Great Lakes and Lock have not provided any numbers.

Out of top 10 dredging companies in the world, Boskalis seems to have the most comprehensive carbon reporting mechanism. In general, there is a lack of clarity on the reported carbon emission's Scope (1,2 or 3). However, it is clear that fuel consumption due to equipment usage forms about 95% or greater portion of the reported carbon emissions for dredging companies. For example : DEME [513] includes Scope 1 and Scope 2 emissions in its carbon footprint. DEME received a positive Verification Assurance Statement for its carbon footprint conformity to ISO14064 for its base year 2011 [514]. ISO 14064 is an international standard, supplying the basis for specific climate change programmes and defines 3 different scopes of emissions reporting.

As at 31 December 2018, the CCCC dredging Group's dredging capacity amounted to approximately 786 million cubic meters under standard operating conditions [515]. Hence, potentially, the dredging vessel fleet of the CHEC alone can emit somewhere between 1.5 million to 3.75 million tons of CO_2.

Carbon Intensity

Carbon intensity is a metric for evaluation of the carbon efficiency of a company. As per the Task Force on Climate-related Financial Disclosures [516], it is defined as

$$Carbon\ Intensity = \frac{\mathrm{CO_2}\ emissions\ [tons]}{Revenues\ [Million\ \$\ ]} \tag{C.1}$$

There are no reported numbers in the industry for this metric. However, 600 tons per million USD revenues seems to be an approximate number for dredging industry (see Table C.4). This can be compared with 1000 tons per million USD revenues for Maersk, the world's largest shipping company.

Table C.4: Carbon Intensity

Company Name	**Carbon Emissions (kilotons)**	**Revenues (Million $)**	**Carbon Intensity**	**Note**
Van Oord	576.5 [510]	954 [512]	604	1.12 $ = 1 €
Dredging Corporation of India	54	92 [517]	587	1 ₹= 0.013 $
Maersk	39,165 [518]	39,019 [518]	1003	

C.3.2. NO_x emission related

The NO_x emission limits as a function of the engine's RPM along with the applicable Tier is given in Figure C.2.

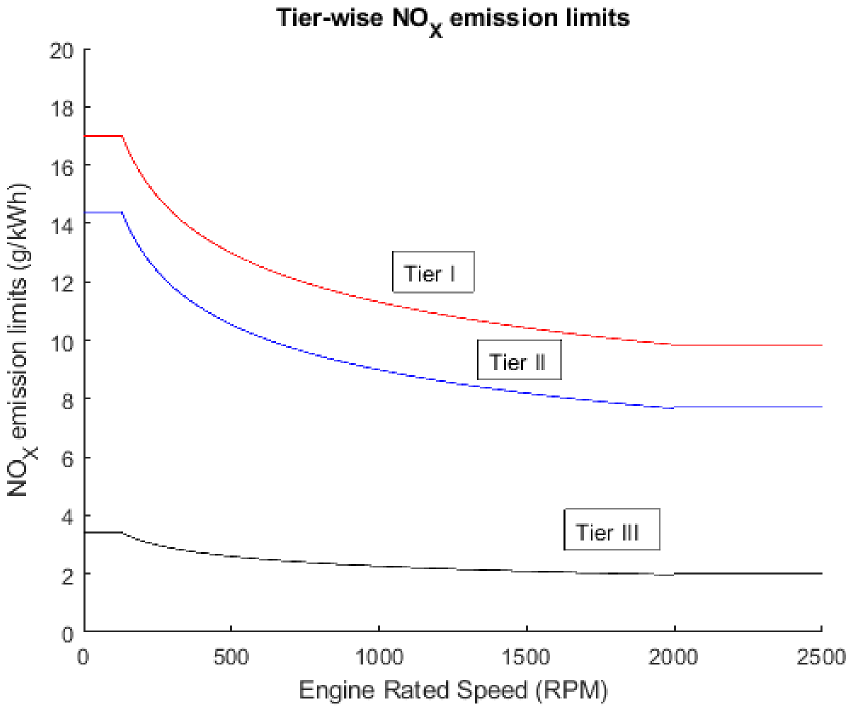

Figure C.2: NO$_x$ Emissions Limit

C.3.3. Carbon Tax

The most successful implementation of carbon tax regime is the Swedish carbon tax. The carbon taxation in Sweden started in 1991. and is levied on all fossil fuels in proportion to their carbon content. Hence, it is not necessary to measure actual emissions, which greatly simplifies the process [519]. The taxes were increased gradually in a step-wise manner from 24 €/tonne in 1991 to the current, 114 €/ton in 2019 .

In 2019, Canada implemented a CA$20 per tonne of carbon dioxide equivalent emissions (t-CO$_2$e) in 2019 and eventually this will rise to CA$50 per tonne. In 2008, first broad based carbon tax in North America was implemented in British Columbia [520]. On April 1, 2019, B.C.'s carbon tax rate rose from CA$35 to CA$40 per t-CO$_2$e. The tax rate will increase each year by $5 per tonne until it reaches CA$50 per tonne in 2021. The 40 CA$ tax translates into 8.89 ¢/litre of Gasoline, 10.23 ¢/litre of Diesel (light fuel oil) and 7.60 ¢/cubic meter of Natural gas.

In the Netherlands, a Bill was introduced to set a minimum carbon price of €12.30 in 2020 and increasing to €31.90 in 2030 [521]. In its current form, it is only applicable for electricity production but the Dutch government is working towards the introduction of carbon tax for industry too. Table 2.2 shows the variation in the carbon tax that is charged in different countries.

C.4. Critical Raw Materials List

As per the Critical Raw Materials List released by the European Commission [522], there are 27 critical raw materials. The The criticality is determined by the economic importance and the supply risks. Table C.5 gives the list of critical raw materials.

Table C.5: List of Critical Raw Materials

Antimony
Baryte
Beryllium
Bismuth
Borate
Cobalt
Fluorspar
Gallium
Germanium
Hafnium
Helium
HREEs
Indium
LREEs
Magnesium
Natural graphite
Natural Rubber
Niobium
PGMs
Phosphate rock
Phosphorus
Scandium
Silicon metal
Tantalum
Tungsten
Vanadium

The heavy rare earth elements (HREE), light rare earth elements (LREE) and and platinum group metals (PGM) are a bunch of elements that are clubbed together. These are give in Table C.6.

Table C.6: Metals in Different Groups

Metals in Different Groups				
PGMs				
Iridium	Palladium	Platinum	Rhodium	Ruthenium
LREEs				
Cerium	Lanthanum	Neodymium	Praseodymium	Samarium
HREEs				
Dysprosium	Erbium	Europium	Gadolinium	Holmium
Lutetium	Terbium	Thulium	Ytterbium	Yttrium

As per the data from Hein et al. [523], some of these critical raw materials are more abundant in the CCZ alone than the entire terrestrial known reserves.

C.5. Code of Safety for Nuclear Merchant Ships

C.5.1. Process Plant Conditions

1. Normal Operation (PPC-1) : These conditions occur continuously or are likely to occur often during the service life of the nuclear ship. Examples of this could be startup/shutdown and ship maneuvering.

2. Minor occurrences (PPC-2) : These are unplanned occurrences and likely to occur several times (infrequently) during the lifetime of the ship. Examples of this could be tripping of turbine/helium blower etc.

3. Major occurrences (PPC-3) : This PPC would occur in a few nuclear ships of the same type during their service life. The likelihood of such a PPC should be very small. Examples : incidents that result in limited unavailability of the ship, injuries or need for external assistance like leakage of radioactive substances from primary pressure boundary (without depressurisation), emergency cooling and containment isolation, stuck control rod etc.

4. Severe Accident (PPC-4a/PPC-4b) : The likelihood of such a condition should be extremely small and should not occur during the total service life but is nevertheless a possibility. Examples of this may involve loss of life or loss of ship and include capsizing or collision with fire/explosion, sinking.

C.5.2. Safety Classes

- SC-1 includes equipment like Reactor Protection systems, scram system, primary pressure boundary.

- SC-2 includes containment structure, Emergency core cooling systems (ECCS).

- SC-3 includes ancillary system providing support for safety systems like compressed air systems, lubricating oil systems for ECC, seawater coolant system.

- SC-4 includes parts of heat removal system that are located outside the containment, structure for the safety enclosure, collision protection.

C.6. Standard Conditions and Fees for Nuclear Authorisation under NNR Act

There are four categories of authorisation for performing nuclear related activities. This also includes the Nuclear Vessel Licences. The standard conditions for a nuclear authorisation according the National Nuclear Regulator [524] include :

- The description and configuration of the authorised facility or action
- Requirements in respect of modification to facilities
- Operational requirements in the form of operating technical specifications procedures or programmes as appropriate;
- Maintenance testing and inspection requirements
- Operational radiation protection programme
- Radioactive waste management programme
- Emergency planning and preparedness requirements as appropriate
- Physical security
- Transport of radioactive material
- Public exposure safety assessment
- Quality assurances
- Safety Case which identifies and characterises all radiation sources and possible pathways for exposure (under normal operating and accidental situations)

As per the latest amendment of the National Nuclear Regulator Act [525], the authorisation fees for such for a dredging ship operator would be to the tune of 463,359 Rands to 1,101,218 Rands (~ 27796 €-66060 €) [2]depending on the fleet size. Further, there would be per hour per person charges for new applications in regards to documents and site verification visits. This could could be upto 200,000 rands (~ 12000 €).

C.7. Nuclear Insurance Pools

Marija [526], websites of Assuratome [527] and Slovak Nuclear Insurance Pool [528] provide details of Nuclear Insurance Pools, their countries and websites. Table C.7 extends the details of these Nuclear Insurance Pool information, most notably the addition of Nuclear Insurance Pools of India, UAE, Turkey and Belarus.

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[2] 1 € = 16.67 ZAR (South African rand)

Table C.7: List of Nuclear Insurance Pools

Name of National Nuclear Pool	**Country**	**Website**
Belarusian Nuclear Insurance Pool	Belarus	https://nuclearpool.by/en/about/
SYBAN – Belgian Nuclear Pool	Belgium	www.syban.be
Bulgarian National Nuclear Insurance Pool	Bulgaria	
Nuclear Insurance Association of Canada	Canada	www.niac.biz
The China Nuclear Insurance Pool	China	www.chinapool.org
Croatian Nuclear Pool	Croatia	
Czech Nuclear Insurance Pool	Czech Republic	www.nuclearpool.cz
Nordic Nuclear Insurers	Finland and Sweden	www.atompool.com
ASSURATOME	France	www.assuratome.fr
Deutsche Kernreaktor - Versicherungsgemeinschaft	Germany	
Hungarian Atomic Pool	Hungary	
India Nuclear Insurance Pool (INIP)	India	
The Japan Atomic Energy Insurance Pool	Japan	
Pool Atómico Mexicano	Mexico	www.poolamx.com.mx
Nederlandse Pool voor Verzekering van Atoomrisico's	Netherlands	https://atoompool.vereende.nl/
Nuclear Energy Insurance Pool of the Republic of China	Republic of China	
Romania Pool for the Insurance of Atomic Risks	Romania	
Russian Nuclear Insurance Pool	Russia	www.atompool.ru
Slovak Nuclear Insurance Pool	Slovakia	https://www.nuclearpool.sk/page/internatio
Nuclear Insurance and Reinsurance Pool, Ljubljana	Slovenia	
The South African Pool for the Insurance of Nuclear Risks	South Africa	
The Korea Atomic Energy Insurance Pool	South Korea	
ESPANUCLEAR	Spain	www.espanuclear.com
Swiss Nuclear Insurance Pool	Switzerland	www.nuklearpool.ch
Turkish Natural Catastrophe Insurance Pool (DASK)	Turkey	
UAE Nuclear Insurance Pool (UNIP)	UAE	
The Ukrainian Nuclear Insurance Pool	Ukraine	
Nuclear Risk Insurers Limited	United Kingdom	http://www.nuclear-risk.com/
American Nuclear Insurers	USA	www.amnucins.com

C.8. Energy Storage

C.8.1. Flywheel

Flywheels have multiple cost elements [249] –

- Elements that scale with power = A: $/kW

- Elements that scale with energy = B: $/kWh

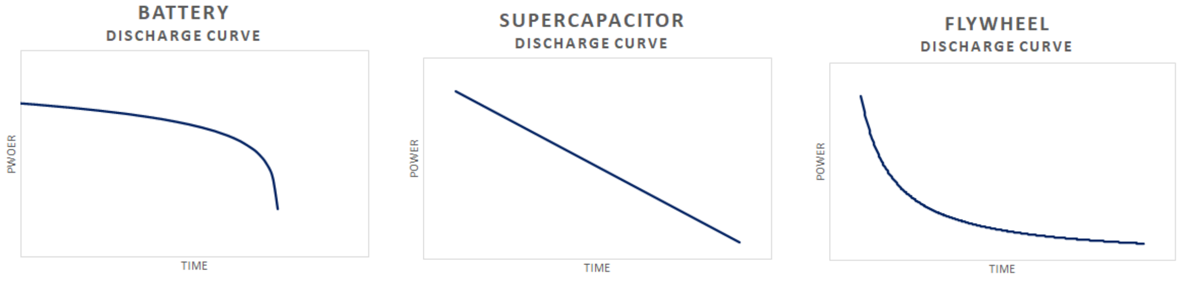
- Elements that are largely fixed = C: $

The total cost is given by :

$$Cost = A \times Power + B \times Energy + C \tag{C.2}$$

C.8.2. Li-ion battery

A battery discharges more or less constantly and stoops rapidly near its depletion capacity. The discharge of flywheel storage represents an exponential decay, while a supercapacitor discharges linearly [529]. The different discharge curves are given in Figure C.3.



(a) (b) (c)

Figure C.3: Discharge Curves

C.8.3. Fuel Cell

Maximum Possible Fuel Cell Efficiency

If it is assumed that all of ΔG , the maximum possible efficiency for a fuel cell operating at 25°C and 1 atm is given as

$$\eta = \frac{\Delta G_f^0}{\Delta H_f^0} = \frac{237.1\frac{kJ}{mol}}{286\frac{kJ}{mol}} = 83\% \tag{C.3}$$

This is based on the HHV value of hydrogen.
If the numerator and denominator of Equation C.3 are divided by nF, the Equation becomes

$$\eta = \frac{\frac{\Delta G_f^0}{nF}}{\frac{\Delta H_f^0}{nF}} = \frac{1.23}{1.48} = 83\% \tag{C.4}$$

The numerator of C.4 is referred to as the theoretical cell potential while the denominator is referred to as the thermoneutral potential (the potential corresponding to hydrogen's HHV).

C.8.4. H_2 production

C.8.5. Steam Methane Reforming

Steam reforming or steam methane reforming is the most dominant method to produce H_2 [3]. The strongly endothermic reaction is given as

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2 \quad \Delta H = 206kJ/mol \tag{C.5}$$

The reactants steam and methane produce syngas (mixture of CO and H_2). Pressure of 3-25 bar and temperature of 950 °C is maintained in the reformer vessel.

C.8.6. What happens when power demand is increased?

When the demand on a prime mover is increased, the prime mover slows down causing a reduction in the frequency and the voltage (both are related to engine RPM). This also leads to a drop in the current. At one point, the prime mover stalls. The fluctuation of frequency and voltage occurs when the load changes. This is due to the response time associated with the prime mover. In a prime mover, in general, a servomechanism adjusts the fuel flow etc. to match the power input.

C.9. Load Bank

The understanding of the load bank and its working is based on the its commercial suppliers [531] and users.

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[3] Globally about 600 billion m^3 of H_2 is produced every year. About 2% of this is produced by water electrolysis while 98 % is via SMR [530].

A Load Bank is a device which applies electrical load to an electrical power source. This power from the electrical source is dissipated as heat. The function of the Load Bank for mimicking the operational load which a power source will be subjected to in real life. The Load Bank provides a controllable load unlike the "real" load, which is unpredictable and uncontrollable. The Load Bank uses the energy output of the power source for testing, tuning, supporting, commissioning, inspection and protecting the power source, generally as standby generator. Load bank testing helps in ensuring whether the power source would perform as expected.

Diesel gensets can carry out peak shaving or serve as as emergency power supply. The operation of diesel gensets for long duration at lower loads lead to the phenomenon of 'wet stacking'. The information on the phenomenon of wet-stacking is based on manufacturers [532] and generator servicing/rental company [533]. Wet stacking is a phenomenon of formation of an dark oily coating in the stack due to the condensation of fuel vapours and soot. This occurs in diesel gensets operating at <30% of rated performance for extended periods of time. The reason for this is that under such conditions, the engine does not reach optimal operating temperature and leaves unburnt fuel and carbon deposits. Wet stacking leads to efficiency reduction, reduction in lifespan, smoke emissions and increase in maintenance costs.

An additional use of load banks is in elimination of 'wet stacking' in engines [534]. The application of additional load via load banks increases the operating temperatures and prevents wet stacking. This additional load is such that the generator operates at more than 75% of its nameplate rating. This raises the exhaust temperature that vaporised the unburnt fuel in the exhaust system and blows out the soot.

Load banks are used in the maritime industry for regular maintenance and operational testing of backup generators, power distribution systems and emergency switchboards.

Natural convection based cooling is possible without the need for forced circulation cooling in load banks up to 20-50 kW.

Types of Load Banks

This text is based on information from the manufacturers [535] [536].

Resistive Load Bank
The most common type of load bank is the Resistive load bank. Power Resistors convert the electrical energy into heat and this heat is dissipated , using either by air or water. Using this load bank leads to equivalent loading of both generator and prime mover. The removal of energy from the complete system can be carried out and impacts all aspects of a power generator.

$$1\ kW_{load\ bank-generator} = 1\ kW_{prime\ mover-generator} \tag{C.6}$$

$loadbank - generator$ = load applied by load bank on generator
$prime\ mover - generator$ = load applied by generator on prime mover

Inductive Load Banks
Inductive loadbanks are used for the simulation of real life loads (transformers, motors, lighting etc.). Full power system can be tested by a resistive/inductive load bank. 80% of the kVA rating [4] can be achieved while using resistive load banks. But for the lagging power factor, an inductive load bank needs to be coupled with a resistive unit. This achieves 100% of the nameplate kVA rating.

C.10. Direct Open and Direct Closed cycle reactors

The Heat Transfer Reactor Experiment No.1 (HTRE-1) and Heat Transfer Reactor Experiment No.2 (HTRE-2) and HTRE-3 were developed in the United States [537] as part of the Aircraft Nuclear Propulsion program. The utilisation of turbine utilising air was explored as part of these experiments for

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[4] For non-resistive loads VA (Volt-ampere) is used while for resistive loads W (Watt) is used.

demonstrating the feasibility for a nuclear-powered turbojet engine and development of the concepts around it. These reactor experiments utilised a direct air cycle reactor. ML-1 was a 40 ton mobile nuclear powerplant prototype that used closed direct cycle which used N_2 with 0.5% O_2 as a heat transfer fluid [538].

C.11. Pure Nuclear based system

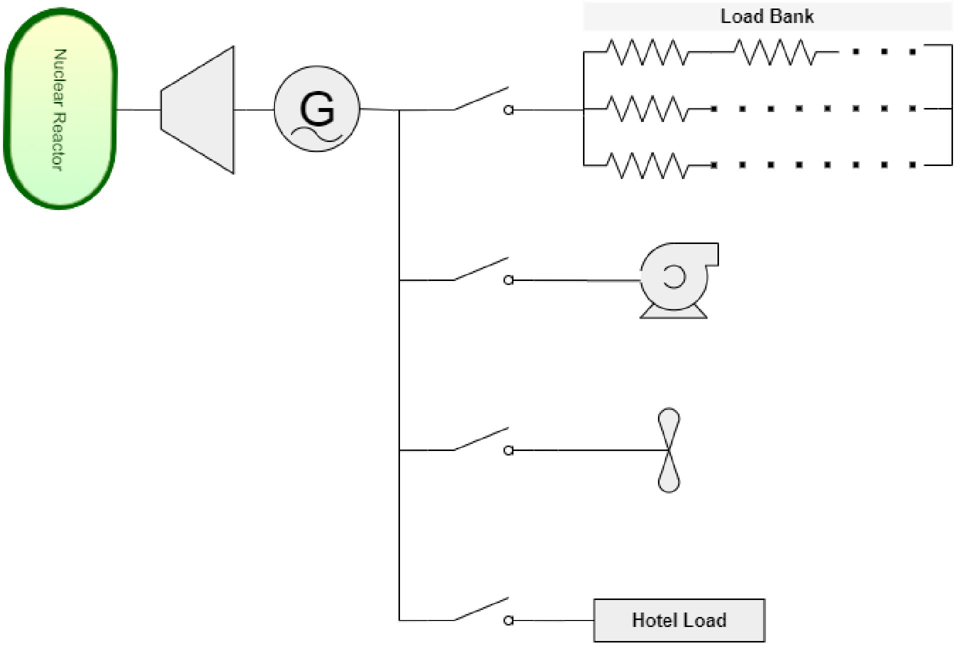


Figure C.4: Nuclear based power generation system without ESS

Another possibility for explored where the power requirements could be met by only the usage of nuclear generation. In case, there is under-frequency in the system (excess power demand in comparison to generation), load shedding can be done. However, in case of load rejection, the generator would trip under over-frequency.

In case the generation of hydrogen/batteries are already overcharged or is not opted. Because of the predictable cyclical nature, a possibility is to use load banks. For example : It is known that the requirement of power is going to increase in 100 minutes, the load bank can be connected and nuclear reactor power can be increased gradually. Ramp up rates of 3%/minute are easily achievable. The excess power generated would need to be dissipated as heat via the use of load banks. When the time comes and the electric load needs to be connected,the power bank would be disconnected and the electrical load connected. The arrangement is shown in Figure C.4. The load bank elements operate at half of their maximum possible rating which gives them almost unlimited life. There could be possible reduction on the life of the load bank due to this constant cycling. However, this is beyond the scope of this work.

C.12. Heat Exchangers

C.12.1. Area density

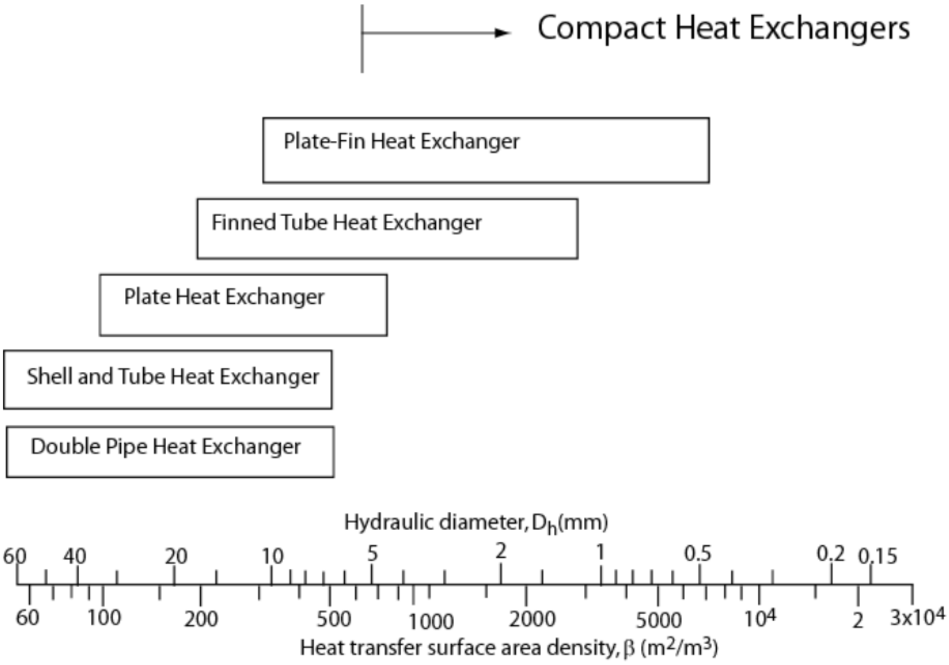
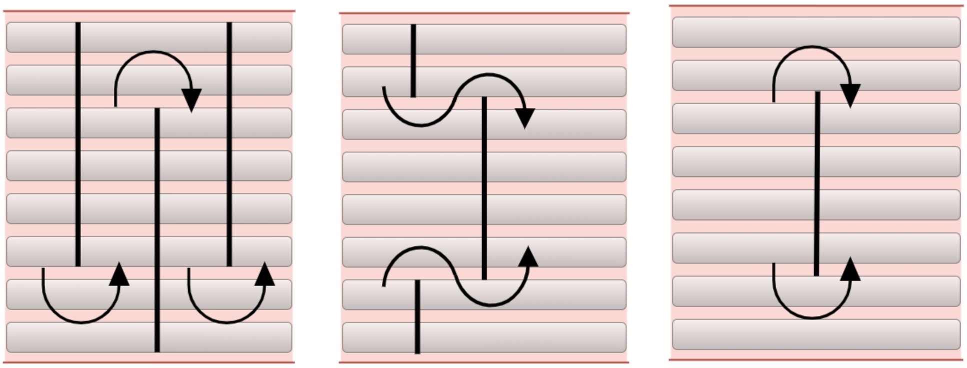


Figure C.5: Compactness of different heat exchangers

Source: [539]

Figure C.12.1 gives the range of area density and hydraulic diameters of various heat exchangers.

C.12.2. Baffles



(a) Single Segmental (b) Double Segmental (c) Disc and Doughnut

Figure C.6: Baffle Arrangement

Source: Adapted from Thermopedia [540]

Baffles serve two main purposes :

- increasing the heat transfer rate
- supporting the tubes

Figure C.6 gives a visual representation of the baffle arrangements inside the Shell & Tube Heat Exchanger. The single segmental is the most commonly used baffle arrangement. While the use of double segmental leads to a lower shell side velocity and pressure drop.

C.12.3. Tube layout

The 30° tube layout has the highest shell-side heat transfer coefficient but also the highest pressure drop. The triangular layout gives a compact heat exchange and 15% more tubes can be accommodated within the shell diameter for these layout [541]. Since, He-He and He-Air would be relatively clean service (not requiring mechanical cleaning) this arrangement is suitable.

C.12.4. Shells

The E-type shells are the most common. If there are more than three baffles with a single tube pass, near counter-current flow is possible. If maximum shellside pressure drop is exceeded X- or J- type shells should be used. F-type shells can be used to obtain pure countercurrent flow by having two tube side passes. However, leakages are possible unless special care is taken.

C.12.5. TEMA Nomenclature

TEMA S&T HX nomenclature is defined as a combination of letters that denote *"Front End Head types-Shell types-Rear End Head types"*. For example TEMA type BEM indicates a bonnet (integral) front end head type, one pass shell having a fixed tubesheet head. There are 5 unique letters denoting the front end head types, 7 unique letters for the shell types and 8 unique letters that denote the rear end head type.

C.13. Uranium Price

Figure C.7 shows the Uranium prices over the years. In the past 4 years, the prices have averaged around 55 \$/kg [5].

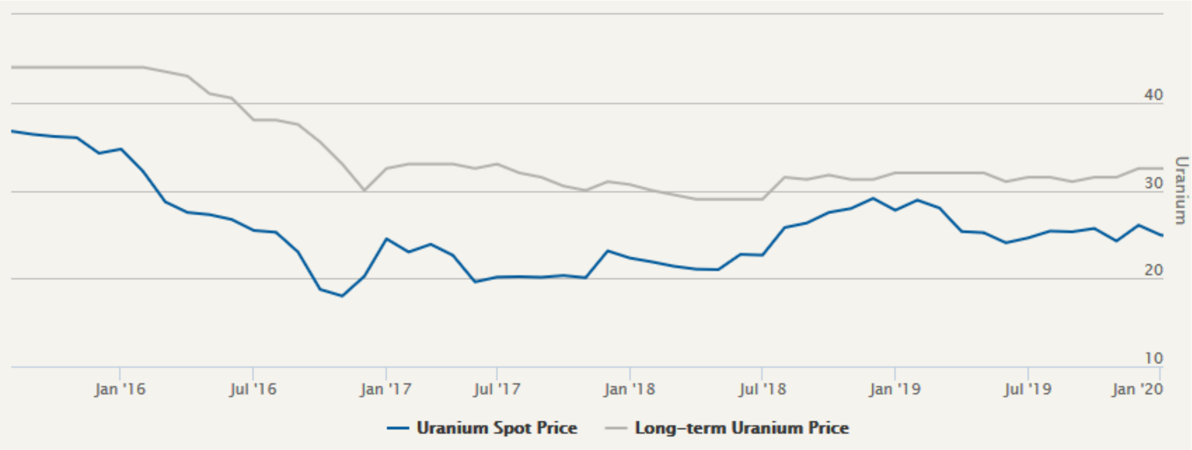


Figure C.7: Uranium Prices in \$/lbs

Source: [542]

C.14. Nuclear Decommissioning

One of the most recent decommissioned reactors in the United States is the 619 megawatt (MW) Haddam Neck plant in central Connecticut, which was shut down in 1997 and decommissioned using the DECON method. Haddam Neck's decommissioning was completed in 2007 at a total cost of \$ 893 million [543]. For submarine decommissioning in Russia, the reactor compartments are water-sealed along with the adjacent buoyancy compartments, and kept in the waterborne storage as "three-reactor

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[5] 1 lb = 0453592 kg

compartment units (3-RCU)". These 3-RCU are about three times the length and 1.5-2 times the weight of a single compartment [373].

C.14.1. Entombed Nuclear Reactors

Only 4 major nuclear reactors have been entombed :

- Chernobyl Reactor Number 4, Ukraine
- RPV and some other auxiliaries of the Boiling Nuclear Superheater (BONUS), Reactor Facility, Puerto Rico
- Containment Vessel of the Piqua Nuclear Generating Station, United States
- Hallam Nuclear Generating Station, United States

C.14.2. Reprocessing of TRISO Fuel

TRISO fuel is chemically stable and hence, extreme methods are required for reprocessing. These methods include :

- Grind-Leach : In this, the particles are ground and the chemical species leached. However, grinding to small particle sizes is problematic, the solid-liquid separations are difficult and the organic species produced in leaching step are troublesome.
- Crush-Burn-Leach is the easiest of the processing techniques, it releases the carbon as CO_2 requirement of large and complex gas processing equipment. Complete extraction of transuranic is hard but carbon capture is a possibility.
- Aqueous grind-leach is one promising technology and has the smallest volume of carbon waste.

C.15. Water Ingress in HTGR

The presence of water in HTGR core increases the neutron moderation which in turn increases the reactivity. The increase in the reactivity is due to the following combined effects :

- H_2 absorbs neutrons and fewer thermal neutrons are available for U-235 fission.
- Fewer high-energy neutrons are available (spectrum softening) leading to an increase in fission cross section and decrease of resonance capture (U-238).
- Neutron leakage from core is reduced.

C.16. Cooling Water

In 2019, due to high temperature of the river waters and lowered water levels due to drought like conditions in France and Germany had some of their nuclear reactors (Golfech (Tarn-et-Garonne) and Tricastin (Drôme) in France and Grohnde reactor in Germany) forced offline [544]. To protect the biodiversity from thermal pollution [545], it is mandated by law to reduce river water consumption for cooling needs of power plants when temperatures go over 28°C (specific temperature depends on the country laws).

However, access to fresh water is not a necessity, per se. For example, United States's largest nuclear power plant, Palo Verde does not cool using river water [546]. Instead, Palo Verde utilises the waste water from surrounding areas (Phoenix city for example).

C.17. Entrepreneurship

This section explains some of the terms from Chapter A.

Equity joint venture : The understanding of this terms is based from the firm Lehman, Lee & Xu [547]. This is a form of Limited Liability Company and the preferred investment vehicle for most manufacturing JVs. The profits are distributed according to the % of capital investment. For example, if 30% of capital investment is made, 30% of the total profits are entitled.

Wholly Foreign Owned Enterprise : The understanding of this terms is based from the firm Lehman, Lee & Xu [548]. A Wholly Foreign Owned Enterprise or WOFE is an entity that is established within mainland China and wholly owned by foreign investors. The liability of foreign investors is limited to the registered capital amount.

D

Additional Methodology

This Appendix contains portions of the methodology that could not find a part in the main report.

D.0.1. PWR weight and Volume

The arrangement of nuclear reactors is different in submarines and surface vessels. In a submarine, the reactor compartment is a horizontal cylinder while in a ship the reactor compartment resembles a rectangular box that is vertical or cylindrical. Weights and Volume of some naval PWR are compiled here.

The Ohio class submarines are powered by S8G PWR which has 220 MW$_{th}$. The reactor compartment weighs 2750 tons. The dimensions are 55 feet long and 42 feet high.

The nuclear powered guided missile cruiser, USS Long Beach's reactor was directly coupled to the propellers and generated 60 MW. The reactor compartment weighed 2250 tons, had a height of 42 feet, length of 38 feet and breadth of 37 feet [549].

For Victor-class submarines, the Reactor Compartment (RC) is about 10 meters in diameter, 10 meters long, and about 900 tons in weight [373].

D.1. Possible Power Conversion Cycles

The Rankine, Open Brayton and Closed Brayton cycles have been discussed in 4.2.4. Figure 4.7a represents a Rankine cycle. The Rankine cycle is based on the generation of work through a turbine that is driven by steam. The steam is raised in a boiler from pressurised water by supplying heat.

In an Open Brayton cycle (given in Figure 4.7b, compressor, heat exchanger and turbine are the main components. Exhaust from the turbine generally has high enthalpy.

Figure 4.7c represents an Closed Brayton Cycle. In a Closed Brayton cycle the exhaust from the turbine is fully recirculated to the compressor. Unlike the open brayton cycle, the working fluid does not exit the system.

Other possible options exists when a bottoming cycle is added to the Brayton cycle (and its variants).

In an Open Brayton Rankine cycle (given in Figure D.1, the Brayton cycle is bottomed by a Rankine cycle. The exhaust from the Brayton cycle turbine goes through a Heat Recovery Steam Generator where steam is raised to drive a steam turbine.

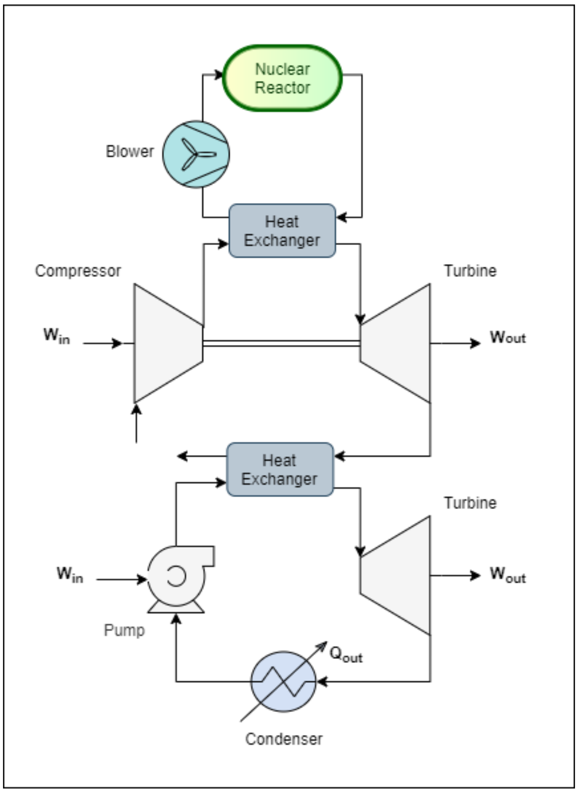

Figure D.1: Open Brayton Rankine Cycle

Figure D.2 represents an Open Brayton Cycle. In an Open Brayton cycle, only the Brayton cycle is used as a power conversion cycle. The exhaust of the turbine generally has enough heat capacity that it can be utilised by adding a bottoming cycle.

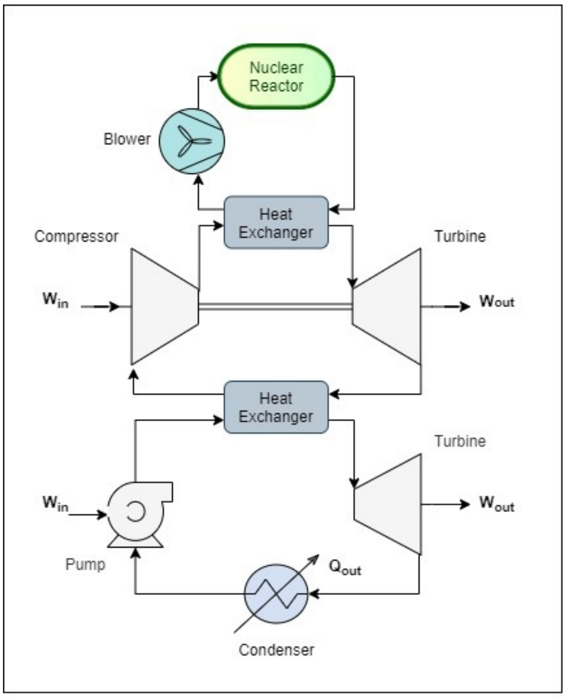

Figure D.2: Closed Brayton Rankine Cycle

A Vapour Absorption based air inlet cooled Nuclear Air Brayton Cycle is given in Figure D.3. The air enters through the evaporator section where the temperature of the inlet air is reduced and exits through the generator where the heat from the turbine exhaust is utilised.

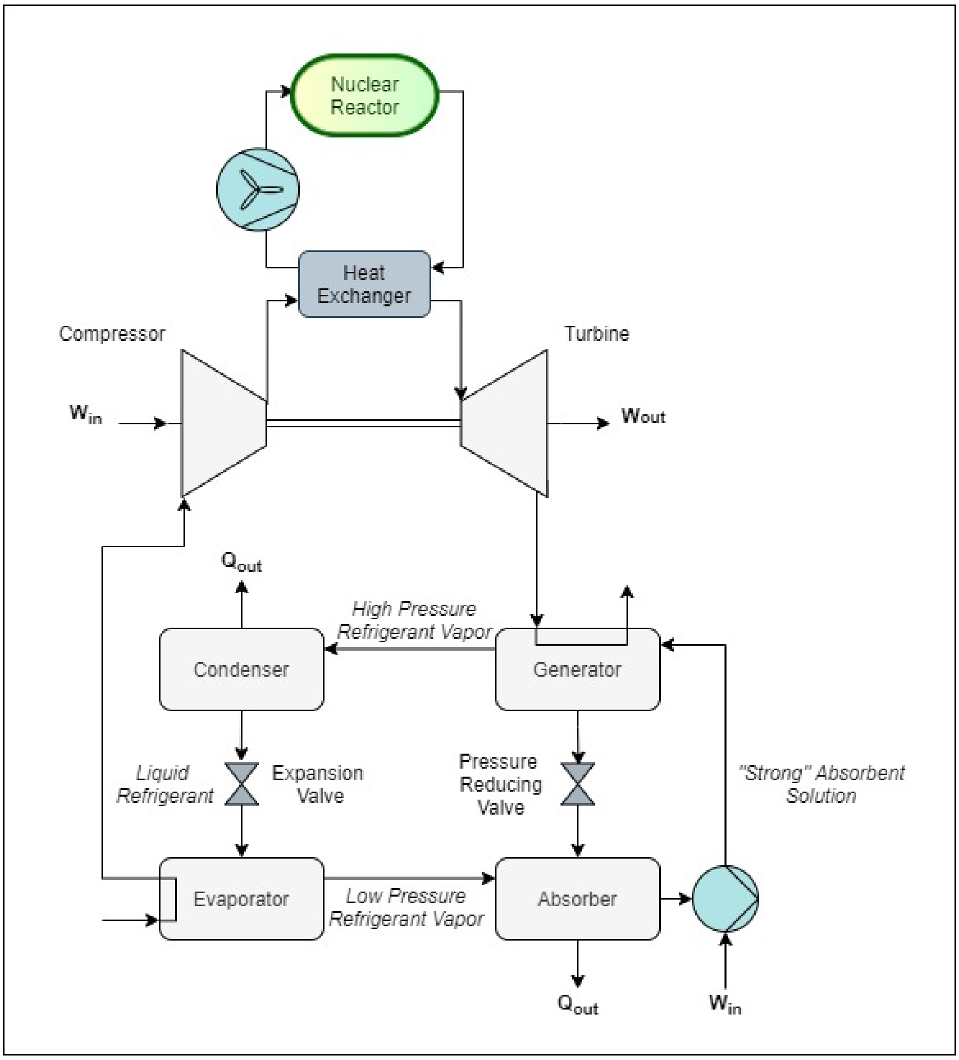

Figure D.3: Vapour Absorption Cycle Inlet Air Cooled Nuclear Air Brayton Cycle

D.2. Additional Power vs. ”X” Trendlines

Figure D.5 and Figure D.5 provides the equation for the trendlines developed in this work with Minnehan et al. [317] when the models that have been dropped by manufacturers are considered. There is still a small difference due to the change in the specifications of the same models.

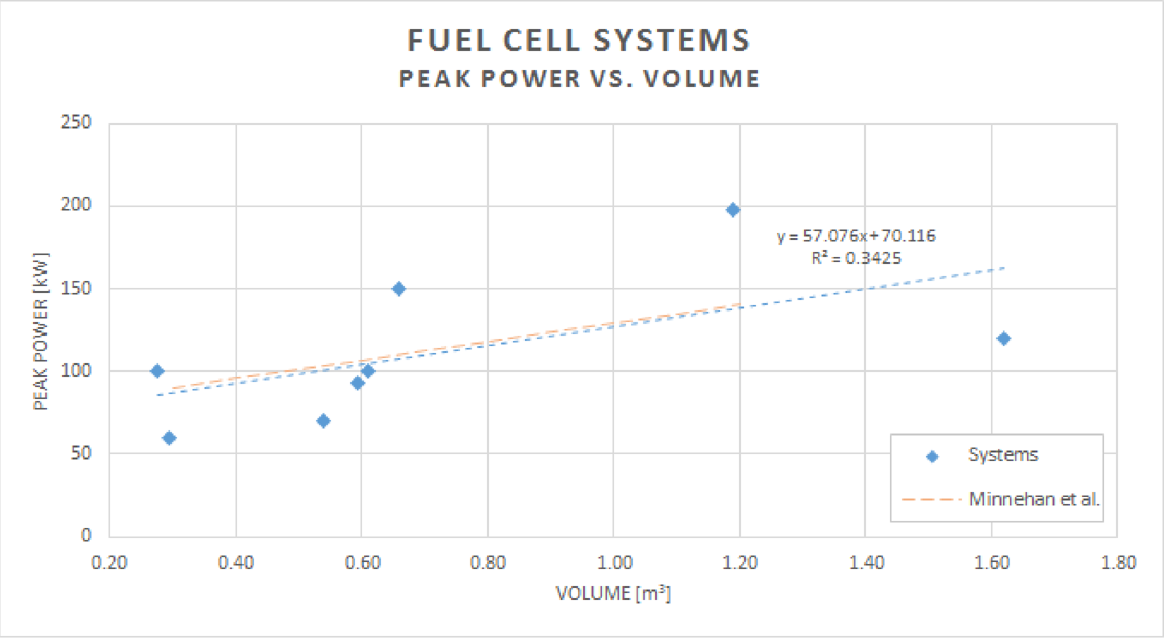

Figure D.4: Fuel Cell Systems Compared to Minnehan et al. (Peak Power vs. Volume)

The equation for the trendline representing Power vs. Volume

$$\begin{aligned} y &= 57.076x + 70.116 \\ R^2 &= 0.3425 \end{aligned} \tag{D.1}$$

In comparison, the equivalent trendline in Minnehan et al. [317] is given as

$$y_{Minnehan} = 55.944x + 73.331 \tag{D.2}$$

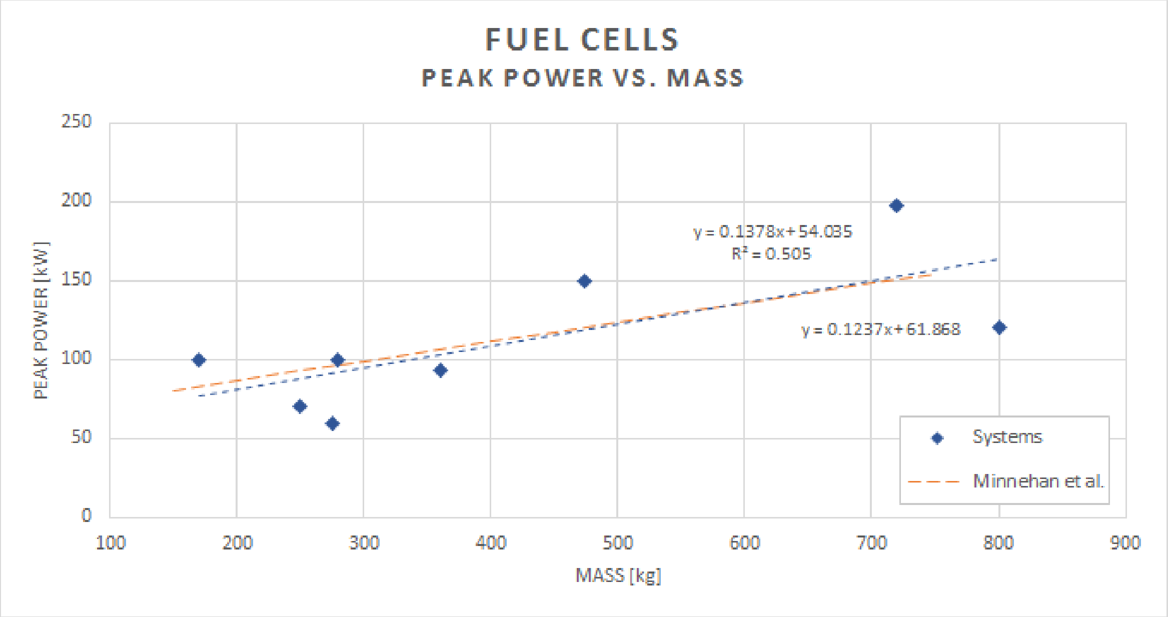

Figure D.5: Fuel Cell Systems Compared to Minnehan et al. (Peak Power vs. Mass)

The equation for the trendline representing Power vs. Mass

$$y = 0.1378x + 54.035 \qquad \text{(D.3)}$$
$$R^2 = 0.505$$

In comparison, the equivalent trendline in Minnehan et al. [317] is given as

$$y_{Minnehan} = 0.1237x + 61.868 \qquad \text{(D.4)}$$

Trendlines between Power vs Mass and Power vs Volume for Fuel Cell (systems and modules) were made. These trendlines are given in Figure D.7 and Appendix Figure D.6 respectively.

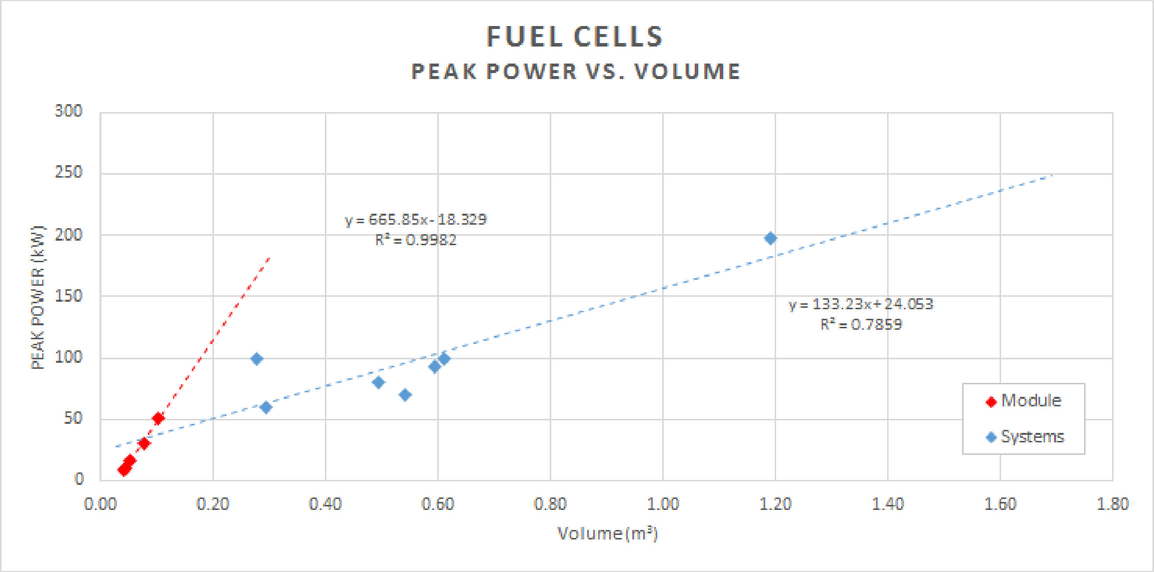

Figure D.6: Fuel Cell Systems & Modules (Peak Power vs. Volume)

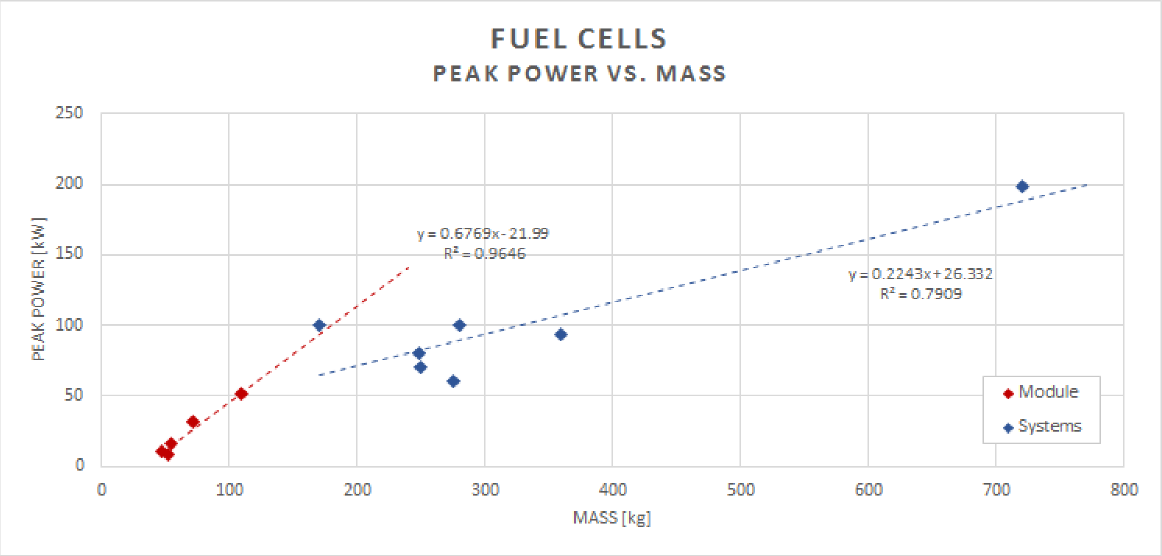

Figure D.7: Fuel Cell Systems (Peak Power vs. Mass)

It can be realised that the R^2 values for modules is much higher than the R^2 values of the mentioned systems. This is because, the description of modules is clearer while the description of the system tend to have certain amount of variation across manufacturers.
The weight and volume data for steam turbines is given in Appendix (Table B.7). This data consists of steam marine turbines from Kawasaki. This data already includes the generator dimensions and weight. Trendlines between Power vs Weight and Power vs Volume for were made. Figure D.8 and D.9 shows these trendlines respectively. These are not used in this work and left for future work.

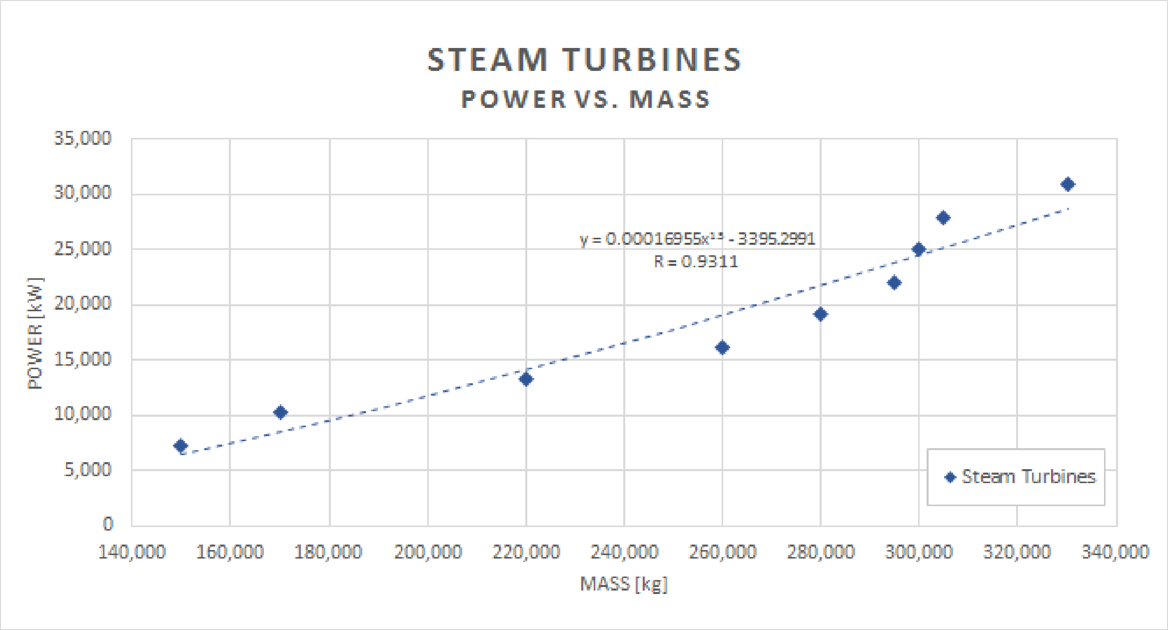

Figure D.8: Steam Turbine Power vs. Mass Data

The relation between Power and Mass is given by the following Equation :

$$Power[kW] = 0.00016955 \times Mass[kg]^{1.5} - 3395.2991 \tag{D.5}$$
$$R^2 = 0.9311$$

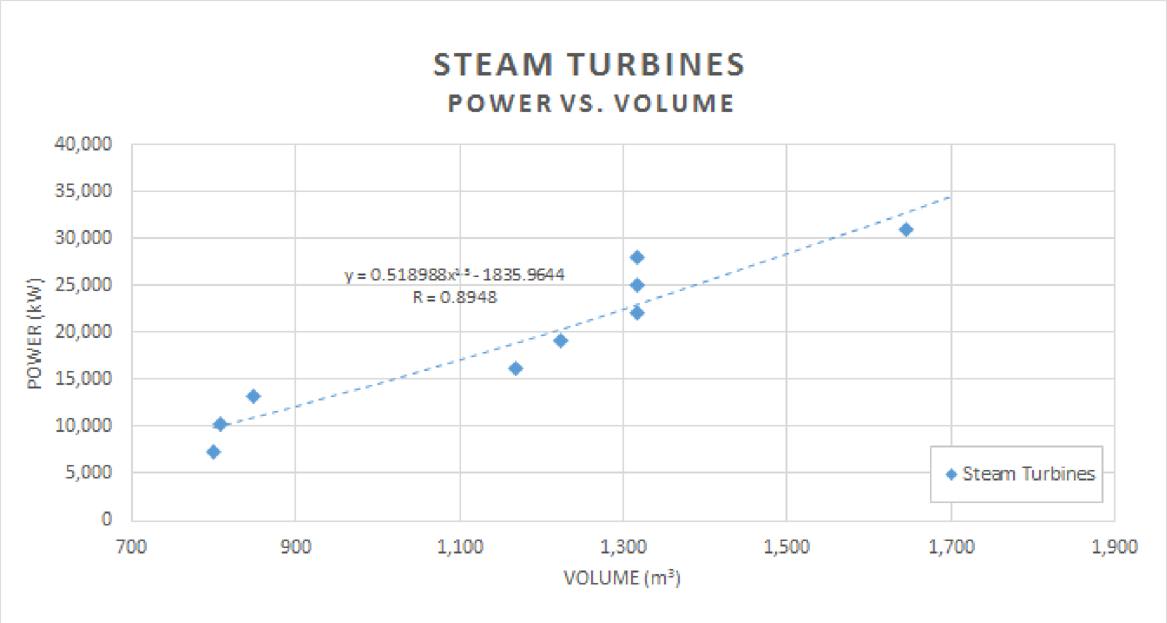

Figure D.9: Steam Turbine Data : Power vs. Volume

While, the relation between Power Power and Mass is given by the following Equation :

$$\begin{aligned} Power[kW] &= 0.518988 \times Volume[m^3]^{1.5} - 1835.9644 \\ R^2 &= 0.8948 \end{aligned} \tag{D.6}$$

D.3. Net Tonnage vs. Displacement

For the calculation of the displacement, submerged volume needs to be calculated first. The submerged volume can be found from Equation D.7. The factor of "0.8" is used as the block coefficient as this is the general value for dredger vessels.

$$\text{Submerged Volume } (m^3) = \text{Draught} \times \text{Beam} \times \text{LBP} \times 0.8 \tag{D.7}$$

The displacement is then calculated by multiplying the submerged volume with the density of the seawater.

$$\text{Displacement } (kg) = \text{Submerged Volume} \times \rho_{seawater} \tag{D.8}$$

Figure D.10 shows the relationship between Net Tonnage and Displacement of all the TSHDs.

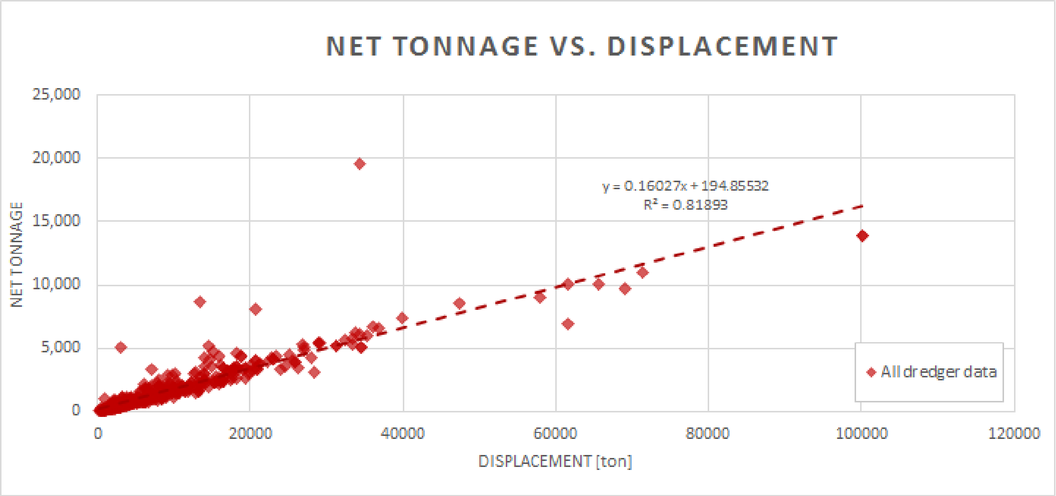

Figure D.10: Net Tonnage vs. Displacement for all TSHDs

The relation is given by the Equation D.9

$$\begin{aligned} Net\ Tonnage &= 0.16027 \times Displacement + 194.85532 \\ R^2 &= 0.81893 \end{aligned} \tag{D.9}$$

As per Figure D.11, there's a good linear agreement between the Net Tonnage and Displacement of the four dredgers considered in this work.

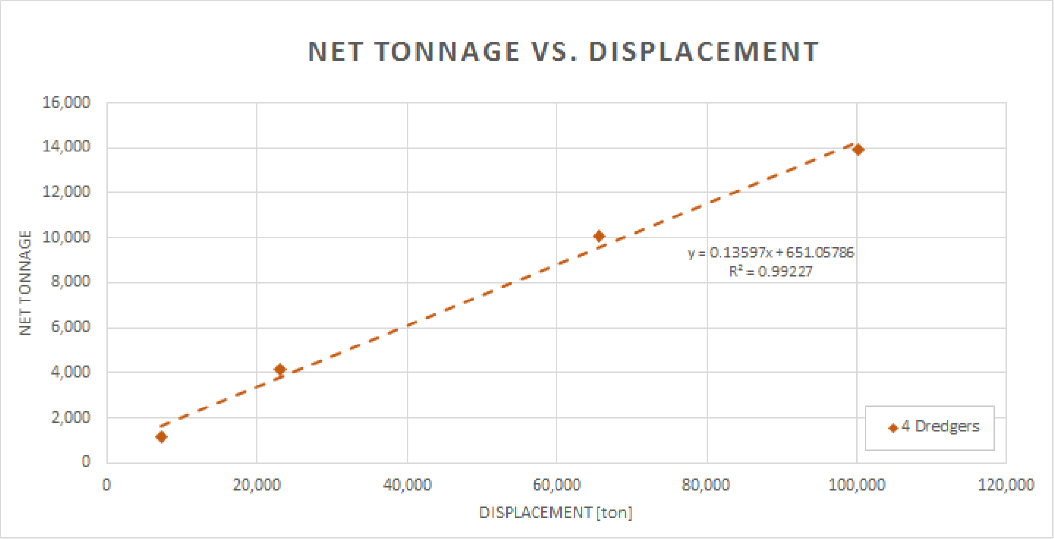

Figure D.11: Net Tonnage vs. Displacement of 4 selected dredgers

Similarly, the available volume in the four dredgers considered in this work scales linearly with the displacement of the dredgers (see Figure D.12).

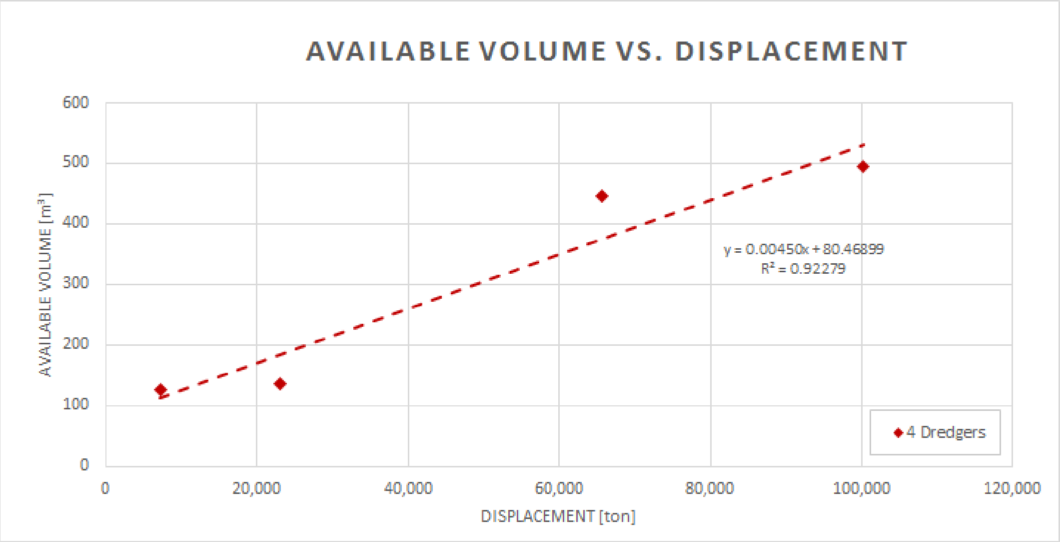

Figure D.12: Available volume vs. Displacement for 4 selected dredgers

Equation D.10 gives the relation between the Net Tonnage and Displacement of the 4 TSHDs considered in this work.

$$Net\ Tonnage_{TSHDs,thiswork} = 0.13597 \times Displacement + 651.05786 \tag{D.10}$$
$$R^2 = 0.99227$$

Equation D.10 gives the relation between the Available Volume and Displacement of the 4 TSHDs considered in this work.

$$Available\ Volume_{TSHDs,thiswork} = 0.00450 \times Displacement + 80.46899 \tag{D.11}$$
$$R^2 = 0.92279$$

It must be remembered that Net Tonnage is related to Hopper Volume. Therefore, Net Tonnage, Hopper Volume and Displacement are linearly related to each other.

D.4. Exhaust Gas Flowrate

The exhaust gas flowrate for 2-stroke and 4- stroke engines can be calculated with Equation D.12 and D.13 respectively. These equations assume ideal conditions and neglect the compressibility.

$$Exhaust\ flow\ rate = Engine\ Displacement\ (m^3) \times RPM/60 \tag{D.12}$$

$$Exhaust\ flow\ rate = Engine\ Displacement\ \ \times RPM/2/60 (m^3/s) \tag{D.13}$$

The engine displacement is calculated as per

$$Engine\ Displacement = stroke\ length \times \pi \times (0.5 \times bore)^2 \times number\ of\ cylinders \tag{D.14}$$

D.5. Calculation of Liability limit based on Brussels Convention on the Liability of Operators of Nuclear Ships

The Convention sets the liability per nuclear accident as 1500 million francs. The franc is a unit of account and equals to 65.5 mg gold of 900 fineness [1]. The 900 fineness is equivalent to 21.6 carat [2].

At a price of 47.5 \$. g^{-1} (for 21.6 carat gold), the current liability cap would be around 4.66 billion \$.

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[1] Fineness refers to the parts per thousand of the pure metal in the alloy. So, 990 fineness implies 990 parts of pure gold per 1000 parts of the total weight of the alloy (pure gold, alloying metals and any impurities)

[2] carat is defined as pure metal part per 24 alloy part

D.6. CIRIA 2005

Additional parts of the CIRIA methodology for calculation of the value of a TSHD are nestled here. This Depreciation and interest calculation is based on annuity basis. The annuity is calculated as

$$A = \frac{i}{((p^n) - 1) \times \frac{1}{u} \times (p^n - z)} \tag{D.15}$$

where,

i = interest rate
n = Service life [yr]
u = utilization [week/year]
z = residual value at rest of service life as a fraction of V
p = 1+i

Hence, Depreciation and interest is calculated as

$$DI = A \times V \tag{D.16}$$

Now, depending on the discharge method the maintenance and repair costs are ascertained from the tabulated values.

The total crew costs are calculated as per Equation D.17-D.18.

$$C_{Lcrew} = 100 \times L - 3660\,€/week \tag{D.17}$$

$$Total\ Crew\ Cost = Expat\ Crew\ Cost\ (from\ Table) + C_{Lcrew} \tag{D.18}$$

The total wear and tear costs depend upon the sediment type and amount. These range from $\frac{0.05\,€}{m^3}$ for silt to $\frac{3\,€}{m^3}$ for coarse sediments.

$$Wear\ and\ Tear\ Costs = f(sediment\ amount\ ,\ type) \tag{D.19}$$

The Specific Fuel Consumption (IFO 380) (sfc) is given as

$$sfc = 0.19 \times Engine\ load\ (sailing) \times Installed\ Propulsion\ Power[\frac{L}{h}] \tag{D.20}$$

Then, fuel consumption ($\dot{m}_{fuel}$) is given as

$$\dot{m}_{fuel} = Engine\ load\ (sailing) \times Installed\ Propulsion\ Power \times sfc \tag{D.21}$$

The cost of the fuel C_{fuel} is given as

$$C_{fuel} = \dot{m}_{fuel} \times c_{unitfuel} \tag{D.22}$$

And the lubricant costs are assigned as 10% of the fuel costs (Equation D.23

$$Lubricant\ costs = 10\% \times C_{fuel} \tag{D.23}$$

D.7. Liability Insurance

There are 98 nuclear power plant sites. Each reactor site has a liability coverage of 450 million $. On average of 1 million USD per reactor is paid up as insurance premium. The core damage frequency of United States nuclear industry is estimated to be 2×10^{-5} [550]. However, the worldwide historical frequency of core melt accident is 1 in 1309 reactor-years [551]. This gives a CDF of 7.6×10^{-4} per reactor year. Eventually, the risk perceived by the insurers is what determines the liability insurance premium.

The premium is related to the expected value [3]

$$\begin{aligned} Premium &= Expected\ value(claim\ amounts\ per\ insuree) && \text{(D.24)}\\ &= Expected\ number\ of\ accidents \times expected\ amount\ per\ accident && \text{(D.25)}\\ &= Expected\ frequency \times Expected\ severity && \text{(D.26)}\\ & && \text{(D.27)} \end{aligned}$$

On top of this would be the profit of the insurance provider. Further, if the pursuit is risky the insurer also adds a factor on top of the Premium calculated in Equation D.28. For example : In life insurance extra additional rate ranges from 125%-500% [552]. Now, these factors are assumed to be clubbed and premium is given as

$$Premium = Additional\ Factor \times Expected\ frequency \times Expected\ severity \tag{D.28}$$

Information about what probabilities or factors the industry is using is not available in public domain [4]. Here, a simplified attempt to capture some information. The premiums for three different probability of breaching the liability limits along with the additional factor value is given in Table D.1. The additional factor is arrived at by comparing the premium values by using Equation D.24 and then comparing it to the US nuclear third party liability premium. The lowest probability is considered to be 10^{-3}, this is half the expected accident frequency if the operation of old Japanese reactors is carried without any safety upgrades (after the Fukushima accident). An additional factor of around 292% is being considered if CDF values from Cochran [551] are being used in the industry.

Actuarially fair premium is when the premium is equal to the Expected claims. This is given by Equation D.29.

$$Actuarially\ Fair\ Premium = Income\ if\ everything\ goes\ WELL\ - Expected\ income \tag{D.29}$$

The expected income can be calculated as

$$\begin{aligned} Expected\ income = {} & Liability\ amount\ \times\ Probability\ (liability\ occurring) + \\ & Probability\ (non-\ occurrence\ of\ liability)\ \times\ Premium\ amount \end{aligned} \tag{D.30}$$

Table D.1 gives the actuarially fair premium. Even with a 10^{-3} frequency, the premium of 1 million USD is unfair.

Table D.1: Accident Frequency and actuarially fair premium

Accident Frequency	**Additional Factor**	**Actuarially Fair Premium [USD]**
10^{-3}	222%	451000
7.6×10^{-4}	292%	342760
2×10^{-5}	11111.11%	9020

In case, an accident occurs, the cost of the accident per unit of electricity generated is given by the metric referred to as "Accident risk cost".

$$Accident\ risk\ cost = \frac{Damage\ cost \times Accident\ Frequency\ (per\ reactor\ year)}{Gross\ Output} \tag{D.31}$$

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[3] Expected value is the weighted average of the variable. It is calculated as the sumproduct of probability of an outcome and value of that outcome

[4] If Equation D.24 is used as it is, the premium is set as if the American insurance industry takes the probability to be 1 incident every 450 years (2×10^{-3} for one nuclear reactor).

D.8. NO emissions

$$\text{NO}emissions[g/s] = \frac{d[\text{NO}]}{dt} \times t \times M_{\text{NO}} \times \frac{\dot{m}}{\rho_{air}} \tag{D.32}$$

$$\text{NO}emissions[g/kWh] = \frac{\text{NO}emissions[g/s]}{Factor_{J-kWh} \times Power} \tag{D.33}$$

where,

$\frac{d[\text{NO}]}{dt}$ = Rate of NO formation [moles/(cm^3 -s)]
t = time [s]
$\dot{m}$ = Mass flow rate [kg/s]
ρ_{air} = Air density [kg/cm^3]
$Factor_{J-kWh}$ = Conversion Factor J to kWh (2.778 $\times 10^{-7}$)
M_{NO} = 30.01 $\left[\frac{g}{mol}\right]$

The NO emissions [g/kWh] increase linearly with time and pressure at a constant temperature of 1100 K. This is shown in Figure D.13.

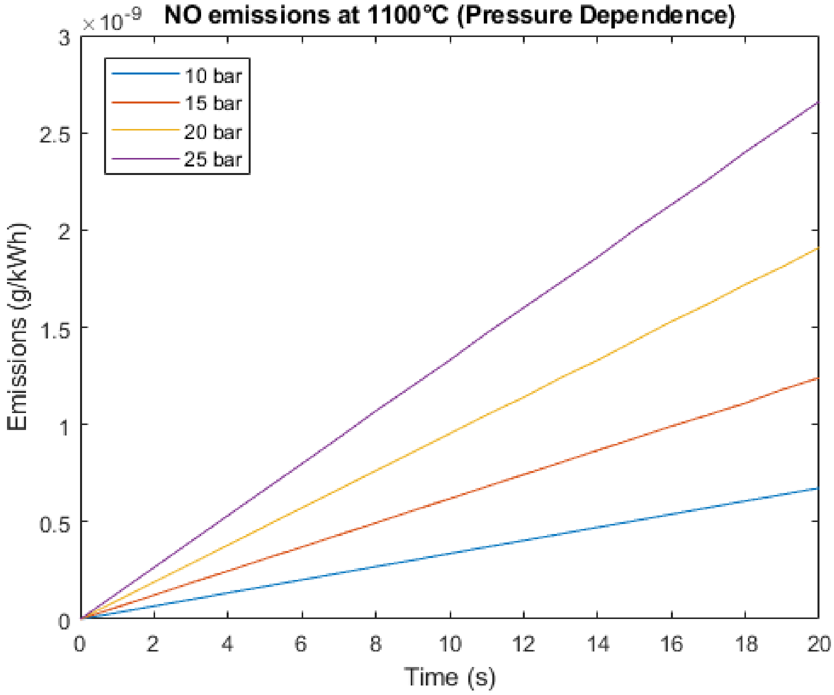


Figure D.13: NO generation at 1100 K with varied pressures

D.9. Decomposition of CO_2

The yearly decomposition of CO_2 to C is given by Equation D.34.

$$m_{\text{C}} = \frac{10^{-15} \times m_{\text{CO}_2}}{M_{\text{CO}_2}} \tag{D.34}$$

$$m_{\text{CO}_2} = \dot{m}_{\text{CO}_2} \times 0.0051 \tag{D.35}$$

where,

$\dot{m}$ = Mass flow rate of air [g/year]
m_{CO_2} = Mass flow rate of CO_2 [g/year]
m_{C} = Mass flow rate of C [g/year]
M_{CO_2} = Molecular Mass of CO_2 (44.01 [g/mol])

D.10. Expected Endurance Calculations (Volume constraints only)

The following set of equations is applicable for the computation of expected endurance when only volume is assumed to be a constraint.

Equations D.36-D.39 are applicable for Fuel Cell based systems.

$$Volume\ of\ \mathrm{H_2}\ tank = 0.70 \times V_{constraint} - Volume\ of\ Fuel\ Cell \tag{D.36}$$

$$Mass\ of\ \mathrm{H_2}\ stored\ (kg) = \frac{Total\ Volume\ of\ \mathrm{H_2}\ tank}{Volume\ of\ one\ tank\ /\ Mass\ of\ \mathrm{H_2}\ stored\ per\ tank} \tag{D.37}$$

$$Energy\ of\ \mathrm{H_2}\ in\ Tank\ = Mass\ of\ \mathrm{H_2}\ \times \frac{119.96}{3.6} \tag{D.38}$$

$$Endurance\ [days] = \frac{Energy\ of\ \mathrm{H_2}\ in\ Tank\ \times Overall\ System\ Efficiency}{Energy\ Requirement\ [kWh/day]} \tag{D.39}$$

Equations D.40-D.42 are applicable for battery based systems.

$$Required\ Energy\ Capacity\ (kWh) = \frac{Energy\ Requirements}{Depth\ of\ Discharge} \tag{D.40}$$

$$Energy\ Capacity\ of\ Battery\ packs\ = \frac{Energy\ Capacity}{Volume} \times 0.70 \times V_{constraint} \tag{D.41}$$

$$Endurance\ [days] = \frac{Energy\ Capacity\ of\ Battery\ packs \times Depth\ of\ Discharge}{Energy\ Requirement\ [kWh/day]}$$

(D.42)

D.11. DWT vs. GT of different diesel-powered TSHDs

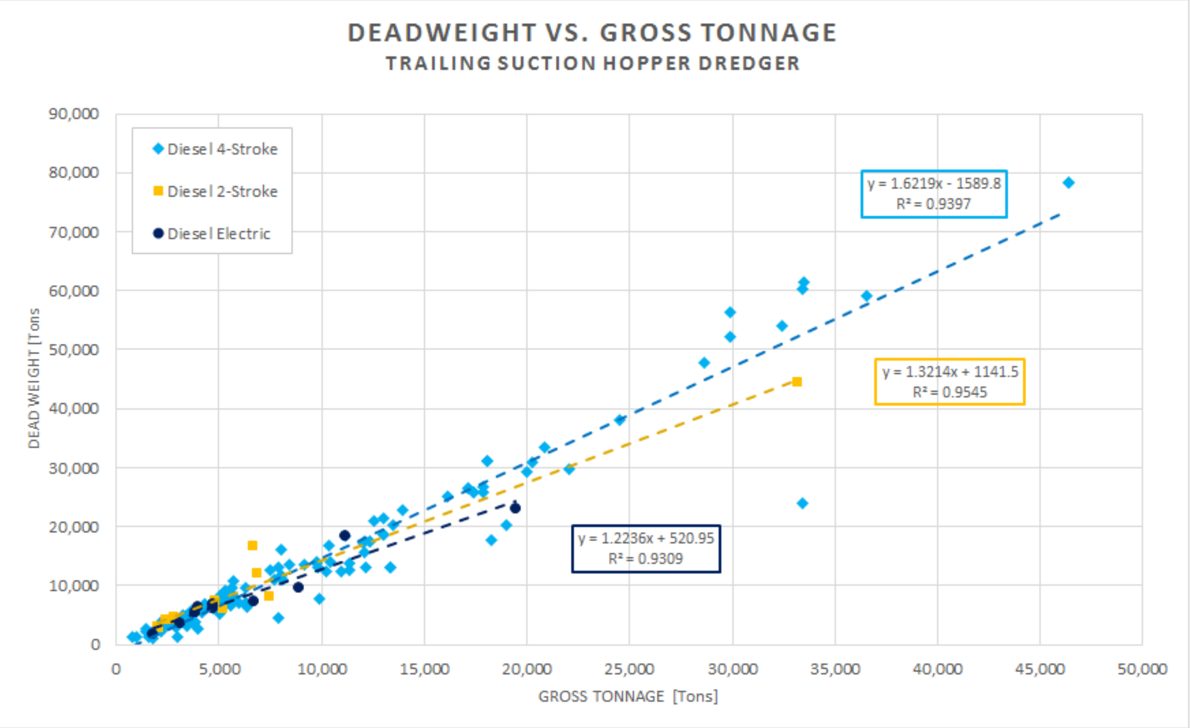


Figure D.14: Deadweight vs Gross Tonnage Correlation of different TSHDs

The relation between the deadweight and gross tonnage of different TSHDs

$$\begin{aligned} DWT_{Diesel4-Stroke} &= 1.6219 \times GT - 1589.8 \\ R^2 &= 0.9397 \end{aligned} \tag{D.43}$$

$$\begin{aligned} DWT_{Diesel2-Stroke} &= 1.3214 \times GT + 1141.5 \\ R^2 &= 0.9545 \end{aligned} \tag{D.44}$$

$$\begin{aligned} DWT_{DieselElectric} &= 1.2236 \times GT + 520.95 \\ R^2 &= 0.9309 \end{aligned} \tag{D.45}$$

E

Theoretical Background : A Crash Course

This Appendix contains some of the theoretical background that might be necessary to understand the report. Additionally, it contains a brief explanation of specific terms.

E.1. Dredging

E.1.1. Terms

Capital dredging is used to refer to the activity of increasing the natural depths for the first time. Capital Dredging includes construction of harbours ports, basins, canals and waterways.

Maintenance dredging is the dredging work carried out for maintaining a particular water depth. Depending on the location and type of vessel, this is carried out every few years or two or three times each year or in some cases, this can also be a continuous operation.

Navigational dredging is the dredging work carried out to improve navigation.

Blue Carbon is the sequestered carbon that is stored in coastal (mangroves, tidal marshes, seagrasses etc.) and marine ecosystems. This carbon storage is both in the plants and the sediment below the plants.

Cycle Time is the total time required for one dredging cycle. The dredging cycle time is a function of sailing speed with empty and full hopper, time spent actually dredging, time spent discharging and time spent manoeuvring to get into position for dredging or discharging.

Overall production is a metric that is defined as $\frac{Hopper\ Load}{Cycle\ time}$. The overall production is highest when the hopper load is as high as possible and the cycle time as short as possible.

Project Origin is some kind of imaginary origin with respect to the coordinate system.So you can not place this project on some specific location in the real world

Borrow area is the area from where the material is excavated to be used at another location.

drag anchor is the vessel drift because of the failure of the anchor to hold.

Net tonnage is approximately the hopper volume × 1.9. The density of water saturated sand is approx. 2.0 ton/m3 and the hopper is not be filled to the full volume capacity.

Bow coupling is the location on the dredger where the floating pipeline is connected to carry out pump ashore discharge.

E.1.2. Discharge Method

Some of the finer fractions of the dredged material will overflow with the excess water from the hopper and these fines will fall back to the seabed again.

Rainbowing For applications which involve discharging huge quantities of dredged material in shallow locations, land reclamation projects or beach replenishment, Rainbowing is an ideal method. This discharge method does not require floating or submerged pipelines, boosters or landlines, it is often the most economical method.

Dumping Discharging through bottom doors is referred to as dumping. This happens through opening up of bottom doors in the hull of the dredger. This allows for quick and direct offloading at a specific location. Only specific circumstances allow for this discharging method.

Pump ashore Pump ashore is the discharging method that utilises a pipeline to transport the dredged material to the construction site. This is generally undertaken when there are for example draft restrictions on the usage of other discharge methods or the borrow area is far away from the construction site.

E.2. Marine Engineering

E.2.1. Terms

stern is the back of a vessel (in the direction when vessel is underway).

bow is the front part of a vessel (in the direction when vessel is underway).

Port side is the side on the left of the observer when facing the bow.

Starboard side is the side on the right of the observer when facing the bow.

aft refers to being near or towards the stern of the ship.

cofferdam are void spaces to prevent mixing of different fluids.

bulkhead forms the barrier between compartments in a ship. It is a vertical partition within the ship's hull.

compartment is the space in a ship between the decks and bulkhead.

Bilge System is a piping system for water removal in the spaces within the vessel. This water could be due to condensation, leakage, washing, fire fighting, etc. Such a system is capable of controlling flooding in the Engine Room but can seldom contain the flooding from a large hull damage for a long time [553].

Heel The expected intentional deviation from longitudinal axis is called as heel.

Angle of list is the degree to which a vessel "heels" (leans) to either side (port or starboard) when no external forces are acting upon it. The possible causes are the uneven load distribution or flooding. This is unintentional or unexpected deviation from the longitudinal axis.

Draft is the vertical distance between the bottom of the hull (keel) and waterline. The minimum depth of water for safe navigation of a vessel is determined by the draft.

Gross tonnage is a non linear function of ship's enclosed volume. This is given by Equation [554]:

$$GT = K_1 V \tag{E.1}$$

where V is the enclosed volume in the ship (in m^3)
K_1 is a constant calculated by $0.2 + 0.02log10V$

Deadweight tonnage is the weight in long tons (1016.0469088 kg) of the contents of ship like cargo, crew and consumables (fuel, water etc.) It is a good indicator for the revenues that can be generated. The Deadweight tonnage is related to the displacement and lightweight.

$$Deadweight\ tonnage = Displacement\ tonnage - Lightweight \tag{E.2}$$

Lightweight is the weight of the steel structures (machinery, equipment, hull etc.)

Net Tonnage is the amount of space available for carrying goods.

Block Coefficient is defined as the ratio of the underwater volume of the ship to the underwater volume of a rectangular block of the same dimensions (length, breadth and depth). The block coefficient C_B is always less than 1.

Short sea shipping is the cargo movement along a coast without crossing oceans.

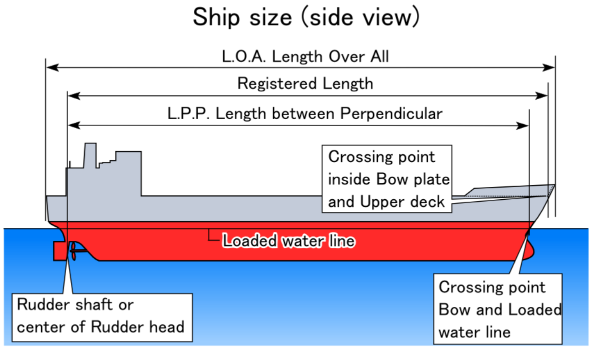


Figure E.1: "Schematic drawing of ship's size" by Tosaka is licensed under CC BY-SA 3.0

E.2.2. Stability

Intact stability is the stability criteria with the vessel in normal operational configuration (hull is not breached in any compartment). The intact stability criteria is defined according to the International Code on Intact Stability (2008).
Damaged stability is the measure of stability when various combinations of watertight compartments are flooded.

E.2.3. Ship Motions

Ship motions are described either as rotational or translational.

Rotational motions

Figure E.2 give the rotary motions that a ship cane be subjected to. The three movements are around three different axis :

- Vertical Axis (Yaw)
- Transverse Axis (Pitch)
- Longitudinal Axis (Roll)

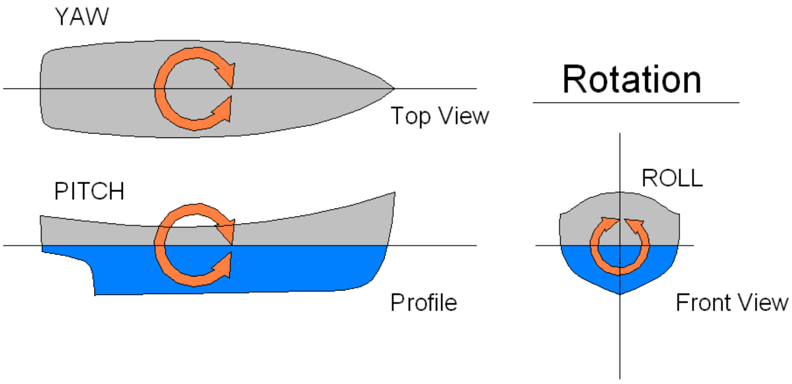


Figure E.2: "Three rotational degrees of freedom of a boat or ship" by Wikimedia Commons

Figure E.3 give the translatory motions that a ship can be subjected to.

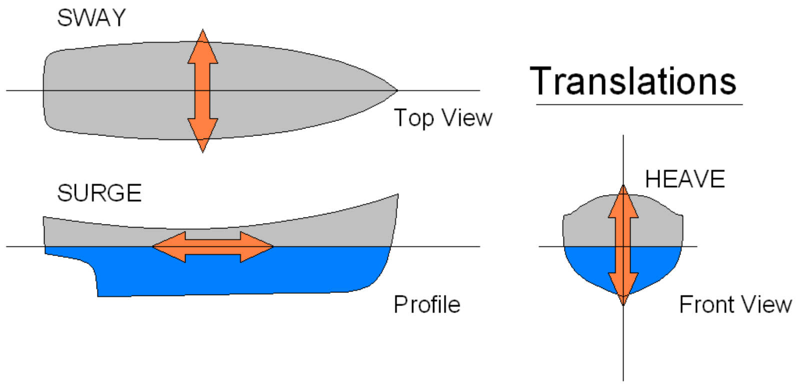


Figure E.3: "Three linear degrees of freedom of a boat or ship" by Wikimedia Commons

The three movements around the three different axis are :

- Vertical Axis (Heave)
- Transverse Axis (Sway)
- Longitudinal Axis (Surge)

E.3. Nuclear

E.3.1. Terms

Burn-up is defined as the fission energy release per unit mass of fuel $[\frac{MWd}{tHM}]$.
Effective Full Power Day is the number of days the core can be powered for at full power.

$$EFPD = \frac{Total\ Uranium\ loading\ [tU]}{Power\ rating[MW]} \times Core\ burnup\ [MWd/tU] \tag{E.3}$$

Reactor year is the unit of time in terms of operation of the nuclear reactor(s). One reactor year can be defined as one reactor operating for one year. Equivalently, ten reactor years could be 10 reactors operating for one year or one reactor operating for 10 years or or 5 reactors operating for 2 years each.
Power History refers to the power of a nuclear reactor over an extended period of time. It is an important metric for calculation of decay heat and fission product poisons.
Core Damage Frequency (CDF) The probability that an accident would cause severe damage to fuel in a nuclear reactor
Neutronic power is the power production in a nuclear reactor even after insertion of negative reactivity/shutdown. This is due to the continuation of the fission process by the delayed neutrons.
Xenon dead time is the time needed for the reactor to outweight the effect of Xenon-135.

E.3.2. Defence-in-depth concept

The defence-in-depth philosophy in the Code of Safety for Nuclear Merchant Ships is covered by four barriers [555] :

- Barrier I (Fuel) : Fuel matrix keeps the fission products.
- Barrier II (fuel cladding) : This essentially retains the fission products from the fuel.
- Barrier III (primary pressure boundary) : This functions to prevent the unintentional release of radioactive material from the primary system.
- Barrier IV (containment structure/safety enclosure) : This contains the primary pressure boundary and limits the leakage of radioactive material from any contained equipment.

E.3.3. HALEU

The U-235 concentration is referred to as ”assay”. High-assay low-enriched uranium (HALEU) is the fuel which has U-235 concentration between 5-20%. HALEU is the fuel of choice for SMRs, making the reactors smaller than they would be in comparison to other land based reactors [556]. HALEU also helps achieve higher ”burnup” rates and reduces refueling frequency.

E.3.4. Fast Neutron Reactors

A fast neutron reactors (FNRs) employs fast neutrons to carry out fission. In a A fast neutron reactor a neutron moderator is not needed as the fuel is rich in fissile material in comparison to thermal spectrum reactors.

Due to the surplus of neutrons from 239Pu fission, the reactor produces more 239Pu than it consumes. The blanket material can then be processed to extract the 239Pu to replace losses in the reactor, and the surplus is then mixed with uranium to produce MOX fuel that can be fed into conventional slow-neutron reactors. A single fast reactor can thereby feed several slow ones, greatly increasing the amount of energy extracted from the natural uranium, from less than 1% in a normal once-through cycle, to as much as 60% in the best fast reactor cycles.

E.3.5. COVRA

Central Organisation For Radioactive Waste (COVRA) located in Vlissingen-Oost is a public limited company and serves the single point for all nuclear waste management in Netherlands. A single entity was made responsible due to the low amount of nuclear waste, specialist knowledge requirement and cost savings [557]. COVRA is the site of storage and processing of the radioactive waste. The low-level and intermediate-level wastes are turned into a stable product after which the waste must be stored in deep geological repository.

E.3.6. Iodine Pit

Out of the known neutron absorbers, Xenon-135 is the most powerful one. During power reduction, the rate of Xe buildup is higher than the rate of Xe decay. The reason for this is the reduced burnup of Xenon (due to reduced neutron flux) and decay of I-135 to Xe-135. At this point, it must be remembered that the half life of the decay of I-135 is 6.6 hours in comparison to the half life of Xe-135 decay (9.2 hours). A Xenon peak is reached and unless there’s additional reactivity present, the reactor cannot be restarted again. This phenomenon is known as Iodine/Xenon pit. For reactors with thermal flux levels ($\sim 5 \text{ x } 10^{12} \frac{neutrons}{cm^2.s^1}$), Xenon decay is the dominant form of Xe removal rather than Xenon burnup [558]. When reactor power is decreased, there is an immediate decrease burnup of Xenon but the production of Xe-135 continues at the higher rate. The Xe-135 concentration continues to rise until the rate of production of Xe-135 is equal to the rate of removal of Xe-135. The magnitude of the Xenon peak is dependent on the initial power level. When reactor power is increased, a phenomenon in reverse occurs.

E.4. Energy Generation and Storage

E.4.1. Terms

Peukert effect is the loss of capacity when battery is charged/discharged at high currents.

E.4.2. Pressure Vessel Tank

Table E.1 is a based on information from the industry sources [559] [560].

Table E.1: Pressure Vessel types and their characteristics

Type	Material	Pressure Capability	Other remarks
Type I	All metal	Pressure 50 MPa	Heaviest and Cheapest
Type II	Metal liner with hoop wrapped composite.	Pressure not limited	Equal load bearing, more expensive than Type I, 30-40 % less weight
Type III	Metal Liner with load bearing composite (axially and hooped wrapped)	For P ≤ 45 MPa	2-3x more expensive than Type I (upfront cost)
Type IV	polymer based liner (generally polyamide or polyethylene plastic) with load bearing axially and hooped wrapped composite	For P ≤ 100 MPa	3-4x more expensive than Type I (upfront cost)

E.4.3. H_2 Storage tanks

Liquid Storage

For the LLNL Gen-3 cryo-compressed tank [332] at 1 atm and 20.3 K, the weight of the stored H_2 is 10.3 kg. While, the same tank when used to store gaseous H_2 at a pressure of 272 atm, only allows for 2.8 kg of H_2 to be stored at 300K. Since LH2 is slightly compressible, the actual storage capacity would depend on the refueling conditions (pressure and temperature). The refueling time is mentioned to be < 5 minutes.

Solid Storage

This is based on the information from a manufacturer [561] of solid H_2 storage. In Solid H_2 storage, the H_2 is stored at a low pressure (~ 1-10 bar) unlike the compressed storage. The H_2 is stored in metal hydride alloys and can be represented by the reversible reaction.

$$\frac{2}{n}M + \mathrm{H}_2 \rightleftharpoons 2/nMH_n + \Delta H \tag{E.4}$$

where,
M : Metal/Alloy
MH_n : Metal hydride
The reaction in Equation E.4 is exothermic when hydrogen is stored and endothermic when hydrogen is released.

Under low T or high P, the H_2 can enter the interstitial sites inside the parent metal/alloy. This allows for increase in the storage capacity of metal hydride storage tanks. The tank vessel body is usually made of Al or Stainless Steel. The whole solid storage system consists of tank vessel, heat exchanger and transport auxiliaries.

E.5. Reaction Control

The kinetic product is the end result of a faster reaction as it has lower activation barrier and a lower transition state energy. While the thermodynamic product is the end result leading to a lower energy of the product. At lower temperatures, the final product has more of the faster reaction, the reaction is under kinetic control. While at temperatures enough to have both the reactions proceed, the more stable product gets formed. The reaction is said to be under thermodynamic control. At high temperatures, the reactions are reversible and the product ratio is dictated by the ratio of equilibrium constants [562].

F

Results

This Appendix contains some of the results that were generated during this work but were of lower priority to be added to the report.

F.1. OPTIMUS (OSTSEE)

1 Day Operations

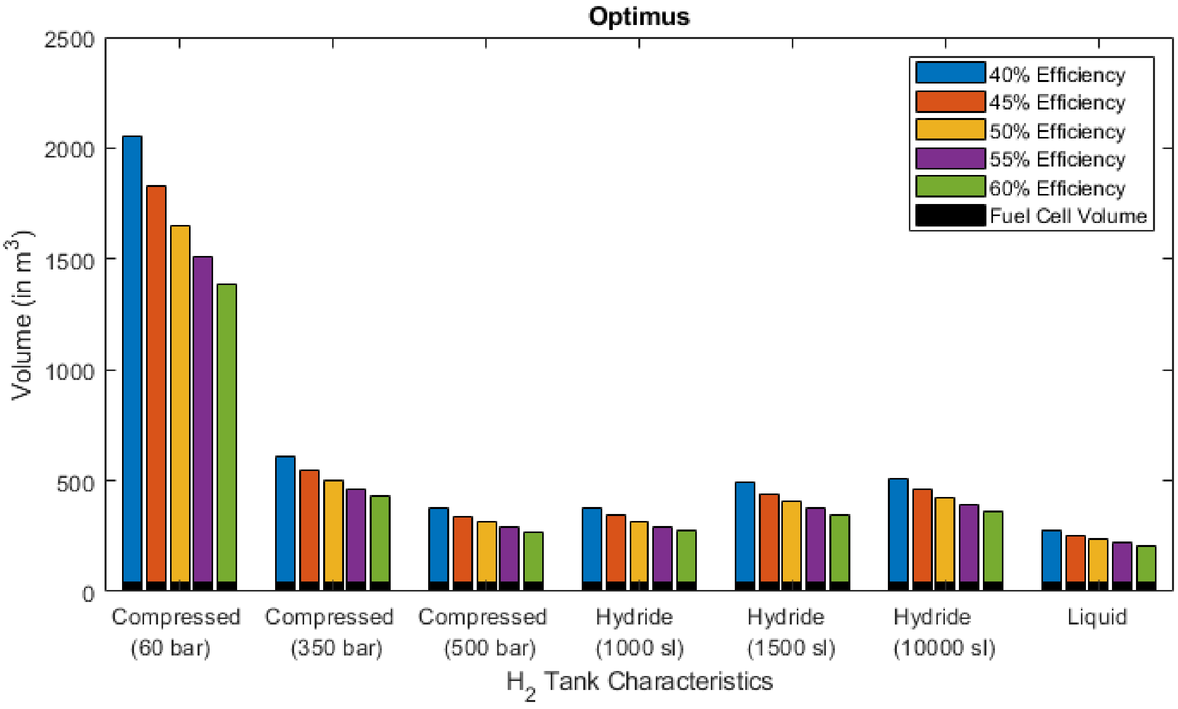


Figure F.1: Volume requirements for various PEMFC systems for 1 day operations of OPTIMUS

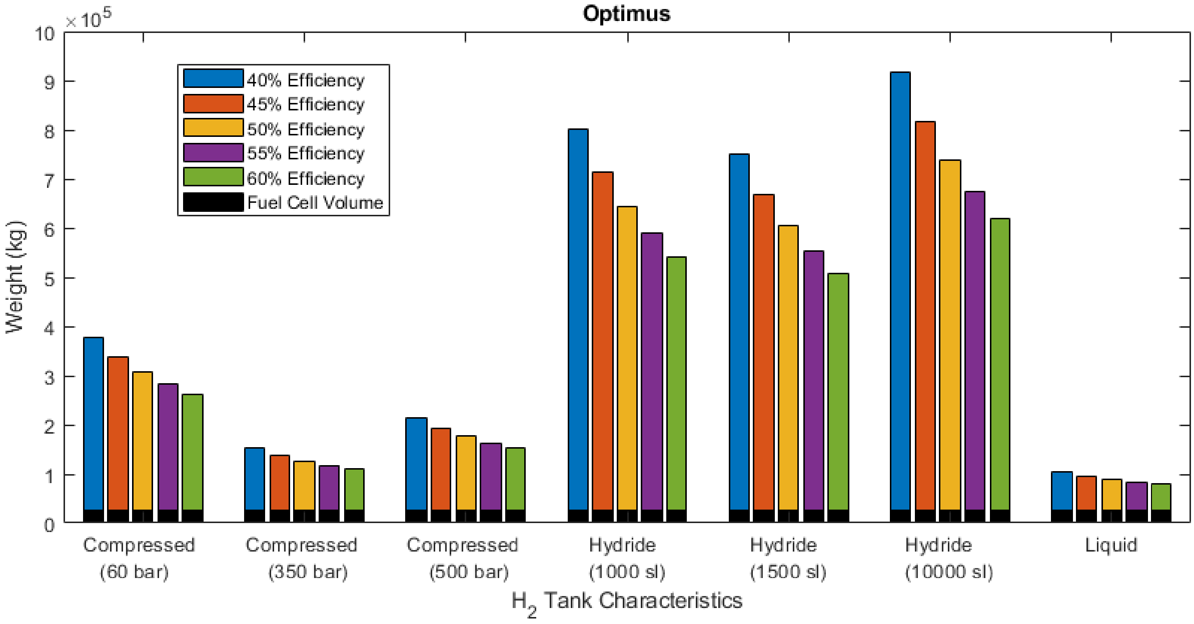


Figure F.2: Weight requirements for various PEMFC systems for 1 day operations of OPTIMUS

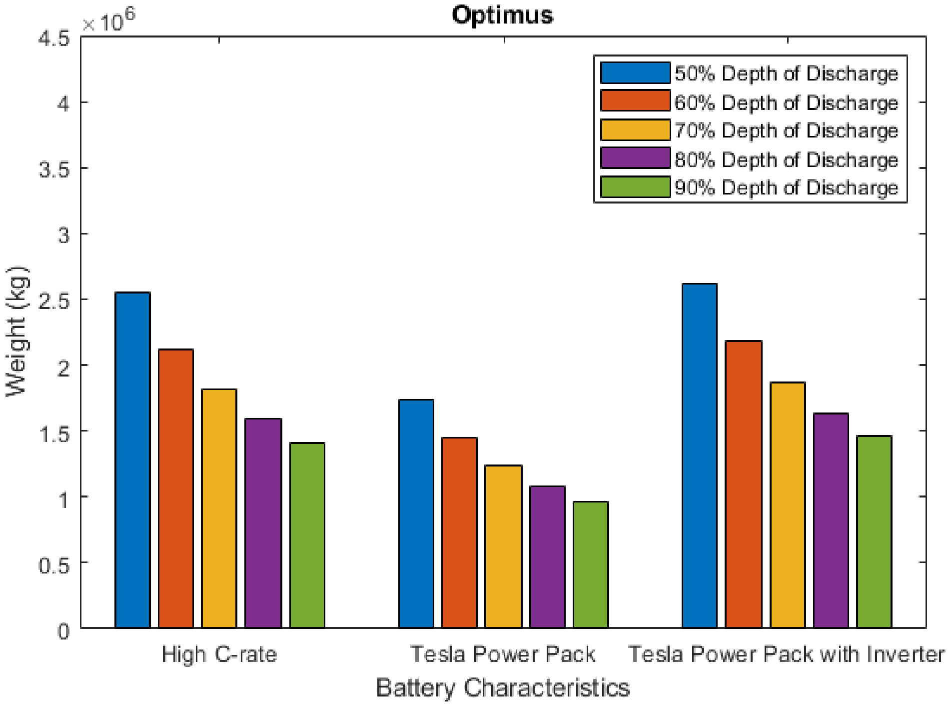


Figure F.3: Weight requirements for various PEMFC systems for 1 day operations of OPTIMUS

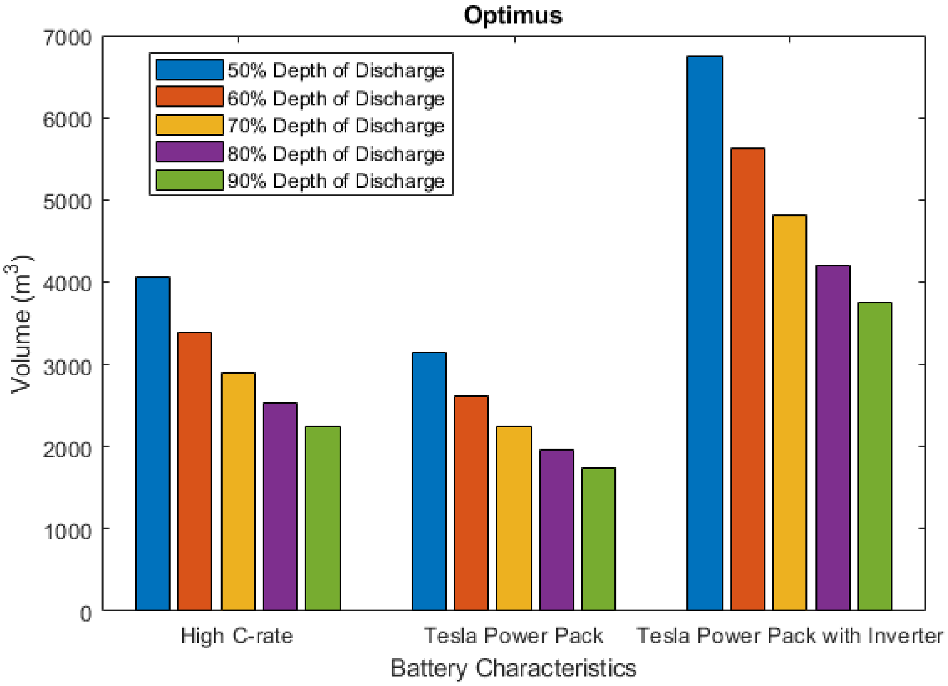


Figure F.4: Volume requirements for Battery systems for 1 day operations of OPTIMUS

F.2. HAM318

1 Day Operations

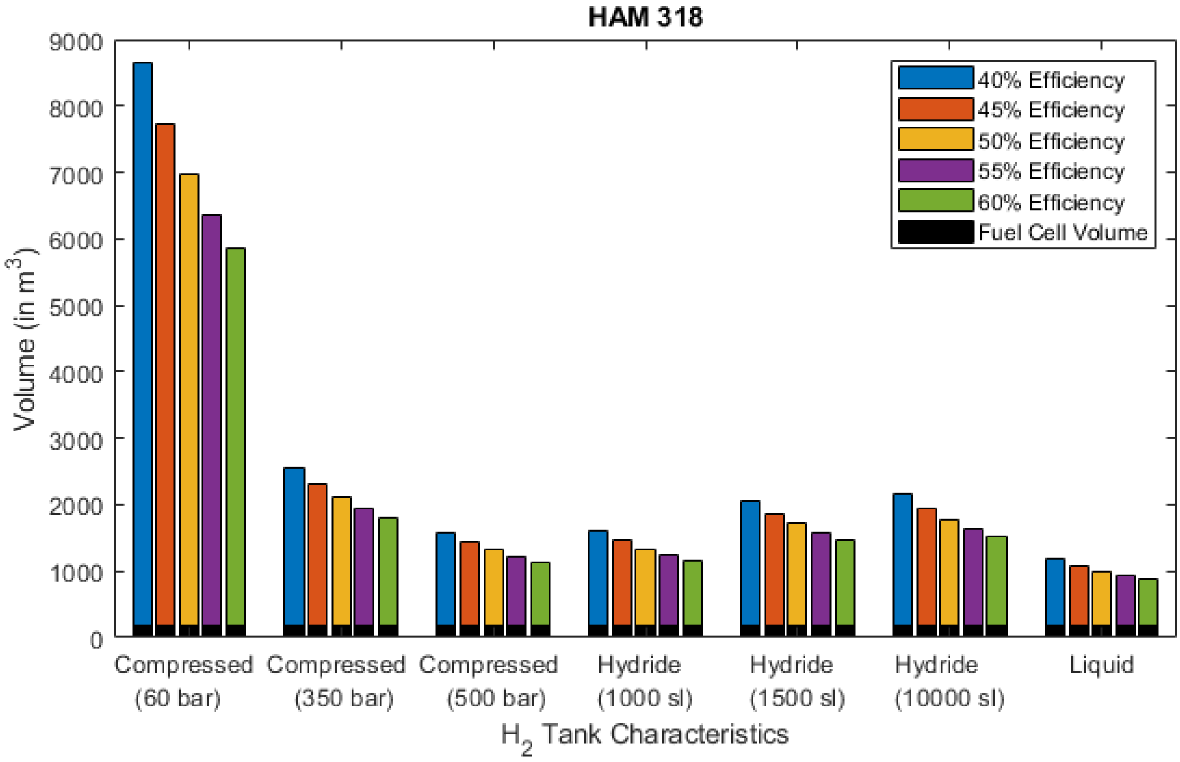


Figure F.5: Volume requirements for various PEMFC systems for 1 day operations of HAM 318

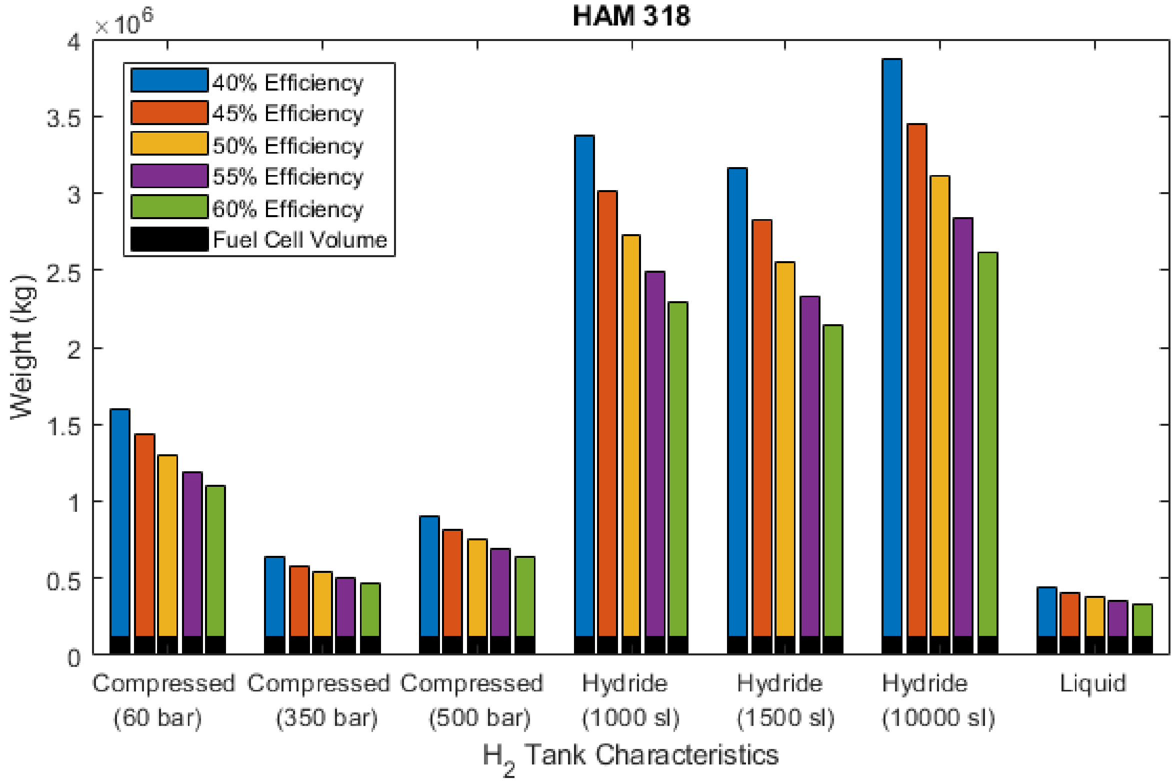


Figure F.6: Weight requirements for various PEMFC systems for 1 day operations of HAM 318

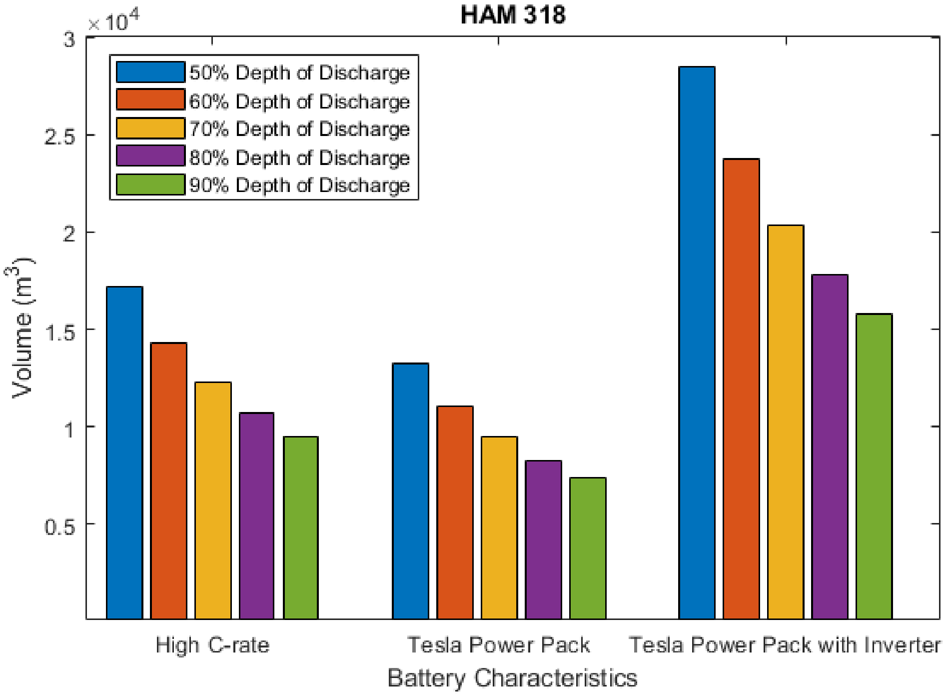


Figure F.7: Volume requirements for various Battery systems for 1 day operations of HAM 318

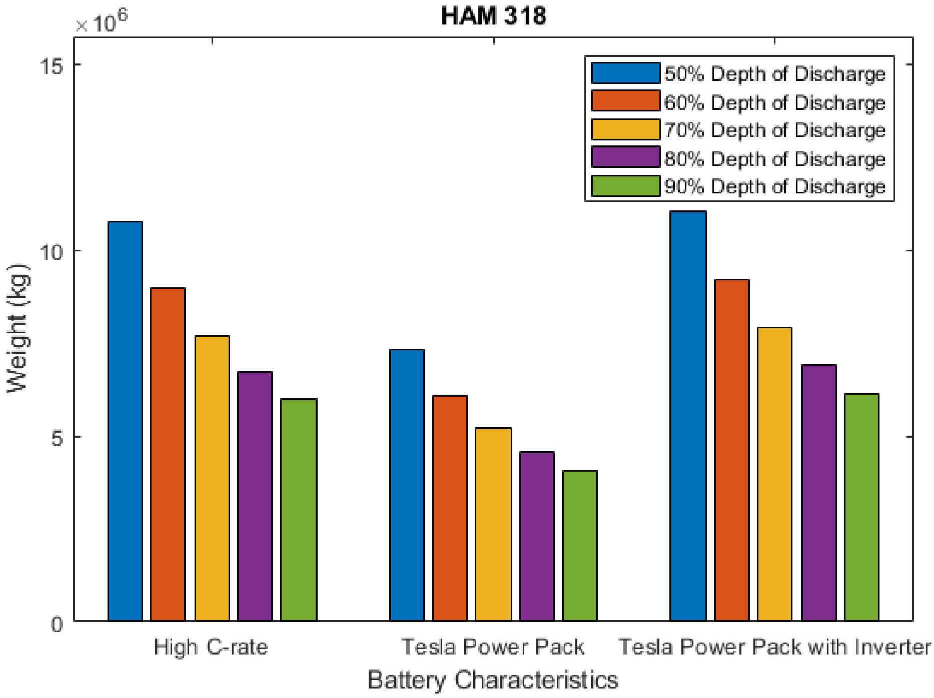


Figure F.8: Weight requirements for various Battery systems for 1 day operations of HAM 318

F.3. CRISTÓBAL COLÓN

1 Day Operations

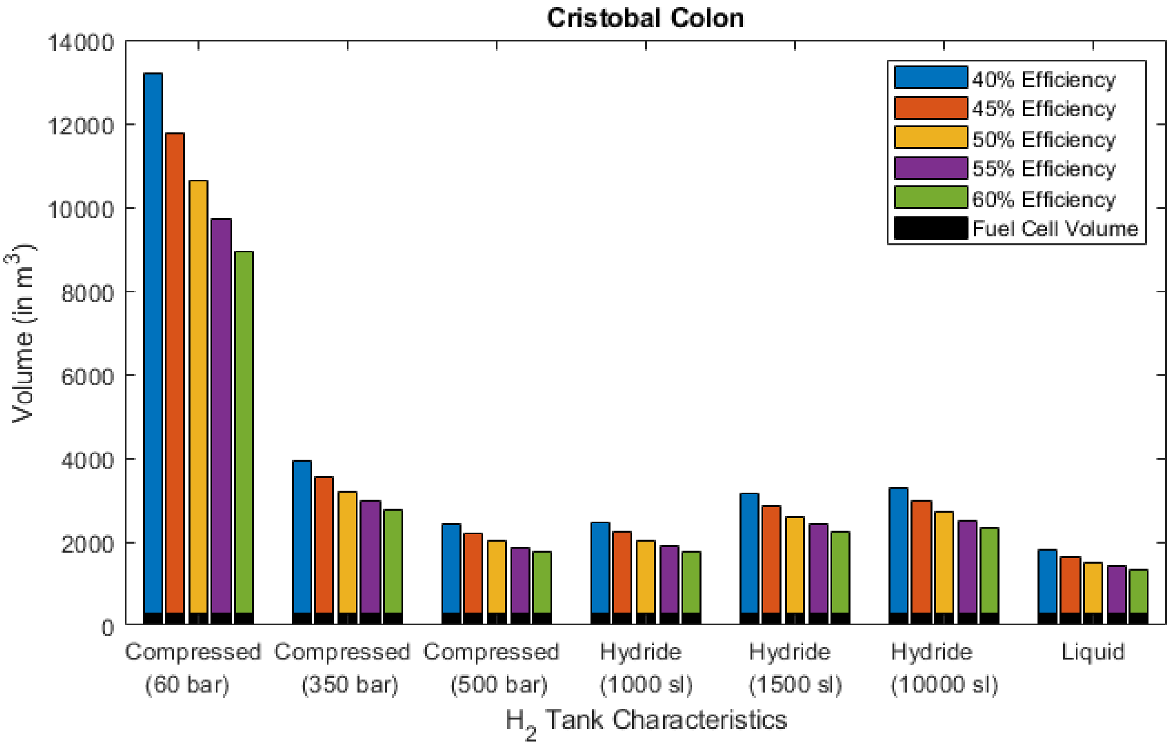


Figure F.9: Volume requirements for various PEMFC systems for 1 day operations of CRISTÓBAL COLÓN

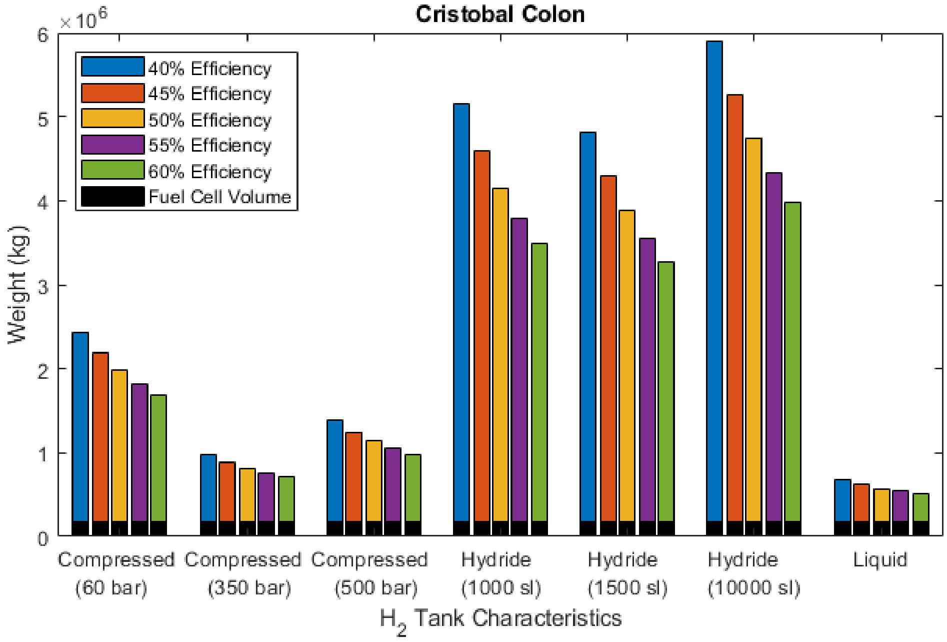


Figure F.10: Weight requirements for various PEMFC systems for 1 day operations of CRISTÓBAL COLÓN

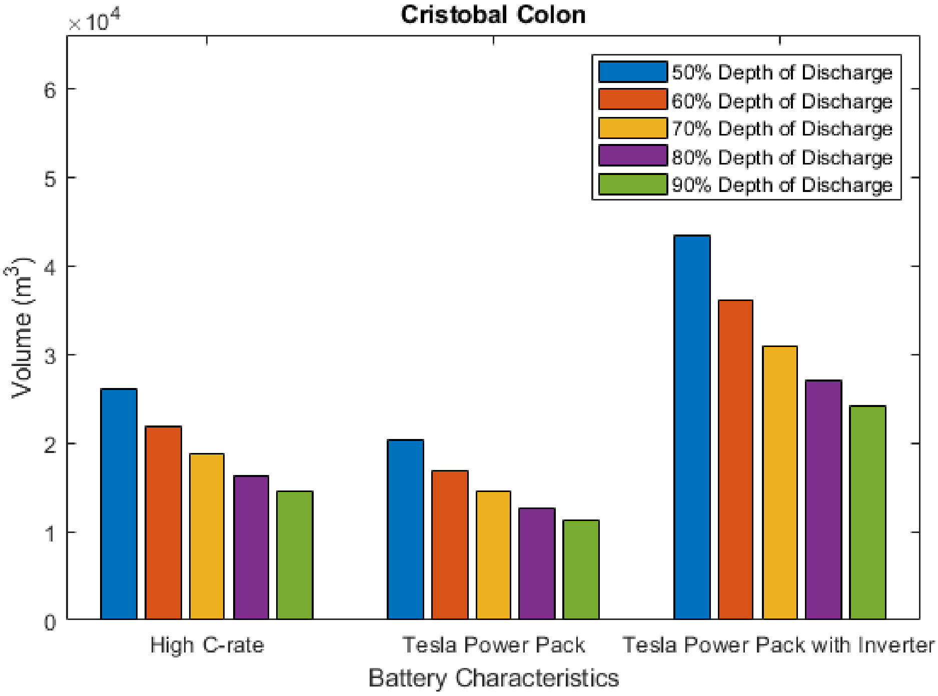


Figure F.11: Volume requirements for Battery systems for 1 day operations of CRISTÓBAL COLÓN

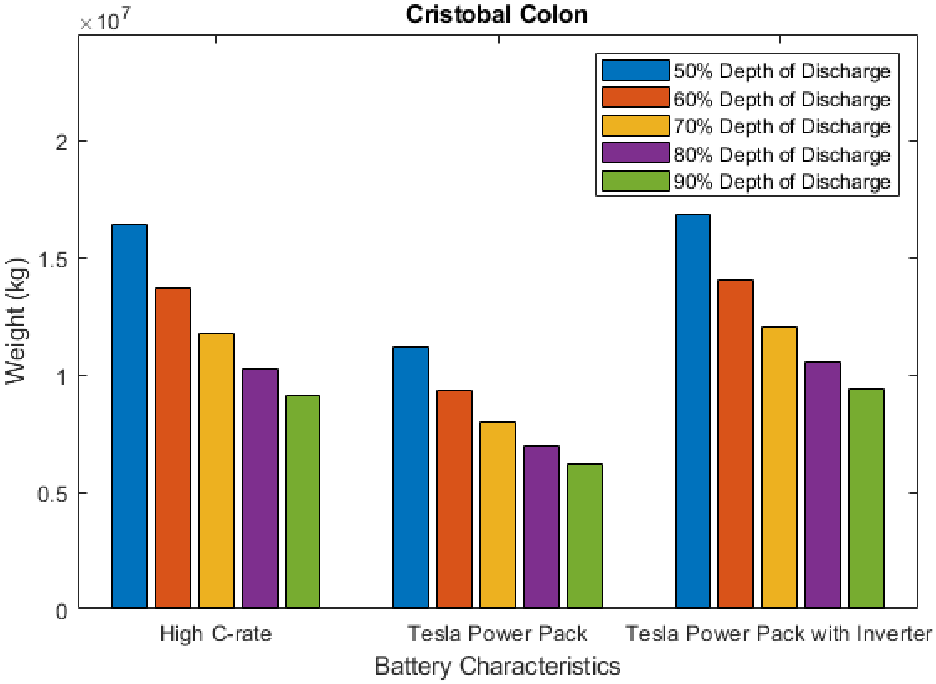


Figure F.12: Weight requirements for Battery systems for 1 day operations of CRISTÓBAL COLÓN

Requirements for 10 Day Endurance

The volume requirements w.r.t. Net tonnage for 10 day endurance for different technologies and TSHDs is given in Figure F.13.

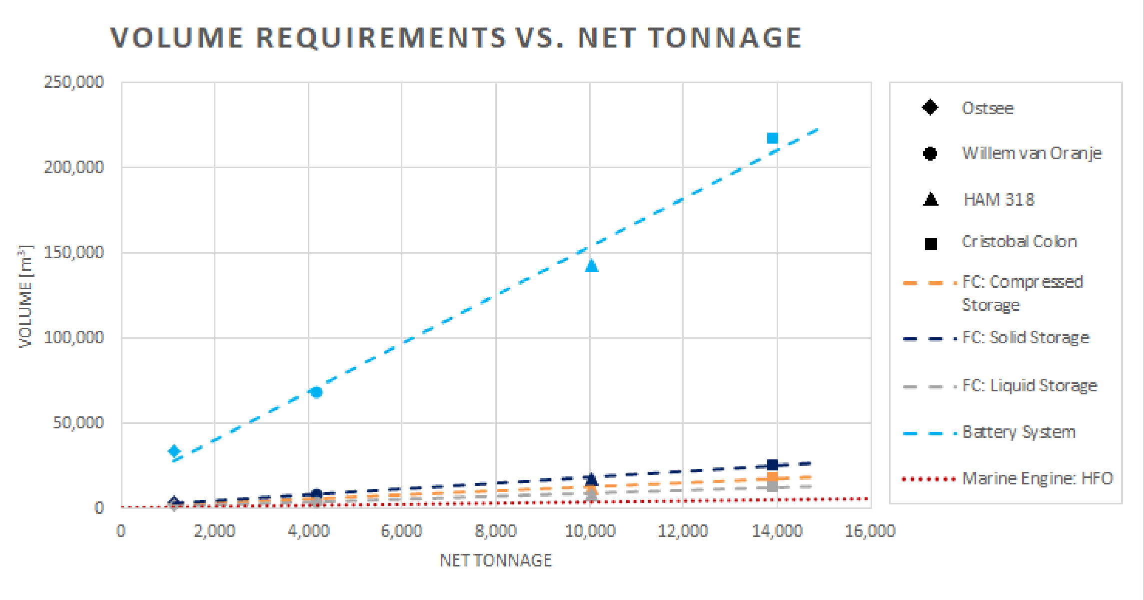


Figure F.13: Required Volume (10 day Endurance) vs. Net Tonnage

Figure F.14 represents the same information as Figure F.13 but with a logarithmic y-axis.

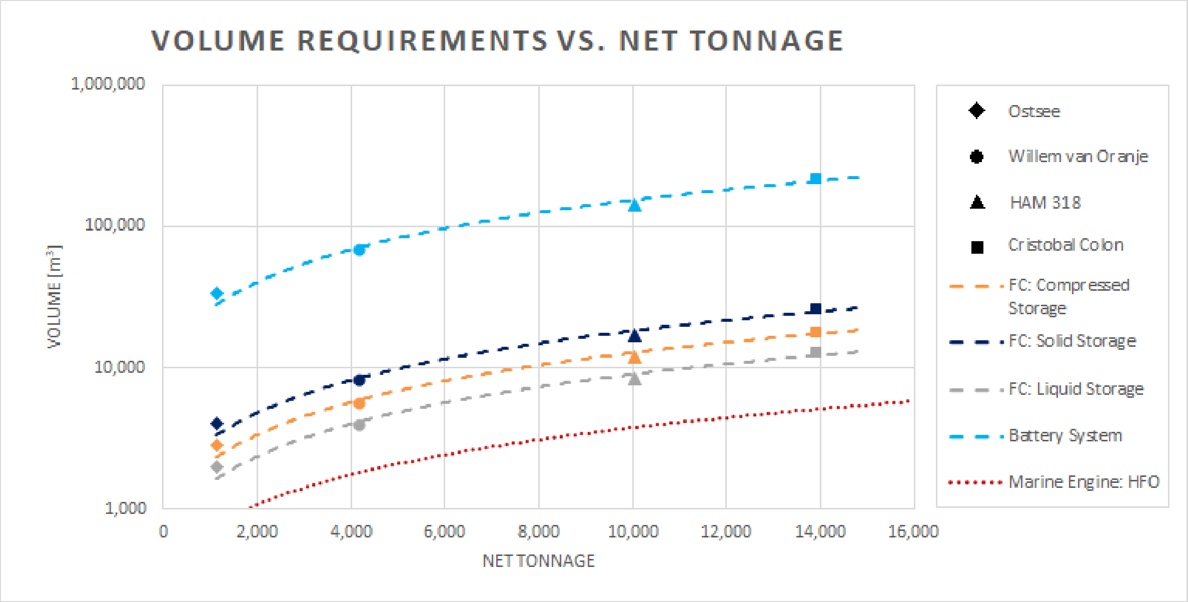


Figure F.14: Semi-Logarithmic Plot of Required Volume (10 day Endurance) vs. Net Tonnage

The volume requirements w.r.t. Displacement for 10 day endurance for different technologies and TSHDs is given in Figure F.15. The y-axis is logarithmic.

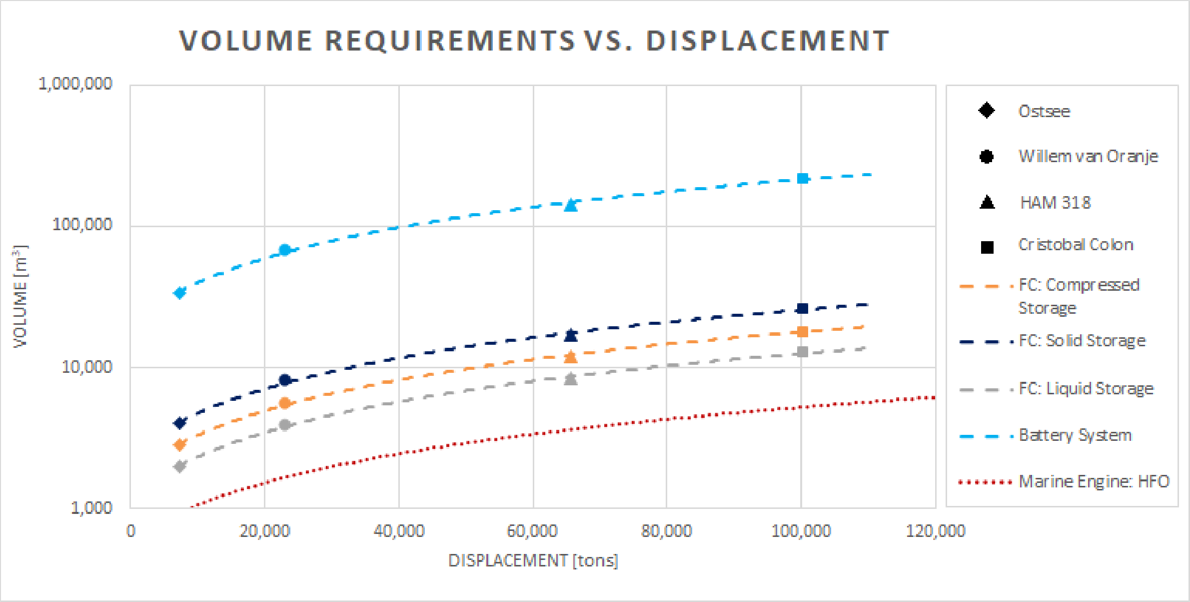


Figure F.15: Semi-Logarithmic Plot of Required Volume (10 day Endurance) vs. Displacement

The mass requirements w.r.t. Net tonnage for 10 day endurance for different technologies and TSHDs is given in Figure F.16.

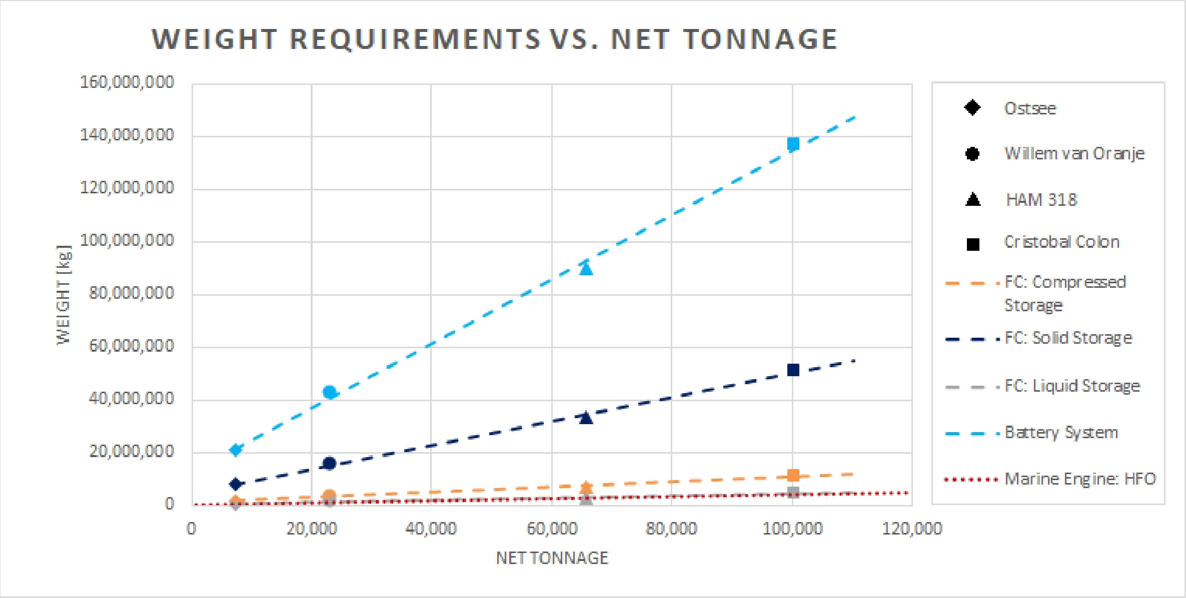


Figure F.16: Mass Requirements vs. NT

Figure F.16 represents the same information as Figure F.13 but with a logarithmic y-axis.

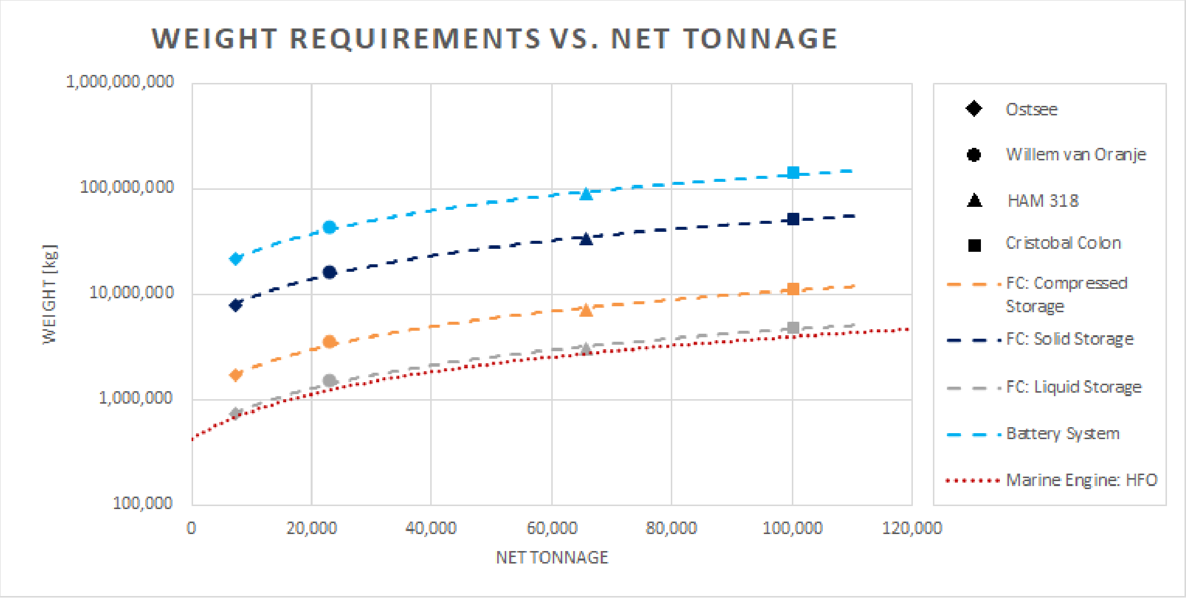


Figure F.17: Semi-Logarithmic Plot of Mass Requirements vs. NT

The mass requirements w.r.t. Displacement for 10 day endurance for different technologies and TSHDs is given in Figure F.18. The y-axis is logarithmic.

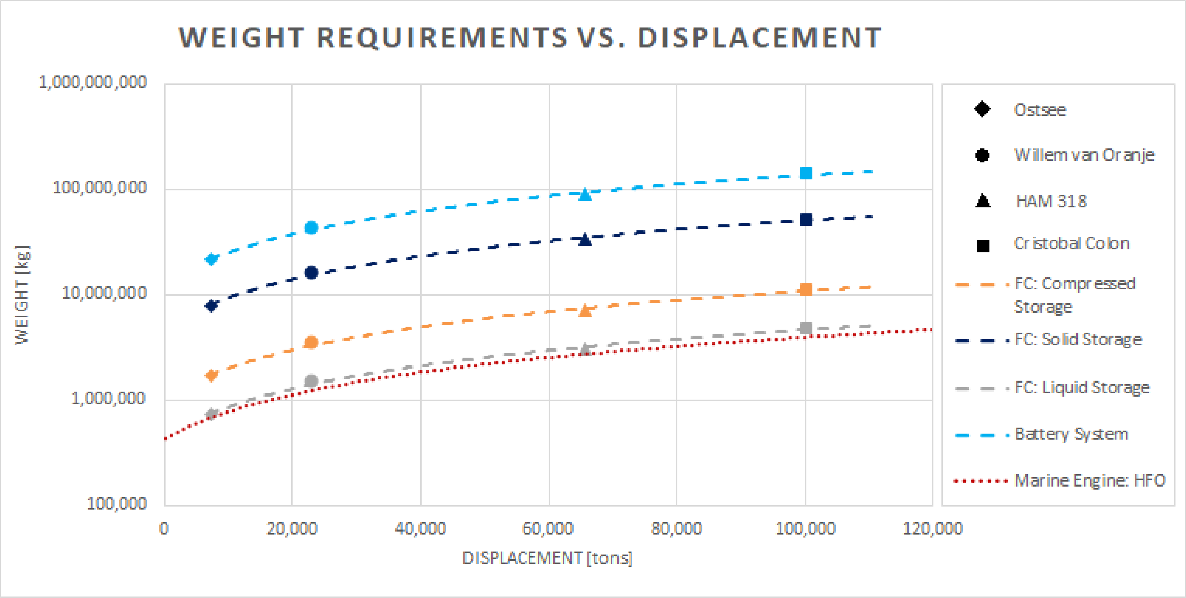


Figure F.18: Semi-Logarithmic Plot of Mass Requirements vs. Displacement

Expected Endurance

Figure F.19 represents the expected endurance of different technologies when the original design endurance is 15 days. Another way to look at it is : Figure F.19 shows the equivalent endurances of different technologies when thee mass and volume of a HFO-based system delivers an endurance of 15 days is a constraint.

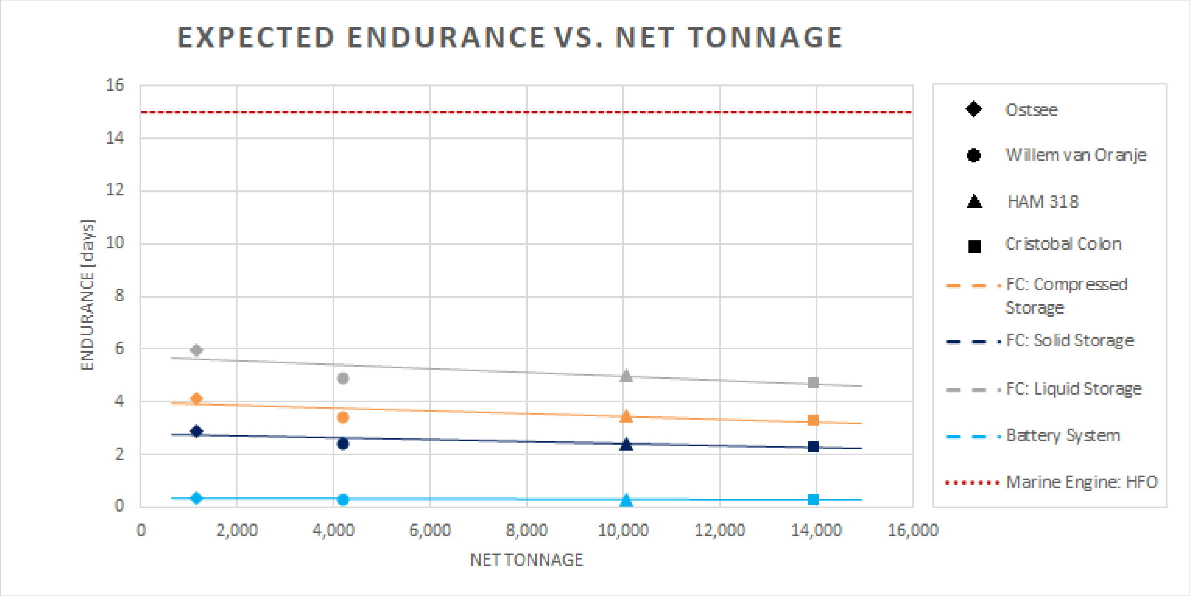


Figure F.19: Endurance vs. Net Tonnage

F.4. Retrofit Map

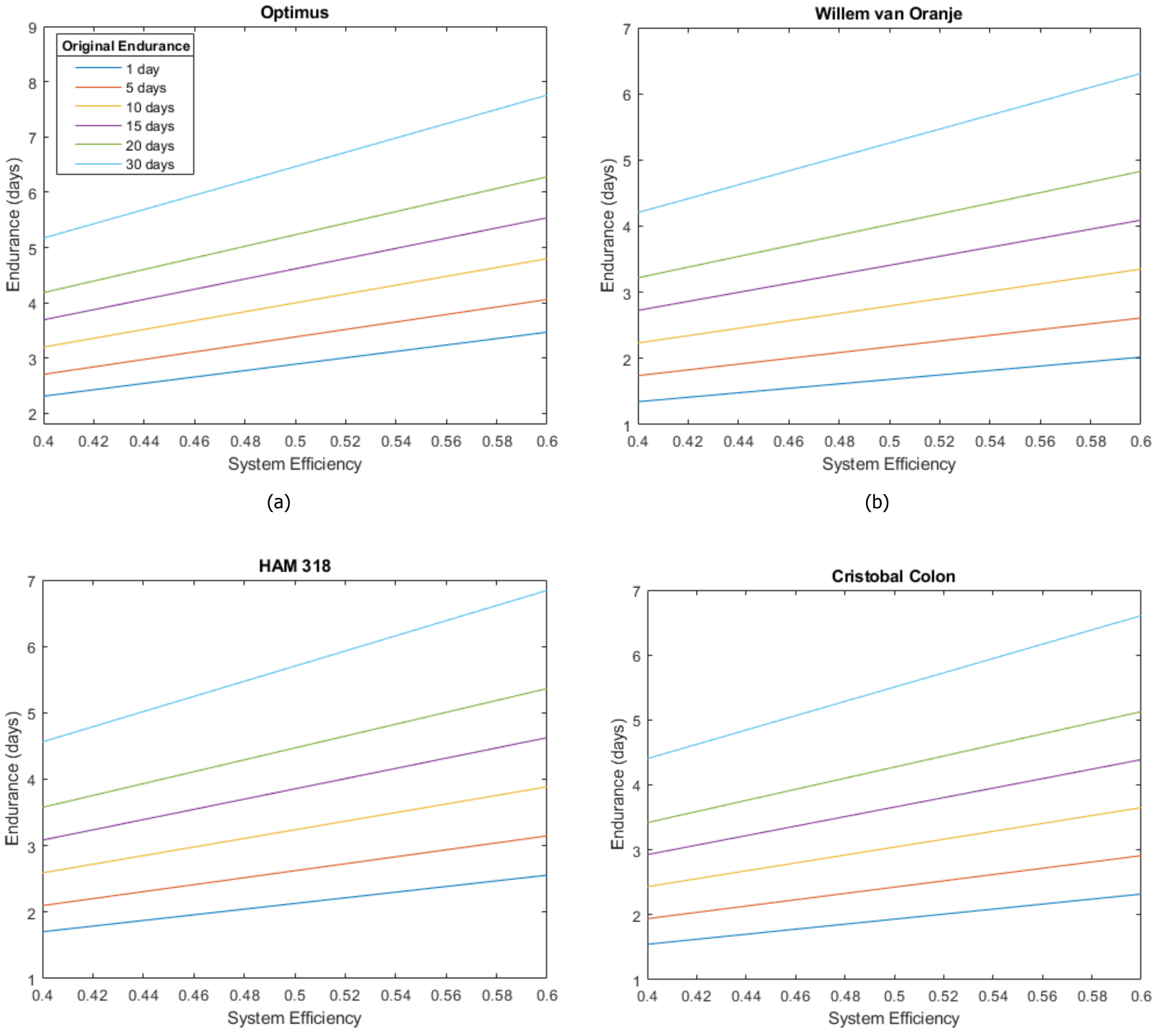
F.4.1. System : PEMFC with compressed H_2 storage

WILLEM VAN ORANJE

Dredgers the size of WILLEM VAN ORANJE are designed for endurance of 15 days. For a retrofitted dredger the size of WILLEM VAN ORANJE the maximum endurance (with the original design endurance of 15 days), an endurance of only 4 days can be achieved (at 60% system efficiency). However, if the dredger had been originally designed for 1 day endurance, the PEMFC system with compressed storage delivers better results than a fossil fuel based system.

HAM 318 & CRISTÓBAL COLÓN

A retrofitted dredger the size of HAM 318 or CRISTÓBAL COLÓN share almost the same characteristic endurances. These vessels are generally designed for 15+ days of endurance. If the original design endurance is 5 days, the maximum endurance (even at 60% system efficiency) is around 4 days. Only if the dredgers had been designed for 1 day endurance, the PEMFC system with compressed storage performs better volumetrically than a fossil fuel based system.



(a) (b)

(c) (d)

Figure F.20: Retrofit Map for PEMFC system running on Compressed Storage

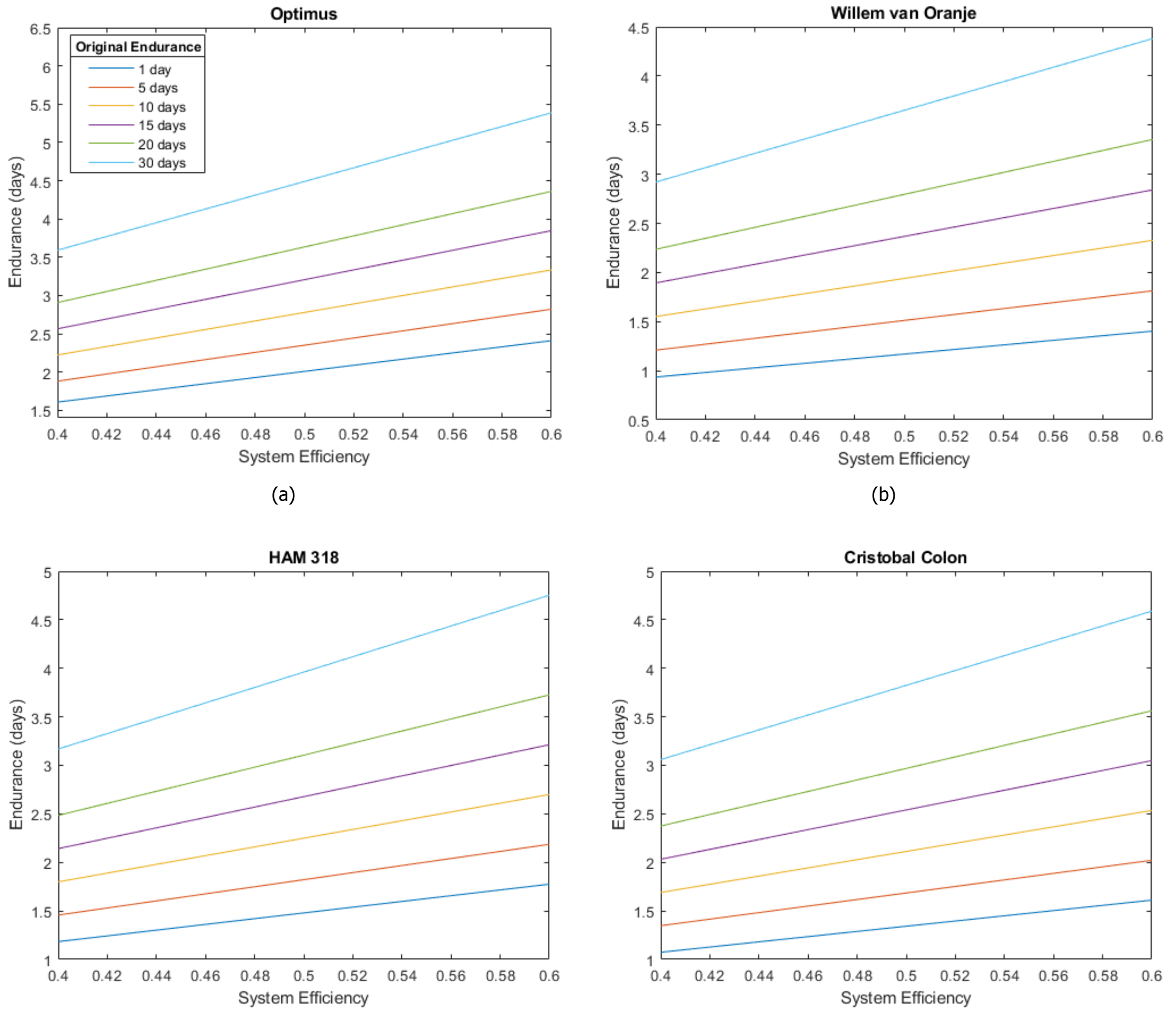
F.4.2. System : PEMFC with Hydride Storage

WILLEM VAN ORANJE

For a retrofitted dredger the size of WILLEM VAN ORANJE (designed for an original endurance of 15 days), the maximum endurance that can be reached is around 3.5 days. If the dredger had been designed for 5 day endurance, the PEMFC system with hydride storage can achieve a maximum endurance of around 2 days.

HAM 318 & CRISTÓBAL COLÓN

A retrofitted dredger the size of HAM 318 or CRISTÓBAL COLÓN share almost the same characteristic endurances. These vessels are generally designed for 15+ days of endurance. The maximum endurance of such a vessel designed for 30 days as original endurance is a little above 4.5 days. Only if the dredgers had been originally designed for 1 day endurance, the PEMFC system with compressed storage performs equally (at 40% system efficiencies) or better (at higher system efficiencies) volumetrically when compared to fossil fuel based system.



(a) (b)

(c) (d)

Figure F.21: Retrofit Map for PEMFC system running on Solid Storage

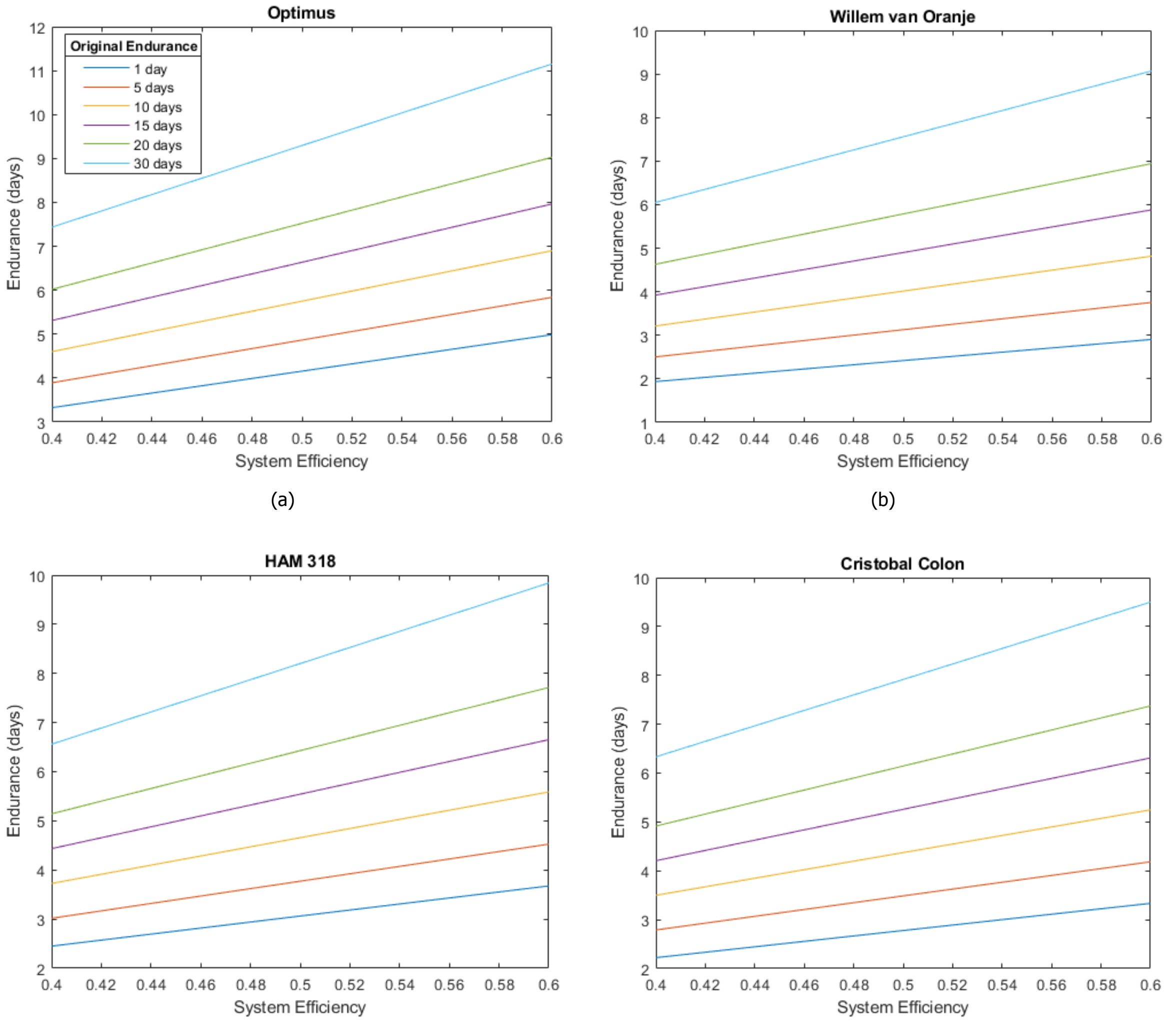
F.4.3. System : PEMFC with LH_2 Storage

WILLEM VAN ORANJE

For a retrofitted dredger the size of WILLEM VAN ORANJE (designed for an original endurance of 15 days or more), the retrofitted dredger's endurance is almost 6 days albeit at 60% system efficiency. However, for original endurances of 1 day, the PEMFC system with liquid storage delivers far better results than a fossil fuel based system.

HAM 318 & CRISTÓBAL COLÓN

For a retrofitted dredger the size of HAM 318 (designed for an original endurance of 30 days, volumetrically there's space to fit only a system that has an endurance of a little above 9 days. However, if the dredger had been designed for 1 day endurance, the PEMFC system with liquid storage can last atleast for 2 days.

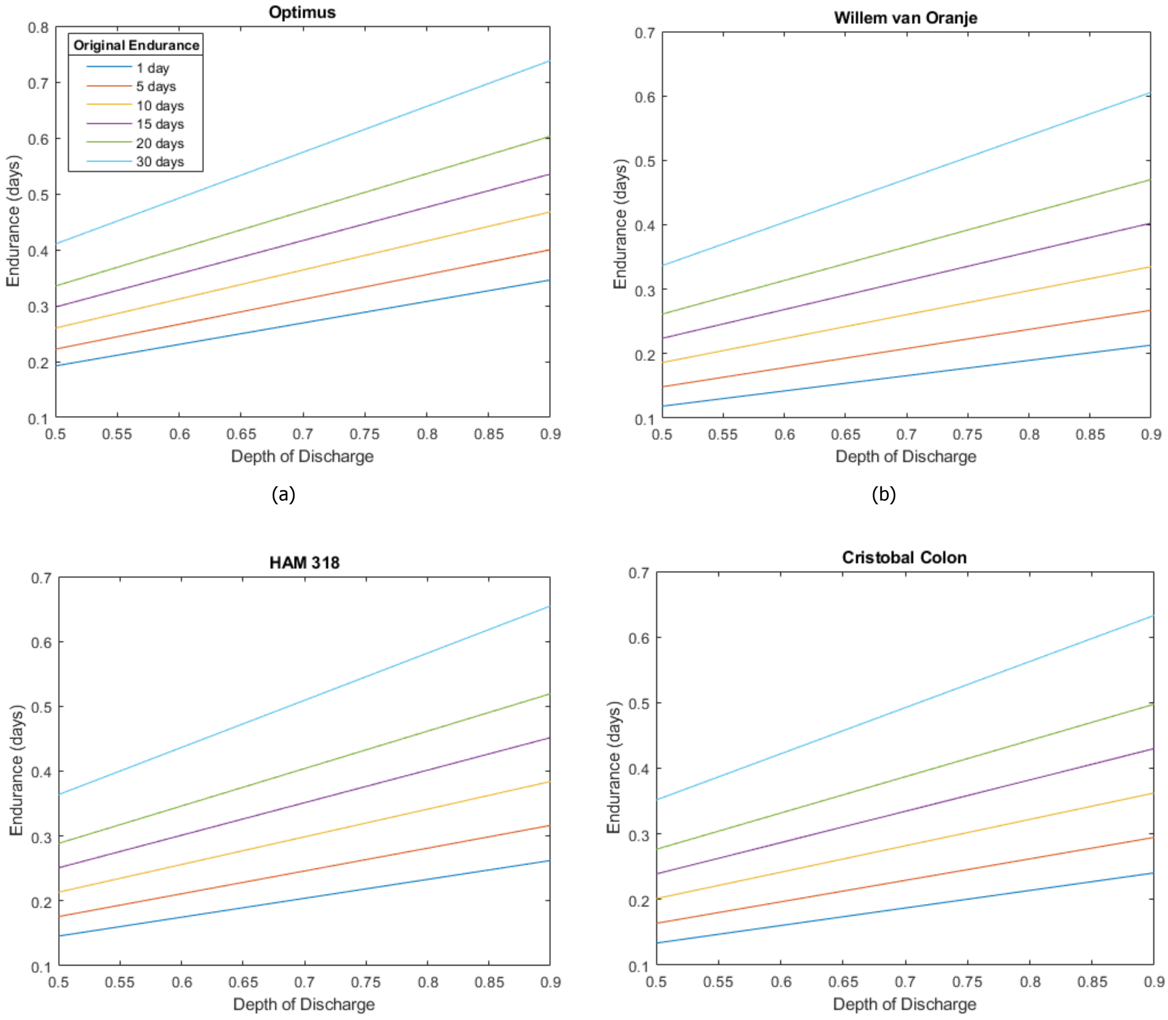


(a) (b)

(c) (d)

Figure F.22: Retrofit Map for PEMFC system running on Liquid Storage Fuel Cell

F.4.4. System : PEMFC with LH_2 Storage



(a) (b)

(c) (d)

Figure F.23: System : Battery Systems

WILLEM VAN ORANJE
If a battery system is used in WILLEM VAN ORANJE sized dredger with an original design endurance of 15 days, at 50% Depth of Discharge, the vessel's expected endurance is ~ 5 hours. The maximum expected endurance is about 14.5 hours is the original design endurance of the dredger is 30 days and the battery DoD is 90%.

HAM 318 & CRISTÓBAL COLÓN
For a retrofitted dredger the size of HAM 318 and CRISTÓBAL COLÓN. the trends are very similar. The expected endurance of the CRISTÓBAL COLÓN is slightly lower inline with other previously discussed powering options. For an original design endurance of 20 days with batteries operating at 90% DoD, the maximum achievable endurance is around 13 hours.

It is to be noted that the original endurance lines are clumped very tightly together in comparison to Fuel cell. The original design endurance does not make much difference in the endurance days of the retrofitted vessel.

F.5. Heat Exchanger

F.5.1. Graphite Heat Exchangers

Graphite should not be used as material for IHX. This is because of the oxidation of because of the oxidation of graphite in contact with air. Additionally, 'carbon corrosion' reaction through the reverse Boudouard reaction also poses a problem. Above 700 °C, the thermodynamic equilibrium and kinetics both favour this reverse reaction [563] as given in Equation

$$C + CO_2 \rightleftharpoons 2\,CO \tag{F.1}$$

Table F.1 gives the weight of the PHX and IHX when a factor of 4.88 kg/m^2 was used for calculation of the weight of the heat exchangers.

Table F.1: Heat Exchanger Weight

	Weight (kg)	
	PHX	**IHX**
OSTSEE	3302	8472
WILLEM VAN ORANJE	6592	16898
HAM 318	13869	35578
CRISTÓBAL COLÓN	21100	54200

Table F.2: Cost and Weight of PHX for different materials (NABC with 25 MW_{th} reactor)

	Common Parameters		
TEMA Type	BEM		
Segmentation	Single		
Orientation	Horizontal		
Tube Orientation	30-Degree Triangular		
Tube thickness (cm)	0.29		
Tube OD	1.905		
Material	**Inconel 600**	**Inconel 625**	**Incoloy 800**
Shell ID (cm)	207.5	197.5	225
Shell OD (cm)	212.9	202.7	239.6
Tube Length (cm)	600	600	600
Number of Tubes	6532	5904	7697
Total Mass $(tons)$	58.81	53.28	87.34
Cost (USD)	26,030,900	30,910,970	27,074,410

Table F.3: Effect of Baffle-cut Orientation for a 100 MW PHX

Common Parameters		
TEMA Type	BEM	
Segmentation	Double	
Material	Inconel 625	
Tube Orientation	30-Degree Triangular	
Tube thickness (cm)	0.29	
Tube OD	1.905	
Shell ID (cm)	250	
Shell OD (cm)	256	
Tube Length (cm)	600	
Baffle Cut Orientation	**Vertical**	**Horizontal**
Number of Tubes	8720	8696
Total Mass (tons)	78.53	78.35
Cost (USD)	293313200	292786800
Hot Side	0.56	1.75957
Cold	0.083	0.083

HX Manufacturer Comparison

As per a comparison by TRANTER [564] (a manufacturer of Shell and Plate Heat Exchangers) between TEMA Shell and Tube Heat Exchanger and Shell and Plate Heat Exchangers, for equivalent duties, the required surface area for Shell and Plate Heat Exchanger is about 4 times less and the dry weight of the heat exchanger is almost 9 times lesser. The dry weight to surface area for TEMA Shell and Tube Heat Exchangers is $\frac{6350}{203}\ \frac{kg}{m^2}$ which is equal to $\sim 31.5\ \frac{kg}{m^2}$.

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