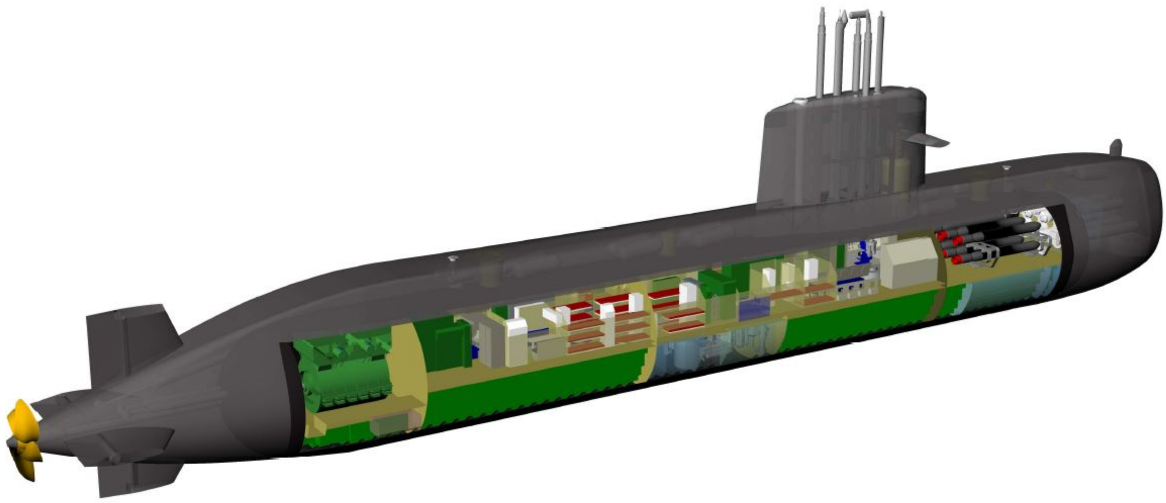
Concept design and feasibility study of an entirely battery powered naval submarine

By

S.A. Los



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Nevesbu NAVAL ARCHITECTS & MARINE ENGINEERS

Thesis for the degree of MSc in Marine Technology in specialization of Ship Design

Concept design and feasibility study of an entirely battery powered naval submarine

By

S.A. Los

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Company supervisor

Supervisor	*Ing. W.P.H.M. Schiks*
E-mail	*W.P.H.M.Schiks@nevesbu.com*

Thesis exam committee

Chair/Responsible Professor	*Prof. ir. J.J. Hopman*
Staff Member	*Rear-Admiral (ret.) ir. K. Visser*
Staff Member	
Company Member	*Ing. W.P.H.M. Schiks*

Author Details

Study number	*4221265*
Email	*svenlos94@gmail.com*

Preface

Abstract

Conventional submarines use a diesel-electric power plant. A diesel-electric power plant makes use of lead-acid batteries to store energy for submerged operations. The energy storage capacity of the batteries is limited. Therefore, battery charging is required regularly. Battery charging is performed with diesel-generators, which are making use of a snorkel installation to obtain fresh air. While snorkelling, submarines are exposed to higher risks of being detected; they can be visually spotted and their radar, thermal and acoustic signature is increased.

The currently used lead-acid batteries are the oldest type of rechargeable batteries. In past decades, developments in battery technologies have led to lithium based rechargeable batteries with high energy storage capacities. Compared with lead-acid batteries, lithium-ion batteries can store more than five times the amount of energy per volume and weight unit. This highly improved energy storage capacity might make an entirely battery powered submarines possible. The implementation of an entirely battery powered system will have multiple operational advantages; it will make the propulsion air independent and it will reduce the signature of the submarine. This contributes to an improvement in stealthiness of the submarine, which is an important tactical advantage. Furthermore, the number of systems on-board the submarine will be reduced. This will provide advantages from a design and maintenance perspective.

The goal of this research is to determine the feasibility of an entirely battery powered submarine. The feasibility of an entirely battery powered submarine is strongly depending on its operational capabilities. The operational capabilities are effected by the design of the submarine. The effects of the integration of an entirely battery powered submarine system on the submarine design are not known. Therefore, the effects on the submarine design need to be investigated before the operational capabilities can be determined.

The effect of an entirely battery powered submarine system on the submarine design is analysed with the use of a diesel-electric reference design. This reference submarine is redesigned into an entirely battery powered submarine. During the redesign, the submarine dimensions and design requirements are kept constant. This enables a fair comparison between the two design.

The effect of the usage of lithium-ion batteries is analysed. Lithium-ion batteries have a high specific energy, a high energy density, a good performance at high discharge currents, a long lifetime at regularly deep discharging and have no maintenance requirements. The integration of lithium-ion batteries is complex. Due to the small cell size, large amounts of lithium battery cells are required. Lithium cells need to be packed into battery modules to achieve this in a structured and save way. A string based battery design is used in which modules will be connected in strings. Each string will be able to provide the required operational voltage. Another challenge of lithium battery integration is the risk of is thermal runaway. When thermal runaway occurs, the lithium battery cell will vent toxic, explosive and flammable gasses. Several safety precautions are required to prevent thermal runway: a battery controlling and monitoring system, a thermal management system, short circuit protection on string level and shock protection. If thermal runaway occurs, the impact on the safety of the submarine can be limited by a gas tight, oxygen free and pressure resistant battery compartment design. The pressure resistant battery compartments require a vent option to prevent the pressure to reach to high values when large scale thermal runaway occurs.

The creation of an entirely battery powered submarine will influence multiple submarine

systems. The removal of the diesel-generators sets will make the diesel-generator support systems unnecessary. Furthermore, the replacement of lead-acid batteries with lithium batteries will reduce the required battery support systems. This has a positive effect on the safety characteristics, because the number of pressure hull penetrations and the risks on fire is reduced. Furthermore, the reduction in systems will reduce the operational duties and the maintenance workload of the crew. Therefore, the submarine crew size can be reduced. Other systems which are effected are: the electric system, the high pressure air system and the heating, ventilation and air conditioning system. Both the electrical system and ventilation system need to be adjusted due to the new propulsion plant. The capacity of the high pressure air system, the oxygen generation system and carbon dioxide removal system needs to be increased due to the increased submerged endurance.

The results of the batteries and system analysis are used to create an entirely battery powered submarine design. The created entirely battery powered submarine design is volume critical. Approximately the same amount of lead ballast as a diesel-electric submarine will be required to achieve a natural buoyant state. Stability is not a problem when the battery compartments are placed low in submarine. The auxiliary load of an entirely battery powered submarine will decrease 7% compared with a diesel-electric submarine, due to the reduction in systems.

The created concept design is used to determine the operational capabilities of an entirely battery powered submarine. The concept design, with a submerged displacement 1905 tons, can achieve a range of 1940 nautical miles and has an endurance of 24 days. This is five times lower than the range and endurance of a diesel-electric submarine with the same displacement. An entirely battery powered submarine is also compared with a diesel-electric submarines with an air independent propulsion (AIP) system. The submerged range of an entirely battery powered design is 1.5 times higher than a diesel-electric submarine with AIP. However, the total range and endurance of an entirely battery powered submarine is three times lower than diesel-electric submarine with AIP. The charging of an entirely battery powered submarine is analysed as well. The charging time is limited by the maximum current capacity of the switchgear and power cables. The total battery capacity on board the concept design can be charged in 15 hours.

From the results of the operational capabilities study can be concluded that an entirely battery powered submarine is feasible for local to medium range missions. Mission profiles with a one week, a two week and a 23 days duration are simulated and conform this. This makes an entirely battery powered submarine an interesting option for navies who use their submarines for homeland defence missions. Independent missions with a long range and endurance are not feasible. However, missions which require a longer range or endurance can be feasible when on sea charging is performed.

The operational capabilities can potentially be improved when the submarine is designed to meet its operational capabilities. Furthermore, the crew reduction can be decreased with 20% when a different manning philosophy is applied. To achieve this reduction, certain operational tasks need to be combined. This is possible due to the reduction of the work load of these tasks.

The long submerged endurance of an entirely battery powered design makes air quality control of great importance. Much attention must be paid to carbon dioxide absorption, oxygen production and the use of safe building materials to keep the air condition safe for the submarine crew.

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Nomenclature

BG	Distance between the centre of buoyancy and centre of gravity	m
c_0	Capacity at 1.2 hours discharge time	Ah/kg
c_5	Capacity at 5 hours discharge time	Ah/kg
c_∞	Capacity at 100 hours discharge time	Ah/kg
$C_{abs_{chalk}}$	CO_2 absorption capacity chalkholder	m^3
$C_{abs_{system}}$	Absorption capacity CO_2 absorption system	m^3
C_{bat}	Installed battery capacity	kW
C_{candle}	Capacity oxygen candle	m^3
GM	Distance between the centre of gravity and the metacentre	m
I	Current	A
I_{dis}	Discharge current	A
I_{SC}	Short circuit current	A
K	Resistance coefficient depending on hull shape	kg/m^3
KB	Distance between the keel and centre of buoyancy	m
KG	Distance between the keel and centre of gravity	m
KM	Distance between the keel and metacentre	m
m	Mass	kg
n_{chalk}	Number of chalkholders per absorption unit	-
n_{crew}	Crew size	-
n_{req}	Required number	-
n_{units}	Number of CO_2 absorption units	-
O_{abs}	Oxygen absorption	l/h
P_{aux}	Auxiliary power load	W
P_B	Brake power	W
p_{CO_2}	CO_2 production	l/h
P_E	Effective towing power	W

P_{loss}	Power loss	W
$P_{propulsive}$	Propulsive load on batteries	W
pct_{limit}	Maximum or minimum gas percentage limit	-
pct_{start}	Percentage of gas before submerged period	-
R_I	Internal resistance	Ω
R_{CO_2}	CO_2 removal rate	m^3h
T_{CO_2}	Time interval of raising CO_2 to limit	h
T_{O_2}	Time interval of dropping O_2 level to limit	h
$T_{operation}$	Operation time	h
T_{sub}	Submerged time of submarine	h
U_O	Open circuit voltage	V
V	Voltage	V
v	Speed	m/s
$\dot{V}_{air}$	Air flow	m^3/h
$\dot{V}_{surplus}$	Surplus volume flow	m^3/h
Δ_{sub}	Submerged displacement	tons
η_e	Motor efficiency	-
η_H	Hull efficiency	-
η_o	Propeller open water efficiency	-
η_R	Relative rotative efficiency	-
η_S	Shaft efficiency	-
η_{elec}	Electrical distribution system efficiency	-
∇_{sub}	Submerged volume	m^3

Abbreviations

AC	alternating current
AIP	air independent propulsion
BMS	battery management system
CCD	closed cycle diesel engine
CO_2	carbon dioxide
CoG	center of gravity
DC	direct current
DG-sets	diesel-generator sets
DoD	depth of discharge
H_2	hydrogen
HVAC	heating, ventilation and air-conditioning
IR	indiscretion ratio
LCB	longitudinal centre of buoyancy
LCG	longitudinal centre of gravity
LFP	lithium iron phosphate
LIB	lithium-ion battery
LO_x	liquid oxygen
MBT	main ballast tank
MCU	module control unit
MEM	main electro motor
NCA	nickel cobalt aluminium
NMC	nickel manganese cobalt
O_2	oxygen
SCU	string control unit
SWBS	ship work breakdown structure
TTA	aft trim tank
TTF	forward trim tank
UPS	uninterrupted power supply

VCG	vertical centre of gravity
WCT	weight compensation tank

Chapter 1

Introduction

Nevesbu is a naval architecture and marine engineering company involved in the design of ships, structures and installations for offshore, naval and specialist vessels. One of their specializations is naval submarines. Nevesbu is active in submarine design since their establishment in 1935. Their first contract was the design of the export submarines Sep and Orzel for the Polish Navy. Nevesbu has been involved in multiple submarine designs from that moment on. One of these designs is the Walrus class submarines, which are currently in use by the Royal Netherlands Navy. Recently, Nevesbu was also involved in the life extension programme for Walrus class submarines.

Nevesbu is continuously trying to improve their knowledge and designs. One way they try to achieve this, is by investigating the possibility of the implementation of new and/or improved technologies in their designs. This research will be performed in this context and will focus on the implementation of new battery technologies in an entirely battery powered naval submarine design.

1.1 Problem definition

Modern naval submarines can be divided into two types; nuclear submarines and conventional submarines. Nuclear submarines use nuclear plants to power the submarine. Nuclear power plants operate without an oxygen supply, which makes nuclear submarines completely air independent. Moreover, the nuclear power plant enables the submarines to sail years at high speeds without needing to be refuelled. Both the air independency and the long endurance and range at high speeds are operational and tactical advantages of nuclear submarines. However, nuclear submarines are generally large and therefore not suitable for operations in shallow coastal waters. Furthermore, the costs of nuclear submarines are high. For these two reasons, nuclear submarines are not used by most navies [16]. Conventional submarines use a diesel-electric power plant. Diesel engines cannot operate without an air supply, therefore energy is stored in lead-acid batteries for submerged operations. Battery charging is performed with diesel-generators, which are making use of a snorkel installation to obtain fresh air. While snorkelling, submarines are exposed to higher risks of being detected; they can be visually spotted and their radar, thermal and acoustic signature is increased. Indiscretion rate (ratio of time snorkelling to time submerged sailing), submerged endurance and submerged range are therefore important design criteria for diesel-electric submarines.

Multiple (non-nuclear) air independent propulsion (AIP) systems have been developed in the past to improve the submerged endurance of conventional submarines. Currently Sterling engines and fuel cells are most commonly used. Both systems improve the submerged endurance significantly, but they have multiple disadvantages: their power output is low, their consumable storage requires a large volume and they affect the signature of submarine [36]. AIP systems are only used as addition to the diesel-electric propulsion, which forces an increase in submarine dimensions, auxiliary power requirements and propulsive power requirements. Thus, the addition of an AIP system adds complexity to design.

Another way to improve the submerged endurance of a submarine is by enlarging the storage capacity of electrical energy. In past decades, the portable electronics and automotive industry invested heavily into research to increase the capacity of batteries. This led to multiple lithium based rechargeable batteries with high energy storage capacities. Figure 1.1 gives an overview of the currently available battery technologies. This graph shows that lithium based batteries can store more than five times the amount of energy per volume and weight unit compared with lead-acid batteries. This highly improved storage capacity makes lithium based batteries very interesting for implementation in submarines.

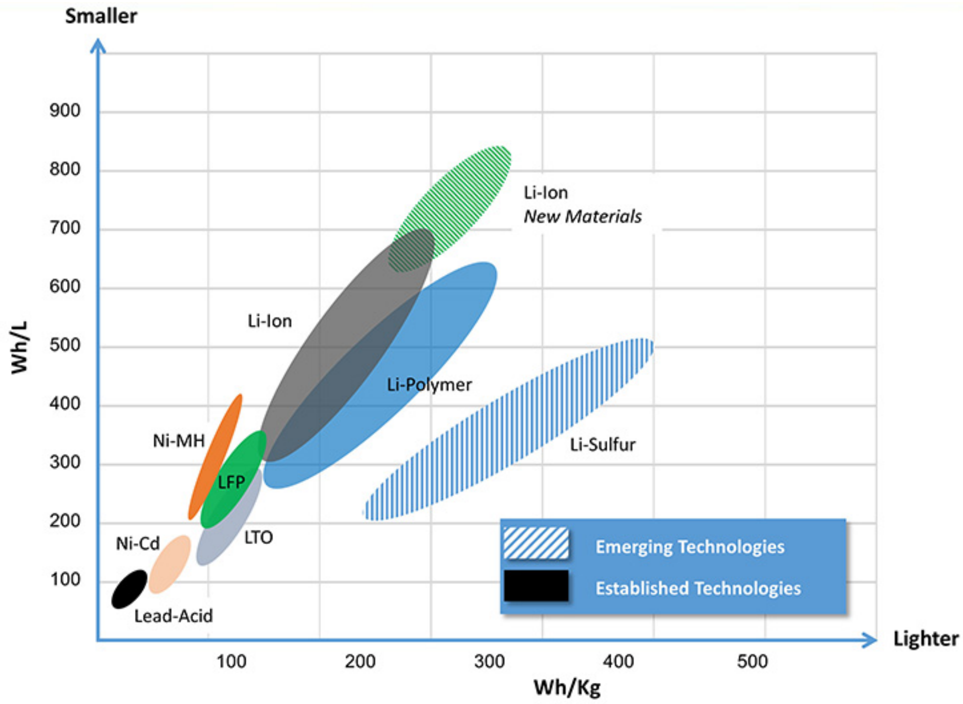


Figure 1.1: Energy density plot of established and emerging rechargeable battery technologies [17]

Recent studies confirm that considerable improvements could be achieved by implementation of lithium-ion batteries diesel-electric submarines [29, 39]. This is also recognised by submarine builders DCNS and ThyssenKurpp. DCNS is offering lithium-ion batteries as a modular option, which can be installed instead of an AIP section [12]. ThyssenKurpp is offering lithium-ion batteries instead of lead-acid batteries in their HDW 216 class submarine design [44]. The Japanese already claim to use lithium-ion batteries instead of lead-acid batteries in their Soryu-class submarine [25]. This indicates that the implementation of lithium based batteries in submarines should also be technical possible.

The improved capacity of lithium-batteries might even make it feasible to create an entirely battery powered naval submarine design. The omission of the diesel-generator sets and their support systems will provide extra space and weight available for the implementation of batteries. Furthermore, the auxiliary power requirements will be reduced. A rough estimation, based on the average weight and volume division of diesel-electric submarines, shows that this will approximately double the weight and space available for the implementation batteries [7]. This will, together with the improved battery technology, lead to a tenfold increase in electrical storage capacity. This increase in electrical storage capacity is expected to be sufficient to make certain operational profiles feasible.

The implementation of an entirely battery powered system has multiple operational advantages; it will make the propulsion air independent and it will reduce the signature of the submarine. This contributes to an improvement in stealthiness of the submarine, which is an important tactical advantage. Furthermore, the number of systems on-board the submarine will be reduced. This will provide advantages from a design and maintenance perspective.

The feasibility of an entirely battery powered design is strongly depending on its operational capabilities. The exact operational capabilities of an entirely battery powered system are not yet known. Furthermore, the effects of the integration of an entirely battery powered system on the submarine design are not known. Design challenges could limit the achievable installed battery capacity, which will limit the operational capabilities. Research is needed to indicate the effect of the integration of an entirely battery powered system on the submarine design, so that a fair estimation of the operational capabilities can be made.

1.2 Objective

The main objective of this research is to determine the feasibility of an entirely battery powered submarine design. To achieve this, two research goals have been set. The first goal is to identify the effects of an entirely battery powered submarine system on the submarine design. The integration of an entirely battery powered power plant design is expected to influence the submarines systems, reliability, safety, maintainability, stability and the required crew size. Furthermore, the limiting factors and design challenges of an entirely battery powered submarine design are unknown. The aim is to create a feasible concept design. This will enable the investigation of the design challenges and limiting factors of an entirely battery powered submarine. The second research goal is to investigate the operational capabilities of submarine designs with an entirely battery powered submarine system. The endurance, range and possible mission profiles will be determined. This will make it possible to compare the operational capabilities of an entirely battery powered submarine design with other submarine designs. The comparison between submarine designs is required to determine the feasibility of an entirely battery powered submarine design.

The objective of this research is summarized in the following research question:

> *"What is the effect of an entirely battery powered submarine system on the design and operational capabilities of a naval submarine and what is the feasibility of such a design?"*

The following sub research questions need to be answered to be able to answer the main research question:

- *"What design requirements are needed for a save usage of lithium-ion batteries in a naval submarine?"*
- *"What is the impact of an entirely battery powered submarine system on a naval submarine design and how will such a design look like?"*
- *"What are feasible operational profiles for a full electric battery powered naval submarine given a range of submarine dimensions and battery capacities?"*
- *"How will a full battery powered submarine perform compared with existing submarine designs?"*

1.3 Report structure

The first part of this report will provide background information about the topic of this research. Chapter 2 will provide background information about conventional submarines and their design. In chapter 3 background information about submarine power plants will be presented. Furthermore, this chapter will introduce the entirely battery powered concept power plant and will describe the used research methodology.

The second part of this report will describe the research performed to answer the main research question. In chapter 4, a literature research into lead-acid batteries and lithium-ion batteries will be presented. This chapter provides background information about both battery technologies and will discuss the required safety precautions for the use lithium-ion batteries. In chapter 5, the effect of an entirely battery powered submarine system on the submarine systems and crew is analysed. Chapter 6 and chapter 7 will describe the creation of an entirely battery powered submarine design. Furthermore, the effect of an entirely battery powered submarine system on the submarine design will be analysed. In chapter 8, the operational capability study will be presented. Chapter 9 will discuss the results of the design and operational capability analysis in a broader prospective. In the last two chapters of this report, chapter 10 and chapter 11, the conclusions are presented and the recommendations are stated.

Chapter 2

Naval submarines

This research will focus on naval submarine design. Naval submarines are sophisticated vessels which can perform stealth missions by sailing below the water surface. Submarines and their designs are, in several ways, not comparable with normal surface vessels. This chapter will therefore provide background information about conventional naval submarines and their design.

2.1 General description of conventional submarines

Submarines differ from normal surface vessels by the ability to sail below the water surface as well as on the surface. This ability gives the submarine its own characteristics. This paragraph will give a short description of the components of a conventional diesel-electric submarine. An artists impression of a diesel-electric submarine is shown in figure 2.1.

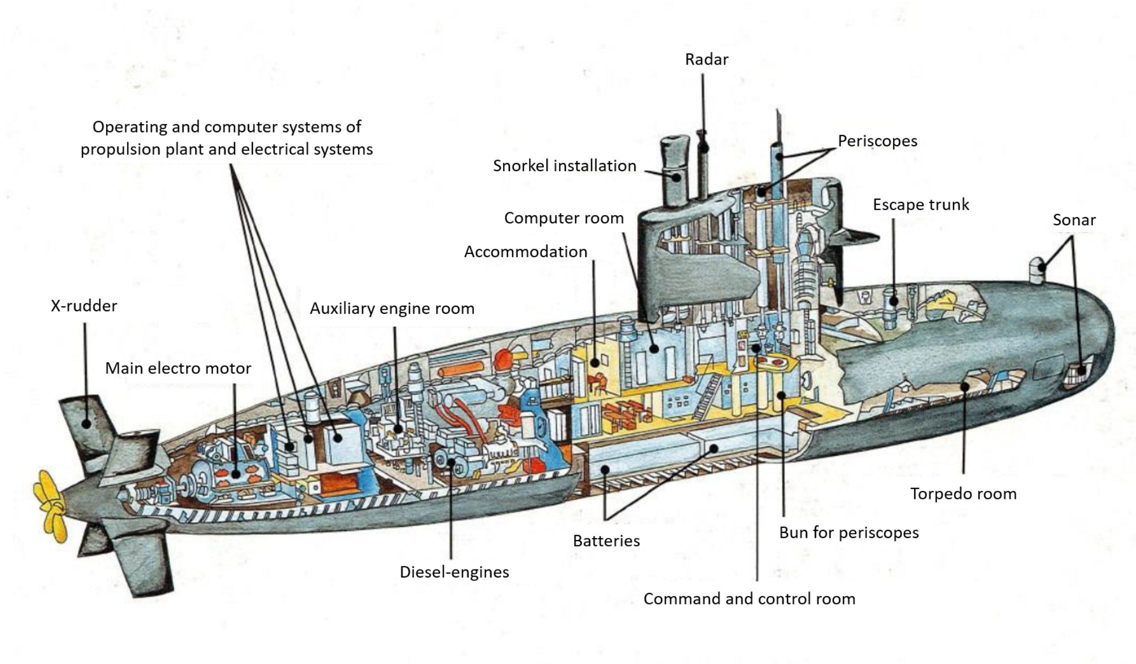


Figure 2.1: Artistic impression of a diesel-electric submarine [32]

Submarines are can operate submerged. To be able to operate at reasonable depths, high strength requirements are imposed on the hull to withstand the diving pressure. The strengthened hull used to withstand this pressure is called the pressure hull. The pressure hull of naval submarines is of a cylindrical shape. In submarine design the distinction is made between double-hull and single-hull submarines. In the case of single-hull submarines, the pressure hull is the external shell of the submarine. In case of a double-hull, only the parts of a submarine that must not be subjected to diving pressure are enclosed by a pressure hull. The outer hull is not pressure resistant and can, for example, be used to store fuel.

The sail of a submarine is a tower-like structure on top of the cylindrical hull of a submarine. The sail has multiple purposes. During surface sailing the sail is used as observation platform. It also provides access to the pressure hull (the elevated sail is needed to provide enough free-board to prevent down flooding). Another function of the sail is to house the snorkel installation, periscope(s) and communication masts.

The propulsion and power generation system of a conventional diesel-electric submarine consists of multiple diesel-generators to provide electric energy, lead-acid batteries to store electrical energy needed for submerged sailing and a main electro motor to drive the propeller shaft. Most submarines are propelled by a single propeller. This makes it possible to use a large diameter propeller, with low rpm, resulting in high efficiency.

Multiple auxiliary systems are presented on board of a submarine. Lubrication oil, cooling water and snorkelling systems are needed for the propulsion and power generation systems. Other present auxiliary systems are: a hydraulic system, a high pressure air system, a water distribution system, a heating, ventilation and air-conditioning (HVAC) system and electrical power distribution systems. Hydraulic systems are mainly used for the actuation of valves and submarine motion control systems. High pressure air systems are required for the discharging of ballast tanks during submerged sailing. Water distribution systems are used to control the trim of the submarine and to eject unwanted water. The HVAC system is of great importance in submarines, because it needs to able control the quality of the enclosed atmosphere during submerged sailing. Except from the normal functionality of a HVAC system, it is also used to keep the oxygen (O_2) and carbon dioxide (CO_2) levels on an acceptable level. An electrical power distribution system is needed to provide electrical power to all systems on board of a submarine.

The tactical payload of a submarine consists out of: sensors, communication, navigation and weapon systems. A computer system is used for the integration and processing of available data from the sensor and weapon systems. This information is provided to the command and control room and provides all information needed for decision making. Available sensor systems are passive and active sonar and radars. The main weapons of a naval submarine are torpedoes, which are launched from torpedo tubes. It is also possible to launch other types of weapons from these tubes (e.g. mines and missiles) [16].

The crew habitat consists out of: accommodations, sanitary and galley with stores. Space on board is limited, so accommodations are generally small. The crew is divided over the accommodation based on rank. Toilets, washing tables and showers are provided. Cold, cool and dry stores are present to store food. A galley is available to prepare meals. A mess is present in which the crew can consume their meal. Normally, separate messes are available for the different ranks.

Multiple tanks are present in a submarine; oil tanks, main ballast tanks, trim tanks, compensation tanks, fresh water tanks and a sanitary tank. Oil tanks are used to store the fuel, lubrication and hydraulic oil. Main ballast tanks are used to provide buoyancy during submerged sailing and are flooded to be able to achieve a submerged condition. Trim tanks are used to compensate the trim of the submarine. A compensation tank is used to compensate for the consumption of consumables, differences in water density and decrease in submarine volume during deep dives (due to the elastic compressibility of the hull) [16]. This is needed so that a natural buoyant condition can be maintained. Fresh water tanks and sanitary tanks are needed for the accommodation of crew. All these tanks can be divided in pressure resistant and non-pressure resistant tanks. Pressure resistant tanks need to be able to withstand the same diving pressure as the pressure hull. Typical pressure resistant tanks are compensation tanks.

The oil tanks, main ballast tanks, trim tanks and fresh water tanks are usually not pressure resistant [7, 16].

2.2 Operational capabilities

Submarines have a wide range of operational capabilities and are considered to be a strategic asset to navies. Their most important characteristic is their operational stealth. By submerged sailing they can perform their operational tasks without being noticed, which give them significant military advantages. A list of their operational capabilities is given below.

- Anti-submarine warfare
- Anti-surface warfare
- Mine warfare
- Missile strike capabilities
- Sea control, sea denial and prevention of conflict escalation
- Intelligence gathering, surveillance and reconnaissance
- Covert deployment of special forces

The operational philosophy of submarines is changing over time due to changing global stability. During the First and Second World War submarines were mainly deployed to attack enemy supply lines and surface war ships. Currently, the emphasis lays on intelligence gathering, surveillance, reconnaissance and the deployment of special forces. The changing operational philosophy of submarines results in changing operational requirements. Each operational capability brings its own requirements to the submarine design.

2.3 Design requirements

Submarines are designed to perform certain operational functions. This role arises from operational studies performed by the navy. From these operational functions the design requirements can be derived. The design requirements consist out of tactical payload requirements, operational requirements and multiple other requirements.

The tactical payload describes the type and number of sensors, communication systems, navigation systems and weapon systems required to perform the operational functions. Furthermore, requirements are imposed to the number of reloads for the weapon systems and number of special forces which can be deployed.

Operational requirements of a vessel consist out autonomy, mobility and environmental requirements. The autonomy requirements describe the required endurance, range, indiscretion rate, submerged endurance and submerged range. All these requirements are given for a range of speeds and are often translated into the mission profile of the submarine. The mobility requirements consist out of the maximum diving depth, attainable speeds in surfaced, snorkelling and submerged condition and manoeuvrability requirements. The environmental requirements describe in which environmental conditions the submarine and its systems should stay fully operational. These conditions are given by a temperature range of the seawater and ambient air, a range of seawater density and maximum relative humidity of air.

Except for the payload and operational requirements, the design will also have to meet many other requirements. These requirements cover issues like: availability, maintainability, reliability, stability, safety, fire resistance, shock loads, signature, quality assurance and level of accommodation. Furthermore, the costs of the design are of importance. The costs and benefits of the systems have to be well balanced.

2.4 Challenges in submarine design

The challenges in submarine design arise from its ability to sail submerged. During submerged sailing, the submarine needs to be natural buoyant. As a result, there is no reserve buoyancy during submerged sailing and only a small reserve buoyancy during surface sailing. This forces a compact design with limited space and weight margins. Furthermore, the cylindrical shaped hull of a submarine poses design challenges with respect to space. The systems are mostly of rectangular shape, making it difficult to efficiently use the available space in the cylindrical shaped hull. Due to these reasons, submarines are generally volume critical.

The small weight margins make it important to have a good weight management during the design and building of the vessel. If the weight limit is exceeded in the production stage, this can only be solved by lengthening the hull of the submarine. This is costly operation and will reduce the performance of the submarine. The mistake made during the design of the Spanish Isaac Peral submarine emphasizes the importance of weight management. The submarine turned out to be 75 tons overweight, causing that it had to be lengthened [18].

Not only the total weight is of importance, but also the location of the center of gravity (CoG) is of great importance. The stability margins are small, due to the small water plane area and small reserve buoyancy during surfaced sailing and the absence of both during submerged sailing. During submerged sailing, the CoG must be located directly below the centre of buoyancy to prevent trim. A good weight balancing can reduce the space and weight needed for trim tanks and lead ballast, which will improve the efficiency of the design.

Another challenge arising from the ability to sail submerged is the absence of an air supply during submerged sailing. A unique propulsion system is needed to be able to function without an air supply. Lead-acid batteries are installed for the energy supply in full submerged condition. The total installed battery capacity and the energy consumption determines the submerged range and endurance. The installation of a bigger battery capacity can increase the submerged endurance, however this will consume weight and volume. The margins for this are small, so this will require an increase in submarine dimensions. Larger submarine dimensions will result in high propulsion and auxiliary power requirements, which can lead to a large and inefficient design. Energy management is therefore important in submarine design.

The most challenging part of submarine design is to achieve an integrated and balanced design. The system integration is difficult due to the small margins and the numerous present systems. Furthermore, the total integration needs to be achieved within requirements for high reliability, safety and a low as possible signature.

Chapter 3

Submarine power plant

This research is focussed on the implementation of a new concept power plant in submarines. This chapter will elaborate on submarine power plants. The goal of this chapter is providing background information about submarine power plant design and the conventional diesel-electric power plant. Furthermore, the entirely battery powered concept power plant will be introduced and the effects of the integration of the concept power plant integration will be identified. In the last paragraph of this chapter, the mythology of this research will be described.

3.1 Submarine power plant design

The propulsion and electrical power supply are two important functions that are needed to fulfil the submarine's mission. The function of the power plant is to provide this power supply. The power plant is designed to meet the operational requirements of the submarine. The operational requirements are often given as a mission profile. The mission profile states requirements as; total range, submerged range and submerged endurance at different speeds. These requirements should be achieved with the use of as less space and weight as possible. Existing diesel-electric submarines show that the power plant and auxiliary systems are responsible for approximately 35% of weight and 50% of the total volume of a submarine [7]. This emphasizes the need of a compact and efficient power plant design.

Reliability, availability and the associated level of redundancy are of great importance in submarine design. All systems related to the propulsion and electrical power generation of the submarine are designed to have redundancy in their functionality. A reduction in capacity is tolerated in case of a failure of a component/subsystem.

The reliability and availability, together with the maintainability, of the power plant will influence the crew size of the submarine. Good reliability, availability and maintainability characteristics will reduce the maintenance workload of the engineering department. The size of the engineering department on-board of a submarine can reach up to one-third of the total crew size. A maintenance reduction could lead to a crew reduction, resulting in a valuable reduction of accommodation, provision demands and hotel load. Furthermore, good maintenance characteristics will limit the maintenance costs and down time of the submarine.

The power plant is one of the main causes of the signature of a submarine. Much attention needs to be paid to reduce the vibration and sound caused by the power plant. Furthermore, the thermal signature needs to be reduced as much as possible.

3.2 Conventional diesel-electric power plant

The conventional diesel-electric propulsion system has become the standard propulsion arrangement since the Second World War [16]. Nowadays this system is still most commonly used; it is for example installed in the Walrus class and the 209 class submarines. A simplified energy flow diagram of this propulsion system is given in figure 3.1. The main components are the diesel-generator sets (DG-sets), lead-acid batteries and the main electro motor (MEM).

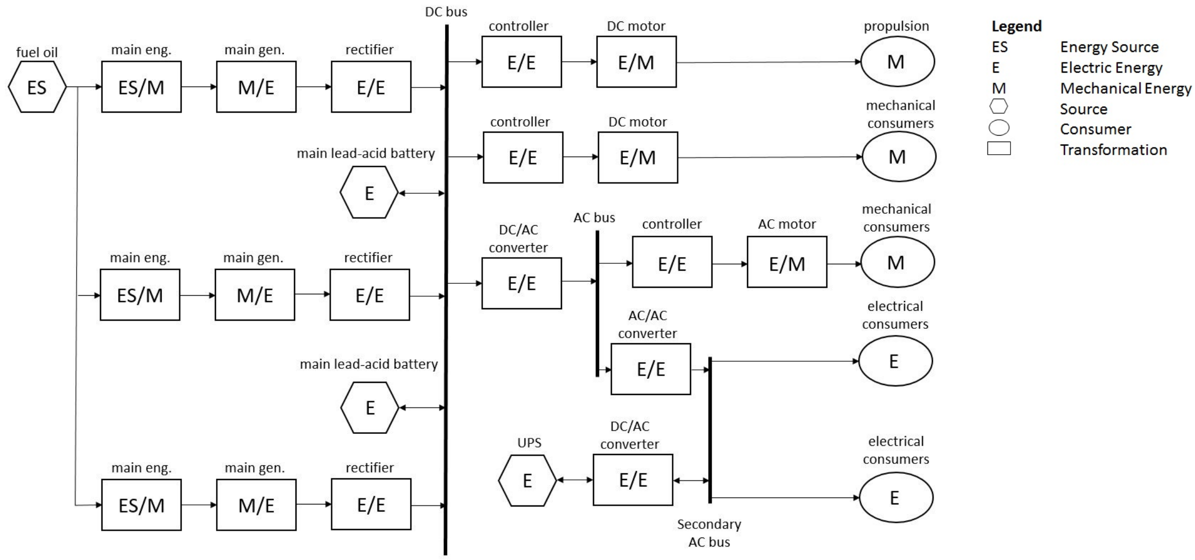


Figure 3.1: Energy flow diagram conventional diesel-electric power plant [43]

The function of the DG-sets is to convert the chemical energy stored in fuel into electrical energy. The DG-sets are used to charge the lead-acid batteries during surfaced or snorkelling condition. When charging the batteries, DG-sets must also be able to supply power to the propulsion and auxiliary systems. The DG-sets determine, together with the charge characteristics of the batteries, the indiscretion rate of the submarine. The required power of the DG-sets is therefore determined by the maximum charge rate of the batteries and the required auxiliary and propulsion power at maximum snorkelling speed. High speed diesel engines are used in the DG-sets for reasons of weight and space. These are modified to be able to operate with a high back pressure on the exhaust side during snorkelling condition. The generator sets are installed on flexible mountings and in sound enclosures to reduce the acoustic signature. Mostly, three or four generators are installed for redundancy and maintainability reasons. Multiple auxiliary systems are needed to be able to operate the generator sets. For example; a snorkel system, an exhaust gas installation, a lubrication oil system, cooling systems and a fuel handling system are required.

Lead-acid batteries are used to power the submarine during submerged sailing. Normally two main battery blocks are used, which can be connect in series and parallel. This provides operational flexibility and redundancy. The battery blocks consist out of multiple cells, which are connected in series to provide an operational voltage. The batteries should be able to provide enough power to the main electro motor (MEM) to achieve the required top speed, while still being able to provide the required power of all other systems on-board. The required number of cells in series is mainly determined by the required operational voltage of the MEM. The capacity of the batteries determines the submerged range and submerged endurance of the submarine. The size of the batteries is therefore dependent on design requirements for these factors. The typical endurance of the installed lead-acid batteries is around one hour at top speed and can be stretched out to multiple days at slow speeds.

Both the DG-sets and main lead-acid batteries deliver electrical energy to the direct current (DC) network. The MEM and all auxiliary systems with a large power usage are driven by the DC network. The task of the MEM is to deliver power to the propeller. The MEM is sized to be able to deliver the required power for the top speed of the submarine. The MEM is a DC motor, which has the advantage of a low vibration level [43]. Most often a DC-compound motor is used, which combines the advantages of both series and shunt windings. The MEM is directly coupled to the propeller shaft. This causes a matching problem. The propeller requires a low rotational speed and a high torque. A large diameter rotor is required to achieve this, which results in a heavy and volume consuming propulsion motor. A tandem system is used, in which two motors are placed on the shaft. This provides operational flexibility, redundancy and reduces the required rotor diameter. Speed control of the MEM is achieved by; switching the two armatures and two batteries in series or parallel, shunt field weakening with shunt field choppers and an armature chopper to create a variable voltage supply for the dead-slow speeds.

A part of the electrical energy is converted from DC to alternating current (AC). On board a submarine 440V-60Hz, 115V-60Hz and 115V-400Hz AC networks are present. 440V-60Hz AC is used to power the large AC consumers, 115V-60Hz AC is used to power the smaller AC consumers and 115V-400Hz AC is used the power the weapon and sensor systems. The DC - 440V-60Hz AC converters and DC - 115V-60Hz AC converters are functional redundant. The DC - 115V - 400Hz AC converters are normally redundant in functionality and capacity. All vital and emergency systems are connected to a battery backup systems to provide an uninterrupted power supply (UPS).

3.3 Entirely battery powered concept power plant

The concept power plant will be entirely battery powered. In this power plant configuration, the DG-sets and lead-acid batteries are replaced with lithium-ion battery (LIB)s. A simplified energy flow diagram of this power plant concept is given in figure 3.2.

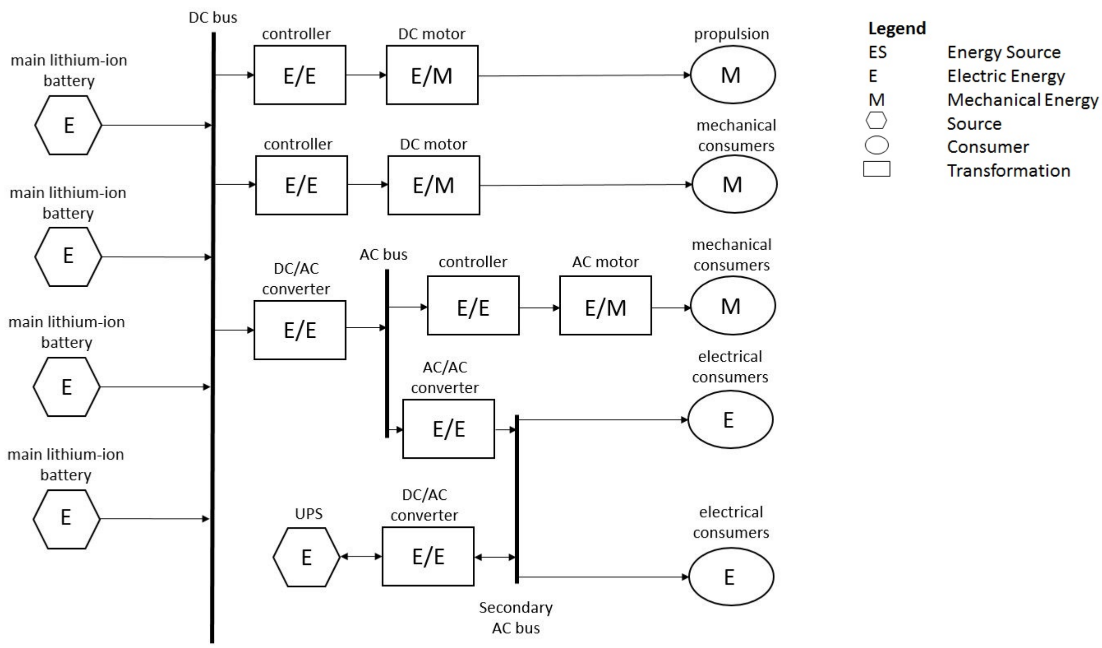


Figure 3.2: Energy flow diagram of the entirely battery powered concept power plant

The submarine loses its self-charging capabilities due to the removal of the DG-sets. The batteries are therefore responsible for the power supply during the total mission of the submarine. The capacity of the batteries needs to be large enough to provide electrical energy for the MEM and all auxiliary systems during the total mission. The total range and endurance of the submarine will become dependent on the storage capacities of the main batteries.

In a conventional diesel-electric power plant typically two main batteries are used. In the entirely battery powered concept the total installed battery capacity will be increased. Therefore, an increase in main battery blocks might be an option. This will increase the redundancy of the battery system. The main battery blocks themselves are expected to change due to implementation of another battery technology. A comparison between the currently used lead-acid technology and lithium-ion batteries is required to determine the differences in the battery design. This comparison will be performed in chapter 4.

The same DC-compound motor as in diesel-electric power plant will be used in this concept power plant. Furthermore, the topology of the electrical distribution systems of the entirely battery powered concept is expected stay similar to the electrical distribution system of diesel-electric power plant. The number of DC and AC networks will stay the same as a diesel-electric submarine. However, the size and number of the converters, switchboards and distribution panels could change. This could be caused by the changes in the supply and demand side of the electrical distribution system.

The main advantage of this power plant concept is its completely air in-dependency. Furthermore, the acoustic and thermal signature of the submarine will be reduced due to the removal of the combustion engines. Those two advantages will improve the stealthiness of the submarine, which is a tactical advantage. Another advantage is the simplification of the propulsion system. The removal of the DG-sets will also make a large number of DG-sets support systems unnecessary.

3.4 Effect of concept power plant integration

The implementation of the entirely battery powered concept power plant will have an impact on the operational capabilities the submarine. Expected is that the total range of the submarine will be reduced. A diesel-generator with a specific fuel consumption of 230 g/kWh can deliver 4350 Wh energy per kilogram fuel, which is more than 20 times higher than the amount of energy a kilogram of lithium-ion modules can deliver. This indicates that the range of an entirely battery powered submarine will be one-twentieth of a diesel-electric submarine. However, this is no fair comparison. Diesel-generators and all their support systems are volume and weight consuming and must be included in this comparison. Furthermore, the operational profile of an entirely battery powered submarine will be different. No snorkelling will be needed, resulting in a lower overall required propulsive power. The auxiliary power requirements will also be lower, due to the reduction of auxiliary systems. The effect on all systems and the design of the submarine must be taken into account before an estimation of a feasible range is possible.

Multiple aspects of the submarine design will be influenced by the implementation of the battery powered concept. One of these is the required crew size. DG-sets, corresponding DG-sets support systems and lead-acid batteries have high maintenance requirements. In the concept, the DG-sets and corresponding auxiliary systems will be removed and the lead-acid batteries will be replaced with lithium-ion batteries which have low maintenance requirements. This will result in a reduction in maintenance requirements and could reduce the required crew size.

Furthermore, the electrical distribution system will undergo changes. The topology is expected to stay roughly similar to that of a diesel-electric submarine. However, the required amount switchgear may change due to the change in the supply side of the electrical distribution system. Furthermore, the required short circuit protection is expected to change. This might affect the required switchboard size.

The submarine will become completely air independent due to the integration of the entirely battery powered power plant. This will not only have an influence on the operational profile, but will also make the HVAC system of greater importance. The HVAC installation will be needed to keep the air quality in healthy conditions for much longer periods. It is needed to investigate what the effect on this system will be. Furthermore, the capacity of the high pressure air system will be influenced. The increase in submerged endurance is expected to lead to an increase in high pressure air storage capacity.

The stability will also be influenced by the implementation of the propulsion plant concept. Normally used lead-acid batteries have a density of about 2800 kg/m^3 and are placed low in the vessel. They have a big contribution to the stability of the submarine. Lithium modules have a density of 1570 kg/m^3. This is a significant reduction compared to the density of lead-acid batteries. This might cause stability problems. Furthermore, the longitudinal centre of gravity of a submarine design might impose limitations. Diesel-electric submarines are volume critical. The low relative low density of lithium modules is expected to make the entirely battery powered concept also volume critical. Possible stability, trim, available weight or available volume problems might limit the achievable installed battery capacity.

Research is needed to identify the effect of the previously discussed aspects on the design of the submarine before an estimation of the range of an entirely battery powered submarine is possible. The methodology of this research will be described in paragraph 3.5.

3.5 Research methodology

The integration of an entirely battery powered power plant will affect the submarine design and its operational capabilities. These effects must be analysed to be able to determine the feasibility of an entirely battery powered submarine design. This paragraph will describe the methodology used to achieve this.

A diesel-electric reference submarine will be used to investigate the effect on the submarine design and operational capabilities. As reference submarine, a diesel-electric single hull design of Nevesbu will be used. The main data of this design is shown in appendix A. The reference design will be redesigned into an entirely battery powered concept. The single hull configuration of the reference design makes it suitable for the implementation of an entirely battery powered power plant. Furthermore, the design process of the reference design is well documented. This can be used to investigate the effect of the concept power plant integration on system and design level.

Before a redesign of the reference design can be made, the effects of the usage of lithium-ion batteries needs to be determined. Furthermore, the effect of the concept power plant integration on system and crew level needs to be analysed. These analysis will be described in the chapters 4 and 5. Both the results of research into battery technologies and the systems and crew analysis will be used to redesign the reference design into an entirely battery powered concept. The creation of an entirely battery powered concept design will provide insight in the limiting design factors and design challenges of an entirely battery power submarine. The dimensions of the reference design will be kept constant during the redesign. This will enable a fair comparison between the operational performance between both designs. The redesign of the reference design will be described in chapter 6 and chapter 7.

The created concept design will provide information about the achievable installed battery capacity and the load characteristics. This makes it possible to determine the range, endurance and feasible operational profiles of the entirely battery powered concept. These results will be compared with the original reference design. This comparison will enable an assessment of the feasibility of an entirely battery powered concept. This analysis will be presented in chapter 8.

The results of the analysis of both the design and feasible operational profiles of the concept design will be used to place the design of an entirely battery powered submarine in a broader perspective. A comparison will be made with other submarine designs and their characteristics. Furthermore, the mission capabilities and employability of entirely battery powered submarine will be discussed. This analysis will be described in chapter 9

Chapter 4

Battery technology

The submerged endurance and submerged range of conventional submarines is strongly dependent on the electrical energy storage capacity of their lead-acid batteries. With the creation of an entirely battery powered submarine even the total range and endurance will become dependent on the capacity of the batteries. An entirely battery powered submarine will therefore only be feasible when batteries with a high storing capacity are used. This requirement will make the use of LIB as energy storage system the only option. However, a high storage capacity is not the only battery characteristic of importance. For example; performance at high discharge currents, reliability and safety are also of importance in a submarine design. Furthermore, the required battery integration characteristics should be taken into account.

This chapter will describe a literature research into the characteristics of both lead-acid batteries and LIB, which will enable a comparison between all battery characteristics. The goal of this chapter is to provide information about both battery technologies and to determine the required safety precautions for the use LIB in a submarine design.

4.1 Lead-acid batteries

Lead-acid batteries are the oldest type of rechargeable batteries and are used in submarines since the first electrical powered submarine in 1887 [16]. The technology has continuously improved itself and is currently a mature and reliable energy storage technology. Lead-acid batteries are still the technology of choice in almost all diesel-electric submarines.

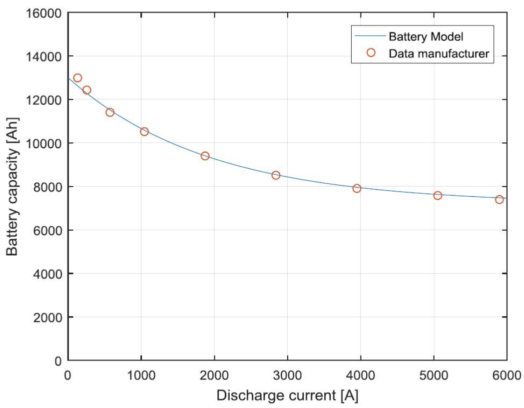
4.1.1 Lead-acid battery cells

The lead-acid battery cell consists out of a lead dioxide cathode, a metallic lead anode and a sulphuric acid solution as electrolyte. During discharging both the cathode and anode convert to lead sulphate. This process reverses during charging. The chemical reaction during charging and discharging also produces oxygen and hydrogen gas. The typical voltage of lead-acid battery is 2.1 volts.

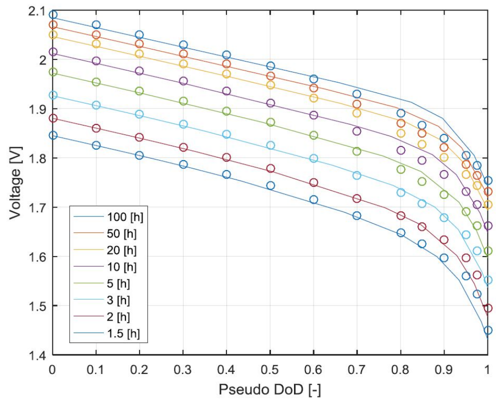
Lead-acid batteries have a specific energy and energy density of 50 Wh/kg and 140 Wh/l. Their specific energy and energy density is strongly influenced by the rate of discharge. This behaviour is shown in figure 4.1a; the battery capacity drops when the discharge current increases.

The available power of the lead-acid battery is depending on the depth of discharge (DoD). The voltage level of the battery cells is dropping during discharging, resulting in a decrease of available power. This is caused by a decrease of acid density during discharging [6]. The voltage drop of typical submarine lead-acid batteries is shown in figure 4.1b.

The temperature is also influencing the capacity of lead-acid batteries. A low electrolyte temperature will slow down the chemical reactions in the battery, which will reduce the capacity of the battery. However, low temperature is no issue in the controlled environment of a subma-



(a) Influence of discharge current on capacity



(b) Battery voltage depending on DoD, for different discharge rates

Figure 4.1: Capacity and voltage characteristics of submarine lead-acid batteries [39]

rine. A high temperature will increase the speed of the chemical reaction, resulting in a higher capacity. However, the rate of corrosion, solubility of metal components and self-discharge also increases with increasing temperature [26]. So, temperature management is important for the capacity and the lifetime of the batteries.

The efficiency (ratio between required charging energy and delivered discharging energy) of the lead-acid batteries ranges from 78% to 86% for slow discharge rates [16].

4.1.2 Submarine application

The lead-acid batteries used in submarines are deep cycle batteries, especially designed for their submarine application. They are optimized for a high capacity and regular deep discharging. Submarine batteries cells are of tubular design with integrated shock absorbers to create a high shock resistance. The cells often use a "double decker" plate structure to reduce the internal resistance of the battery cells, which improves the capacity at high discharge currents. The cells have large dimensions, which enables a high storage capacity. For example; the lead-acid cell used in the reference design has a length of 360 mm, a width of 386 mm, a height of 1450 mm and weights 565 kg. These dimensions enable a storage capacity of 13900 Ah. Submarine lead-acid batteries have a high density; the battery of the reference design has a density of 2800 kg/m^3. An example of the construction of a submarine lead-acid cell is shown in figure 4.2a.

Lead-acid batteries are placed in closed compartments to prevent hydrogen (H_2) gas to enter the boat's atmosphere. H_2 gas is produced during charging and discharging of batteries and is highly explosive. Except for the closed compartments, battery compartment ventilation, H_2 detection system and H_2 burners are also installed to ensure safe operation of the batteries. Other required support systems are: battery terminal cooling system, distilled water system, acid agitation system, battery monitoring system and a battery handling system for the replacement of the heavy batteries. The structure of the battery compartments needs to be able to withstand contact with the highly corrosive acid solution of the batteries. Acid spilling can occur due to submarine roll angles or shock loads. Special materials are used for the battery compartments to prevent corrosion due to acid spilling.

Lead-acid batteries require a high level of maintenance. The acid-level in the cells is dropping over time and needs to be re-filled when needed. Also, the spilling of battery acid requires regularly battery cleaning. Due to these two maintenance requirements, the tops of battery cells need to be accessible. This limits the packing density of lead-acid cells in the battery compartments. An example of a battery compartment is shown in figure 4.2b. Lead-acid batteries do require maintenance charges at certain intervals. Maintenance charging is needed

(a) Construction of submarine lead-acid cell [28]

(b) Battery compartment Dolfijn-class submarine

Figure 4.2: Lead-acid cells for submarine application

to "reset" the chemical characteristics of the battery. This prevents lead plate sulfation, which is the conversion of lead sulfate into lead crystals which causes premature battery ageing [16].

The typical life time of submarine lead-acid batteries is depending on the number of cycles of loading and discharging and the depth of discharging. The average life time of the lead-acid battery is 5-7 years or up to 1500 cycles [3, 39]. The life time of a lead-acid battery decreases when deep discharging is performed regularly. The ageing of a lead-acid battery starts when the lead-acid batteries are filled with the acid solution.

4.1.3 Reliability and safety

Lead-acid batteries are proven technology; the reliability is high and the risks of usage are well known. Possible failure modes normally occur due to corrosion and will occur at the end of the batteries lifetime [26]. These failure modes will cause a reduction in capacity, but will not impose safety risks. External short circuit could damage the battery early in its lifetime. Short circuit protection is therefore present at battery block level to protect the batteries against an external short circuit.

When a cell fails, it needs to be disconnect from the battery block. A failing battery cell will result in a reduction in capacity and available power. The disconnecting of a battery cell needs to be performed manually. This is another reason why the tops of the battery cells need to be accessible.

The biggest risk caused by lead-acid batteries is the risk of explosion due to the production of H_2 gas. The closed battery compartments, battery compartment ventilation, H_2 detection system and H_2 burners reduce this risk significantly.

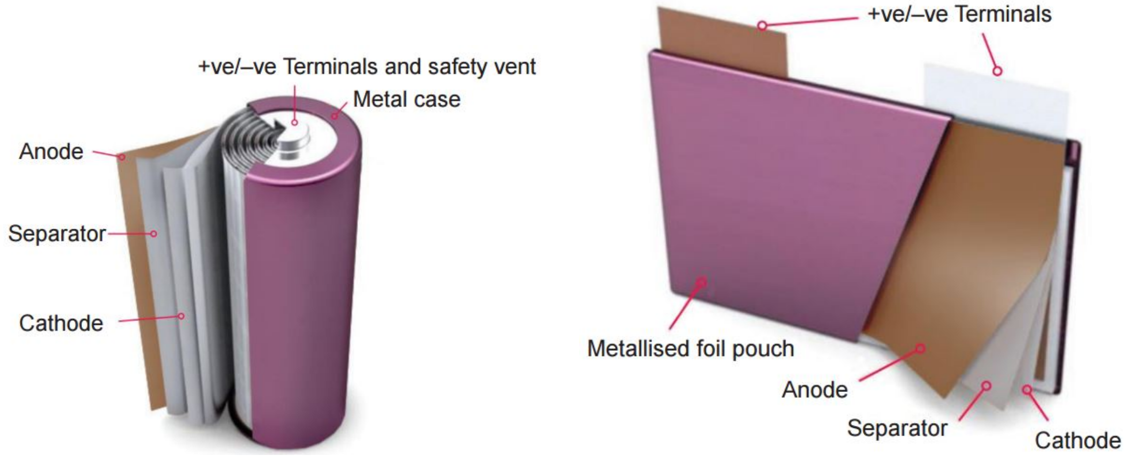
The sulphuric acid used in lead-acid batteries is highly corrosive and will cause chemical burns when it comes in contact with human skin. Therefore, it needs to be treated carefully. Closed battery compartments with special materials prevent possible spilled acid to cause damage to structural components.

4.2 Lithium-ion batteries

Lithium-ion batteries (LIBs) are a relatively young technology and are commercially available since 1991. The LIB has become the technology of choice for portable electronics and the electric car industry, mainly due their high energy density and high specific energy. These characteristics of the LIB make them interesting for implementation in submarines.

4.2.1 Lithium-ion battery cells

LIBs refer to an entire family of battery chemistries. In all these LIBs, lithium ions are moving between the electrodes during charging and discharging. A LIB consists out of a negative electrode, positive electrode and a separator soaked with electrolyte. LIBs have a typical voltage of 4.2 volts. Two examples of the construction of a LIB cell are shown in figure 4.3.



(a) Typical construction of a cylindrical cell (b) Typical construction of a pouch cell

Figure 4.3: Two commonly used lithium-ion cell constructions [31]

Different material chemistries can be used for the components of the LIB. The choice of chemistry strongly influences the characteristics of the LIB. An overview of the most used batteries chemistries and their characteristics is given in figure 4.4. The chemistry choice is often a trade of between the different characteristics shown in figure 4.4. For high specific energy applications, such as the electric car industry, nickel cobalt aluminium (NCA) or nickel manganese cobalt (NMC) chemistries are currently most commonly used [4].

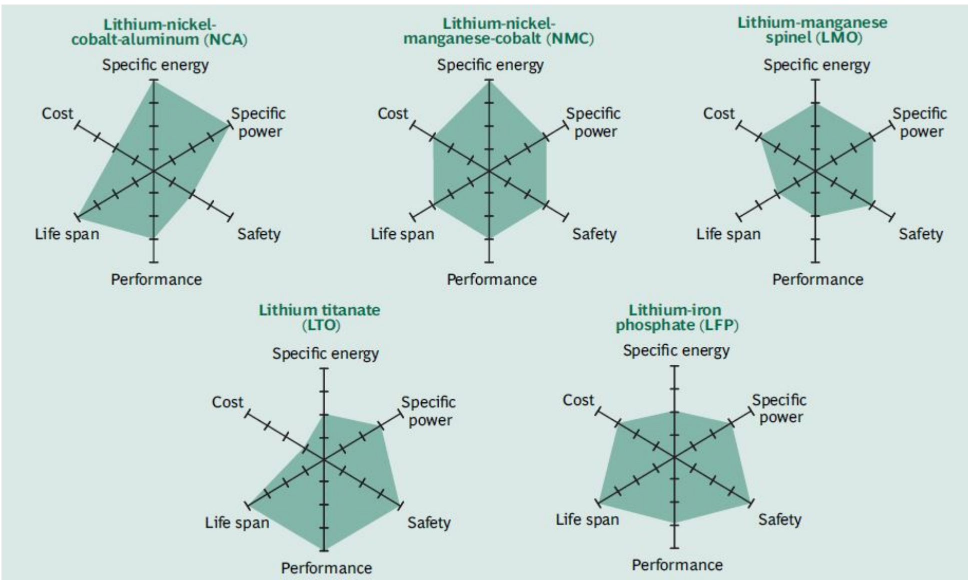
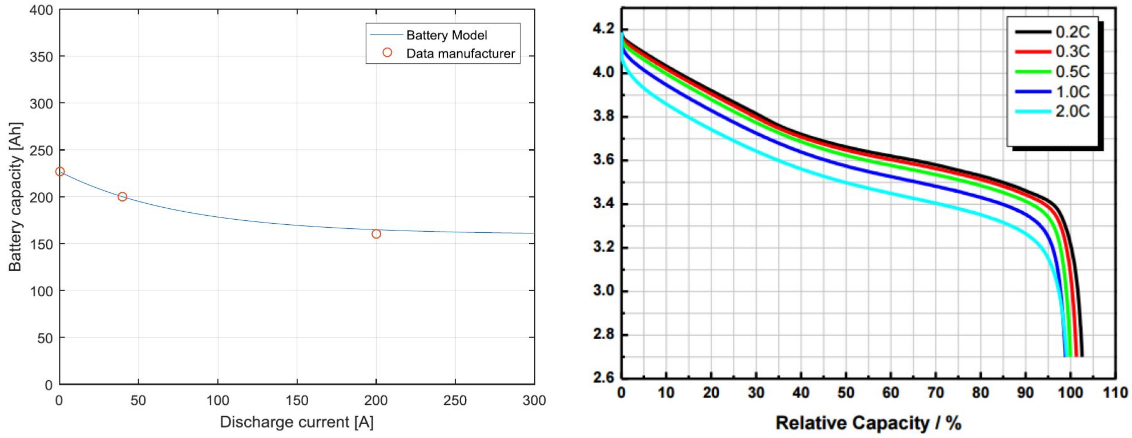


Figure 4.4: Radar charts of the characteristics of most common lithium-ion chemistries [13]

LIBs are characterized by their high specific energy and energy density. Commercial LIB cells can currently reach specific energy and energy densities up to 265 Wh/kg and 675 Wh/l [24, 42]. They also have a relatively high capacity at high discharge rates. An example of the influence of the discharge current on the capacity of an LIB is shown in figure 4.5a. Another characteristic of LIBs is their relatively flat voltage discharge curve, which can be seen in figure 4.5b. The available power of the LIB is therefore less influenced by the state of charge. The capacity and voltage characteristics shown in figure 4.5 are for a LIB cell with a NMC chemistry. Other chemistries will have slightly different characteristics.



(a) Influence of discharge current on capacity [39]

(b) Battery voltage depending on DoD, for different discharge rates [22]

Figure 4.5: Capacity and voltage characteristics of NMC LIB cell

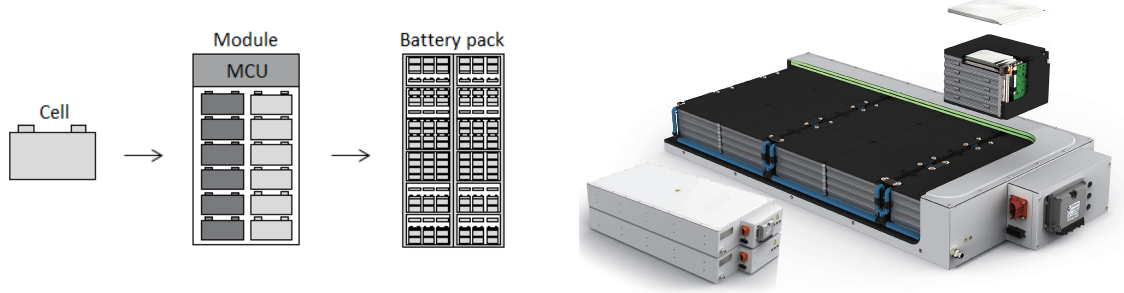
The capacity of LIBs is also influenced by their temperature. Cold temperatures will result in a decrease in capacity and high temperatures will result in a slight increase in capacity. However, high temperatures bring risks for LIBs. Thermal management is therefore important to ensure safe usage. These risks will be discussed in detail in section 4.2.3.

The efficiency of LIBs is high, efficiencies of 96% can be achieved at slow discharge rates [24]. Also, the charging characteristics of lithium ion-batteries are good.

4.2.2 Submarine application

LIBs cannot be produced in large cells such as lead-acid batteries can. The largest commercial available cylindrical LIB cell has a capacity of 485 Ah [15]. Pouch cells are currently available up to a capacity of 240 Ah [24]. These relatively high capacity LIB cells are specially designed for high capacity applications. However, most commonly used, produced and developed LIB cells are much smaller and have capacities of less than 20 Ah. Due to the relatively low capacity of LIBs, large numbers of cells are required for applications which require a high energy storage capacity. A commercial example is the Tesla Roadster, which uses approximately 6800 LIB cells of 3.2 Ah [30, 42]. The required number of cells can be reduced when large capacity LIB cells are used, but will remain high compared with lead-acid batteries. For example; a battery cell of the reference design has a capacity of 13900 Ah and an average voltage of 1.97 V. This gives the battery an energy storage capacity of 27400 Wh. 37 LIBs with a capacity of 200 Ah and an average voltage of 3.7 V are required to achieve the same energy storage capacity.

Packing of LIB cells into modules is used to handle the large amount of LIB cells required for high energy storage capacity applications. A schematic representation of the packing of LIB cells and a commercial example are shown in figure 4.6. LIB modules are always equipped with module control unit (MCU), which communicate with a battery management system (BMS). The BMS monitors the cells, protects them against possible failure modes and optimizes their performance. Cell balancing is used to optimize the performance of the battery pack by balancing the state of charge of each single cell. Active cell balancing will make sure the capacity of each single cell is fully used, which maximizes the battery pack capacity [51]. In the modules cooling systems and other safety measures are integrated to keep the cells at the right temperature and to protect the cells against potential risks. The safety measure and potential risks will be discussed in more detail in the section 4.2.3.



(a) Schematic representation of the packing of lithium-ion cells into modules [3]

(b) Commercial lithium-ion module [23]

Figure 4.6: Packing of lithium-ion cells into modules

The need of packing increases the complexity of the battery systems and decreases the achievable specific energy and energy density. In a recent study, into the optimization of a propulsion plant for a submarine, LIB modules with a specific energy of 135 Wh/kg and an energy density of 222 Wh/l were used [39]. These values were based on a 200 Ah, 176 Wh/kg and 356 Wh/l Kokam NMC pouch cell. A packing factor of 1.3 for weight and 1.6 for volume were used for the packing of the cells into modules. These packing factors were acquired from lithium module manufacturer EST-Flowtech. Currently, improved 150 Ah lithium cells from Kokam reach a specific energy and an energy density of 261 Wh/kg and 505 Wh/l [24]. Applying the same packing factors on this cell results in a module with an energy density of 200 Wh/kg and 315 Wh/l. These modules are expected to have a density of approximately 1570 kg/m^3, which is based on the same scaling factor for weight and volume.

The integration of LIBs into a submarine has multiple advantages from the design perspective. The, LIB cells and modules require no maintenance. Therefore, the LIB modules do not need to be accessible. This is on the condition that the integrated sub module controllers have a high reliability. Furthermore, the size of modules can be optimized for their implementation, providing an increase in design freedom. Due to these two reasons, a higher packing density of the battery compartments is possible. Moreover, a reduction of peripheral equipment is possible; acid circulation, distilled water and water de-ionizer systems are not required for LIB. This will decrease the integration constraints and will reduce the required space and weight for support equipment.

The life time of LIB is about ten years [3]. Furthermore, a large number cyclic loads with deep charging and discharging are possible. Manufactures claim that more than 4000 deep discharging and charging cycles should be possible before the cell reaches 80% of its original capacity [22]. The ageing of lithium batteries start directly after manufacturing. This must be taken into account during the design and building process.

4.2.3 Reliability and safety

LIB have different and more severe risks compared to lead-acid batteries. In the last years, several accidents with LIB batteries have occurred. An example of an accident is the fire on-board of Boeing Dreamliner caused by lithium batteries [11]. Other recent examples are the accidents occurring with battery of the Samsung Note 7 mobile phones, which caught fire [2]. All these fires are caused by thermal runaway, which is an energetic failure of the LIB cell. Cell thermal runaway refers to a rapid self-heating of a cell, derived from the exothermic chemical reaction of the positive and negative electrodes. A cell releases all its stored energy rapidly during a thermal runaway reaction.

When thermal runaway occurs, several things will happen. The internal cell temperature will increase and can reach temperatures of 600 °C [30]. This temperature increase is combined with a pressure increase inside the cell. The pressure increase occurs due to the vaporizing and decomposition of the electrolyte and the decomposing of cathode materials. If the internal pressure gets too high, the cell will start venting the gasses. The pressure at which this occurs is depending on the cell design. The vent gasses are toxic and can ignite and explode [30, 37]. The gasses are not"self-igniting"; there must be significant oxygen in the surrounding environment and there must be a competent ignition source. Cell components can reach temperatures at which ignition of vent gasses occurs [30].

Root causes of thermal runaway

The thermal stability limits of a LIB can be exceeded by internal and external causes. The root causes of thermal runaway can be classified into [30]:

- Thermal abuse
- Mechanical abuse
- Electrical abuse
- Manufacturing defects
- Poor electrochemical design

Thermal abuse is heating of the LIB cell above its self-heating temperature of approximately 70-90 °C. From the self-heating point on, the cell will heat itself and eventually thermal runaway will occur. The process from the self-heating point until the beginning of thermal runaway takes approximately two days. This duration will be shorter when the initial temperature is higher. When LIB are extremely heated, thermal runaway will occur immediately [30]. Thermal abuse can be caused by internal and external heat sources. An example of an internal heat source is the heat produced during fast charging or discharging of a cell. An external heat source can be a fire outside the battery module. A defect cell with thermal runaway can be an external heat source to cause thermal runaway in its neighbouring cells as well. Thermal runaway of one cell can therefore cause a chain reaction in the battery pack. Thermal management systems inside the battery modules prevent thermal abuse of a battery cell caused by internal sources and small external sources. Cooling systems provide a heat sink in the battery modules and will keep the cell temperature in a safe zone. Even when the self-heating point of a cell is reached, the cell can still return to its stable state when enough cooling is applied. In the automotive industry, active thermal management systems are currently used. These are based on air or liquid cooling. Liquid cooling is regarded the best solution based on weight, volume and power effectiveness [50]. A new development is passive thermal management with the use of phase change materials [41, 50, 52]. The advantage of this system is that they cannot fail and have no power requirements. This makes it a very promising solution. However, more research is needed before implementation is possible.

Mechanical abuse is crush or perpetration damage of the cell. In submarines, mechanical abuse can for example be caused by shock loads. Mechanical abuse can cause an internal short circuit, which can immediately initiate thermal runaway or can results in a cell fault causing thermal runaway much later. A robust cell and module design, a good battery compartment integration and shock protection can reduce the risks of mechanical abuse. Shock protection can be integrated on sub module, module or compartment level. Extensive shock testing is needed to reduce this risk in submarine designs.

LIB cells can be electrical abused in a several ways; overcharging, over-discharging and by an external short circuit. Overcharging and over-discharging can cause internal damage to the LIB cells. These risks are eliminated by the control of charging and discharging by module controllers. An external short circuit can cause extreme high currents, which will cause high internal heating due to the internal resistance in the cell. Short circuit protection is needed to prevent this.

Small failures caused during the manufacturing of lithium cells can cause thermal runaway. The gross of failures due to manufacturing defects inevitably occur during, or immediately after the first charging [30]. Multiple control techniques exist to detect these defects. However, very subtle defects can be missed and can allow thermal runaway to occur after years. High quality assurance during the production process can limit the risks of manufacturing defects.

The last root cause of thermal runaway is poor electrochemical design. This risks is currently eliminated by extensive testing before a cell becomes commercial.

Severity influence factors and suppressing methods

The severity of thermal runway will be strongly affected by the total energy stored in the cell. The total stored energy is a combination of chemical energy and electrical energy. The cell chemistry determines the amount of chemical energy stored. For example, the use of a non-combustible electrolyte will reduce the stored chemical energy significantly. This is currently an active area of research, but not yet commercial available. Also, the choice of cathode material influences the cell safety [14]. For example, lithium iron phosphate (LFP) LIB cells are considered safer due to their relatively low self-heating rate and relatively low temperature during thermal runaway (below the igniting temperature of the vent gasses) [14, 30]. Another influencing factor is the state of charge of the battery, which has a great impact on the severity of thermal runaway. The more electrical energy is stored in a cell, the more energetic a thermal runaway reaction will be.

When a thermal runaway results in a fire, multiple suppressing methods will be effective in suppression the combustion. Inert gas fire suppression is considered the best option to extinguish LIB fires [5, 30]. However, it will not cool the cells and will not prevent thermal runaway propagation. Therefore, LIB cells will continue to vent and re-ignition will occur when enough O_2 is present. Tests showed that Halon 1301 can extinguish LIB fires and can prevent the reoccurring of fire, which makes it the best suppressing method. However, thermal runaway and venting of cells continued [30]. Both the vent gasses and the Halon gas are toxic, so gas tight battery compartments are needed to ensure safety of the crew in a submarine design. When large scale thermal runaway propagation will occur, the pressure in the battery compartment will rise due to the vent gasses. The battery compartment needs to be designed to withstand this pressure until safe overboard venting of the toxic gasses is possible. The pressure increase is depending on the number of cells and the volume of the battery compartments. It is needed to investigate this when a battery compartment design is made.

Reliability

The reliability of LIB cells and protection equipment is important for the safety and reliability of the total system. Most failures with LIBs in the past were traced back to poor cell manufacturing or the lack of safety measures [3]. For example, the failures of Boeing battery and the Note 7 mobile phone were both traced back to manufacturing failures resulting in an internal short-circuit [34, 35]. High standard manufacturing quality insurance can make the risks of manufacturing defects very small. However, the risks of failure of single cells will still be considerable due to the large number of cells required. Large capacity cells are preferred to be able to reduce the number of cells and therefore the risks of a single cell failure as much as possible.

The small size of LIBs creates the opportunity to reduce the impact of a single cell failure. A good battery management system should be able to detect a failing cell in an early failure stage. Separating this cell or module will eliminating the risks of a thermal runaway failure and will reduce the capacity loss. A smart battery topology could even limit the loss of capacity when a large scale thermal runaway failure occurs.

4.2.4 Future prospects

LIBs are a relatively young technology. Since their first commercial production in 1991 by Sony significant improvements have been achieved. Fifteen years ago, a specific energy of about 140-150 Wh/kg could be achieved with LIB cells [40]. This means that LIB cells have improved 60% in specific energy in the last fifteen years. Multiple industries are still investing into research to improve the energy storage capacity of LIBs. The use of new high capacity materials and new battery structures could result in an increase of specific energy to 400 Wh/kg in the next several years [4]. This is still not the limit of the capabilities of LIB. Theoretically energy densities should be possible of around 900 Wh/kg for conventional LIB and 2600 Wh/kg lithium-sulphur batteries (which are still in the development phase) [1]. When research continues, this could indicate that capacity improvements can be expected in the near future.

The increase in capacity is not the only topic of research. Lately, the focus of research also includes topics to improve the safety of LIB cells and modules. The focus lies on safer battery chemistries or other solutions to prevent thermal runaway or thermal propagation. Examples are researches into; non-flammable electrolytes, thermal-triggered flame retardant separators and the integration of phase change materials [27, 52, 53]. Improvement of the safety characteristics is therefore expected in the near future as-well.

4.3 Comparison battery technology

The energy density plot in figure 1.1 already showed the difference between lead-acid batteries and different LIB chemistries. However, this graph is comparing technologies on cell level and does not including packing of LIBs. Currently, LIB modules should be possible with a specific energy of 200 Wh/kg and an energy density of 315 Wh/l. The MORAY lead-acid battery has a specific energy of 50 Wh/kg and 140 Wh/l. So, LIB can store 4 times as much energy per weight unit and 2.25 times as much energy per volume unit.

The performance characteristics of LIB are better than lead-acid batteries. Figure 4.7 compares the discharge characteristics of both battery technologies. Multiple LIBs are required in parallel to require the same capacity as the MORAY lead-acid battery, which is required for a fair comparison. Figure 4.7 clearly shows that the LIBs perform better a high discharge currents. Furthermore, the voltage-discharge characteristics of LIBs are generally preferable to the voltage-discharge characteristics of lead-acid batteries. The power characteristics of LIB will therefore be less dependent on the state of charge of the batteries [3].

LIBs have no maintenance requirements, which gives them an advantage compared to lead-acid batteries. The lifetime characteristics of LIB are also more preferred; lead-acid batteries have a lifetime of 5-7 years or up to 1500 cycles and LIB have a lifetime of 10 years or 4000 cycles.

The integration of LIB in submarines has the advantage of a higher packing density of modules into the compartments and a reduction in battery support systems. A disadvantage is the higher complexity of the battery design due to large amount of LIB cells and modules required. Furthermore, the safety characteristics of LIB are worse than the safety characteristics of lead-acid batteries. Thermal runaway is a large risk of LIBs.

4.4 Conclusion

The conclusion can be made that all operational characteristics of LIBs are better than those of lead-acid batteries. However, the integration of LIBs will have a high complexity and the

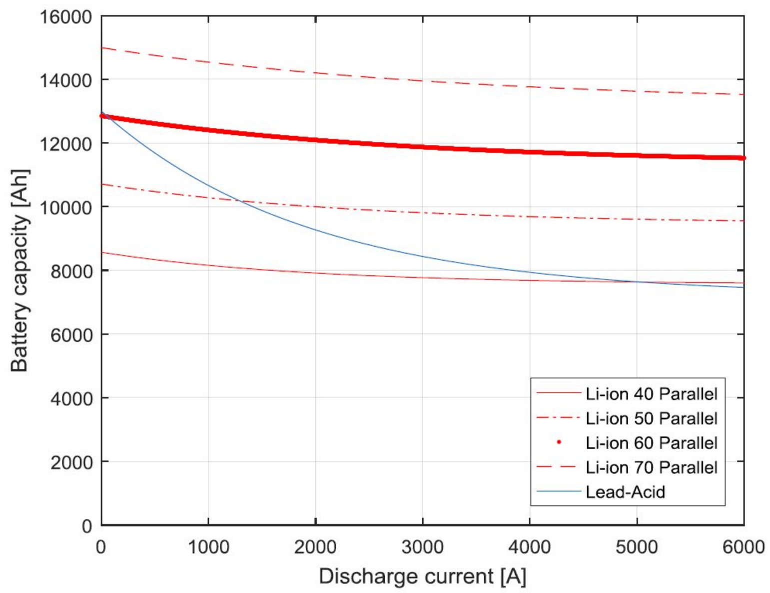


Figure 4.7: Discharge characteristics 200 Ah NCM LIB cells and submarine lead-acid cell [39]

safety characteristics are worse than lead-acid batteries. The complexity of the battery design will limit the achievable energy density of integrated battery systems and safety characteristics will results in design requirements and required safety precautions.

The relatively small size of LIB and its required control systems add to the complexity of the battery systems. Packing in LIB into modules is required to achieve required energy storage capacities. The currently expected achievable specific energy and energy density are respectively 200 Wh/kg and 315 Wh/l. The density of a lithium module is expected to be 1570 kg/m^3.

The safety characteristics of lithium cells make a safe integration of LIB cells challenging. The choice of cell chemistry will influence safety and operational characteristics of the battery. Batteries with a LFP chemistry are the safest type of LIB, however their energy storage capacity is worse than for example LIBs with a NMC chemistry. The choice of chemistry will therefore be a consideration between capacity and safety. The extent to which the extra safety risks of higher capacity battery chemistries can be mitigated will influence the choice between chemistries.

Thermal runaway is the largest risks of lithium batteries and can occur due to thermal abuse, electrical abuse, mechanical abuse or manufacturing faults. Thermal abuse can be prevented by a good thermal management system, which includes a cooling system. Electrical abuse can be prevented by the MCU, which will prevent overcharging and over-discharging, and by short circuit protection. Mechanical abuse can be prevented by protecting the lithium cells against shock loads. Shock protection can be applied on module or battery compartment level. The risks of manufacturing faults can be limited by high quality control, but cannot be eliminated.

When thermal runaway occurs, the LIB will vent toxic, explosive and flammable gasses. Gas tight battery compartments will be required to prevent the toxic gases to enter the submarines atmosphere. When fire occurs inherent gas suppression with Halon 1301 is the best methods to suppress the fire. However, it will not prevent thermal runaway propagation. Large scale thermal runaway will result in a pressure increase, so the battery compartments need to be able to withstand a pressure increase.

Chapter 5

Systems and crew analysis

The integration of the concept power plant into the reference design will have an influence on the required systems and crew size. Leaving out DG-sets and replacing the lead-acid batteries with LIBs will make some systems unnecessary. This will lead to a reduction of the workload for the crew, which might make a crew reduction possible. Furthermore, the concept power plant will have an influence on the electrical system, the high pressure air system and the HVAC system. The influence of the integration of the concept power plant on these aspects will be analysed in this chapter.

5.1 Reduction of systems

The replacement of a conventional diesel-electric power plant with an entirely battery powered power plant will result in a reduction in systems. The DG-sets will be removed, which also makes several auxiliary systems unnecessary. Furthermore, the implementation of LIBs will result in a reduction of battery support systems. An analysis of the equipment on board of the reference design has been made to identify which systems will become unnecessary. An overview of all unnecessary systems is given in table 5.1.

Table 5.1: System reduction due to implementation of concept power plant into the reference design

SWBS	
	Batteries
2232	Battery cooling water deionizing system
2233	Distilled water system
2234	Battery agitation system
	Diesel-generator sets
2331	Diesel engines
2332	Generators
2333	Lubrication oil system diesel engines
2334	Fresh water cooling system diesel engines
2335	Starting air system diesel engines
2336	Fuel oil inject system diesel engines
2511	Air intake system
2522	Diesel engine start - stop system
2561	Diesel sea water cooling system
2591	Exhaust gas system
2611	Fuel oil service and conditioning system
5411	Fuel oil transfer and compensation system

In table 5.1 a subdivision is made between systems which will be removed due to the replacement of the lead-acid with LIBs and systems which will be removed due to removal of the DG-sets. The reduction of most systems is self-evident, but for the battery cooling water deionizing system, the distilled water system and the air intake systems an explanation might be needed.

The battery cooling water deionizing system is used to deionize the cooling water of the lead-acid battery. This is required because the lead-acid batteries are cooled at the battery terminals. The cooling water is therefore deionized to prevent a short circuit. LIBs are not cooled at the battery terminals. Therefore, deionizing of the cooling water will not be required.

Distilled water is used to re-fill the lead-acid batteries. The distilled water systems supplies the distilled water to the battery compartments. In the battery compartments, the battery can be filled by means of charging pistols. LIBs do not require refilling with distilled water, which makes this functionally unnecessary. Furthermore, the distilled water system is also used to fill up the fresh water cooling systems of the diesel engines and the battery cooling water systems in case of incidents. A battery cooling system will still be required when LIBs are used. An option might be to make the cooling supply redundant in the concept design. When this is done, the distilled water system will become unnecessary.

The main function of the air intake system (snorkel system) is to provide combustion air to the DG-sets during surfaced or snorting condition. However, it is also used to supply fresh air to the engine room and, via mechanical ventilation and air-condition systems, to other compartments of the ship. The removal of the air intake system will therefore influence the HVAC system, which needs to be investigated. Due to removal of the DG-sets, the functionality of the snorkel will certainly become unnecessary. The system, as currently installed, is therefore not efficient. It could be an option to replace the air intake systems with a system with a different functionality. The analysis of the HVAC system, described in paragraph 5.5, will be used to determine this.

5.2 Electrical system

The implementation of the concept power plant will influence the electrical distribution system. Both the supply and demand side of the electrical distribution system will change. This might influence the layout and the weight and space requirements of this system. An analysis is made to identify the possible changes.

5.2.1 Electrical system MORAY

The electrical distribution system on board of the MORAY consists out of AC networks, a DC network, switchboards, converters and electrical distribution panels. The DG-sets, batteries or shore supply can feed the DC network via one of the switchboards. The DC is provided to the MEM and distributed, via multiple DC distribution panels, to the DC consumers and DC/AC converters. The DC/AC converters feed the 440V-60Hz, 115V-60Hz and 115V-400Hz AC networks. The different frequencies of AC are distributed to the consumers via multiple electrical panels. A principal diagram of the electrical distribution system is given in appendix C.

For this analysis, a distinction is made between DC and AC distribution systems. First, the DC distribution system, including the DC supply and the switchboards, will be discussed. The ACdistribution system, including the converters, will be discussed thereafter.

5.2.2 DC distribution system

In the MORAY design, the DC supply is provided by either the main batteries, diesel generators or a shore supply. Both main batteries and the shore supply are connected in the battery switchboard. The battery switchboard has a connection to the manoeuvring switchboard and to the DC distribution system. Connections for the MEM and diesel generators are present in the manoeuvring switchboard.

In the battery switchboard, the short circuit protection and the parallel/series switch of the main batteries are present. The size and weight of the main battery switchboard is mainly determined by the size of the switchgear and short circuit protection of the main batteries. The size of the switchgear is depending on the nominal current, voltage and breaking capacity. The current and voltage are mainly depending on the operational limits of the MEM, which will not change in the concept design. The size of the switchgear is therefore not expected to change. However, an increase in the amount of main battery blocks can increase the number of required battery switches. This must be taken into account during the design process of the concept.

The topology of lithium modules might make switch gear at a lower level in the battery pack possible. The large required number of cells connected in parallel will reduce the current at a lower level in the battery pack, which will enable the use of smaller switch gear. Integrating switchgear at a low level in the battery pack will increase the operational flexibility and redundancy of the battery system. Furthermore, the required switchboard size will be reduced. However, more research is required to investigate the feasibility of this option.

The size of the short circuit protection is depending on the voltage and the potential short circuit current of the battery. The short circuit current (I_{SC}) of a battery is depending on the open circuit voltage (battery 100% charged) of a cell (U_O) and the internal resistance (R_i). The short circuit current can be calculated with equation 5.1.

$$I_{SC} = \frac{U_O}{R_i} \tag{5.1}$$

Both the open circuit voltage and the internal resistance will change when implementing LIBs in the design. Table 5.2 gives the short-circuit current of a single lead-acid battery and a single LIB cell.

Table 5.2: Short circuit current MORAY lead-acid cell and 200Ah NMC LIB cell [22]

	Lead-acid	lithium-ion	
U_O	2.1	4.2	[V]
R_i	0.035	0.45	[mΩ]
I_{SC}	59.6	9.3	[kA]

In a lead-acid battery block, all batteries are connected in series. Therefore, the short circuit current of the total battery block is equal to short circuit current of a single cell. When using LIBs, the topology of the battery will change. Large number of cells in parallel will be required to reach the required capacity. The short circuit current of the total battery block will be equal to the sum of all short circuit currents in parallel. The short circuit current of total battery block will therefore increase significantly. For an integrated design, a short circuit current of approximately 400 - 500 kA is expected [48]. Such large currents cannot be controlled by short circuit protective devices. Therefore, short circuit protection on a lower level in the battery pack is required to reduce the short circuit current [3, 37, 48]. Furthermore, current limiting devices have been developed to deal with high short circuit currents. Current limiting devices make use of a resistor to lower the current in the case of a short circuit [48]. The use of current limiting device will enable the use of small and reliable switch gear and fuses. Applying short circuit protection on a lower level in a battery pack will make the short circuit protection in the main battery switchboard unnecessary. This can possibly lead to a decrease in switchboard size. However, a space reservation for the implementation of short circuit protection is needed at a lower level in the battery system design.

The manoeuvring switchboard of the MORAY houses the ahead, astern, slow speed and cruise speed switches of the MEM. Furthermore, connections and isolators of the DG-sets and an optional AIP section are present in the manoeuvring switchboard. The size of the switchgear is, just as the battery switches, not expected to change. The number of connections to the manoeuvring switchboard will decrease, due to the absence of diesel generators in the concept design. However, it could be an option to feed the manoeuvring switchboard separately from multiple battery blocks to increase the reliability of the system. The size and weight of the manoeuvring switchboard is mainly determined by the size and the number of switches. The influence of the number of connections is expected to be less important. Therefore, it can be assumed that the size and weight of the manoeuvring switchboard will stay approximately constant in the concept design.

High current cables connect the batteries to the battery switchboard, the battery switchboard to the manoeuvring switchboard and the manoeuvring switchboard to the MEM. The high current requirements of these cables make them relatively heavy. An increase in required cable length is expected due to an increase in the amount of installed batteries. The weight increase due to an increase in cable length must be taken into account during the design process.

The number and size of the DC distribution panels are determined by the number of consumers, their location and redundancy requirements. The number of consumers will stay approximately the same and the redundancy requirements stay similar. So, no changes are expected to the size and weight requirements of the DC distribution panels. The DC consumers, fed by the DC distribution panels, are low current consumers. Therefore, the cables are relatively lightweight. A possible change in cable length is therefore expected to be negligible.

5.2.3 AC distribution system

Multiple conversion systems are installed to convert DC to multiple voltages and frequencies of AC. The amount and the size of converters is determined by the power requirements of the different consumers and redundancy requirements. The total power requirements for the 440V-60Hz, 115V-60Hz and 115V-400Hz distribution system will be slightly reduced. However, it is not expected that this small reduction will lead to smaller or a reduction in the number of converters. The redundancy requirements will stay similar as well, so no changes are expected for the converters.

The size and the number of electrical distribution panels is determined by the number of consumers, their location and redundancy requirements. There is a small reduction in systems, but this will have negligible influence on the electrical panel requirements. Also in this case, the redundancy requirements stay similar. So, no changes are expected to the total number and size of the electrical panels. However, a redesign of the submarine can result in a location change or redistribution of electrical panels. This might have a small influence on the required cable length. The AC cables are relatively lightweight, so small changes in required cable length is expected to be negligible.

5.2.4 Conclusion

The intergeneration of an entirely battery powered power plant will have an influence on the battery switchboard, manoeuvring switchboard and the required high current cable length. The short circuit protection will be removed from the battery switchboard and implemented at a lower level in the battery pack. This is required due to a high short circuit current at battery block level. Furthermore, an increase in battery switches is expected due to the increase in the number of battery blocks. Both the removal of the short circuit protection and the increase in battery switches are expected to have an influence on the space and weight requirements of the battery switchboard. This must be taken into account during the design process. The number of connections to the manoeuvring switchboard will reduce, due to the absence of DG-sets.

However, this will have a limited effect on the manoeuvring switchboard size and weight. An increase in the amount of installed batteries will increase the required high current cable length will, which will cause an increase in the weight requirements. The influence on the DC and AC distribution systems and DC/AC converters is expected to be negligible due to the limited change at the demand side of the electrical distribution system.

5.3 Crew size

As identified in paragraph 3.4, the crew size might be reduced by the implementation of the concept power plant. The original manning analysis for the MORAY design is used to analyse the possibility of a crew reduction. The same steps will be used as in the original manning analysis. In this way, a fair comparison between the old and new situation stays possible. The objective of the manning analysis is to assess the minimum number of crew required to safely and efficiently operate the submarine.

5.3.1 Starting points manning analysis

The manning analysis for the MORAY class submarines has multiple starting points and these will be kept unchanged for this analysis. The manning analysis has been carried out for the"Patrol/Potential Threat-state". This operation state generates the second highest workload. Only the "Attack/Threat-state" has a higher workload, but this operational state will only take place for short periods. The crew must be able of cope with "Patrol/Potential Threat-state" for a duration of multiple weeks. During this state a two-division watch system is applied.

At sea, maintenance is restricted to the essential maintenance. Essential maintenance is defined as maintenance to safeguard the submarines ability to safely and effectively carry out its mission. Essential maintenance consists of the servicing of systems and corrective maintenance of failing systems. Scheduled maintenance is mostly taken care of in the home port. However, it may be decided to carry this out at sea when sufficient crew capacity is available. Especially during long missions this might be required. A quantitatively estimation of the required scheduled maintenance is needed to get insight into the inherent workloads.

Peak loads in work (e.g. emergency situations) are not considered, because in such situations the entire crew will be called upon to assists.

5.3.2 Manning analysis

The operational tasks on board the submarine are divided in essential and additional tasks. The essential tasks are all tasks necessary for the save and efficient execution of the submarines mission. These tasks can be divided in operational duties and essential maintenance. All other tasks are called additional duties. These tasks are the scheduled maintenance and domestic, medical and administrative duties. All addition duties can be skipped temporary, but must to be taken into account to determine the total workload of the crew. The effect of the implementation of the concept power plant on the crew size is investigated by analysing the effect on the operational duties, maintenance and the workload of the crew.

Operational duties

The operational duties can be divided into four main duty functions: platform safety, navigation, combat and communication. Each main duty function exists out of multiple duty roles. The operational state of the submarine determines the required duty roles. The hierarchy, different duty roles and duty stations are shown in figure B.1 and figure B.2 in appendix B.1. Three duty roles, which are under platform safety, will be influenced by the implementation of the concept power plant. Firstly, the monitoring and control of machinery systems (diesel generator systems, battery systems and propulsion system) by the mechanical system operator. Secondly, the local surveillance, servicing and corrective maintenance in the main motor room, auxiliary engine room and engine room. Those two duties will remain, but the workload is expected to be reduced when implementing the concept power plant. Lastly, the duty of the local machinery surveyor in the engine room will be influenced. When implementing the concept power plant, the engine room will disappear. This makes the duty of local surveyor in the engine room unnecessary. Duties to fulfil the navigation, combat and communication functions are not directly influenced.

The duty role of local machinery surveyor in the engine room can be left out, resulting in a possible reduction of one crew member per watch. This can lead to a reduction of two crew members in total, due to the two-division watch system. However, the crew size should remain large enough for the rotation of console duties. The rotation of console duties is required to prevent concentration loss. The duty of the local machinery surveyor in the engine room is performed by two mechanical engineers (see figure B.3 in appendix B for total manning matrix). Those two engineers are also used for the rotation of the platform system operator and mechanical system operator. The rotation of these duties needs to be taken over by other personnel. This could be done by the mechanical engineering officer. So, from the operational duties perspective a reduction of two crew members is possible.

Maintenance

The crew size of the engineering department should remain large enough to fulfil the required maintenance with specialized personnel and an acceptable work load. A possible reduction of two mechanical engineers might cause an excessive workload. An analysis of the maintenance requirements is needed, so that a workload analysis is possible. During this analysis, the maintenance reduction will be determined. The results of the maintenance analysis are given in table 5.3.

Table 5.3: Estimated maintenance reduction during a seven week mission in hours

	MORAY	Concept
Essential maintenance	545	364
Scheduled maintenance	1055	616
Total maintenance	1600	980

The essential maintenance is reduced, due to a reduction of both servicing and corrective maintenance. The service maintenance is reduced by 90 hours, which is purely based on crossing out the service maintenance required by the DG-sets. The corrective maintenance is reduced by 91.5 hours. This is based on the estimation that corrective maintenance of the propulsion plat is reduced 75%, due to a reduction from four main systems (MEM and three DG-sets) to one main system (only the MEM). Based on aforementioned argumentation, the scheduled maintenance of mechanical and electric systems is also reduced 75%. This results in a scheduled maintenance reduction of 439 hours. A more detailed explanation of the maintenance reduction and an overview of the maintenance requirements of the original design and concept design are given in appendix B.2.

Workload

Both the workload of the engineering department and the total crew size should be kept acceptable. Therefore, a workload analysis of both the engineering department and the total crew is made. The workload of the engineering department is calculated, based on the operational duties and the maintenance requirements. The result of this analysis is shown in table 5.4 and shows that only a reduction of one crew member is possible.

Table 5.4: Workload analysis engineering department during the "Patrol/Potential Threat"-state per day in hours

	MORAY	Concept
Available man hours	48	36
Required for watch standing duty	27	24
Required scheduled maintenance	14.4	5.4
Hours available for additional activities	6.5	3.8
Required essential maintenance	6.4	2.7

The man-hours required for watch standing duties is reduced by three hours. This reduction is based on the left out of the duty of local machinery surveyor in the engine room. The local machinery surveyor is only required during snorkelling, which is estimated on a workload of three hours per day in the original manning study. Therefore, the required watch standing duties can only be reduced three hours. The required maintenance is based on the maintenance activities performed by the engineering department. A part of the total required maintenance will be performed by weapon engineers and is therefore not included in this analysis (see table B.5 in appendix B.2 for the subdivision). Required essential maintenance will be performed during the watch standing duties and are therefore not included in the workload. The remaining available time for additional activities can be calculated. The time available for additional activities is five hours less for the concept. However, the required essential maintenance during watch standing duties will also be less. The increase in work load is therefore acceptable.

The workload of the total crew is calculated as well. This analysis is shown in table 5.5. The daily workload will be reduced from 346.4 hours to 327.8 hours. This reduces the required crew size for a 12 hours shift to 27.4. This is on the boundary of a possible reductions of two crew members. However, this would increase the total workload of the crew and would increase the work load of the engineering department to much. Therefore, a 28 crew members would be required. This indicates a reduction of one crew member.

Table 5.5: Daily workload estimation in hours during "Patrol/Potential Threat"-state for original design and concept design

	MORAY	Concept
Control and supervision	24	24
Platform and safety	123	120
Navigation during snorkling	3	0
Combat	99	99
Comunication	9	9
Essential maintenance	11.1	7.4
Non essential maintenance	21.5	12.6
General	55.8	55.8
Total	346.4	327.8
Needed crew size (based on 12 hours shift)	28.9	27.4

Manning layout

The analysis of the operation duties, maintenance and workload of the crew showed that a reduction of one mechanical engineer is possible. This reduction creates a new division of operational tasks. The reduced mechanical engineer had two operation tasks; the rotation of the mechanical system operator and local machinery survey during snorkelling. The latter becomes unnecessary for the new design. The rotation of the mechanical system operator is taken over by another mechanical engineer, who also had the task of local machinery survey during snorkelling for the original design. His workload will therefore not increase. A new layout of the crew during the "Patrol/potential threat"-state have been made, this is shown in table B.1 appendix B.1.

5.3.3 Conclusion

The implementation of the concept power plant will make a crew reduction of one mechanical engineer possible, without increasing the workload of the crew. This reduces the total crew of the submarine from 34 to 33 crew members.

This reduction is possible due to a reduction in operation duties and maintenance requirements. The operational duty of local machinery surveyor during snorkelling will become unnecessary. The implementation of the concept power plant will cause the maintenance requirements to drop from 1600 hours to 980 hours for a seven week mission. The estimated workload for operational duties, maintenance and general duties will drop from 346.4 to 327.8 man hours/day.

5.4 High pressure air system

High pressure air is used for several systems in diesel-electric submarines. Air is stored in high pressure bottles to provide these systems with high pressure air during surfaced sailing. These bottles are filled during snorkelling or submerged sailing. The expected prolonged submerged periods of the concept design might increase the required amount of high pressure air, which will influence the required high pressure air storage capacity. An analysis of the high pressure air consumption is made to determine if an increase in installed high pressure bottles is required.

The working pressure of the high pressure air consumers is not equal. Therefore, the consumed air volume is expressed as the air volume related to an environmental pressure of 1 bar and a temperature of 273 Kelvin. This is called normal air volume [Nm^3]. The different high pressure air consumers are shown in table 5.6. As first estimation, a 600 hours submerged period is taken. This is a first rough estimation of the achievable submerged endurance of the entirely battery powered design.

Table 5.6: High pressure air balance for a 600 hours submerged period

Consumer	Number	Frequency	Consumption each		Total consumption [Nm^3]
Fresh water tanks	-	cont	0.06	[Nm^3/h]	36
General users	-	cont	1	[Nm^3/h]	600
Engine room	2	18.75 hours	10.2	[Nm^3/h]	382.5
Sewage tank	1	1/day	9.12	[Nm^3]	228
Garbage ejector	1	1/day	0.6	[Nm^3]	15
Blowing all MBT's	-	1	320	[Nm^3]	320
				Total	**1581.5**
Torpedo tubes	2	1	7.7	[Nm^3]	15.4
Signal ejectors	2	1	0.47	[Nm^3]	0.9
				Total	**1597.8**

The high pressure air consumption of the MORAY design is used for this analysis. Only, the component engine room is adjusted. The engine room consumers consists of the workshop and portable tools working on high pressure air. The maintenance requirements are expected to be less, as discussed in paragraph 5.6. The total maintenance requirements for mechanical engineering are expected to be halved. Therefore, the use of the workshop and potable tools is halved as well. The air consumption for blowing the main ballast tank (MBT), shown in table

5.6, is for a water depth of six meters. The torpedo tubes and signal ejectors are considered as incidental consumers. Therefore, the use of air compressors is permitted for these consumers when needed. However, this is not preferable.

In the MORAY design nine high pressure air bottles with a capacity of 885 litres and a pressure 275 bar are installed. These bottles provide a capacity of 2190.4 Nm^3, which is sufficient to cover the operational period shown in table 5.6. In total the capacity of 6.6 high pressure air bottles will be required.

The required number of high pressure bottles for the MORAY design are based on an emergency blow of 40% of the MBT volume at a depth of 225 meters. This requires the capacity of approximately 8.1 high pressure air bottles. In the original calculations for the MORAY design, no requirements are stated that a emergency blow should be possible after the consumption of a normal mission period. However, the submerged periods of the MORAY design are much shorter and have a factor ten lower high pressure air consumption than the concept design. Therefore, the effect of a previous mission period is small. In the case of the concept design the effect of the previous mission period will be much larger. Therefore, it is desirable that an emergency blow should be possible after the consumption of a normal mission period. This would require an addition of approximately five high pressure air bottles.

5.5 HVAC

The reduction in systems, crew members and the increase in underwater time will change the requirements for the HVAC system. The functionality of the HVAC system can be divided in the sub-functions; temperature control, humidity control, ventilation, CO_2 adsorption and O_2 generation. The effect on each sub function will be discussed in this section.

5.5.1 Temperature control

The temperature control system consists out of a heating and cooling system. The heating system uses air heaters in the air condition system and local compartment heaters to increase the temperature. The cooling system consists out of a chilled water system. The chilled water is partly used to cool the air in the air condition system and is partly used to cool equipment directly.

The required heating capacity is based on a “dead ship” situation, so without the heat dissipation of equipment. The influence of the reduction of one crew member will be negligible in this analysis. The required heating capacity will therefore stay equal to the heating capacity in the MORAY design.

The required cooling capacity is depending on the total heat load in the submarine. The total heat load consists out of; sensible and latent heat emission of the crew, transmission heat flow and heat dissipation of equipment. The reduction in the number of installed systems will reduce the total heat load on board. From these systems, the DG-sets are the biggest heat source. They have a heat dissipation of 99000 W into the engine room of the MORAY design. However, the engine room is cooled by the incoming combustion air and by heat transmission via the submarine hull. Therefore, the heat load of the cooling systems will not be influenced by the reduction of the DG-sets. The reduction of other systems system and the reduction of one crew member have a negligible effect on the total heat load. The cooling capacity of the concept design will therefore stay similar to the cooling capacity of the MORAY.

5.5.2 Humidity control

The humidity control on board the MORAY class is only able to decrease the humidity in the submarine. The system is not able to increase the humidity on board. The humidity is decreased by the cooling of air, so that the water in the air condenses. This causes a humidity reduction. When the right humidity is reached, the air is reheated to the desired temperature.

The humidity can be changed by latent heat produced by the crew and by the entering of fresh air into the submarine. The change in latent heat production due to the reduction of one crew member is negligible. The requirements of the maximum humidity of fresh air, in which the system should be able to operate, stays equal to requirements of the MORAY design. Therefore, no adjustments to humidity control system will be necessary.

5.5.3 Ventilation

The function of the ventilation system on board the MORAY is depending on the condition of operation. During submerged condition, the function of ventilation system is to ensure optimum equalizing of the air through the submarine. This is required to equalize gasses, such as O_2 and CO_2. During surfaced and snorkelling condition, the function of the ventilation system is to ensure good air refreshment. The ventilation system is also used to cool the air in the main motor room, engine room and auxiliary engine room and to ventilate the exhaust gasses from the galley and sanitary spaces.

The design of the ventilation system is depending on; the total enclosed volume of the different sections, the arrangement of the sections and the heat load of the engine room, auxiliary engine room and main electro motor room. The number of systems on board the concept design will be reduced, which will cause a decrease in heat load. Furthermore, the arrangement of the different sections will change. Moreover, the air intake will change due to the absence of the combustion air intake. The influence of these changes on the ventilation system will be analysed for both the submerged and surfaced condition.

During submerged condition, no big changes to the ventilation system are required. The DG-sets will not be used during submerged sailing. The change in heat load will therefore be negligible. Furthermore, the enclosed volume of the submarine will stay similar. The arrangement of the submarine is expected to change. However, this is expected to have a negligible effect on the ventilation requirements. Only the location of fans, valves and filters will change. Due to these reasons, no big changes to the equalizing ventilation are expected.

Changes are required for operations during surfaced condition. In the MORAY design air refreshment is achieved via both the combustion air intake and the sail hatch. Fresh air for the mid ship and forward section of the submarine is sucked in by the air conditioning units, via suction plenums located at the sail hatch. Fresh air for the aft section is sucked in by the DG-sets via the combustion air intake. The exhaust air of the mid and forward section of the submarine are transported to the engine room. The diesel-generators consume the exhaust air and transport it, via the exhaust gas systems, overboard. When the DG-sets are not running, all fresh air is acquired via the sail hatch. Air refreshment of the aft section is achieved via the exhaust air of the forward and aft section. Air outlet will be possible via the combustion air intake in this case. The situation in the concept design will be comparable with this situation. However, no combustion air intake will be present in the concept design. Therefore, no air outlet will be available. A good air circulation will therefore not be possible. Another air outlet duct will be required to enable air refreshment. However, this air refreshment duct will not require the same functionality as snorkel. It only needs to be used during surfaced condition. A duct through the sail and a pressure hull penetration are required. It might be necessary to install an extra ventilator to stimulate the air flow.

5.5.4 CO_2 absorption

The function of the CO_2 absorption system is to absorb CO_2-gas in submerged conditions. In the MORAY design CO_2 scrubbers with chalkholders are used. The air flow is let through the chalk holders, that absorb the CO_2. The chalkholders must be replaced when they are saturated.

This absorption systems has no power usage and is therefore commonly used in diesel-electric submarines.

The design of the CO_2 absorption system is depending on the total inboard volume of the submarine, the crew size and submerged endurance without air refreshment. Both the crew size and submerged endurance will change for the concept design. This will influence the absorption system. The CO_2 production by the crew will be reduced, but the submerged endurance will be increased. This will increase the required amount of chalkholders, which will increase the volume and weight requirements for the storage of chalkholders. A calculation is made to analysis this. The result of this calculation is shown in table 5.7. The original CO_2 absorption system calculation is based on 35 crew members, creating a margin of one crew member. This same margin is also used for the concept design. The submerged period of 600 hours for the concept design is a rough estimation of the achievable endurance. The calculations for the CO_2 absorption system are shown in appendix D.1.

Table 5.7: Effect of concept power plant on CO_2 absorption system

	MORAY	Concept	
Number of crew	35	34	
Submerged periods	3x 25, 1x 160	1x 600	[h]
Required number of chalkholders	432	1288	
Weight chalkholders	1944	5670	[kg]
Volume chalkholders	1728	5040	[l]

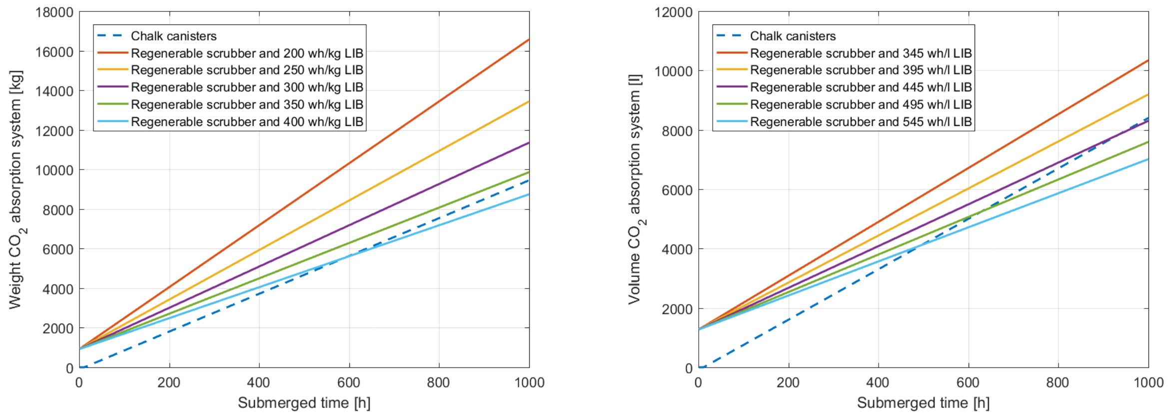
The expected increase in volume and weight requirements of the CO_2 absorption system might make the installation of a regenerable system preferable. These systems make use of a regenerable chemical reaction to absorb CO_2. This enables the system to reuse its absorbent. A large supply of absorbent material is therefore unnecessary. A disadvantage is the power required for the separation of the CO_2 from the absorbent. Their power consumption can be translated into a required battery capacity. A comparison between a scrubber using chalk canisters and a regenerable scrubber is made to determine the best option. The required battery weight and volume required for the power consumption of the regenerable are included in the comparison. The calculations of this comparison are shown in appendix D.1. This comparison is based on a regenerable scrubber of the TP Group [45]. The results of this analysis are shown in figure 5.1. Both the weight and volume requirements of both systems are shown for a range of submerged duration, because the exact submerged time is still unknown.

The results of figure 5.1 show that, with current available battery technology, a regenerable scrubber will not become preferable. The regenerable scrubber might become preferable, when improved battery technologies become available. The break-even point from a weight perspective will only be reached when the specific energy of lithium modules is doubled. The break-even point from a volume perspective will be reached sooner, as can be seen sin figure 5.1b.

5.5.5 O_2 generation

An oxygen generation system is used to generate oxygen during submerged sailing. In the MORAY design, oxygen candles are used to produce oxygen. These candles store oxygen in a chemical solid. The chemical reaction, which occurs when the candles are ignited, releases the oxygen.

The required number of oxygen candles is depending on the inboard volume, crew size and submerged endurance. The increase in submerged endurance will result in an increase in the required amount of oxygen candles. This will increase the volume and weight requirements for the storage of oxygen candles. A calculation is made to determine this increase for a submerged



(a) Required weight comparison (b) Required volume comparison

Figure 5.1: Comparison between a chalkholder CO_2 scrubbing system a regenerable CO_2 absorbtion system including required battery capacity

endurance of 600 hours. The results of this calculation are shown in table 5.8. The detailed calculations can be found in appendix D.2.

Table 5.8: Effect of concept power plant on O_2 generation system

	MORAY	Concept	
Number of crew	35	34	
Submerged periods	3x 25, 1x 160	1x 600	[h]
Required number of oxygen candles	46	163	
Weight oxygen candles	575	2037.5	[kg]
Volume oxygen candles	391	1385.5	[l]

Other options for oxygen generation are the production of oxygen by means of electrolysis of seawater or with the use of liquid oxygen (LO_x) vaporization. Electrolysers are commonly used on nuclear submarines. However, a minimal power usage of 10 kW makes them unsuitable for diesel-electric submarines and also for the concept design [46]. Generation of oxygen by means of LO_x vaporizing might be a feasible alternative. The oxygen production per volume unit of LO_x is two times as high as that of an oxygen candle [33]. However, LO_x needs to be stored in isolated pressure tanks. This makes the weight and volume requirements of the storage of LO_x comparable with oxygen candles (based on a commercial LO_x storage tanks [10]). The shape of a LO_x tanks makes them not preferable for implementation inside the pressure hull. The production of oxygen with the use of oxygen candles will therefore be the best option from a design perspective.

The exact achievable submerged time is not yet known. The volume and weight requirements for the storage of oxygen candle are calculated for multiple submerged endurances. The results are shown in figure 5.2.

Conclusion

The HVAC system has five sub-function; temperature control, humidity control, ventilation, CO_2 absorption and O_2 generation. The temperature control and humidity control systems are not influenced. The integration of the concept power plant will influence the ventilation. The combustion air intake system and exhaust system are removed, due to removal of the DG-sets and their support systems. At least one of these systems is required for a good air refreshment

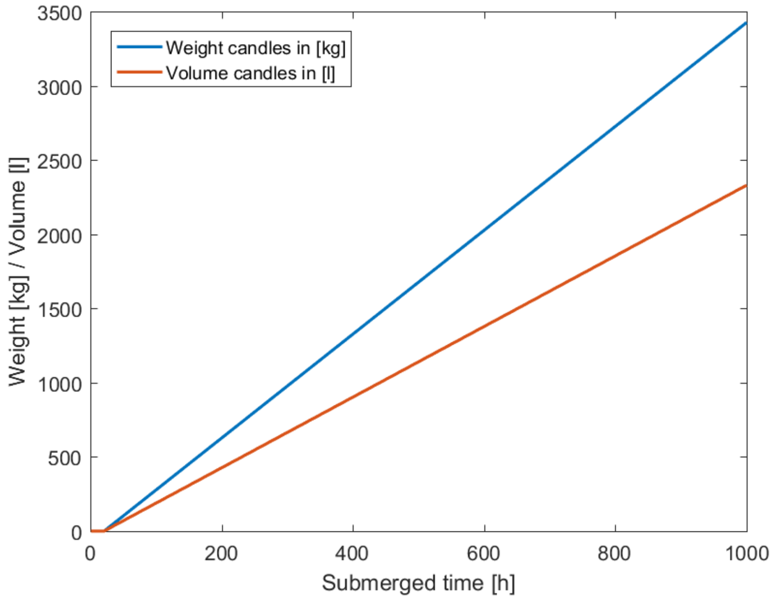


Figure 5.2: Volume and weight requirements for the storage of oxygen candles

during surfaced condition. Therefore, another air refreshment duct and hull penetration are required. This duct will be placed in the sail, at the location of the old snorkel. However, this air refreshment duct will not require the same functionality as snorkel. It only needs to be used during surfaced condition.

Both the increase in submerged endurance and change in crew size will influence the CO_2 absorption and O_2 generation systems. The expected increase in submerged endurance will increase the required amount of chalkholders and oxygen candles. Therefore, the volume and weight requirements of the CO_2 absorption and O_2 generation systems are expected to increase respectively 300% and 400%. However, the exact increase is depending on the submerged time. The option of a regenerable scrubber system, as alternative for the chalkholder scrubber system, is investigated. The regenerable scrubber requires a power supply, which requires a battery capacity. There is concluded that a regenerable scrubber is not preferable from a volume and weight perspective. Other options for oxygen generation are investigated as well. Oxygen production by the means of electrolysis is no option due to the high power usage. Oxygen production by the vaporizing of LO_x might be an option, but is not expected to be preferable from a volume and weight perspective.

Chapter 6

Pre-design analysis

This chapter will describe the pre-design analysis of the effect of the concept power plant integration into the MORAY design. The results of chapter 5 will be translated to a reduction in weight and volume. This analysis will be used to be used to determine the limiting design factors and to indicate possible design problems. The results of this analysis will be used to during the design of the entirely battery powered concept.

6.1 Weight analysis

The reduction and/or change in systems and crew size will influence the submarines weight. In this paragraph, a weight analysis of the concept design will be made. The goal of this analysis is to determine the available weight for the integration of lithium modules. Furthermore, the effect on the centre of gravity will be determined to make stability and trim analysis possible.

The weight analysis is based on the weight balance of the MORAY design. Based on the results of the analysis in chapter 5, the effect on the different weight components are determined. Both the weight balance of the original design and the results of the weight analysis are shown in table 6.1. The results will be discussed per ship work breakdown structure (SWBS) group.

Table 6.1: Results weight analysis on SWBS group level

	Total of SWBS groups	MORAY			Concept		
		Weight [t]	VCG [m]	LCG [m]	Weight [t]	VCG [m]	LCG [m]
100	Hull structure	581	3.51	34.77	531	3.65	35.12
200	Propulsion plant	427	2.53	31.68	104	3.40	14.88
300	Electrical plant	21	4.22	32.42	21	4.22	32.42
400	Command and surveillance	44	6.10	44.09	44	6.10	44.09
500	Auxiliary systems	106	4.52	31.46	108	4.54	31.58
600	Outfitting and furnishings	49	4.14	39.70	49	4.14	39.70
700	Armament	68	2.55	57.42	68	2.55	57.42
F	Variable loads	507	2.69	37.37	320	3.38	40.38
M	Margins and ballast status	102	1.87	34.74	102	1.87	34.74
	Total	1905	3.09	35.70	1347	3.56	36.04

The reduction in the SWBS component hull structure is mainly caused by a reduction in soft tanks. All fuel tanks, the settling tank, distilled water tanks and the snorting tank are superfluous in the concept design. The removal of these tanks will result in weight savings. These weight savings are based on the achievable reduction in soft tank area, which leads to a reduction in steel weight. This results in a weight reduction of 44 tons. The other part of the weight reduction is related to the removal of the foundations of the DG-sets. This leads to a total reduction of 50 tons.

The weight change of the propulsion plant is mainly caused by the removal of the lead-acid batteries, which have a weight of 259 tons. The weight of the high current power cables is expected to increase, due to an increase in installed battery capacity. A doubling in weight is the first estimation, which leads to a weight increase of 8.5 tones. The remaining reduction in weight is caused by the removal of the battery support systems, DG-sets and DG-sets support systems. Together, this leads to a weight reduction of 168 tons. The weight of the propulsion plant, excluding lithium modules, is 104 tons.

The weight requirements of the electrical plant are expected to stay constant. The battery switchboard is kept constant as first estimation. The number of switches in the battery switchboard will increase, but the short circuit protection will be removed. Therefore, the estimation is made that the weight requirements will be approximately constant. The manoeuvring switchboard will be kept constant, as discussed in section 5.2.2. The weight of the converters, power cables and distribution panels will be kept constant as well.

The group auxiliary systems is the only group where a small increase in weight is expected. The ship fuel and fuel compensation system will be removed, but an increase in the weight requirements of the ventilation system is expected. As discussed in paragraph 5.5, an adjustment to the ventilation system is required to ensure air refreshment based on weight reservation for hull valves and piping in the sail.

The weight of the SWBS groups outfitting and furnishing and armament are not expected to change. The reduction of one crew member will not result in a reduction of crew cabins, so the influence on the group outfitting and furnishing will be negligible. Furthermore, the armament of the concept design will be kept similar to the armament of the MORAY.

The weight of the variable loads is mainly reduced due to the removal of fuel. There is also a small weight reduction due the reduction of some other liquids, such as distilled water and liquids in the settling tank. The weight of the storage is increased. This is caused by the increase in required O_2 candles and CO_2 chalk absorbers, based on the first estimation shown in chapter 5.5.

The margins will be kept similar to the margins used for the MORAY design. The ballast status might change. However, this can only be determined during the design process. As starting point, the ballast status of the MORAY design will be used.

After applying all weight changes, the total weight of the concept design is 1347 tons. So, in total the weight is reduced 558 tons compared with the MORAY design. This means that approximately 558 tons can be used for the integration of the new battery system. The vertical centre of gravity (VCG) is increased by 0.47 meters and the longitudinal centre of shifts 0.34 meters forward, due to reductions in weight. This increase needs to be compensated with the implementation of the battery system, to be able to meet the stability requirements without increasing the ballast status.

6.2 Volume analysis

The reduction and/or change in systems and crew will also lead to an increase in available volume for the implementation of lithium modules. An analysis is made to determine the total amount of available volume in the concept design. Also, the locations of the available spaces are determined so that stability estimations are possible.

A 3D model of the MORAY design is used to analyse the availability of volume. In this model, the location and size of the superfluous systems and tanks are determined. This analysis is limited to the space inside the pressure hull, because the space outside the pressure hull cannot be used for the implementation of lithium modules. The reduction of one crew member is not taken into account. The reduction of one rating will not lead to a reduction of cabins in the current design. Therefore, the space required for berthing and messing spaces is unchanged. The results of volume analysis can be seen in table 6.2. These volumes are the total available volumes, including space required for passageways, decks, piping, cabling and frames.

Table 6.2: Results volume analysis

Component	Volume [m^3]
Battery compartments	178
Engine room	147
Fuel tanks	199
Other tanks	19
total	543

The available volume is 543 m^3. The engine room and battery rooms are together responsible for a volume of 325 m^3. The other 218 m^3 is tank volume. The locations of the available space in MORAY design can be seen in figure 6.1. The centre of the total available volume lies at 29.5 meters in longitudinal direction and at 2.4 meters in vertical direction.

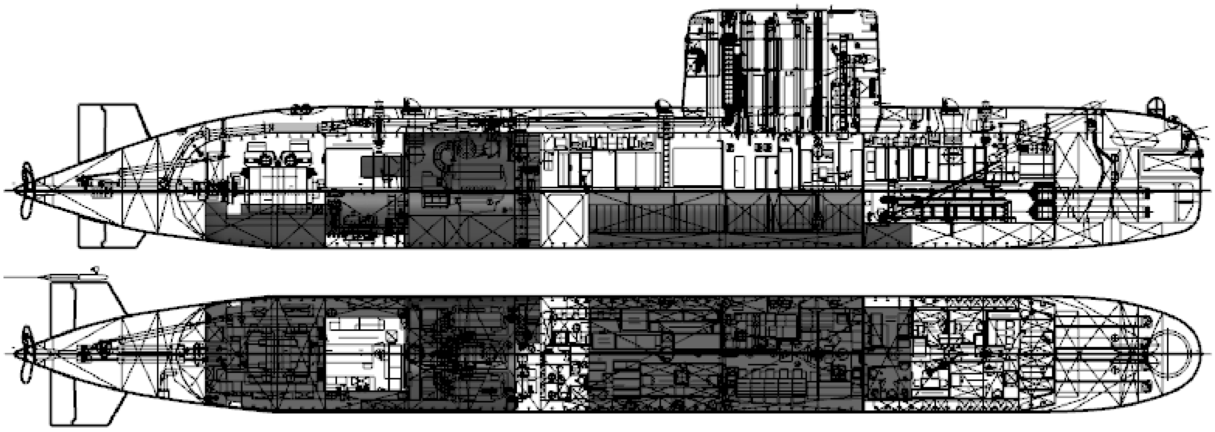


Figure 6.1: Available space in MORAY design for the implementation of lithium-ion batteries

6.3 Expected limiting factors and design problems

The results of paragraph 6.1 and 6.2 are used to make an analysis of the limiting factors in the design. Furthermore, there is tried to identify potential design problems. Determining this in the early design stage will make the design process more efficient.

In paragraph 6.1 and 6.2 is concluded that 558 tons and 543 m^3 is available for the implementation of the battery system. Based on the density of lithium modules, there can be estimated how much volume needs to be filled with lithium modules to reach a natural buoyant state. Lithium modules have a density of 1570 kg/m^3. This means that approximately 65.5% of the available volume needs to be filled with lithium modules to achieve a neutral buoyant design. Using 65.5% of the available volume for the implementation of lithium modules might not sound challenging. However, the total available volume cannot be used completely for the implementation of lithium modules. Passageways, framing and the circular hull shape will limit the volume usage.

An estimation is made of the usable volume in the battery compartments and engine room. This enables an estimation of achievable integration of lithium module weight into these locations. Based on the achievable integration of lithium modules in the engine room and battery compartments, the required usable tank volume can be determined. Furthermore, this module distribution can be used to determine the effect on the VCG and longitudinal centre of gravity (LCG) of the design.

The volume in the battery compartments can be used almost completely for the implementations of lithium modules. In the engine room a passageway is required. Also, the shape of the hull and the transfers frames will limit the usable space in the engine room. Estimated is that about 90% of the battery compartment volume and about 65% of the engine room volume can be used for the implementation of lithium modules. This would mean that about 57% of the tank volume is required for the implementation of lithium modules. Tanks are often small and are located to the side/bottom of the hull. Furthermore, they include transverse framing of the pressure hull. Therefore, they are not convenient for the placing of lithium batteries. Using 57% of the tank volume is a challenging amount and is expected to be difficult to achieve. Therefore, the entirely battery powered concept is expected to be volume critical.

A first estimation of the centre of gravity of the concept is made to identify possible stability and trim problems. This estimation is based on the volume distribution as discussed before; 90% of the battery compartments, 65% of the engine room and 57% of the tank volume is used for the implementation of lithium modules with a density of 1650 kg/m^3. Assumed is that the weight of the modules is equally distributed over the volumetric components. The centre of gravities of the different components are determined with the use of the 3D model of the MORAY. The results are shown in table 6.3.

Table 6.3: First estimation of effect concept power plant on vertical and longitudinal centre of gravity

		Weight [ton]	VCG [m]	LCG [m]
Concept design	Weight excluding lithium modules	1347	3.56	36.18
	Modules in engine room	150	4.54	25.17
	Modules in battery compartments	214	1.95	39.87
	Modules in tanks	195	1.37	28.16
	Total	1905	3.23	34.81
MORAY		1905	3.09	35.70
Difference MORAY and concept design		0	0.14	-0,89

The implementation of the concept power plant is expected to have a significant impact on the location of centre gravity, as can be seen in table 6.3. Based on the first estimation the vertical centre of gravity will be increased by 0.14 meter and the longitudinal centre of gravity will shift 0.89 meter to the aft of the submarine. Due to the shift of the CoG of the concept design, the design will not meet its trim and stability criteria. A rearrangement of the design will be required to meet both trim and stability requirements. The lithium modules need to be equally distributed over the submarine length the reduce the trim problems. Furthermore, the modules should be located below the main deck as much as possible. This will remedy the stability problems. When this can be achieved, trim and stability are not expected to be limiting design factors.

Chapter 7

Creation of concept design

The concept design will be a redesign of the MORAY design. The dimensions (the submarine hull) of the concept design will be kept constant with the MORAY design. Furthermore, the design requirements of the concept design will be kept the same as the design requirements of the MORAY design. Only the requirement of the required range is not held. The goal is to create a feasible design, which comes as close as possible to the range of the MORAY design.

This chapter will describe the design requirements, design approach and the created concept design. Furthermore, the impact of the concept power plant integration on the submarine design will be analysed. This makes it possible to determine the limiting design factors during an entirely battery powered submarine design.

7.1 Design requirements

This paragraph will describe the design requirements for the concept design. Not all design requirements will be addressed. The described design requirements are limited to the design requirements which either directly influence the design or help to place the design in perspective.

The tactical payload requirements state that six torpedo tubes are required and that in total 20 weapons need to be able to be stored. The torpedoes need to be placed in a dedicated torpedo compartment.

The operational requirements state that the following speeds must be attainable:

- Surfaced :maximal 12 kn
- Periscope depth: maximal 12 kn
- Submerged: minimal 2 kn, maximal continuous 20 kn (one hour), maximal burst 21,5 kn

Furthermore, the submarine will have a maximum operational diving depth of 300 meters and an incidental diving depth of 360 meters. The submarine needs to be able to operate in seawater densities between 1.010 tons/m^3 and 1.030 tons/m^3.

The submarine will have a minimum required submerged stability (BG) of 0.3 meters. In surfaced condition the stability (GM) will be at least 0.2 meters. Both required stabilities are excluding free surface effects and need to be met at departure condition with a seawater density of 1.025 tons/m^3. The trim and weight compensation systems must able to compensate for the differences in loading on board of the submarine and must be able to compensate for a possible change in seawater density. A weight margin of 2.5 tons and a margin in trimming moment of 80 ton-meters are required.

No strict requirements are given for the arrangement of submarine and the accommodation of the crew. However, there is stated that the general arrangement needs to be based on a strict functional separation of compartments, with emphasis on good habitability. Furthermore, there will be no combined sleeping/eating or sleeping/storage rooms and each crew member will have a private bunk and locker.

7.2 Design approach

As mentioned in the introduction of this chapter, the design goal is to create a feasible design which comes as close as possible to the range of the original MORAY design. To achieve this goal, as much battery capacity as possible needs to be installed. This paragraph will describe the design approach used to achieve this.

The concept design is created in Rhinoceros, which is a 3D design tool. The use of a 3D tool makes it possible to ensure that all components fit in the cylindrical hull of the submarine. For the creation of this concept design, the original 3D model of the MORAY is used and adjusted. By doing this, the exact same hull and system dimensions can be used. This enables a fair comparison between the two designs.

In the design process, three iterations steps were made. The starting point of the design process was the original MORAY design. All unnecessary systems were removed from the design and a rearrangement of battery compartments was made. The goal of the relocation of the battery compartments was to overcome the stability and trim problems, as indicated in paragraph 6.3. In this first iteration step, the weight of the battery compartments were estimated, based on module density and an expected packing density of battery modules in the battery compartments. During the second iteration step, a detailed rearrangement of submarines main deck and a rough battery design were made. This iteration step ensured that all required rooms fitted in the new arrangement. During the last iteration step, a detailed battery system design was made and implemented in the concept design. Furthermore, the tank arrangement was made. Also, the fine-tuning of the stability and trim was performed during this last iteration step. The final design and all design considerations will be discussed in detail in the following paragraphs.

7.3 General arrangement

The general arrangement of the entirely battery powered concept design is shown in figure 7.1. Transverse section views are added in appendix E.1. The MEM room is located aft. The manoeuvring room is located before the MEM room. The accommodations are situated between the manoeuvring room and the control room. The accommodations are divided based on rank. At midship, close to the control room, the officers and petty officers accommodations are situated. Furthermore, the radio room and electronic room are located in this area. The accommodations of the ratings and leading ratings are located aft, between the manoeuvring room and the officers accommodations. The galley and stores are also located in the aft compartment of the submarine, close to the ratings messing. Both the officers and ratings accommodation areas have their own sanitary units. The torpedo room is located in the front of the submarine at main deck level. The battery compartments are placed low in submarine and are equally distributed over its length. The forward and aft battery compartments are separated by the weight compensation tank and the auxiliary room. The MEM and aft battery compartment are separated by the MEM room bulkhead. The forward and torpedo battery compartment are separated by the forward water tight bulkhead. The water tight bulkheads are kept on their original location of the MORAY design.

The tank arrangement has become simple, due to the huge decrease in required tank volume. The main ballast tanks are located forward and aft outside the pressure hull. The weight compensation is located midship, close to the longitudinal centre of buoyancy (LCB). The aft and forward trim tank are located as far aft and in front as possible, which enables them to generate large trim moments. The weapon compensation tank is located below the weapon storage. The torpedo handling water tank is located directly below the torpedo tubes. The lubrication oil and dirty lubrication oil tank are both located below the MEM, which is currently the main lubrication oil user. The fresh water, sewage tank and hydro oil tank are located inside

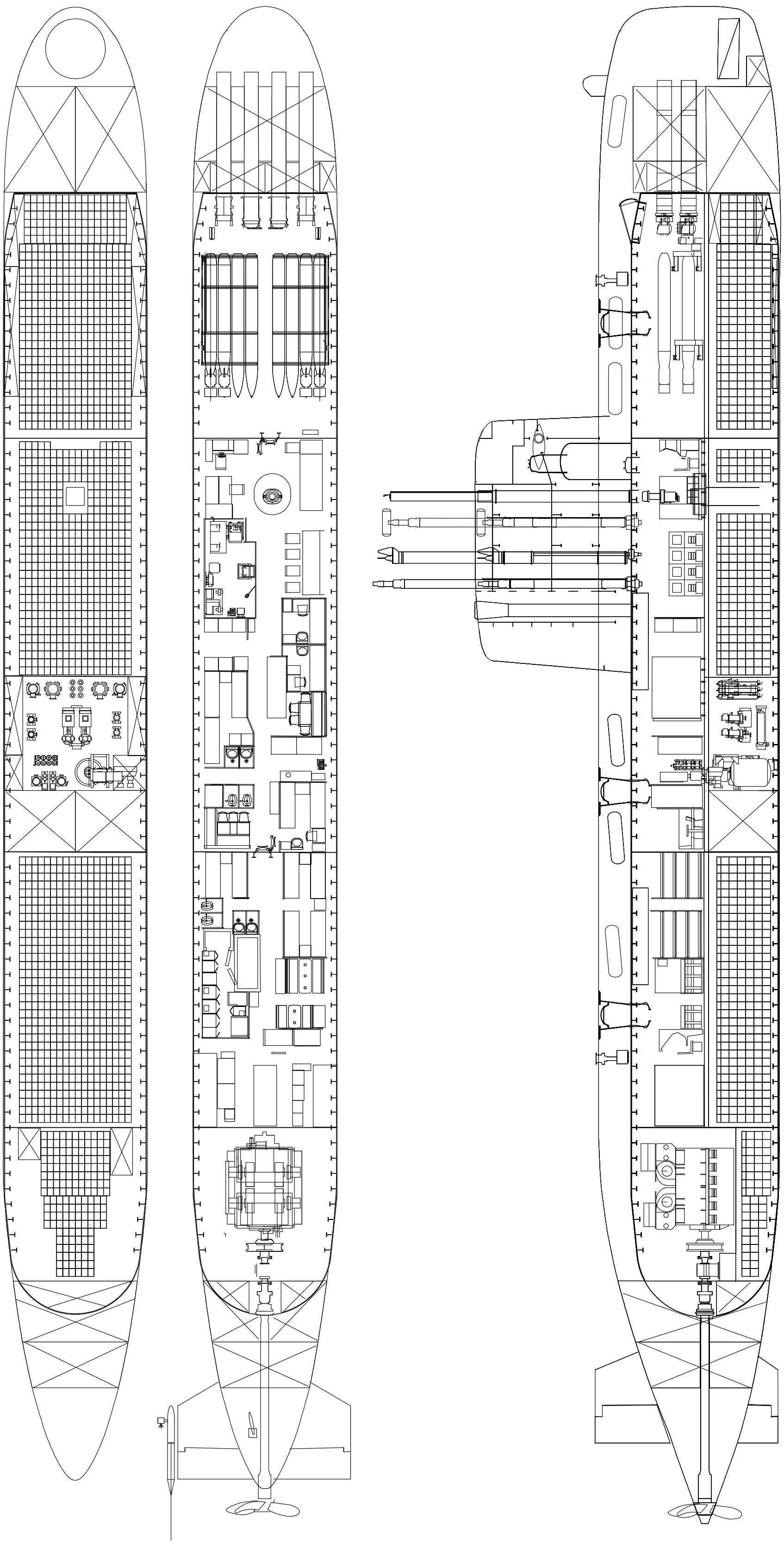


Figure 7.1: General arrangement entirely battery powered concept design

the auxiliary room.

With respect to the original MORAY design, three big arrangement changes have been made (see figure ?? for the original arrangement). The first change is the relocation of the torpedo room from the lower deck to the main deck. This relocation was required due to stability and trim problems. However, it also has the big advantage that all manned spaces are now located at the same deck level. The officers and petty officers accommodation and radio room need to be replaced, due to the relocation of the torpedo room. It is desirable to keep these rooms close to the control room. Therefore, the ratings accommodation and the galley are relocated to the location of the engine room in the MORAY design. This makes it possible to keep the officers accommodation and radio room closely located to the control room. The relocation of the accommodations has the advantage that no unnecessary movements through the control room are needed. The last arrangement change is the relocation of the auxiliary room to the forward side of compensation tank. This was required for trim reasons.

The size of each room is kept as constant as possible, compared to the original room sizes of the MORAY design. The layout of the MEM room, manoeuvring room, galley, ratings mess, ratings cabin, electronic room and control room are unchanged. Other rooms have changed layouts, but the area of each room is kept constant with the area of the rooms in the MORAY design. The accommodation for the petty officers has changed the most. Two five-person cabins are changed into one ten-person cabin. However, also here the area is kept approximately constant. This enables a fair comparison with the original design

7.4 Battery design

The battery design is an important aspect of the entirely battery powered design. This paragraph will describe the cell and module choice, the battery block design, the compartment design and the safety and reliability aspects of the battery design.

Cell and modules

LIB cells are available in multiple chemistries, cell constructions and sizes. The cell choice and module design will influence the performance and safety characteristics of the battery, as discussed in paragraph 4.2. Furthermore, the module size will influence the possible packing density of modules into the battery compartments. It is therefore important to use a realistic module design, based on realistic cell dimensions.

The choice is made to base the modules on the dimensions of the Kokam 150 Ah ultra-high energy cell. This cell has a high energy density and a high specific energy of respectively 505 Wh/l and 261 Wh/kg. The Kokam 150 Ah ultra-high energy cell is a pouch cell with a NMC chemistry [24]. The advantage of the used pouch cell construction is the large surface area, which enables a high heat-transferring capacity. The 150 Ah storage capacity of the cell is relatively high. This decreases the total required number of battery cells and therefore also the chance of a single cell failure.

The used NMC chemistry is not the most safe battery chemistry. For example, LFP based cells have better safety characteristic. Their thermal runaway temperature is lower. Therefore, thermal runaway propagation can be prevented when the right safety precautions are taken. Furthermore, the cell temperatures will stay below the igniting temperature of the vent gasses. So, the risks of fire and explosion is lower. However, these battery chemistries have a much lower energy storage capacities. Therefore, a choice needs to be made between safety and energy storage capacity. The choice is made to base the design on NMC chemistry cells, so that the potentials of an entirely battery design can be shown. The extra safety risks must mitigated in the design of the battery compartments.

Per module, several cells will be placed in series. The total required number of cells connected in series is determined by the required voltage level of the battery block and the cell voltage level. The required voltage of the battery block is depending on the voltage characteristics of the MEM and other power electronics. There is chosen to use a battery block voltage equal to that of the MORAY battery block voltage, so that it is suitable for all installed systems in the design. Table 7.1 shows the voltage characteristics of both the concept design and the MORAY design. The voltage discharge characteristics of the Kokam 150 Ah ultra-high energy cell are unfortunately not available. Therefore, the voltage discharge characteristics of the Kokam 200 Ah high energy cell are used as reference for the concept design (also shown in figure 4.5b) [22]. This cell is uses the same cell chemistry and is made by the same manufacturer. Therefore, the voltage characteristics are expected to be comparable.

Table 7.1: Voltage charcteristics on cell and battery pack level

	Concept	MORAY
Max. cell voltage	4.1	2.09
Avg. cell voltage	3.7	1.95
Min. cell voltage	3.4	1.75
Number of cells in series	108	210
Max. block voltage	442.8	437.9
Avg. block voltage	399.6	409.5
Min. block voltage	367.2	367.5

To achieve the required operational battery block voltage, 108 LIB cells in series are required. These 108 cells are divided over six battery modules. So, each module will consists out of 18 cells. The dimensions of the modules are based on the cell dimensions of the 150 Ah ultra-high energy cell and the module packing factor for volume of 1.6. The length, height and width of the cells dimensions are multiplied with the third power root of the module packing factor for volume, to determine the module dimensions. The 18 cells will be placed next to each other in the width of the battery module, which determines the total width of the module. The cell and module dimensions are shown in table 7.2.

Table 7.2: Kokam 150 Ah ultra-high energy cell and used module dimensions [24]

	Cell	Module	
Height	30	36	[cm]
length	29	35	[cm]
Width	1.3	27	[cm]

Battery block and compartment design

The battery blocks are based on a string based module integration, as shown in figure 7.2. A battery string consists out of six modules, which are switched in series, and a string control unit (SCU). In the SCU short circuit protection and switch gear are integrated. The SCU will communicate with MCUs and the BMS. It will enable active cell balancing on string level, which will maximize the performance of each string. Furthermore, it will make it possible to switch off a string in case of a failure in the string. The integrated short circuit protection in the SCU will protect the string against an external short circuit. Integrating short circuit protection on string level will limit the short circuit current to cell level, which makes it possible to use relatively small and reliable switch gear and protective devices in combination with an electric current limiter as discribed in paragraph 5.2. All battery strings will provide the required operational voltage and are switched in parallel to create a battery block.

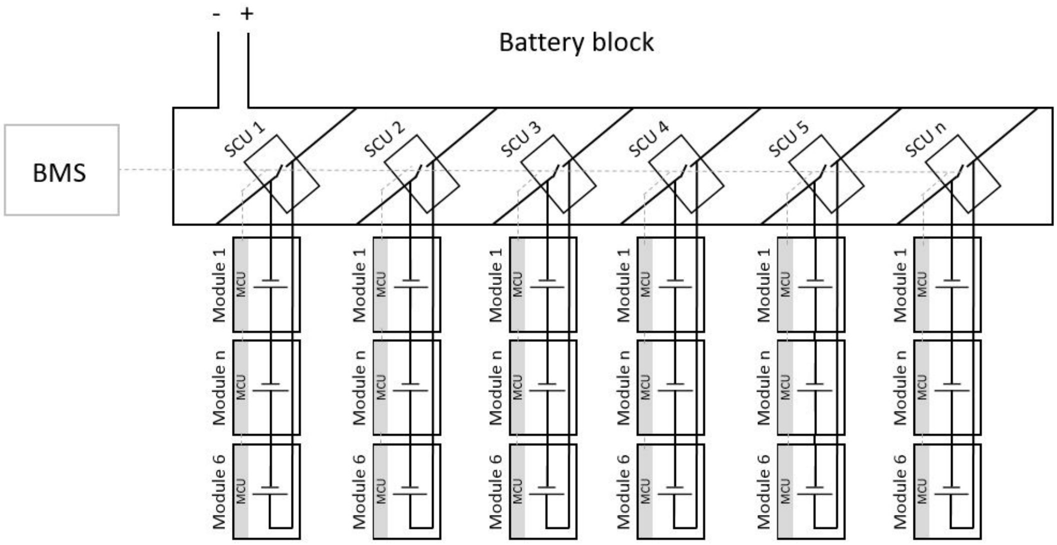


Figure 7.2: Topology of created lithium battery blocks

The total size and total capacity of the battery block is determined by the number of strings connected in parallel. The achievable number of strings connected in parallel is determined by the available space inside the battery compartments. The modules are integrated into the 3D model to determine this. For this integration, the module dimensions from table 7.2 are used. The size of the SCU unit is estimated half the size of a module, which is based on reference string based lithium battery designs [3, 20]. Figure 7.3 shows a cross-section of the integrated battery compartment.

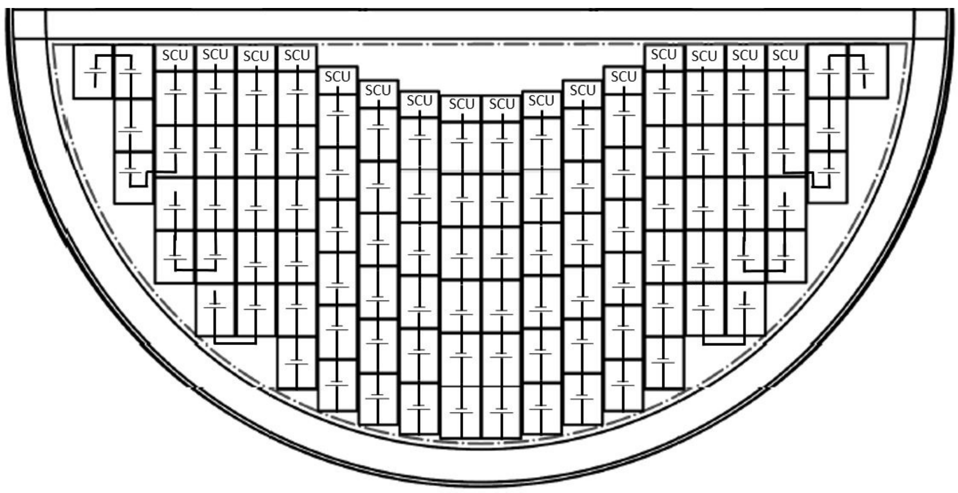


Figure 7.3: Integration of lithium modules intro battery compartments

There is chosen to couple the modules directly to the submarine structure. Therefore, the modules and SCU need to be designed shock proof. A minimum margin of five centimetres is kept between the modules and frames for the integration of structural support for the modules. The same margin is kept between the highest modules and SCU and the main deck. The minimum margin line is shown as a dotted line in figure 7.3. Between the modules a one centimetre margin is applied. This small distance is possible due to the integration of a liquid cooling system. So, no air circulation is required inside the modules. The one centimetre distance between the modules will provide enough space for the release of vent gasses in the case of a thermal runaway reaction.

The strings are placed vertical into the battery compartments. This makes it possible to locate all string control units at the top of the compartment, which minimizes the required cable length. Furthermore, compartment interruptions and length differences will not influence the battery block voltage level. This decreases the complexity of the battery integration. Close to the centre line of the submarine, the strings fit entirely into the height of the battery. Closer to the sides, the circular shape of the submarine hull will decrease the available space. Therefore, the strings area split horizontally to still be able to use the space as efficient as possible. This battery compartment integration reaches a space usage efficiency of approximately 82%, compared with the space available within the margins of the dotted line in figure 7.3. Compared with the total space available, from pressure hull to the main deck, a space usage efficiency of approximately 70% is achieved. Higher space usage efficiencies are possible when smaller modules and cells are used. However, this will increase the complexity of the battery design and installation. Also, the safety characteristics of the total battery blocks will deteriorate.

The lithium modules can be installed or replacement via the battery compartment hatches. The relatively small size and weight of the lithium modules makes this easily possible. The battery strings can be created inside the battery compartments. A structured installation or decommissioning schedule will prevent problems and will enable a maximum usage of the battery compartment space. The modules, furthest away from the hatch, can be installed firstly. From there, modules can be installed towards the hatches. The modules directly below the battery compartment hatch can be installed last, which enables the use of the total battery compartment. The modules do not require maintenance. The SCU should also be designed to be maintenance free. This will make the accessibility of the battery compartments not required.

The battery layout of figure 7.3 is used in the aft battery compartment, the forward battery compartment and in the torpedo room battery compartment. In the MEM battery compartment and the conic front section of the torpedo room battery compartment, a slightly different layout is used. This is required due to the lower deck height in the MEM room, the decrease in available space due to the conic forward and aft sections of the pressure hull and due to the required trim tanks. The battery strings are placed into these sections using the same methodology as used for the layout shown in figure 7.3. The cross sections of these parts can be seen in appendix E.1.

The amount of installed battery strings is shown per battery compartment in table 7.3. Also, the installed battery capacity is shown in this table. The battery capacity is based on a 150 Ah capacity and average voltage of 3.7 volts per cell. A total battery capacity of 88.5 MWh is achieved for this concept design, which is approximately seven times the battery capacity originally installed in the MORAY design.

Table 7.3: Installed amount of battery strings and capacity per battery compartment

	Number of strings	Capacity [MWh]
MEM compartment	68	4.1
Aft compartment	528	31.6
Fwd compartment	440	26.4
Torpedo compartment	440	26.4
Total	1476	88.5

A lithium battery desing makes an infinite number of switching options possible. The installation of switchgear at a low level in the battery design, as shortly discussed in paragraph 5.2, might be an interesting option in future designs. For example, two strings could be to connected to one SCU which includes switch gear. The SCU could be used to switch the strings in parallel or series, which enables a large operational flexibility and reliability. However, more research is required to investigate the feasibility of this option.

The conventional switching systems, via a battery switchboard, has multiple switching options. Each battery string provides the required battery voltage. This makes the choice of battery block size completely independent of the voltage level. The forward and torpedo room battery compartments have the same battery capacity. A logical option is to provide a switch option to connect these compartments in series or parallel. The MEM and aft battery compartments have completely different installed battery capacities. An option is to connect the batteries in the MEM and aft battery compartment directly to the manoeuvring switchboard. This will limit the required battery switchboard size and high current cable length. However, the switching option to create the voltage level, required for the high speed range, will then not exist. This will limit the endurance of the high speed range to the capacity of the forward and torpedo room compartments. Another option is to use the installed in the MEM battery compartment as back-up batteries. These can for example be used during an unexpected decrease in battery capacity. For this concept design, the choice is made to create two equal size battery blocks of batteries installed in the MEM and aft battery compartment. Each battery block will consist out of 298 battery strings connected in parallel. The battery blocks will be connected to a battery switchboard and a switch option will be present. This will maximize the operational capabilities, especially at high speed ranges.

Safety

Safety and reliability are important aspects of the battery integration. Section 4.2.3 did discuss the safety and reliability characteristics of LIBs. Several safety precautions have been taken, based on the knowledge gathered in section 4.2.3. This section will describe these precautions.

Thermal runaway is the largest risk of LIBs. Safety precautions are required to prevent three root causes of thermal runaway. Mechanical abuse, due to shock loads, can be prevented by a shock resisting module design or shock resisting battery compartments. In the concept design is chosen to use shock resisting module design, which is also used in reference lithium modules designs for submarine applications [3, 20]. A shock proof module design has no influence on the concept design and is expected to be to most efficient in both weight and volume. Furthermore, a shock proof module design will also protect the battery cells against handling shock loads. However, it is expected that shock resisting module design will decrease the achievable specific energy and energy density of the modules. The option of a shock proof battery compartment design will have an influence on the design. The required shock dampers, the construction of the battery support structure and required shock clearance will be both weight and volume consuming. Figure 7.4 shows a rough sketch of a possible shock proof battery compartment solution. A margin of 200 mm is taken for the battery support structure, shown as the blue line. A shock clearance of 75 mm is applied, which is shown as the red dashed line. Due to the shock proof battery design less space will be available for the installation of battery modules. This will lead to a reduction in installed battery capacity of 18.75%.

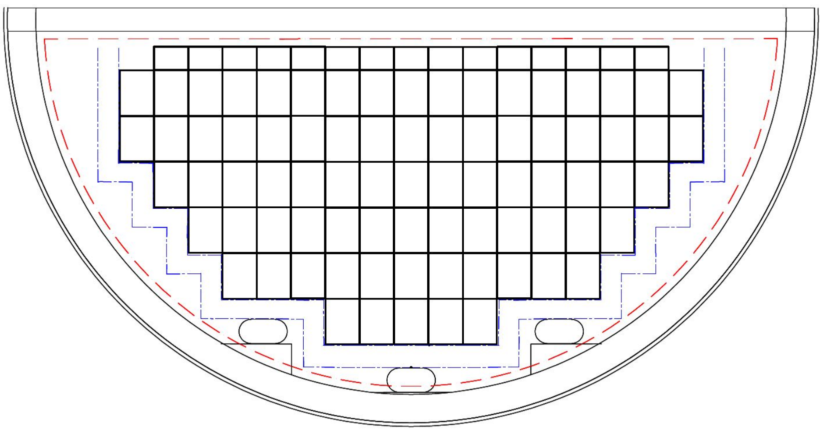


Figure 7.4: Integration of lithium modules including shock free battery compartments

Electrical abuse is prevented by the SCU, MCU and BMS. Short circuit protection in the SCU will prevent electric abuse caused by an external short circuit. Furthermore, the MCU will prevent over discharging and over charging of the battery cells. The risk of thermal abuse is reduced by an active thermal management system using liquid cooling. Furthermore, the MCU will monitor the cell temperatures. When cell temperatures reach dangerous values, for example due to high discharge currents, the BMS can decide to switch off certain strings.

A battery cooling system is required to perform liquid cooling. Not only the battery cells require cooling, also the SCU requires cooling of the integrated short circuit protection. In the MORAY design, a liquid cooling system is used as well. The required cooling capacity is calculated and compared with the MORAY battery cooling system design. This will give inside in weight, volume and power consumption of the required cooling system.

The power loss per battery cell can be calculated with equation 7.1.

$$P_{loss} = I_{dis}^2 \cdot R_I \tag{7.1}$$

In this equation I_{dis} is the discharge current per cell and R_I the internal resistance of a cell. The power loss per cell is equal to the produced heat. The required cooling capacity is equal to the sum of the power losses of all cells. The required cooling capacity is determined for the maximum discharge current of 6000 A. The discharge current per battery cell is depending on the amount of battery cells switched in parallel. Both the forward and torpedo room battery compartments have the least amount of battery cells in parallel. Therefore, the required cooling capacity is calculated for these two battery blocks. The input and the results of the power loss calculations are shown in table 7.4. The 200 Ah high energy cell of Kokam is used as reference for the internal resistance of the LIB cells [22]. The heat losses of the MORAY batteries block is calculated as well and is also shown in table 7.4. The total heat loss of smallest battery block in the concept design is 3.98 kW, which is low compared with the heat losses of the MORAY battery. The difference is caused by the large amount of strings in parallel, which lowers the maximum discharge current per cell drastically.

Table 7.4: Input and results of battery heat losses calculations

	Concept	MORAY	
I_{dis} battery block	6000	6000	[A]
Number of strings	440	1	
I_{dis} cell	13.64	6000	[A]
R_I	0.45	0.035	[mΩ]
P_{loss} cell	0.084	1260	[W]
P_{loss} battery block	3.98	264.6	[kW]

The battery cooling system of the MORAY design is dimensioned for a five hours discharge rate. The cooling system of the MORAY has a cooler with a capacity of 40 kW and a cooling water pump with a capacity of 42 m^3/h. The capacity of the cooler and the capacity of the cooling water pump is more than sufficient to cool the 3.98 kW heat generated by the battery cells. However, a surplus in cooling capacity is preferable to have a cooling margin and to be able to limited the speed of thermal runaway propagation from module to module in the case of large scale thermal runaway. Furthermore, the SCU needs to be cooled as well and the internal resistance of the cooling water piping is expected to increase significantly. This is caused by an increase in piping length, a decrease in diameter and an increase in the number of corners. Therefore, a decrease in cooler and pump capacity is not expected to be possible. The original cooler and pump are used as reference in the concept design.

The taken safety precautions cannot decrease the risk of thermal runaway to zero. Therefore, the effect of thermal runaway occurrence must be limited. When thermal runaway occurs, the battery cells will vent toxic, flammable and explosive gasses. The margins taken between the modules will enable the modules to vent its gasses safely into the battery compartment. Safe venting of the modules is required to prevent the pressure in the modules to reach high values, which can cause them to expand or explode. The battery compartments will be designed gas tight and pressure resistant. The gas tight battery compartment design will prevent toxic gasses to enter the submarines atmosphere. The risks of fire and explosion of the vent gasses can be eliminated in two ways; the use of Halo 1301 when cell venting occurs or the creation of oxygen free battery compartments with inert gas. Both methods eliminated the risks of fire and explosion, but create other risks as well. Halon 1301 is relatively safe, but can cause safety risks at overexposure or exposure at high concentrations. The most significant response under overexposure circumstances is central nervous system depression [47]. Therefore, the risks of Halon leakage need to be minimized when used. The creation of oxygen free compartments with the use of inert gasses brings other risks. Inert gasses themselves are not toxic, however an inert gas leakage can cause a quick drop in oxygen level. This is very dangerous, especially in the relatively small enclosed volume of a submarine. Using inert gas is only required after the installation of the battery modules. So, no inert gas systems are required on board. This will limit the risks of inert gas leakage to battery compartment leakages. The creation of oxygen free compartments is the most reliably option to prevent fire and explosion. However, the gas tight battery compartments are of great importance.

The afore mentioned safety measures will limit the safety risks for the platform and crew, but will not prevent thermal runaway propagation in the battery compartment. Even without catching fire, the cells can still produce enough heat to cause thermal runaway in neighbouring cells and modules. This will eventually cause large scale thermal runaway. A surplus in cooling capacity and heat barriers installed on module level can reduce the speed of thermal runaway propagation. For example, heat reflecting materials can be used in the module designs to limit thermal runaway propagation from module to module. If large scale thermal runway occurs, the pressure in the battery compartments will rise. This will be caused by the large amount of released vent gasses. Research showed that pouch cells will vent approximately 0.33 litre per Watt-hours when thermal runaway occurs at a 100% state of charge [8]. Table 7.5 shows the amount of produced vent gas during large scale thermal runaway in forward battery compartment.

Table 7.5: Vent gas production during large scale thermal runaway in forward battery compartment

Vent gas production	0.33	[l/Wh]
Installed battery capacity	26.4	[MW]
Produced vent gas	8703	[m^3]
Battery compartment volume	155	[m^3]

The amount of produced vent gas is several times as high as the battery compartment volume. This will, together with an increase in temperature, lead to a pressure increase. This pressure increase can be estimated with the use of the ideal gas law. The amount of moles per volume unit vent gas is calculated with the use of the vent gas composition (shown in appendix F). The temperature increase is depending on the speed of the thermal runway propagation and heat transmission of the battery compartment. This is an unknown factor. Therefore, the battery compartment temperature is made variable during the pressure calculations. The compartment pressure, after a large scale thermal runway event, is shown in figure 7.5.

It will not be feasible to create a pressure resistant battery compartment, which will be able to withstand the pressure increase more than 60 bars. An overboard vent option will be required to prevent too high battery compartment pressures. The battery compartments need to be designed to withstand a pressure increase, so compartment venting at a save depth is possible. Thermal runway will always start on a small scale. This will provide the submarine

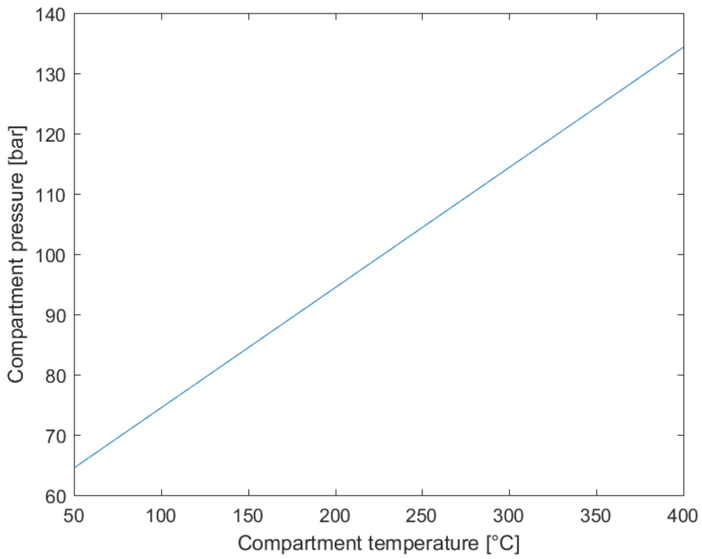


Figure 7.5: Expected pressure increase in battery compartments due to large scale thermal runaway

enough time to safely reach a depth in which overboard venting is possible.

Reliability

The reliability of the total battery system is high. The main battery blocks are integrated in four separate battery compartments. This will prevent thermal runaway propagation between battery blocks. The creation of more separate battery blocks is easily possible, due to the string based design. However, this will result in capacity loss of approximately 960 kWh per extra separation. Four separate battery blocks provide already a higher reliability than the MORAY battery design, so the creation of extra compartments is not necessary. Except from the redundancy between the battery blocks, each battery block itself will also have multiple levels of redundancy. Active cell balancing in each battery string will reduce the effect of a poor performing battery cell. When one or multiple battery cell are failing completely, the SCU can switch of the battery string. This will reduce the capacity of the total battery with 60 kWh, but it will remain operational. The large amount of battery strings will provide a large redundancy per battery compartment. The redundancy between the battery compartments and the multiple levels of redundancy per compartments will provide a highly reliable energy supply.

7.5 Weight, stability and trim

This paragraph will discuss the weight, stability and trim characteristics of the concept design. Furthermore, these characteristics will be compared with the characteristics of the MORAY design.

The weight balance of both the MORAY and concept design are shown in table 7.6. The different weight components are shown on SWBS group level. Most weight changes are already discussed in paragraph 6.1. However, some unforeseen weight changes have occurred during the design process. Furthermore, the new battery system is integrated and included in the weight balance. Likewise, all weight components received a new VCG and LCG based on the new arrangement. The unforeseen weight change of the hull structure group and the weight of the battery system will be discussed shortly.

The biggest unforeseen weight change is in the component hull structure. Three different components contributed to this change. Firstly, the soft tank area reduction was less than

Table 7.6: Weight balance of MORAY and concept design

	Total of SWBS groups	MORAY Weight [t]	MORAY VCG [m]	MORAY LCG [m]	Concept Weight [t]	Concept VCG [m]	Concept LCG [m]
100	Hull structure	581	3.51	34.77	572	3.54	35.44
200	Propulsion plant	427	2.53	31.68	621	2.06	33.80
300	Electrical plant	21	4.22	32.42	21	4.24	32.19
400	Command and surveillance	44	6.10	44.09	44	5.58	43.57
500	Auxiliary systems	106	4.52	31.46	108	4.70	33.43
600	Outfitting and furnishings	49	4.14	39.70	50	4.11	32.53
700	Armament	68	2.55	57.42	68	4.21	57.42
F	Variable loads	507	2.69	37.37	320	3.09	39.40
M	Margins and ballast status	102	1.87	34.74	102	1.87	20.54
	Total	1905	3.09	35.70	1905	3.05	35.52

expected. This is caused by the tanks around the torpedo battery compartment, which need to be built in a difficult shape (see figure E.2 in appendix E.1). Secondly, an increase in deck length was required. In the MORAY design, the deck of the engine room consisted out of DG-sets foundations and the tank top of the fuel tanks. Therefore, this weight component was under the weight groups propulsion plant support structure and soft tanks. In the concept design, a new deck is created in the old engine compartment. This needs to be included in the weight balance. This weight component was scaled based on deck length. Lastly, the battery foundations were not taken into account in the pre-design analysis. In the MORAY design, the batteries are placed on a stiffened tank top. In the concept design, a tank top will not be present in most battery compartments. Therefore, a structure must be created to place the modules on. This weight post is estimated, based on the required support structure area. In total, this leads to a weight increase of 41 tons compared with the pre-design analysis.

The new battery system has a weight of 517 tons. The total system consists of the lithium modules, SCUs and a battery cooling system. The weight of the battery modules is based on the module dimensions and the estimated lithium module density of 1570 kg/m^3. The assumption is made that the SCUs will have the same density as the lithium modules. The total weight of installed lithium modules is 473 tons and the total weight of the installed SCUs is 38 tons. The weight of the battery cooling system is based on the original cooling system of the moray. The weight of the equipment is kept similar and the weight of the cooling water piping is scaled, based on the increase in battery compartment length. In total, the battery cooling water system is estimated at 6 tons.

During the design process, there is established that the design of an entirely battery powered submarine is indeed volume critical. However, the available space is used less efficient than in the MORAY design. This is mainly the case in the battery compartments, where the placing of the modules is limited by the hull shape and frames. These locations are normally used for tanks. However, the required tank capacity for an entirely battery powered design is low. So, the space around the hull frames cannot be used efficiently. In total 65.5 tons of lead ballast is required to reach a natural buoyant state. This is coincidentally the same amount of lead ballast as was required in the MORAY design. However, the stability limitations are different. The results of stability calculations of the MORAY and concept design are shown in table 7.7 and 7.8. The MORAY design meets its stability requirements exactly, as can be seen in table 7.7. This indicates that the amount of installed lead ballast was required to be able to meet the stability requirements. In the concept design, this is not the case. A stability margin of four centimetres is available in the concept design. Therefore, an increase in weight could be possible

Table 7.7: Submerged stability MORAY and concept design

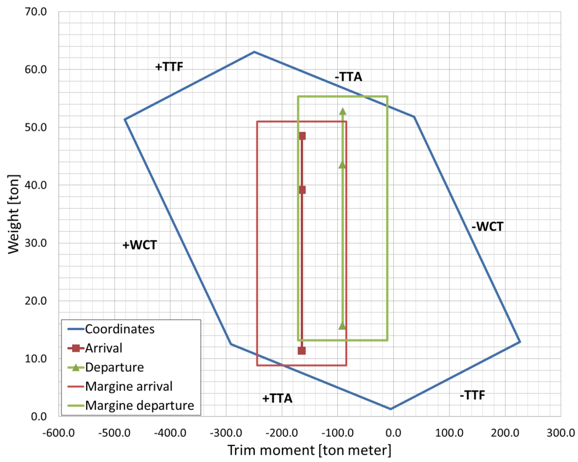
	MORAY	concept	
KB	3.39	3.39	[m]
KG	3.09	3.05	[m]
BG	0.30	0.34	[m]
Required BG	0.30	0.30	[m]

Table 7.8: Surfaced stability MORAY and concept design

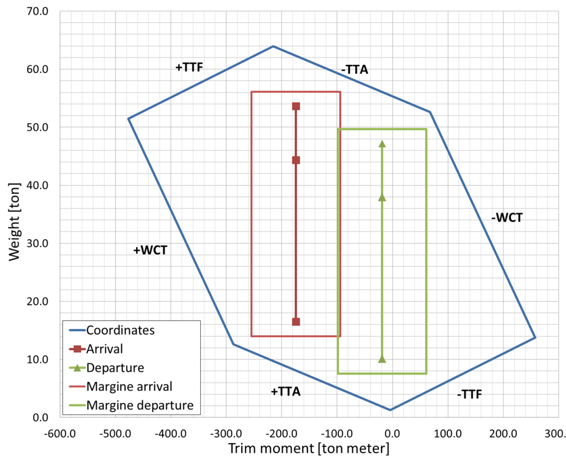
	MORAY	Concept	
KM	3.26	3.26	[m]
KG	3.00	2.93	[m]
GM	0.26	0.32	[m]
Required GM	0.20	0.20	[m]

without getting stability problems. This also means that a larger battery capacity could be installed, if more space was available.

The trim and the weight compensation capacity are checked with the use of a trim polygon. The trim polygons, of both the MORAY and concept design, are shown in figure 7.6. Figure 7.6b shows that the concept design will meet its trim and weight compensating criteria. This is achieved without changing the capacity of the weight compensation tank (WCT). The capacity of both the forward trim tank (TTF) and aft trim tank (TTA) are slightly increase. This was easily possible, due to the limited amount of required tank volume.



(a) Trim polygon MORAY design



(b) Trim polygon concept design

Figure 7.6: Trim polygon of MORAY and concept design

What stands out when comparing the trim polygon of the MORAY and concept design, is that the shape of the trim polygon fits the trim and weight compensation requirements of the concept better than the MORAY. The shape of the trim polygon of the MORAY design can be explained. The MORAY design is prepared for the addition of a modular AIP section, which would be placed between the engine room and the MEM room. When this section is added, the shape of the trim polygon would match the trim and compensation requirements. Another thing that stands out, when comparing the trim polygon of the MORAY and concept design, is that the location of the arrival and departure coordinates have been switched. For the MORAY design, the required weight compensation capacity for departure condition is higher than for the arrival condition. This is caused by the compensation of fuel in the fuel tanks. Sea water has a higher density than fuel, therefore the required weight compensation capacity is less in arrival condition. In the concept design, no fuel is used. So, the difference between the arrival and departure condition is only caused by the consumption of consumables. This also increases the difference in required weight compensation capacity between the arrival and departure condition, which increases the total required weight compensation capacity. Furthermore, the required trim moment of the concept design is increased compared with the MORAY design. This is caused by the relocation of the stores, which are placed further from the LCB.

A large amount of lithium modules are placed in the concept design. The weight of the lithium modules is based on the expected density of lithium modules. However, the density of lithium modules has an uncertainty. Therefore, the sensitivity of the module density on the concept design is analysed. In this analysis, the effect of the module density on installed battery weight and the required lead ballast are determined. This is also translated into an installed battery capacity. A stability and trim stability check is performed, to determine possible trim or stability limitations. During this analysis, the total installed battery volume and the specific energy of lithium modules are kept constant. Keeping the specific energy constant makes an estimation of the installed battery capacity possible. The result of the sensitivity analysis is shown in figure 7.7.

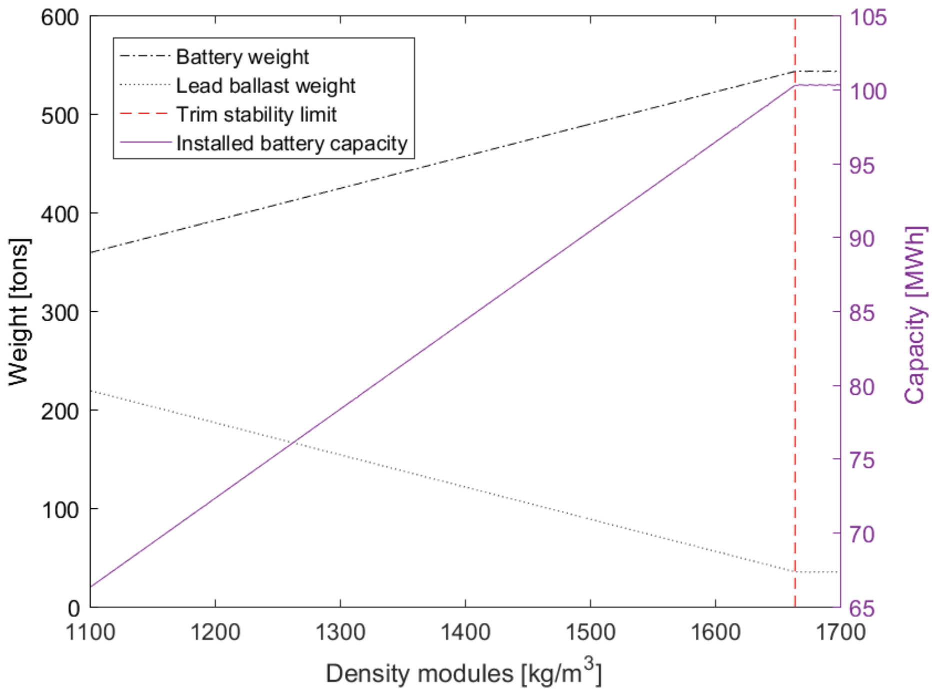


Figure 7.7: Sensitivity of lithium module density on concept design

The possible installed battery weight and capacity drops significantly when the module density drops. This is as expected, due the volume critical design. The densities are given up to a density of 1100 kg/m^3, which is the lower limit of most commercial lithium modules [9, 23]. At a module density of 1665 kg/m^3, a trim stability limit would be reached in the current design. To overcome the trim stability limit, a rearrangement would be required to increase the installed battery capacity. If a rearrangement is made, the weight limit would be reached at a module density of approximately 1770 kg/m^3.

7.6 Electrical load balance

The redesign of the MORAY design in an entirely battery powered submarine design changes the electric load balance. This change is caused by the removal of the DG-sets and replacement of the lead-acid batteries with LIBs. An overview of the electric load balance of the concept design is shown in table 7.9. In the electrical load balance, different auxiliary load states are shown. Each operational state has an influence on the load factor of the systems. The difference with the MORAY design is shown in this table 7.9 as well. The reason of the changes in the electrical load balance will be shortly discussed.

Table 7.9: Electrical load balance concept design

		Patrol Deep			Surfaced		
	Installed	Survival	Minimal	Nominal	Minimal	Nominal	
115V-60HZ	73.8	13.12	19.53	41.3	24.42	43.85	[kW]
440V-60Hz	161.12	17.63	55.59	59.57	71.47	78.31	[kW]
115V-400HZ	16.09	1.81	1.81	1.81	5.64	5.64	[kW]
DC 300-600V	356.4	17.3	18.4	34.04	29.68	76.78	[kW]
Concept total	608.41	49.86	95.33	136.72	131.21	204.58	[kW]
Total MORAY	647.06	50.52	100.19	146.98	132.01	203.88	[kW]
Difference	-5.97%	-1.31%	-4.85%	-6.98%	-0.61%	0.34%	[kW]

Due to the implementation of the new propulsion plant, the systems shown in table 5.1 are removed from the load balance. There are also two new components added to the load balance; the LIB control units and an exhaust air fan. The LIB control units (MCU and SCU) will have a low energy consumption and will be fed directly from the battery pack. All LIB control units together are expected to have an energy consumption of 2 kW. They will be required during all operational states. A reservation of 1.5 kW is made for the installation of an extra exhaust air fan. This might be required due, to the change in the ventilation system. This will only be required during the surfaced operational states.

The concept power plant will have a lower auxiliary power load all submerged operation states. During the minimal surfaced state, the decrease is very small. There is even a small increase during the nominal surfaced state. This can be explained. During surfaced sailing the DG-sets pre-heaters are not used in the MORAY design. The DG-sets are running, so they do not have to be pre-heated. Furthermore, the fresh water circulation pump for DG-sets is not required during surfaced sailing. The DG-sets cooling water system will ensure the water circulation. The DG-sets cooling water system, and other DG-sets support systems, are not present on the electrical load balance. They will be directly driven by the DG-sets and are included in the efficiency of the DG-sets.

7.7 Conclusion

A concept design is created, which meets all design criteria. The concept design has all manned spaces on the same deck level. The battery compartments are located in the bottom of the submarine and they are distributed over the total length. The battery design is a string based design, in which each string provides the required operational voltage. Each string is connected to the battery block via a SCU. The SCU can switch of the battery string and includes short circuit protection. An installed battery capacity of 88.5 MWh is achieved for the concept design.

Creating a safe battery design is the most challenging part of the integration of LIBs. Several safety precautions are required; a good battery controlling and monitoring system (including MCUs, SCUs and a BMS), a thermal management system, short circuit protection and shock protection. If thermal runaway occurs, the impact on the safety of the submarine can be limited by; a gas tight, oxygen free or Halon 1301 protected and pressure resistant battery compartment designs. Large scale thermal runaway will cause the pressure in the battery compartments to increase above 65 bar. An overboard vent option will be required to prevent too high pressures in the battery compartments.

The design of an entirely battery powered naval submarine is volume critical. The total available volume can be used less efficiently than in diesel-electric submarine designs. This is caused by the limited packing of lithium modules in submarine hull, due to the hull shape and submarine frames. Therefore, optimizing of the size and energy density of the lithium modules is of importance to maximize the installed battery capacity. An entirely battery powered submarine is expected to become weight critical from a module density of approximately 1770 kg/m^3. Stability is not expected to be a problem in an entirely battery powered submarine. This is mainly caused by the large amount of relatively heavy and low placed battery modules. The required weight compensation capacity of an entirely battery powered submarine will be higher than a diesel-electric submarine. This caused by the absence of fuel compensation in fuel tanks, which has a limiting effect on the required compensating capacity of a diesel-electric submarine. During submerged sailing, the auxiliary load of an entirely battery powered submarine will be five to seven percent less than a diesel-electric submarine. During surfaced sailing, the auxiliary load is comparable with a diesel-electric submarine.

Chapter 8

Operational capabilities study

This chapter will describe the operational capability study of the concept design. The feasibility of an entirely battery powered concept design will be strongly depend on its operational capabilities. The operational capabilities are determined in two ways; by determining the maximum range and endurance and by analysing possible mission profiles. The results will be compared with the MORAY design. This will provide insight in the differences in operational capabilities compared with diesel-electric submarines.

Furthermore, a design variation with a modular lithium-ion section will be introduced. This design variation will be used to compare the operational capabilities of an entirely battery powered design with a diesel-electric design with AIP.

8.1 Power plant model

During the operational capabilities study a submarine propulsion plant model is used. The submarine propulsion plant model is created by L.P.W. Rietveld [39]. This Matlab/Simulink model is based on first principles and is originally intended for optimization of diesel-electric propulsion plants. The model is adjusted, so that it can be used for the operational capabilities study of the entirely battery powered submarine. The models of the different propulsion plant components are not changed, only their arrangement and the equipment parameters. This enables the use of the model, without the need of extensive validations.

In the propulsion plant model, the propulsive load characteristics of the MORAY design are used as input. These are the same as the concept design, because the same hull dimensions are used. Figure 8.1 shows the required shaft power during both submerged and surfaced sailing. The values of table 7.9 are used for the auxiliary load characteristics.

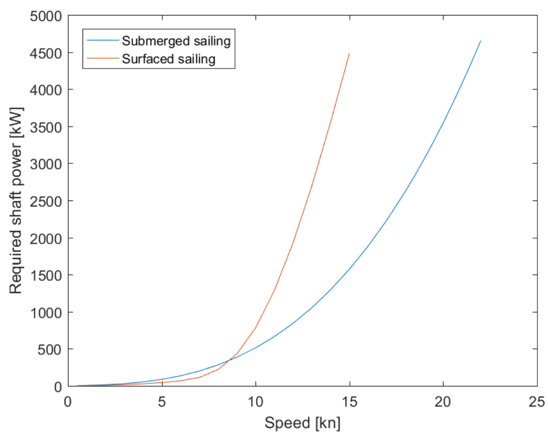


Figure 8.1: Required shaft power during submerged and surfaced sailing

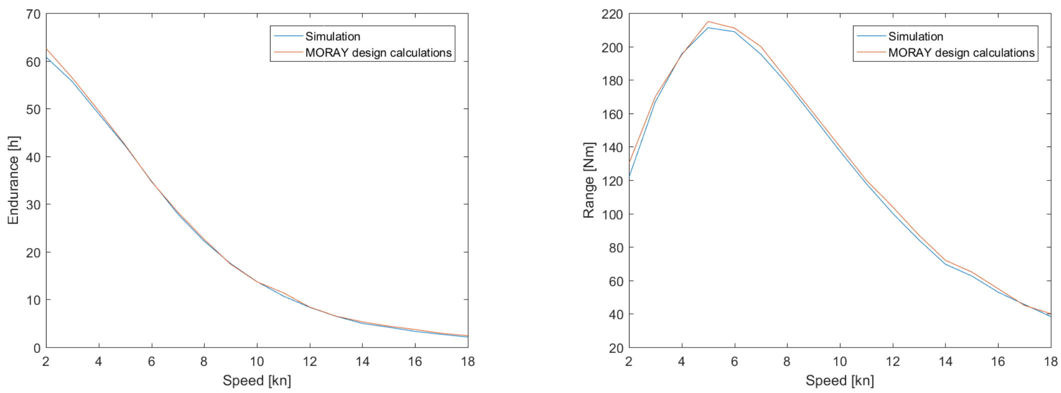
Switchgear settings, battery parameters and MEM parameters are adjusted in the power plant model. The switchgear settings are adjusted to the switchgear settings of the MORAY design, because the same battery voltages and the same MEM are used in the concept design. The switchgear settings are shown in table 8.1. During the deadslow speed range, the armatures will be supplied by an armature chopper to be able the control the voltage. Furthermore, shunt field choppers are present to make speed control possible.

Table 8.1: Switch gear settings

Speed	Armature [V]	Power [kW]	Method of operation
Deadslow	217-192	14-52	batteries parallel, armatures series
Slow	216-189	52-281	batteries parallel, armatures series
Cruise	429-355	281-1571	batteries parallel, armatures parallel
High	826-683	1571-2630	batteries series, armatures parallel
High	771-677	3550	batteries series, armatures parallel
High	745-730	4360	batteries series, armatures parallel

In the MEM model, the rotor length is the only variable parameter. The MEM rotor length is adjusted to match the power output of the MEM used in the MORAY design. A rotor length of 1.49 meters is used to achieve the maximum power output of 4360 kW.

Both the switch gear settings and the MEM model are validated with the use of the submerged range and endurance calculations of the original MORAY design. The submerged endurance and submerged range are specified as the time between snorkelling periods. In the power plant model of L.P.W. Rietveld, the MORAY lead-acid batteries are used as reference. Therefore, the battery parameters do not have to be adjusted before the validation. The results of the validation are shown in figure 8.2.



(a) Submerged endurance

(b) Submerged range

Figure 8.2: Validation of MEM performance and switchgear settings

The results of the power plant simulation matches the original MORAY design calculations, as can be seen in figure 8.2. Small differences can be noted in the figure 8.2a and figure 8.2b. However, these can be explained by the simplifications made in the original design calculations and possible measurement errors (no digital results of the original MORAY design calculations are available). In the MORAY design calculations, the cell voltage and internal resistance are stepwise approached. This simplification is not made in the power plant model, which might cause small differences in calculation results.

In the original power plant model of L.P.W. Rietveld, 200 Ah NMC lithium cells of Kokam are used as reference. The storage capacity (Ah/kg) of the reference battery cell will be scaled to match the Kokam 150 Ah ultra high energy cell. This cell has a higher specific energy and a higher energy density than the 200 Ah Kokam cell. The cell parameters of both the 200 Ah high energy cell and the used 150 Ah ultra high energy cells are shown in table 8.2.

Table 8.2: Lithium battery cell parameters [22, 24]

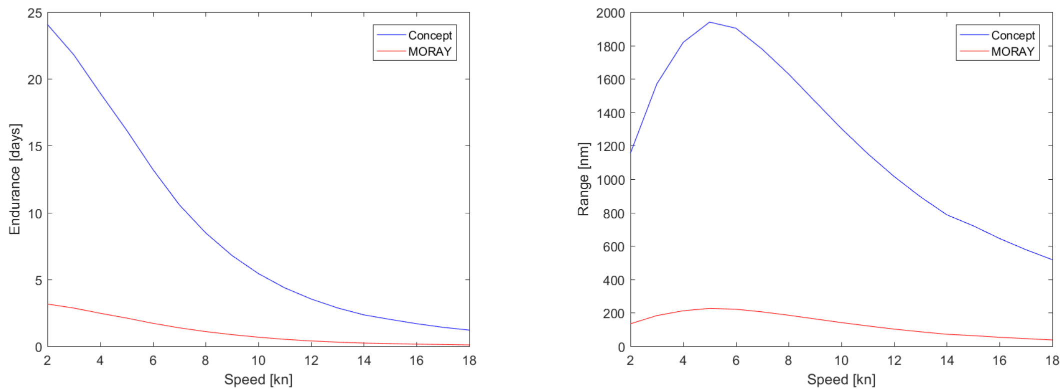
		200 Ah high energy cell	150 Ah ultra high energy cell	
m	Battery mass	4.2	2.12	[kg]
c_∞	Capacity at 100 h discharge time	51	76.5	[Ah/kg]
c_5	Capacity at 5 h discharge time	47.6	71.4	[Ah/kg]
c_0	Capacity at 1.2 h discharge time	45	67.5	[Ah/kg]
$U_O(0.0)$	Open cell voltage fully charged	4.2	4.2	[V]
$U_O(0.7)$	Open cell voltage at 0.7 DoD	3.6	3.6	[V]
$U_O(1.0)$	Open cell voltage fully discharged	3	3	[V]
-	Energy density	356	505	[Wh/l]
-	Specific energy	176	261	[Wh/kg]

8.2 Range and endurance

The power plant model is used to determine the range and endurance of the concept design. The nominal auxiliary power is used during the simulations, unless stated otherwise. Furthermore, in all simulations the batteries are discharged from a DoD of 0.0 to a 0.9 pseudo DoD. The pseudo DoD indicates the DoD relative to the capacity at the given discharge current. At a pseudo DoD of 1.0, the battery is unable to discharge further at that specific current. However, the battery can be discharged further if one is prepared to lower the current. A pseudo DoD is also used during the original calculations of the range and endurance of the MORAY design, which will be used as comparison in this paragraph.

Range and endurance concept design

The results of the range and endurance calculations are compared with the range and endurance of the MORAY design. This gives an indication of the operational performance of the concept design. Figure 8.3 shows the submerged range and endurance of both the concept and MORAY design.

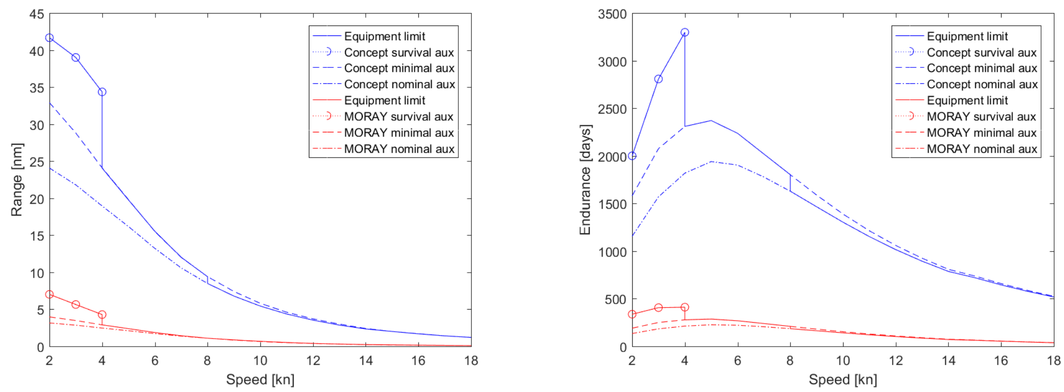


(a) Submerged endurance (b) Submerged range

Figure 8.3: Submerged endurance and range of concept and MORAY design

The maximum submerged endurance of the concept design is 24 days, which is 7.6 times higher than the MORAY design. The maximum submerged range of the concept design is determined to be 1940 nautical miles, which is 8.6 times the maximum submerged range of the MORAY design. The maximum submerged endurance is achieved at a speed of five knots. At this speed, there is an optimum between the propulsive and auxiliary power load. The difference between the concept and MORAY design increases with increasing speeds. This is caused by the difference in battery performance at high discharge currents. LIB perform better at high discharge currents than lead acid batteries, as discussed paragraph 4.3. At a speed of 18 knots, the submerged range and endurance of the concept is 13.9 times as high as the submerged range and endurance of the MORAY design. This clearly shows the difference in battery performance at high discharge currents.

At the low speeds ranges, the auxiliary power load is relatively high compared to the propulsive power load. For example, at a speed of two knots the propulsive load is 14 kW and the nominal auxiliary load is 137 kW. Therefore, the range and endurance are strongly dependent of the auxiliary load during slow speeds. The different auxiliary load states of the electrical load balance (see table 7.9) are used to indicate the influence of the auxiliary on the submerged range and endurance. The results of this analysis are shown in figure 8.4.



(a) Submerged endurance

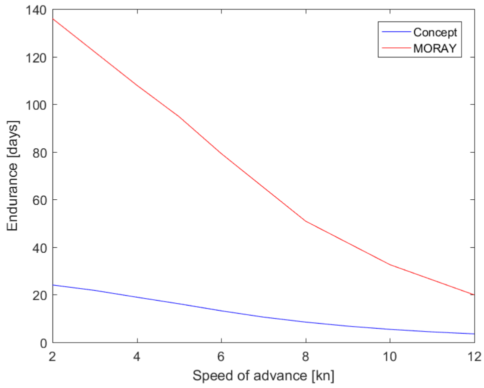
(b) Submerged range

Figure 8.4: Influence of auxiliary load on submerged endurance and range

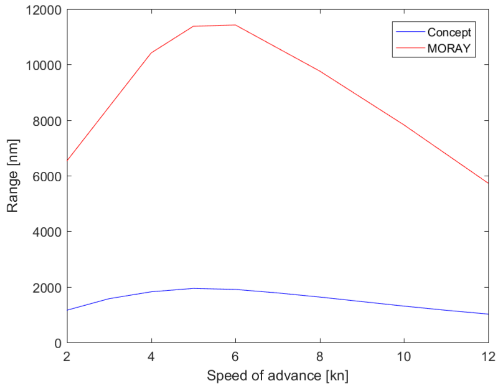
Figure 8.4 clearly shows the influence of the auxiliary load. The maximum achievable endurance and range can be stretched to 42 days and 3300 nm, when survival auxiliary load is used. However, this is not realistic for normal operations. The minimal auxiliary load limit is speed dependent. Several auxiliary systems will be required to be able to operate at certain speeds. For example at the survival auxiliary load, the field chopper cooling fans will be disabled. However, for speeds above four knots the field choppers need to be cooled otherwise they will overheat. This limits the minimal auxiliary load. An indication of this limit is given with solid lines in figure 8.4.

The feasibility of an entirely battery power concept design will depend on the total achievable range and endurance. The total achievable range and endurance of the concept design are equal to the submerged range and endurance. The range and endurance are compared with the total range and endurance of the MORAY in figure 8.5. The range and endurance of the MORAY design is determined for a ratio of one to one for snorkelling speed and submerged speed, which is an optimum with respect to the indiscretion ratio (IR). The total range and endurance calculations are limited to twelve knots, because at higher speeds the drag force on the mats becomes too high.

Figure 8.5 shows that there is a big gap between the maximum achievable range and endurance. The maximum achievable range and endurance of the MORAY design is 5.6 times as high as the concept design. This ratio between the concept design and MORAY design is



(a) Total endurance

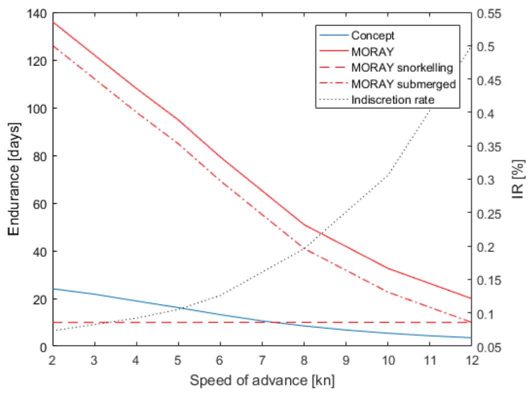


(b) Total range

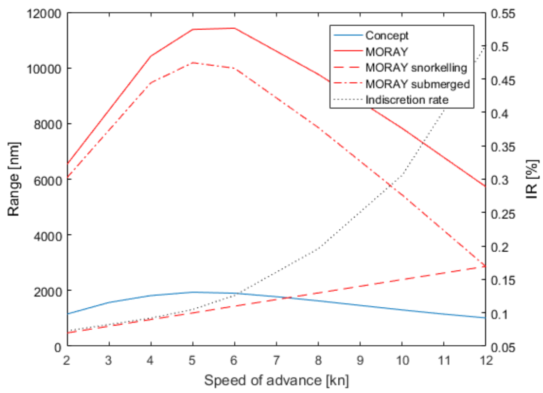
Figure 8.5: Comparison of endurance and range of concept and MORAY design

almost constant for the total speed range. Only above eight knots the difference is reduced slightly, caused by a resistance increase due to wave making resistance and a larger influence of the difference in battery performance. From the results of figure 8.5 can be concluded that an entirely battery powered submarine is currently not an option for independent ocean going mission profiles. The range and endurance are too low.

The total range and endurance of the MORAY design consists out of a snorkelling part and submerged part. High percentage of snorkelling time makes a submarine vulnerable. Therefore, the total range and endurance of the MORAY design are subdivided in submerged and snorkelling components in figure 8.6. This provides inside into the tactical advantages the entirely battery concept might have relative in comparison with diesel-electric submarines.



(a) Total endurance



(b) Total range

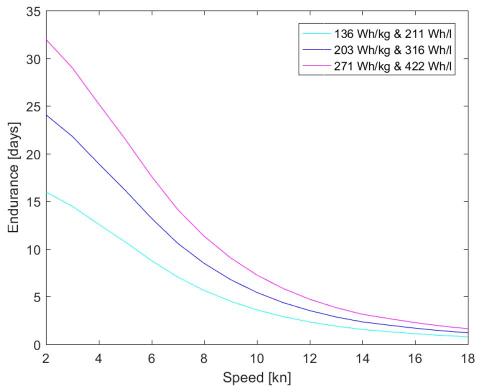
Figure 8.6: Comparison total endurance and range and tactical advantages

The indiscretion rate of the MORAY design is relative low and constant at the low speed range, which is a result of the shape of submerged resistance curve and the relatively large auxiliary load. Due to the low indiscretion rate, the largest part of total range will be sailed submerged. At higher speeds the indiscretion ratio will increase steeply, due to the quadratic resistance curve and a decrease in battery performance. This means that the submarine will sail a large percentage in snorkelling condition. At a speed of twelve knots, the submerged need to sail as much in snorkelling condition as surfaced condition. At higher speeds of approach, the IR will increase more steeply because the snorkelling speed cannot be further increased. This provides an entirely battery powered submarine tactical advantages when an operational profiles with a relatively small range and high speeds are required.

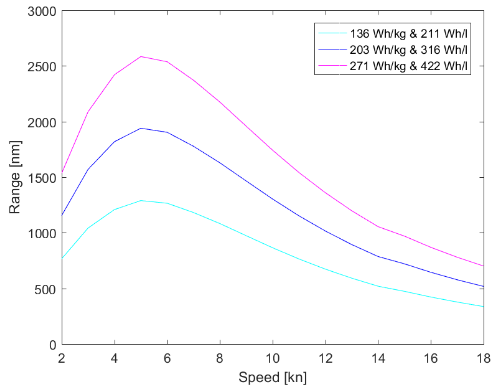
Influence of battery capacity and chemistry

The energy storage capacity of the lithium modules strongly influences the achievable range and endurance of the concept design. Therefore, the influence of the energy storage capacity on the range and endurance of the concept design is determined. This provides insight in the sensitivity of used energy storage capacity. Furthermore, the results can be used to estimate operational capabilities with expected future battery technologies.

The results of the battery capacity analysis are shown in figure 8.7. The dark blue lines in figure 8.7a and 8.7b are the modules used in the concept design. The energy storage capacity of the modules is scaled by increasing/decreasing of the energy storage capacity of the used lithium cells with 50 Ah. This leads to an increase of 33% and a decrease of 50% in energy density and specific energy of the used lithium modules. An increase in 33% in specific energy and energy density is a realistic value for the nearby future, as indicated in figure 1.1.



(a) Submerged endurance



(b) Submerged range

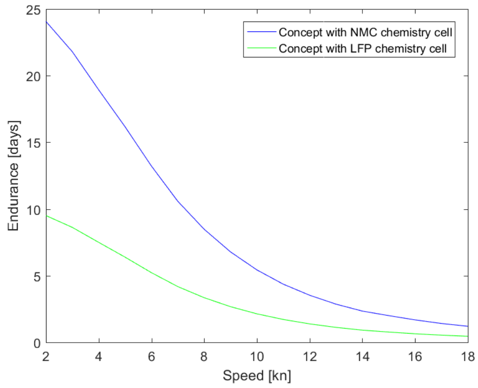
Figure 8.7: Influence of specific energy and energy density on range and endurance

Figure 8.7 shows that the increase or decrease in endurance and range are equal to the increase or decrease in energy storage capacity. This is as expected, because only the energy storage characteristics are scaled. Other battery characteristics, such as battery voltage and the influence of the discharge rate on the capacity are kept constant. A lithium cell with a different cell chemistry is used to investigate the effect of these factors. There is chosen to use a LFP cell for this analysis, because this cell chemistry has the best safety characteristics currently available. The used cell parameters are shown in table 8.3. Due to the lower voltage level of

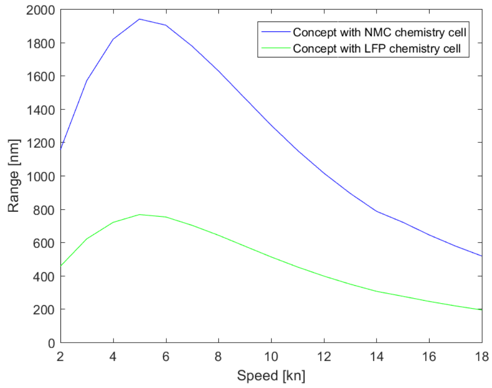
Table 8.3: LFP battery cell parameters [19]

m	Battery mass	6.2	[kg]
c_∞	Capacity at 100 h discharge time	34.7	[Ah/kg]
c_5	Capacity at 5 h discharge time	32.7	[Ah/kg]
c_0	Capacity at 1 h discharge time	31.3	[Ah/kg]
$U_O(0.0)$	Open cell voltage fully charged	3.5	[V]
$U_O(0.7)$	Open cell voltage at 0.7 DoD	3.3	[V]
$U_O(1.0)$	Open cell voltage fully discharged	2	[V]
-	Energy density	147	[Wh/l]
-	Specific energy	100	[Wh/kg]

the battery, more battery cells in series are required. This will reduce the number of cells in parallel, which increases the discharge current per cell. This effect has been taken into account during the analysis. The results are shown in figure 8.8.



(a) Endurance



(b) Range

Figure 8.8: Effect of the use of LFP chemistry lithium cells on range and endurance

The results of figure 8.8 show a large decrease in range and endurance. Therefore, the conclusion can be made that the use of a LFP chemistry cell is not an option for the creation of an entirely battery concept. The improved safety characteristics are at the expense of a large reduction in energy density and specific energy. The decrease in endurance and range is equal to decrease in energy density and specific energy. This is the case for the total speed range. Therefore, there can be concluded that the influence of other battery characteristics than capacity can be assumed negligible. However, this is only the case when comparing large lithium battery packs. In other situations, the influence might be different.

8.3 Feasible operational profiles

The previous paragraph discussed the maximum achievable range and endurance of the concept design at constant load conditions. In reality, this never occurs. The submarine will undergo different load conditions during a mission. These load conditions are translated into a mission profile. In this paragraph, three possible operational profiles are analysed. Furthermore, an analysis of the charge characteristics is made. This will provide insight in the performance during different mission scenarios and possible charging options.

Mission profiles

From the range and endurance analysis in the previous paragraph, the conclusion could be made that independent ocean going missions are not feasible for the concept design. Therefore, three relatively short mission profiles are simulated; a one week mission, a two week mission and a mission with the duration of 23 days. The analysis of these mission profiles will provide more information about the operational capabilities of the concept design.

The one week mission profile is given in figure 8.9. This mission profile has repetitively high speeds and can be seen as a threat interception mission. The period of 12 knots is the repetitively high speed submerged transit towards to potential threat. This is followed up by a surveillance and attack phase. First, slow speed surveillance is executed. Secondly, manoeuvring to an ideal attack position is performed at speeds of 14 knots. This is followed by an attack and lastly a fast gateway to a safe location is performed. The high speed sprint to a save location has a duration of one hour. After the surveillance and attack phase, the submarine will head back to its home port in a submerged transit at a slow speed.

The mission profile of figure 8.9 is translated into propulsive and auxiliary power requirements. The propulsive power requirements are shown in figure 8.10a. The high peaks in propulsive load are corresponding with the high speed periods from the mission profile. The auxiliary

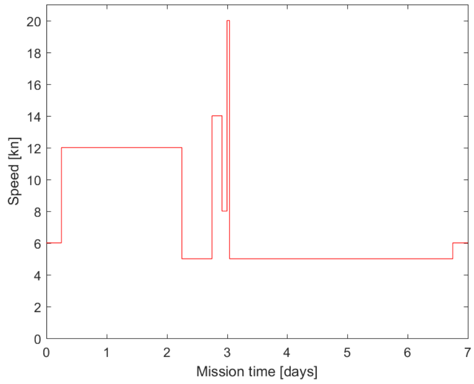
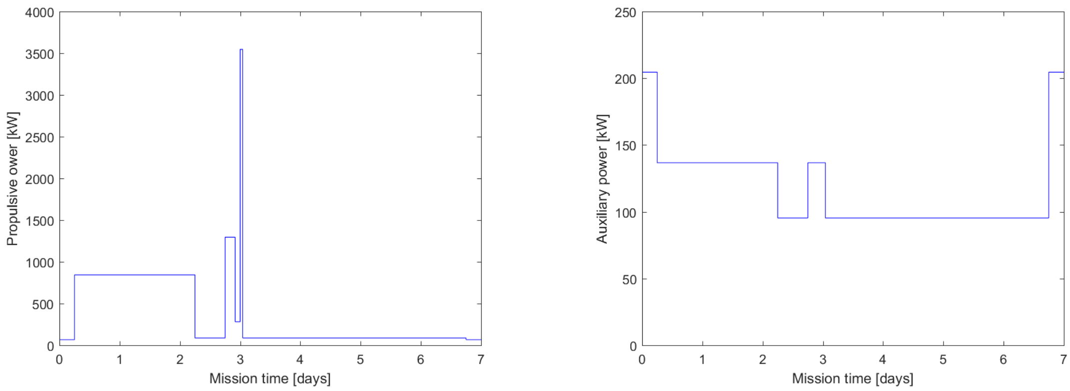


Figure 8.9: Mission profile with a one week duration

power requirements are shown in figure 8.10b. At the beginning and at the end of the mission profile the auxiliary load is high. During these periods surfaced sailing in or out of the harbour is performed. For these periods the nominal surfaced auxiliary load of table 7.9 is used. In the submerged part of the mission, the nominal auxiliary load is used for the high speeds and the minimal auxiliary load is used for the low speeds.



(a) Propulsive power (b) Auxiliary power

Figure 8.10: Power requirements during one week mission profile

The load characteristics of figure 8.10 are used as input for the power plant model. A simulation of the entire mission profile is made with the use of the power plant model. With this simulation, the battery capacity is analysed. The analysis of the battery capacity makes it possible to analyse the feasibility of this operational profile. During this analysis, the batteries are discharged to a maximum DoD of 0.9. The results of the analysis are shown in table 8.4.

Table 8.4: Results of one week mission profile analysis

Duration	7	[weeks]
Travelled distance	1245	[nm]
DoD MEM and aft battery blocks	0.9	
DoD fwd and torpedo battery blocks	0.8	
Remaining battery capacity	5.3	[MWh]

The results in table 8.4 show that this mission profile is feasible. There is a surplus battery capacity of 5.3 MWh. This remaining battery capacity is determined relative to the discharge of all battery blocks to a DoD of 0.9. The surplus in battery capacity would enable the submarine to sail approximately 30 hours at 5 knots. This provides enough margin for this mission profile. In extreme emergency cases to batteries could be discharged completely. This would provide another 9 MWh hour capacity. However, using the last 10% of battery capacity is not preferable with respect to battery lifetime.

The two week mission profile is shown in figure 8.11. This mission can be seen as a surveillance mission. During this mission profile, slower speeds will be used, to be able to achieve a longer endurance. A transit at the speed of 8 knots is performed for approximately 2 days. This will bring the submarine 325 miles from its base. From this moment on the surveillance and attack phase starts. The attack phase is similar to the attack phase during the one week mission profile. After the attack phase, the submarine can continue its surveillance before it will start its slow speed return transit.

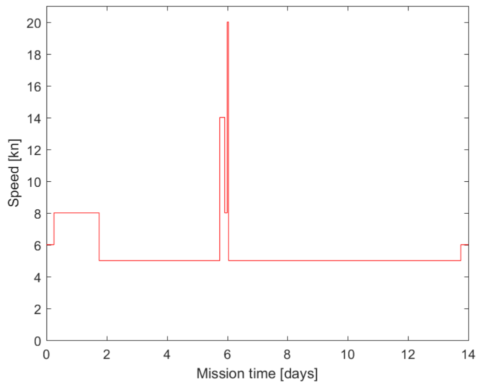
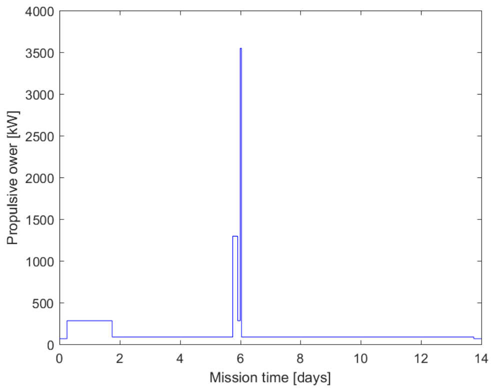
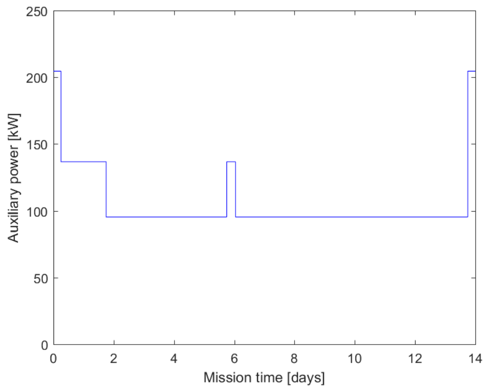


Figure 8.11: Mission profile with a two weeks duration

The power requirements during the two week mission profile are shown in figure 8.12. The auxiliary load is determined the same as for the one week mission profile. At the slow submerged speeds the minimal auxiliary load is used and at high submerged speeds the nominal auxiliary load is used. During surfaced sailing the nominal surfaced auxiliary load is used.



(a) Propulsive power



(b) Auxiliary power

Figure 8.12: Power requirements during two weeks mission profile

This mission profile is used as input for the power plant model as well. The results of the battery capacity analysis are shown in table 8.5. This mission profile is feasible for the concept design. A surplus in battery capacity of 5.8 MWh is available. The surplus in battery capacity would enable the submarine to sail approximately 33 hours at 5 knots. This will, together with the remaining 10% battery capacity in case of emergencies, provide enough margin.

The mission profile with a duration of 23 days is shown in figure 8.6. During this mission

Table 8.5: Results of two week mission profile analysis

Duration	14	[weeks]
Travelled distance	1857	[nm]
DoD MEM and aft battery blocks	0.9	
DoD fwd and torpedo battery blocks	0.79	
Remaining battery capacity	5.8	[MWh]

profile very slow speeds are used. This will enable a maximum mission endurance. The transit speed during this mission profile is five knots. During the surveillance, the submarine will sail at a dead slow speed of two knots. Halfway the mission profile an attack phase will be performed. This attack phase is similar to the attacks phase of the one week and two week mission profiles.

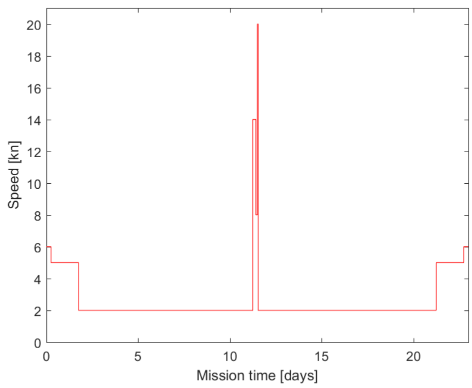


Figure 8.13: Mission profile with a 23 days duration

The mission profile of figure 8.6 is translate into propulsive and auxiliary requirements. This is done using the same methodology as used during the one and the two week mission profile. The propulsive and auxiliary power requirements are shown in figure 8.14.

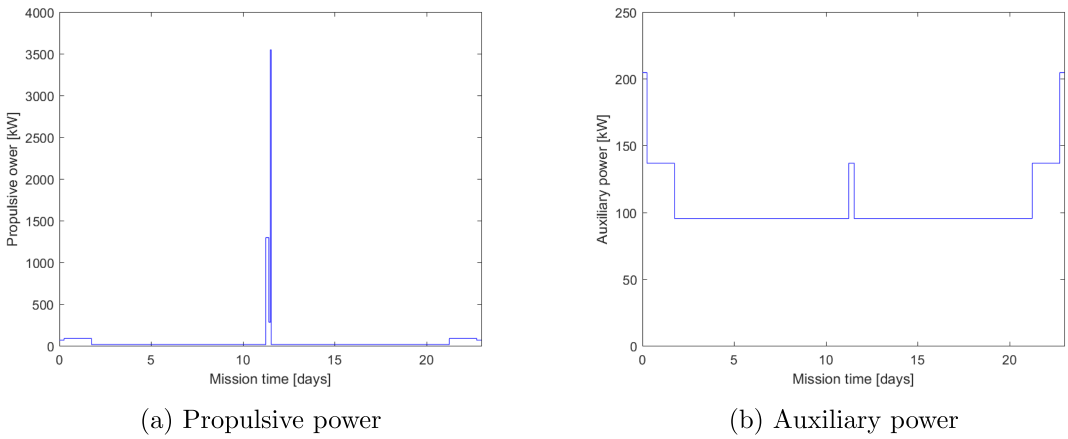


Figure 8.14: Power requirements during a 23 days mission profile

The power plant model is used to determine if the 23 days mission profile is feasible. The results of the power plant simulation are shown in table 8.6. After this mission profile the submarine will have a 5.8 MWh battery capacity remaining, which equal to the remaining battery capacity of the two weeks mission profile. This provides the submarine a marine of 33 hours sailing at 5 knots. Therefore, this mission profile is a feasible mission for the concept design.

Table 8.6: Results of a 23 days mission profile analysis

Duration	23	[weeks]
Travelled distance	1622	[nm]
DoD MEM and aft battery blocks	0.9	
DoD fwd and torpedo battery blocks	0.79	
Remaining battery capacity	5.8	[MWh]

Charge characteristics

The concept design has a large amount of battery capacity installed. This is expected to cause relatively long charge times. The charges characteristics of the concept design are analysed to be able to determine the charge times and charge limitations. Based on this analysis, the feasibility of different charge options can be determined.

The duration of a battery charge is depending on the charge current. In the concept design, the charge current is limited by the current limit of the high current cables and switchgear. This is caused by the large number of battery strings switched in parallel, which limits the charge current per battery string. For example, the forward and torpedo battery compartments each have 440 strings in parallel. Charging each cell on a 1C charge rate (150 A), which is the fastest charge time specified by the manufacturer and enables charging a battery charge in 80 minutes [22], would require 66 kA. This is more than ten times the maximum current of the switchgear and high current cables. The power cables and switchgear are currently designed on the maximum discharge current, which is limited by the MEM on 6000 A.

The power plant model is used to determine the charge time for a range of charge currents. The power plant model is only able to simulate the first charging stage. Therefore, the calculated charge times will be lower than the real charge times. However, the difference is expected to be low. The duration of the second stage charge is depending on the first stage charge current. At a charge rate 45 A, the second stage charge duration is 6.25% of the total charge duration of the [22]. The maximum cell charge rate in the performed calculations is 27 A. Therefore, the results are expected to differ less than 5% than the total charge duration. During the charging simulation, the batteries are charged from a depth of discharge of 0.9. The submarine will still have an auxiliary power consumption during battery charging. Therefore, the minimal surfaced auxiliary power is included in the calculations. The results of the charge duration calculations are shown in figure 8.15.

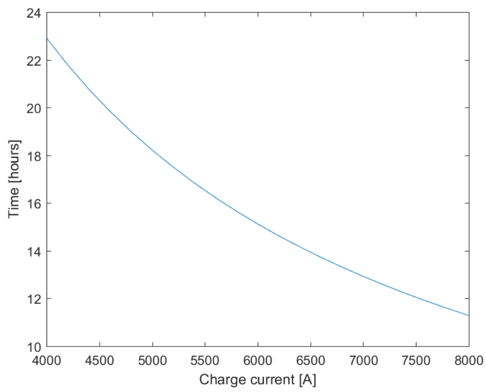


Figure 8.15: Influence of charge current on charge time

Charging the total battery system will take approximately 15 hours at the maximum charge current of 6000 A. Increasing the maximum charge current, by increasing the capacity of the switch gear and power cables, can improve the charge rate. However, this is not interesting when harbour charging is performed. It might become interesting when charging at sea is performed. For example, a support vessel could use their generator power to charge the submarine. This will enable the submarine to achieve a long range and endurance. The charge duration for a range of available generator powers is shown in figure 8.16. For these calculations, the submarine is supposed to have no propulsive power requirements. Furthermore, losses in the long charging cables for the support vessel to the submarine are not taken into account. So, the results of figure 8.16 shows an optimistic view.

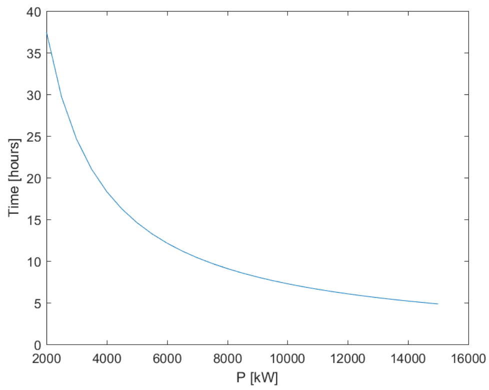


Figure 8.16: Influence of available generator capacity on charge time

The result of figure 8.16 shows that theoretically charge rates of five hours could be achieved when large amount of generator capacity is available. However, this will require high capacity power cables and switchgear. At a generator power of 15000 kW, the batteries will be charged with 17000 A. This would require heavy and large diameter power cables and switchgear, which will result in several problems with the respect to the submarine design and the operational aspect of charging at sea. Therefore, this is not expected to be feasible. The current charge current limit, of 6000 A, will be achieved at a generator capacity of approximately 5000 kW. However, charging at this rate will take 15 hours. This is a long period of charging in which both vessels will be vulnerable.

8.4 Design variation with modular lithium-ion section

A design variation with a modular lithium-ion section is made to investigate the achievable increase in range and endurance by lengthening the submarine hull. Furthermore, the lengthening enables a comparison with the MORAY design version with an additional modular AIP section. This provides insight in the performance on an entirely electric submarine in comparison with a diesel-electric submarine with AIP. Moreover, the performance of a lithium-ion AIP section as addition to a diesel-electric submarine can be determined.

Design of modular lithium-ion section

The MORAY with AIP uses two closed cycle diesel engine (CCD) systems as AIP option. A CCD makes use of LO_x as oxygen supply. The LO_x storage capacity determines the achievable range and endurance of the CCD section. The length of the modular AIP section of the MORAY design is 9.4 meters and is located between the MEM room and the manoeuvring room. The addition of the CCD section increase the submerged weight to 2233 tons. A CCD system has never been sold. However, the energy storage capacity of the integrated system is comparable with AIP systems using fuel cells and a methanol reformer system and a AIP sections using Stirling engines [36]. Therefore, the results of this analysis are also applicable for these two AIP systems, which are currently used in multiple submarines.

The modular lithium-ion section will be made the same size as the CCD section, which enables a fair comparison. The modular lithium-ion section will have its own battery battery support systems. The arrangement of the lithium-ion section can be seen in figure 8.17. A transverse section view of the lithium-ion section can be found in appendix E.2

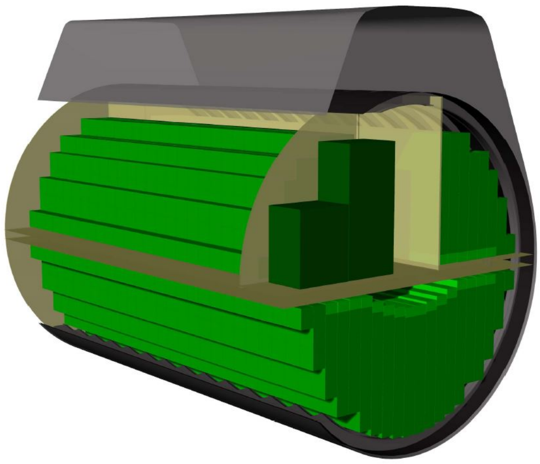


Figure 8.17: Modular lithium-ion section

In the modular lithium-ion section, lithium modules will be placed both below and above the main deck. The battery support systems are placed at the forward side of the section, close to the manoeuvring room. The used modules are the same as used for the concept design. In total 682 battery strings are installed. The total modular lithium-ion section will have an installed capacity of 40.9 MWh. This will increase the installed battery capacity of the concept design with 46%.

A weight estimation is performed to make sure the modular lithium-ion section is not weight critical. The hull structure and deck weight are kept equal to the hull structure and deck weight of CCD section. The weight of the battery system is determined as described in paragraph 7.5. The result of the weight analysis is shown table 8.7. The result shows that a weight margin of ten tons is available. So, the modular section is expected to be volume critical. Adding the modular lithium-ion section to the concept design will influence the stability, trim and required weight compensation capacity. However, this is not expected to cause problems in the concept design and is not examined further.

Table 8.7: Weight estimation modular lithium-ion section

Available for modular section	326	[t]
Hull structure	57.26	[t]
Deck	7	[t]
Battery strings	237	[t]
Battery support structure	11	[t]
Battery support equipment	4	[t]
Weight margin section	10	[t]

Effect on range and endurance

The propulsion plant model will be used to determine the range of the concept design with an addition of a lithium-ion section. The increase in submarine length will have a small effect on resistance of the submarine. This must be taken into account during the simulations. The required shaft power of the MORAY design with CCD section and the original MORAY design are shown in figure 8.18. The auxiliary load of the concept design is assumed not to increase. Therefore, the nominal auxiliary load of table 7.9 will be used during the simulations. The batteries will be discharged to a 0.9 pseudo DoD during the simulations.

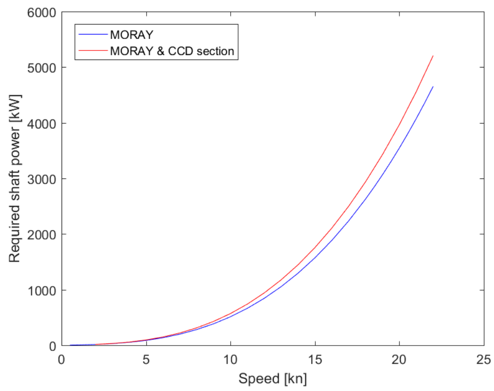
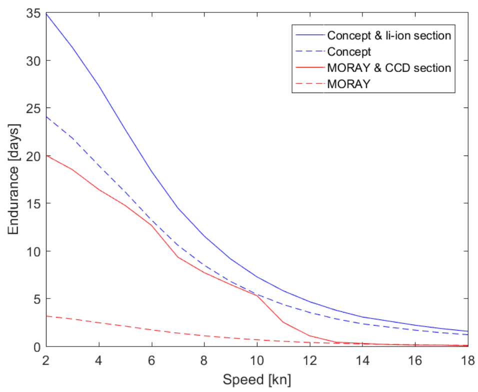
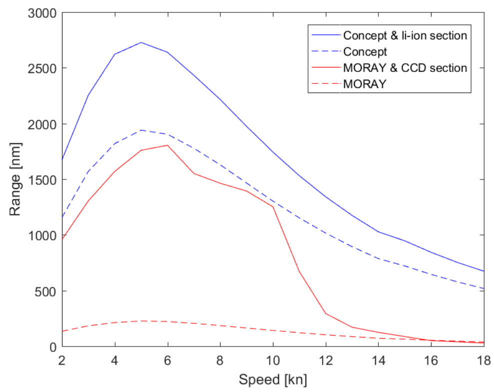


Figure 8.18: Increase in required shaft power during submerged sailing due to addition AIP section

The submerged endurance and range of the concept design with an additional lithium-ion section and MORAY design with additional CCD section are shown in figure 8.19. In this figure, the submerged endurance of the concept design and the MORAY design are shown as well. In the original calculations for the MORAY design with CCD, the CCD is used as the only power provider. This requires the CCD to operate away from its ideal operating point. Using the CCD as switch-on or switch-off system in combination with the batteries would improve the efficiency. Therefore, the results are pessimistic. In figure 8.19, a kink in the line of MORAY with CCD can be seen. This is caused by switching on an extra CCD system to reach the required power output. This influences the load of the CCD and therefore the efficiency of both systems.



(a) Submerged endurance

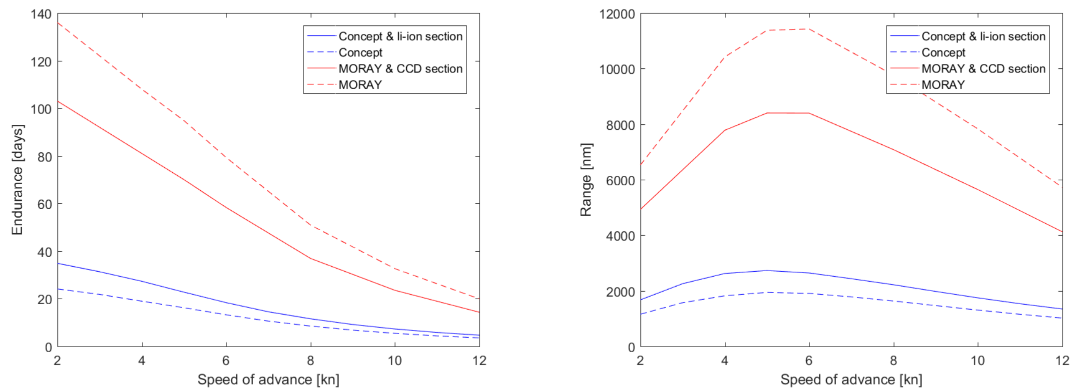


(b) Submerged range

Figure 8.19: Comparison of submerged endurance and range of concept and MORAY design including additional lithium-ion and CCD section

The addition of a modular lithium-ion section to the concept design increases the endurance and range to 35 days and 2640 nautical miles. So, the lengthening of the concept design improves the range and endurance with 36%. The MORAY design with CCD reaches a submerged endurance of range of 20 days 1800 nautical miles. So, the improvement in submerged range and endurance of the concept design is only 47% relative to the MORAY design including a CCD. Only at the high speed ranges, the improvement of submerged range and endurance are significant. This is caused by the power output limit of the CCD. Furthermore, figure 8.19 shows that the submerged endurance and range of the MORAY design with AIP section is comparable with the range and endurance of the concept design. So, adding a AIP section to a diesel-electric submarine makes diesel-electric submarines already compatible to an entirely battery powered submarine on the aspect of submerged range and endurance.

Figure 8.20 shows the comparison between the total range of both concept designs and MORAY designs. The diesel-electric submarines with an AIP system keep their advantage of endurance and range. However, the difference between the concept design and MORAY is decreased. The total range of the MORAY with AIP section is 2.9 times as far as the range of the concept design with lithium-ion section. This is half the original difference in range. The modular CCD section does not store energy, only a LO_x storage is included in the section. The CCD uses the same fuel as the normal diesel engines. Therefore, total energy storage capacity of the MORAY design with CCD is not increased. The energy storage capacity of the concept design with modular lithium-ion section increases the energy storage capacity with 46%. This is approximately equal to the reduction in the difference in achievable range and endurance.



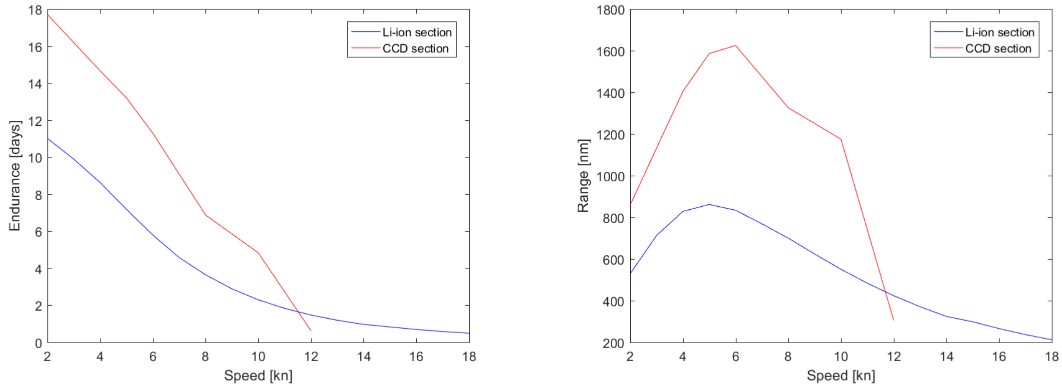
(a) Total endurance

(b) Total range

Figure 8.20: Comparison of endurance and range of concept and MORAY design including additional lithium-ion and CCD section

Figure 8.21 shows a comparison between the modular sections separately. The modular CCD section increases the submerged range and endurance 1.9 times as much as a modular lithium-ion section. So, the CCD is performing better as an AIP option. However, a modular lithium-ion section could have its advantages when implemented on a diesel-electric submarine. It could be recharged as many times as fuel is available for the DG-sets. Furthermore, it will significantly improve the submerged endurance and range in the high speed ranges. The achievable increase in submerged endurance and submerged range would be slightly reduced when the lithium-ion section would be implemented in a diesel-electric submarine. The auxiliary load would be slightly higher, which will drain the lithium models faster. Moreover, second order effects on the design might limit the installed battery capacity. Therefore, more research is required to determine the performance of a modular lithium-ion section as AIP option for a diesel-electric submarine.

Another interesting option is to create a submarine design with a propulsion plant which consists out of an AIP system and lithium-ion batteries. The energy storage capacity of an integrated AIP systems is at least 1.9 times higher than integrated lithium modules, as shown in figure 8.21. Scale effects are expected to increase the difference in energy storage capacity even more. The AIP option could be used as a switch-on/switch-off system and will be able to charge the batteries when required. The lithium batteries would still enable the submarine to achieve high speeds. In this way, the range and endurance is expected to be approximately twice as high compared with the created entirely battery powered concept design. However, more research is needed to determine the feasibility of such a concept.



(a) Submerged endurance (b) Submerged range

Figure 8.21: Comparison of submerged endurance and range of CCD AIP section and lithium-ion section

8.5 Conclusions

The range and endurance of the concept design are 1940 nm and 24 days. This can be stretched to 3300 nm and 42 days when the lowest possible auxiliary load is used. However, this is not feasible during a normal operation. The submerged range and endurance of the concept design are 7.6 times as high as the submerged endurance and range of the MORAY design. However, the range and endurance of the concept design are 5.6 times lower than the total range and endurance of the MORAY design. This means the energy storage capacity of the batteries should increase 600% before the same range can be achieved. Such a large energy storage capacity is not technical feasible. Therefore, an entirely battery power submarine is not an option independent ocean going mission profiles.

The influence of the battery chemistry and capacity are determined. Using a safer battery chemistry, such as LFP, is no option for an entirely battery powered design. The energy storage capacity of these chemistries are too low. The range and endurance of an entirely battery powered submarine are strongly dependent on the energy storage capacity. Other factors, such as battery voltage, are negligible for large size lithium battery packs. Therefore, it is possible to make an estimation of the achievable range and endurance in the near future. It is expected that the LIB capacity will improve approximately 33% in the upcoming years. Such an increase would mean that a range and endurance of 2600 nm and 32 days could be achieved.

Operational profiles with a relatively low required range and endurance might be feasible for an entirely battery powered submarine. Three mission profiles are simulated to determine the feasibility of these operational profiles. The first mission profile is a one week mission with a relatively high transit speed, a short surveillance period and a total travelled distance of 1245 nm. The second mission profile is a two week mission with lower transit speeds, a long surveillance period and a total travelled distance of 1857 nm. The third is a mission has a duration of 23 days, slow transit speeds, a dead slow surveillance speed and has a total distance of 1662 nm. All mission profiles include an attack phase with a high speed gate away of 20 knots. The concept design can perform all three missions, while keeping a battery capacity margin. This indicates that operational profiles with a relatively low required range and endurance are feasible.

The charging of the concept design is analysed. The charge time is determined by the current capacity of the power cables and switchgear. The total battery capacity can be charged in approximately 15 hours. When the capacity of the power cables and switchgear is increased, the charging time can be reduced. This is unnecessary for harbour charging, but it might be interesting for charging at sea. A support vessel could use its auxiliary power to charge the battery. Theoretically a charge time of 5 hours could be possible when 15000 kW generator power is available. However, the power cables and switch gear need to be able to withstand

17000 A to make this possible. Such a large increase is not expected to be feasible.

A design variation of the concept design is made to compare the concept design with a MORAY design with modular AIP option. The addition of a modular lithium-ion section to the concept design increases the endurance and range to 35 days and 2640 nautical miles, which is an improvement of 36%. The addition of an AIP section to a diesel-electric submarine will results in a larger improvement in submerged range and endurance. This limits the difference submerged range and endurance to 50%. The total range and endurance of an entirely battery powered submarine is three times lower than a diesel-electric submarine with AIP. This is almost 50% less than comparing an entirely battery powered submarine and a diesel-electric submarine without AIP. Due to the difference in achievable range, an entirely battery powered submarine design is not compatible with a diesel-electric submarine for ocean going missions.

The use of a modular lithium-ion section as AIP option for a diesel-electric submarine is an interesting option. The improvement in submerged range and endurance is approximately two times as low as conventional AIP systems. However, a modular lithium-ion section can be recharged several times during a mission period. Furthermore, it is also able to improve the submerged range and endurance for the high speed ranges.

Chapter 9

Entirely battery powered submarine designs

The feasibility study of an entirely battery powered submarine is mainly focussed on the comparison with the MORAY design. During this chapter the design and capabilities of an entirely battery powered submarine will be discussed in a broader perspective. Furthermore, the mission capabilities and employability of an entirely battery powered submarine will be discussed.

9.1 Range and endurance comparison for multiple submarine dimensions

The created concept design has a submerged displacement of 1905 tons, which can be seen as average size compared with the world-wide fleet of diesel-electric submarines. Certain missions will require small size submarines. For example, coastal defence submarines are often required to be small due to limited water depth in coastal regions. Therefore, it is interesting to investigate the effect of the submarine dimensions of on the achievable range and endurance. Furthermore, this will enable a broader comparison between entirely battery powered submarines and diesel-electric submarines.

Range-displacement relation of entirely battery powered submarines

The submarines propulsive power load, auxiliary power load and the installed battery capacity are needed to be scaled to be able to determine the effect of the submarine dimensions on the achievable range and endurance. The propulsive load of a submarine is depending on the submarines resistance and the efficiency of the propulsive chain. The effective towing power is estimated with the use of equation 9.1 [7].

$$P_E = K \cdot \nabla_{sub}^{2/3} \cdot v^3 \tag{9.1}$$

In this equation K is a coefficient which depends on the submarine hull. For this calculations a K value of 16 is taken, which based on the data of reference vessels used in a recent study [29]. The required propulsive power load can be determined with the use of the propulsive and transmission efficiencies. Furthermore, the efficiency of the electro motor must be taken into account to determine the discharge load of the battery system. The required brake power can be calculated with equation 9.2.

$$P_B = \frac{P_E}{\eta_H \cdot \eta_o \cdot \eta_R \cdot \eta_S} \tag{9.2}$$

The propulsive load on the batteries is determined with the use of equation 9.3

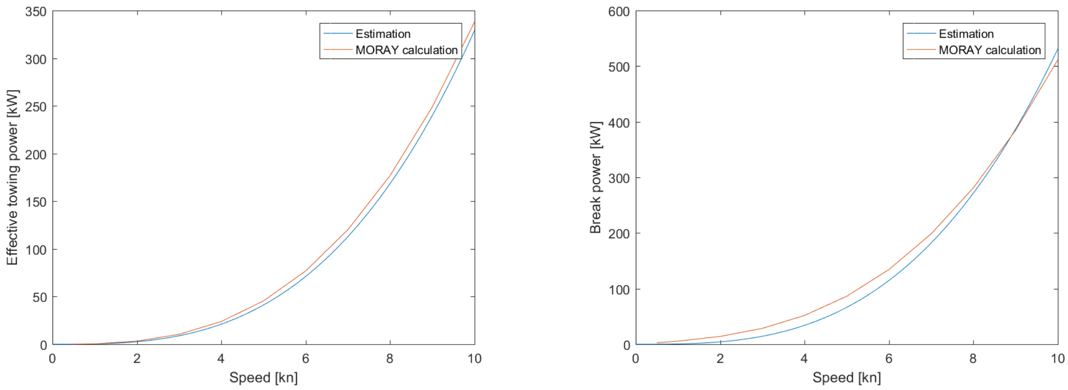
$$P_{propulsive} = \frac{P_E}{\eta_e \cdot \eta_{elec}} \tag{9.3}$$

The used efficiencies are typical values for a single screw submarine and are shown in table 9.1.

Table 9.1: Efficiencies propulsive chain [29, 38, 43]

Hull efficiency	η_H	1.30
Propeller open water efficiency	η_o	0.65
Relative rotative efficiency	η_R	1.05
Shaft efficiency	η_S	0.70
Efficiency MEM	η_e	0.95
Efficiency electrical distribution system	η_{elec}	0.97
Total chain efficiency	η_{total}	0.57

Both the effective towing power estimation and the break power estimation are compared with the results of the MORAY design calculations, which can be seen in figure 9.1. Both estimated values are comparable with the MORAY design calculations. The trend of the break power is different, because the efficiencies are assumed to be constant. In reality, this is not the case. Especially the shaft efficiency is strongly influenced by the speed.



(a) Effective towing power

(b) Break power

Figure 9.1: Comparison between estimated values and the MORAY calculation values

In general, large size submarine have a heavier payload, a larger propulsion plant and more crew [7, 29]. Therefore, the dependency between the auxiliary load and submarine displacement may be assumed linear. In a recent study, the auxiliary load of diesel-electric submarines is determined with the use of multiple reference boats [29]. The founded trend is shown in equation 9.4.

$$P_{aux} = (0.0368 \cdot \Delta_{sub} + 19.1) \cdot 10^3 \tag{9.4}$$

This study showed that the auxiliary load of an entirely battery powered submarine is slightly less than a diesel-electric submarine. Therefore, a correction of equation 9.4 is made. This correction is based on the difference in minimal submerged auxiliary load between the concept design and MORAY design, which is 4.85%. The auxiliary load of equation 9.4 is based on the minimal auxiliary load. The constant value of equation 9.4 is corrected based on the difference in nominal and minimal auxiliary load of the MORAY design, to be able to estimate the nominal auxiliary load. The relation between the displacement and auxiliary load of an entirely battery powered submarine is shown in equation 9.5.

$$P_{aux} = (0.0350 \cdot \Delta_{sub} + 62.7) \cdot 10^3 \tag{9.5}$$

In figure 9.2, the relation between the auxiliary load and displacement is shown. The auxiliary load of the concept design is also shown in this figure. There is a 5% difference between the estimation and the determined auxiliary load of the concept design

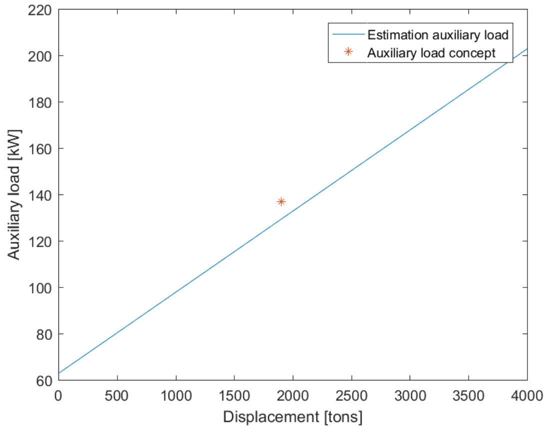


Figure 9.2: Auxiliary load estimation

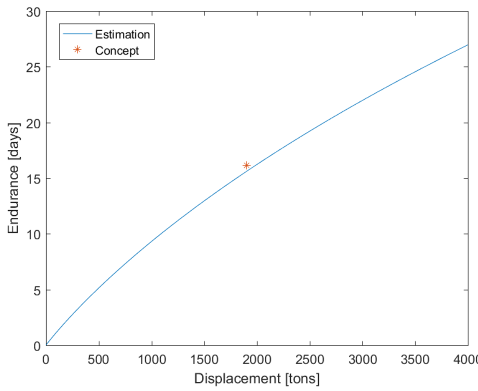
The installed battery capacity is scaled based on the submerged displacement. The battery capacity is assumed to be linear depended on the submarine displacement. The installed battery capacity is estimated with equation 9.6. This relation is based on the installed battery capacity and the submerged displacement of the concept design.

$$C_{bat} = 46.48 \cdot \Delta_{sub} \tag{9.6}$$

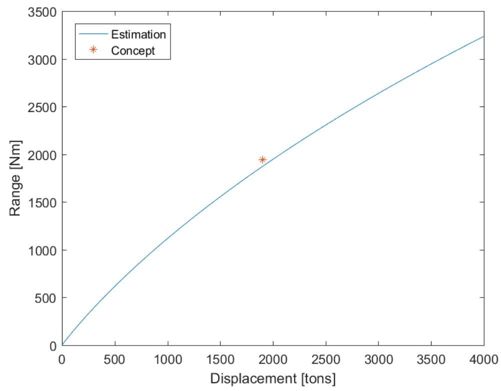
The endurance of a submarine is estimated with the use of equation 9.7. In this calculation, the batteries are discharged to a DoD of 0.9.

$$Endurance = \frac{0.9 \cdot C_{bat}}{P_{aux} + P_{propulsive}} \tag{9.7}$$

The endurance is estimated for a range of submarine displacements. The results are shown in figure 9.3a. The calculated endurance is determined for a speed of five knots, which is the most economical speed with respect to maximum achievable range. Based on the speed and achievable endurance, the range is calculated. The estimated range is shown in figure 9.3b. The results, shown in figure 9.3, are a rough estimation. Non-linear effects, as for example the lengthening of the hull with an additional section, are not considered during this estimation. Furthermore, the submarines design considerations will influence the achievable endurance and range. For example, a reduction in payload or system redundancy will provide extra space for the installation of batteries.



(a) Endurance



(b) Range

Figure 9.3: Achievable range and endurance estimation for a speed of five knots

Comparison with diesel-electric submarines

A comparison between the displacement-range relation of entirely battery powered and diesel-electric submarines is made in figure 9.4. The displacement-range relation of diesel-electric submarines is based on the data of reference boats. The dataset of reference boats consists out of reference boats available at Nevesbu and of reference boats collected from public sources. The used diesel-electric reference boats do not have an AIP systems.

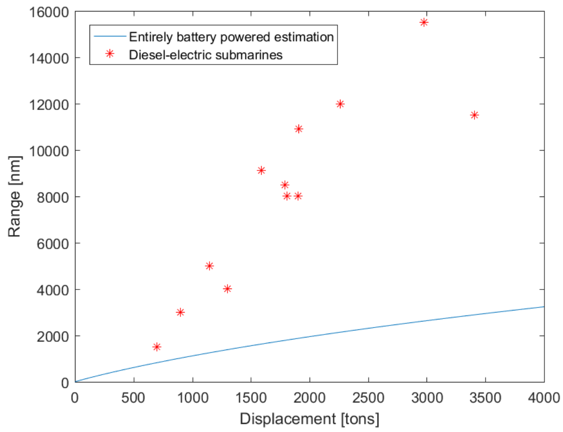


Figure 9.4: Displacement-range relation of entirely battery powered and diesel-electric submarines

The trend of the displacement-range relation of diesel-electric submarines is similar to the trend of the estimated displacement-range relation of entirely battery powered submarines. This is as expected. The resistance of both submarines types scale the same, which will lead to a similar increase in propulsive load. Furthermore, the auxiliary load is also expected to scale approximately the same (as discussed in the previous paragraph). Moreover, the percentage of submarine weight and volume occupied by the power plant is expected to stay roughly constant [7].

From figure 9.4 can be concluded that the range of diesel-electric submarines is approximately four to six times as far for the total range of displacements. The spread in the displacement-range relation can be explained by payload design choices, which can have an large influence on the operational capabilities.

9.2 Mission capabilities and employability

The mission capabilities of a submarine are depending on the submarines size, stealth, its payload and the operational capabilities. In the previous chapter, the operation capabilities of concept design are determined. This paragraph will elaborate on the possible mission capabilities of an entirely battery powered submarine. Furthermore, the employability of an entirely battery powered submarine will be discussed.

The mission capabilities are usually specified in early design stage by the operators of the submarine. The required mission capabilities determine the required payload, range, autonomy, submerged endurance, level of accommodation and will influence many other design factors. An overview of several submarine designs and their mission capabilities is given in figure 9.5. The mission capabilities are specificity as coastal defence, crisis management and ocean patrol/hostile waters. Coastal defence missions are often in shallow waters of the submarines homeland. Crisis management missions are missions of middle long duration at a conflict location. Submarines can be deployed at crisis locations for the prevention of conflict escalation, sea control or sea denial by a maritime blockade. Ocean patrol/hostile water missions are mostly missions of a long duration at a large distance from the home port of the submarine. These missions are often intended for intelligence collection.

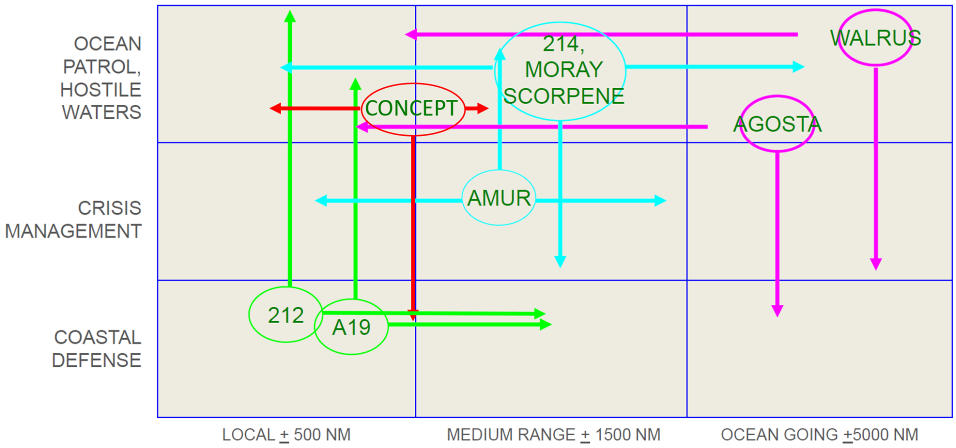


Figure 9.5: An overview of mission capabilities of multiple submarine designs

The submarines are placed in figure 9.5 at the locations for which they are designed. For example, both the type 212 submarines and the type A19 (Gotland class) submarines are designed for homeland defence missions. This has led to several design choices. For example, the German type 212 submarine is designed for operations in the Baltic Sea, North Sea and north Atlantic. The Baltic and North Sea are relatively shallow, therefore the choice is made to use non-magmatic steel. This will limit the dive depth of the submarine, but will make them more difficult to detect by air planes and helicopters [21]. Furthermore, the both the type 212 and A19 have an AIP systems. This improves the stealthiness of the submarine, which is a big tactical advantage with a limited water depth. Although the type 212 and A19 submarines are designed for coastal defence, they are still able to perform crisis management or ocean going patrols. However, their autonomy and range are limited. In reality, these submarines are often used for relatively short mission periods.

The Walrus class submarines are designed for the other side of the spectrum. The Walrus class submarines are designed for ocean going missions and missions in hostile waters far from their home bases. For example, the Walrus needs to be deployable around the Dutch Islands in the Caribbean. This requires a large achievable range, a high autonomy and a good habitability on board of the submarine. Furthermore, redundancy and maintainability will become of greater importance. The submarine does also have a deep diving capability, which can be used to its potentials in deep oceans. The long range capabilities of the Walrus submarines makes them employable in local to ocean going mission areas. This makes them very valuable for the Royal Netherlands Navy, the NATO and the EU. However, the ocean going mission requirements make the Walrus class relatively large for a diesel-electric submarine. Therefore, the Walrus class submarine are less suitable for coastal defence operations.

The created concept design is placed in the overview of figure 9.5 as well. The concept design is a re-design of the MORAY design. So, the vessel is designed for the same mission capabilities as the MORAY design. The MORAY design is designed for ocean patrol. However, the concept design does not have the operational capabilities for ocean going missions. This makes the design inefficient, as will be discussed in paragraph 9.3. The range of the concept design can be classified as local to medium range. Compared with the MORAY design, the stealth of the concept design is improved due to the long submerged endurance. This makes it suitable for operations in limited water depths. When an entirely battery powered submarine is designed for its operational capabilities it should be placed in figure 9.5 at the location of the type 212 and A19 submarines.

The stealth capabilities of an entirely battery powered submarine make them suitable for coastal defence missions, crisis management missions and missions in hostile waters. However, their range is limited. This limits the employability of an entirely battery powered submarines. The results of the mission profile calculations of paragraph 8.3 are used to give an indication of possible regions of employability. An example is given for the two weeks mission profile. During a two weeks mission with relative lower speeds, a travelled distance of 1857 nautical miles is possible. A possible round trip of 1857 nautical miles in the Baltic Sea is shown in figure 9.6. This mission can be performed without surfacing once, which will provide a large tactical advantage. It is not likely that a Navy will perform a round trip, as is shown in 9.6. However, it shows clearly the potentials of an entirely battery powered submarine in seas with a limited size.

Figure 9.6: Example of a two weeks mission profile

The employability of an entirely battery powered submarine can possibly be enlarged when it is used in cooperation with friended countries. Charging of the submarine can then be performed in a harbour closer the to the mission area. For example, when an entirely battery powered submarine is deployed by an European Union member its area of employability will be enlarged enormously. Another way to enlarge the employability is by performing on sea charging of the submarine. On sea charging can be performed with the use of a support vessel. This will not only enlarge the employability, also the mission duration can be enlarged. Furthermore, ocean going missions will become feasible when on sea charging is performed.

It might be an option to investigate charging options at the sea bottom. For example, the submarine could connect to an underwater power source. An example could be a connection to the sub-sea power cables of for example an off shore wind farm. Such an underwater power source will provide a stealth charging option. A network of underwater charging locations could keep charging unpredictably. Furthermore, its will enable the submarine to perform surveillance missions for long periods at distances further away from there base. However, this is an futuristic idea and research is required to determine the feasibility of sub-sea charging options.

9.3 Discussion

The created concept design is a re-design of the MORAY. During the design process the same design philosophy as the MORAY is used, which enabled a fair comparison between the two designs. This means that aspects as crew size, system choices, stores and armament are based the design philosophy and operational capabilities of a diesel-electric submarine. However, the operational capabilities of an entirely battery powered submarine are not comparable with a diesel-electric submarine. Furthermore, the installed number of systems and their safety characteristics are different. Therefore, another design philosophy is required when an efficient and safe entirely battery submarine design needs to be made. This paragraph will elaborate on design aspects which will be different for an entirely battery powered design. Furthermore, the effects of these design aspects will be discussed.

9.3.1 Design for operational capabilities

The MORAY is designed for prolonged ocean-going missions and has therefore a high endurance and a high autonomy. From chapter 8 and paragraph 9.1, the conclusion could be made that ocean going missions are not feasible for an entirely battery powered design. This will influence several aspects of the design.

The total endurance of diesel-electric submarines is higher than entirely battery powered submarines. For example, the MORAY design has a total endurance of 65 days. The created entirely battery powered submarine is expected to have a total endurance of 24 days. This means that the stores of the concept design are unnecessarily large. The size of the stores should match the operational capabilities to be efficient. Furthermore, the limited operational capabilities might influence design choices for fresh water, sewage and garbage. The required tank volume in an entirely battery powered submarine is small. Therefore, enough space for extra tank volume is present. It might be an option to make the capacity of the freshwater and sewage tanks large enough for the total mission endurance. This will make a freshwater maker unnecessary. Furthermore, no blowing of sewage tanks will be required. The same can be said about the storage of garbage.

Another aspect, which might be influenced by the limited endurance, is the maintenance philosophy. Currently designed ocean going submarines have a high level of autonomy. This means that the crew should be capable to perform all required maintenance at sea, without the workload of the crew getting to high. Furthermore, the crew needs to have the knowledge about a large amount of systems. The limited endurance might take away the need of being able to perform all maintenance at sea. The choice can be made to perform almost all maintenance at the home port. This will limit the maintenance on board to corrective maintenance which is required for the safety of the submarine. This change in maintenance philosophy will influence the required crew size. Furthermore, the number of systems is reduced drastically in an entirely battery powered submarine. Therefore, the system knowledge required by the crew is smaller as well. This is an advantage from a trainings perspective.

The philosophy of the submarines payload might also be influenced by the shorter endurance. For example, the created concept design can store 20 weapons. It is questionably if such a large payload is required when the submarine has a mission endurance of the maximum of 24 days. A reduction in weapon stores will provide space for other systems. The submarines payload falls outside the scope of this study. However, a re-analysis is recommended when an entirely battery powered design is created.

The above mentioned aspects are depending on the operational usage of the submarine. When the choice is made to perform charging of the submarine at sea, the total endurance will increase. This will have an influence on the on the required stores and the maintenance philosophy and needs to be considered during the design process.

9.3.2 Possible reduction in crew size

During the creation of the concept design, the same manning philosophy as the MORAY design is used. This means that the crew size of the entirely battery powered concept design is based on the manning philosophy of a diesel-electric submarine. Therefore, all console function were unchanged. Only the operational duty of local surveillance during snorkelling was eliminated.

Furthermore, the same maintenance philosophy as the MORAY was used. This led to a crew reduction of one crew member. The manning philosophy of an entirely battery powered submarine will be different. This will lead to a smaller submarine crew as used in the concept design. This section will describe the possible crew reduction of the concept design, when another manning philosophy is used. This analysis will be based on the operational duties shown in appendix B.1.

The first change, which is expected to be possible compared to the concept design, is eliminating the local machinery surveyor. This is possible because the number of systems is reduced significantly. Furthermore, the risks of the present systems are reduced. There are less pressure hull penetrations. Moreover, the risk of fire is reduced as well. Due to the reduction of systems and risks the engine rooms can be made unmanned.

The console functions, belonging to platform safety, can be reduced as well. Currently, there is a platform systems operator, machinery systems operator, a steering operator and a submerged operation officer. The platform system operators is responsible for the monitoring and control of the underwater systems. The work load of this task is reduced. For example, the trim and weight disturbances are expected to reduce significantly due to the reduction of consumables and the absence of fuel. The machinery system operator is responsible for the control and monitoring of all propulsion systems. The work load of this task will also be reduced, because the number of propulsive and propulsion support systems are decreased drastically. Due to the reduction in workload of these two tasks, the workload of the submerged operations officer is reduced as well. Therefore, the tasks of the systems operator, machinery systems operator and submerged operations officer can be combined to one function.

The above mentioned changes will lead to a crew reduction of eight crew members, compared with the MORAY design. This will reduce the engineering department to three crew members. This is expected to be too small. The crew size needs to be enlarged slightly to be able to rotate the console functions, which is required to prevent concentration loss. Furthermore, the crew needs to be able to perform corrective maintenance when required. Therefore, two extra crew members will be required. This is expected to be sufficient to rotate console functions and to perform corrective maintenance when required. All scheduled and service maintenance will be performed at the port. Thus, the engineering compartment of five crew members is possible.

The smaller size of the engineering compartment will also reduce the size of the management of the submarine. The mechanical engineering officer has less than half the crew bellow him as in the original crew size of the MORAY. Therefore, this tasks should be combined with the sewaco officer. This is also usual in other submarine designs. Potentially the task executive officer can be eliminated as well. However, this would influence the tasks required by all officers. Therefore, this reduction is questionable and depending on the wishes of the navy ordering such a design.

From this analysis, the conclusion can be made that a reduction of seven to potentially eight crew members is possible. This will reduce to total crew size of the concept design to 27 or 26 crew members. A manning matrix based on this manning philosophy can be seen in table B.2 in appendix B.1. The reduction to 27 or 26 crew members is a reduction of more than 20% compared to created concept design, which will have a large effect on the submarine design. It will for example influence the space used for cabins, the required amount of stores and the load of HVAC systems.

9.3.3 System choices

The created concept design has a submerged endurance of 24 hours. Therefore, air quality control is of great importance to ensure the safety of the crew. To ensure a good air quality, the choice of some systems should be made different than as is for diesel-electric submarines. Furthermore, the possible reduction in crew size will influence the choice of systems. This section will elaborate on the system which should be reconsidered when creating an entirely battery powered submarine.

The currently used CO_2 absorption systems is a CO_2 absorption system using chalk canisters. The usage of a chalk holder systems is labour insensitive. All chalk holders need to be replaced once in the 5-7 hours, depending on the crew size. With a small submarine crew, each crew member should have as little additional tasks as possible. Therefore, this system in not preferable. Furthermore, the performance of this system is worse than for example a regenerable scrubber system. The air CO_2 content will fluctuate during the operational period of chalk holders. A scrubber systems, which does not require any labour and has can keep a constant CO_2, should be used in an entirely battery powered submarine design. This could be a regenerable scrubber systems. The only disadvantage is the power usage of this systems the system. However, this is expected to be relatively small due to the smaller crew size.

The same can be said about the currently used O_2 systems; the oxygen candles. This system is also labour intensive. Furthermore, the quality of the system is worse than other available options for oxygen supply. The oxygen level in the submarine will fluctuate constantly when oxygen candles are used. A constant oxygen supply, supplied by a system which does not require labour is preferable. This could be an oxygen supply by either the use of the vaporization of LO_x or with the use of electrolysis. Both systems will be able to provide a constant oxygen supply without the need of labour of the submarine crew. Both systems have their advantages and disadvantages. The effect of the usage of LO_x vaporization is relatively small. However, it uses a consumable and needs to be compensated and refilled. The use of an electrolysis systems will enable the oxygen generation without a consumable source. However, this system requires a relatively large amount of power. These effects should be considered during the design process.

Another aspect which will influence the air quality is the usage of high pressure air during long submerged periods. The usage of high pressure air inside the pressure hull, for example for the usage of portable working on high pressure air, will increase the pressure in the submarine hull. This is not preferable with respect to the safety of the crew. Pressure fluctuations need to be prevented as much as possible. Furthermore, high pressure air is used to empty the sewage tank and to eject garbage overboard. After emptying the sewage tank or using the garbage ejector, they both need to be ventilated before they can be used again. This results in a pressure will increase and unwanted gasses can enter the submarine environment. Therefore, it might be better to create large sewage tanks which can store the sewage of the total submerged period. This is expected to be feasible due to the smaller crew size and the shorter operational periods. The same can be said for the garbage. It will also be a better choice to use electrical equipment, when equipment is required. For example, an electrical sewage pump can be installed when overboard pumping of sewage is required.

Not only the system choice will influence the air quality. The choice of materials will also influence the air quality. Certain materials release an amount of gas and some gasses can be toxic for humans at a certain concentration [49]. In normal usage, with a constant air refreshment, this will not lead to safety risks. However, in the closed environment of a submarine this can certainly lead to safety risks. Due to the longer submerged periods of an entirely battery powered submarine this is extra important. Therefore, much attention must be paid to the safety aspects of materials used in an entirely battery powered design.

9.3.4 Effects on submarine design and performance

All aspects discussed in the previous sections of this paragraph will influence the design and performance of an entirely battery powered naval submarine. An overview of these aspects and their effects is given in table 9.2. This table shows that that each influence factor will influence multiple other aspects of the design. Therefore, each factor will also have an influence on the performance of the submarine. This clearly indicates the challenge of submarine design; each small change will have an effect on a number other aspects in the submarine design.

The influence factors, shown in table 9.2, will also influence each other. For example, the decrease in crew size and the limited endurance will make the removal of the fresh water maker

Table 9.2: Influence of possible design changes on submarine design and performance

Influence factors	**Effects**	**Influence on design**	**Influence on performance**
Limited endurance	Smaller stores	Weight reduction, volume saving and reduction in auxiliary load	Lower electric load and the possibility to either increase the installed battery capacity or decrease to submarine size. All will increase the endurance and range.
	Smaller sewage storage	Reduction in tank volume and weight, or decrease in HP air usage	
	Smaller fresh water storage	Reduction in tank volume and weight or fresh water maker usage	
Decrease in crew size	Decrease in CO_2 production	Decrease in load of CO_2 absorption system	Storage consumables or electrical load decreases, both have positive influence on endurance and range.
	Decrease in O_2 absorption	Decrease in load of O_2 absorption system	
	Decrease in management	Less officer cabins	Either a smaller design or an increase in installed battery capacity.
	Decrease in required accommodation	Decrease in cabins	
	Decrease in console stations		
	Decrease in stores	Weight reduction, volume saving and reduction in auxiliary load	Lower electric load and the possibility to increase the installed battery capacity or decrease to submarine size. All will increase the endurance and range.
	Decrease in sewage production	Reduction in tank volume and weight or decrease in HP air usage	
	Decrease in fresh water usage	Reduction in tank volume and weight or fresh water maker usage	
Using a regenerable scrubber system	Improvement in air quality	-	Improvement in safety crew.
	Absence of chalk canister storage	Reduction in required stores volume and weight	Reduction in range and endurance.
	Increase in energy consumption	-	
Using an electrolysis system	Improvement in air quality	-	Improvement in safety.
	Absence of chalk canister storage	Reduction in required stores volume and weight	Reduction in range and endurance.
	Increase in energy consumption	-	
Limiting high pressure air usage	Sewage storage for total mission/pumping sewage overboard	Increase in require sewage tank volume and compensation capacity or installation pump	Enough space for tank volumes available; no influence. Installation pump will decrease submarine endurance.
	Garbage storage for total mission	Space required for garbage storage	Reduction in space available for batteries, this will decrease the endurance and range.
	Using electrical equipment, increase in energy consumption	-	Decrease in endurance of the submarine.
Removing fresh water maker	Reduction in number of systems	-	Improvement safety.
	Fresh water tank with capacity for total mission required	Increase in required tank volume	Enough space for tank volumes available; no influence. Installation pump will decrease submarine endurance and range.
	Decrease in energy consumption	-	Increase in submarine endurance and range.

feasible without large negative effects. Another example is the relation between the crew size and air quality control solutions. The decrease in crew size will reduce the load of the regenerable scrubber system and electrolysis system. Furthermore, it will be possible to increase the installed battery capacity due to smaller crew size. Therefore, the effects of the increase in auxiliary load will be limited.

The operational capabilities of the created concept design are expected to improve when all the influence factors of table 9.2 are applied in the design. The operational capabilities of an entirely battery powered submarine, as calculated in chapter 8 and paragraph 9.1, are therefore expected to be slightly pessimistic. This mainly because the decrease in crew size is expected to have the largest influence on the design. It will decrease the deck area required for cabins with approximately eight square meters. The space which will become available will be even larger; the stores will be smaller, there will be less console stations and the size of the messes can be decreased. This space could be used to install extra battery capacity. The expected increase of auxiliary load due to the usage of a regenerable scrubber and electrolysis system will have the largest negative effect on the submarines operational capabilities. However, this increase of auxiliary load will also be partly compensated due to the load reduction of the other consumers. Therefore, this effect is expected to be smaller.

Chapter 10

Conclusion

In an entirely battery powered submarine design lithium-ion batteries will be used instead of the normally used lead-acid batteries. The usage of lithium-ion batteries will influence the battery system design and the safety characteristics of the battery pack. In this thesis, a string based battery design is proposed, which consists out of strings of six battery modules connected in series. Each battery module consists out of eighteen cells connected in series. In this way, each string each provides the required operational voltage. The high short circuit current of lithium battery packs require that short circuit protection is integrated at string level. Furthermore, a good battery controlling and monitoring system, a thermal management system and shock protection is required to prevent the occurrence of thermal runaway. If thermal runaway occurs, the impact on the safety of the submarine can be limited by; a gas tight, oxygen free and pressure resistant battery compartment design. The pressure resistant battery compartment requires a vent option to prevent the pressure to reach to high values when large scale thermal runaway occurs.

Implementing an entirely battery powered submarine system into a submarine design will have a large effect on the design of a submarine. The diesel-generators and all support systems will be removed. This will reduce the number of systems on board the submarine drastically. Furthermore, the removal of the diesel-generators will result in a large reduction in required tank volume. The space provided by the reduction of these systems can be used to increase the number of installed batteries. Furthermore, this will result in a reduction of the auxiliary load of approximately seven percent. The reduction in systems will also have multiple second order effects. The safety characteristics will improve; there will be less pressure hull penetrations and the risks of fire decreases. Furthermore, the crew size can be reduced with approximately 20%. There are also several other systems which will be influenced by the implementation of the new power plant; the high pressure air system, the HVAC system and the electrical system. The design of an entirely battery powered naval submarine will be volume critical. Approximately the same amount of lead-ballast as a diesel-electric submarine will be required to reach a natural buoyant state. Stability is not a problem when all battery compartments are created low in the submarine design.

The operational capability study of this thesis showed that independent local to medium range missions are feasible for an entirely battery powered submarine. For example, the concept design created in this thesis has a displacement 1905 tons and will be able to reach a range of 1940 nautical miles and has an endurance of 24 hours. This makes an entirely battery powered submarine an interesting option navies who use their submarine for homeland defence missions. Independent missions with a long range and endurance are not feasible, due to the limited range and endurance of an entirely battery powered submarine. The range and endurance of an entirely battery powered submarine is expected to be four to six times lower than the range of a diesel-electric submarine. Missions which require a longer range or endurance can be feasible when on sea charging is performed. The charge time of an entirely battery powered submarine is limited by the maximum current limitations of the switch gear and power cables. The total charge time of the create design concept design is 15 hours at the maximum charge current.

An entirely battery powered submarine has the advantage of an air independent propulsion, therefore the total range and endurance can be sailed without needing to surface. Compared with a diesel-electric submarine with an AIP system, the submerged endurance of an entirely battery powered submarine is 1.5 times higher. However, the total range and endurance of an entirely battery powered submarine will be three times as low. The long submerged endurance of an entirely battery powered design makes air quality control of great importance. Much attention must be paid to CO_2 absorption, O_2 production and the use of safe building materials to keep the air condition safe for the submarine crew.

Chapter 11

Recommendations

This chapter describes the recommendations which can be made after this research. The different recommendation will be discussed per topic.

Research restrictions

This research is restricted to the re-design of the MORAY design. When more design freedom is available, the efficiency of the design can possibly be increased. This can possibly lead to an increase in operation capabilities.

Furthermore, the effect on the submarine design and operational capabilities might be different when a comparison is made with other submarine designs and dimensions. In this thesis, the operational capabilities are scaled to other submarine dimensions with the use of estimation methods. It would be interesting to make designs of other dimensions to be able to see if this estimation is valid.

Made assumptions

The assumed energy density and specific energy of the lithium-ion modules is based on an applied packing factor of a lithium module manufacturer. This packing factor has an uncertainty and is not based on modules with a civilian application. The energy density and specific energy have a strong influence on the operational capabilities of an entirely battery powered submarine. Therefore, the packing factor will influence the results of the operational capability study of this thesis. Additional research into the design of lithium-ion modules for submarines will provide insight in the achievable energy density and specific energy of lithium modules. This information can be used to reduce the uncertainty in the operational capability study of an entirely battery powered submarine.

The dimensions of the string control units are estimated to be halve the size of a lithium module. This assumption is based on reference lithium-ion system designs. The size of the string control units will influence the battery integration. An increase or decrease in module control unit size will influence the total installed battery capacity and therefore also on the operational capabilities.

In the design process, the assumption is made that a shock proof module design is possible. When this is not the case, a shock proof battery compartment will be required. This will decrease the installed battery capacity. Therefore, research into shock proof module designs is required.

Safety

The safety characteristics of lithium-ion batteries are the biggest challenge of the usage of lithium-ion batteries. Additional research into thermal runway prevention is required to ensure the safe usage of lithium-ion batteries in submarine designs. Modules need to be especially designed for their submarine application and they need to be extensively tested. Shock protection, thermal management and short circuit protection are the biggest points of interest during those tests. Testing the different solutions of thermal runaway prevention in harsh conditions is required to gain confidence in the technology. Another safety characteristic which needs additional research is thermal runaway propagation prevention. When thermal runaway occurs in a battery cell, the propagation of thermal runaway needs to prevented as much as possible. The implementation of heat barriers on module level could prevent thermal runaway propagation from module to module, which will improve the safety and redundancy characteristics of the battery design significantly. Addition research is required to determine possible solutions for thermal runaway propagation prevention, without a large reduction in achievable energy density.

An entirely battery powered submarine will have a prolonged submerged endurance. Air quality control is therefore an important safety aspect. In this thesis, air quality control is limited to O_2 production and CO_2 absorption. However, multiple other gasses can originate during long submerged periods. For example, it is known that building materials and consumer products can have a small emission of toxic gasses. Without ventilation, the concentration of these gasses can reach dangerous values. This can cause safety risks for the submarine crew. When an entirely battery powered submarine is created, research in the safety of all used building materials is required.

Life cycle costs

This thesis looked into the technical and operational feasibility of an entirely battery powered submarine. Costs are not taken into account. The creation of an entirely battery powered submarine will influence the investment costs, operational costs and maintenance costs of the submarine. The investment costs of lithium-ion batteries are currently relatively high. However, the longer life time of lithium-ion batteries, the reduction in crew members, the reduction in consumable usage and the reduction in maintenance might make an entirely battery powered submarine also interesting from an economical perspective. Therefore, it is interesting to investigate the life cycle costs of an entirely battery powered submarine.

At sea charging

The possibility of charging at sea is shortly mentioned in this thesis. The possibility of charging an entirely battery powered submarine at sea will increase the operational capabilities and the operational flexibility of the submarine.

Charging the submarine at sea could be performed with the use of a support vessel. Research is required with respect to safety characteristics and the limitations of such a charging option. Furthermore, a charging method needs to be developed.

Underwater charging might be an interesting option for an entirely battery powered submarine. Underwater charging could be performed with the use of an underwater charging stations. These charging options could be created at the location of sub-sea power sources, such as electrical power cables or offshore wind farms. Sub-sea charging options will provide tactical advantages. Addition research is required to determine the operational feasibility of sub-sea submarine charging.

Design options

It might be an interesting option to investigate the feasibility of the design of an air independent non-nuclear submarine design which combines a conventional AIP systems (such as fuel cells) and lithium-ion batteries. During the operational capabilities study in this thesis is concluded that a conventional AIP section can storage approximately two times as much energy as a modular lithium-ion section. Therefore, the combination of conventional AIP systems with lithium-ion batteries is expected to increase the range and endurance of the submarine. In such a combination, the lithium-ion batteries can be used for the required high speeds. Research is required to determine the impact on the submarine design, operational capabilities and feasibility of such a power plant concept design.

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Appendix A

Reference design

Table A.1: Main data of diesel-electric reference design design

Dimensions	length	66.5	m	
	hull diameter internal	6.5	m	
	sail height above base	13.3	m	
Displacement	surfaced	1704	t	
	submerged	1907	t	
Storage	fuel	174	t	
Combat system	launching tubes	6		
	weapons	20		
Diving depth	max. operational	300	m	
	incidental	360	m	
Speed	max. surfaced	12	kn	
	max. snorting	12	kn	
	min. submerged	2	kn	
	max. submerged	20	kn	for one hour
		21.5	kn	burst
Machinery	3 DG-sets, total electrical output	2940	kW	
	Main electric motor	4360	kW	
Batteries	2 sets of	210	cells	
	cell capacity (100 h)	15500	Ah	
Indiscretion rate		13	%	at 6 knots
Autonomy	submerged endurance	145	h	at 2 knots
	total range	10900	nm	at 6 knots
	endurance	65	days	
Accommodation	crew & trainees	38		

Appendix B

Manning analysis

B.1 Operational duties

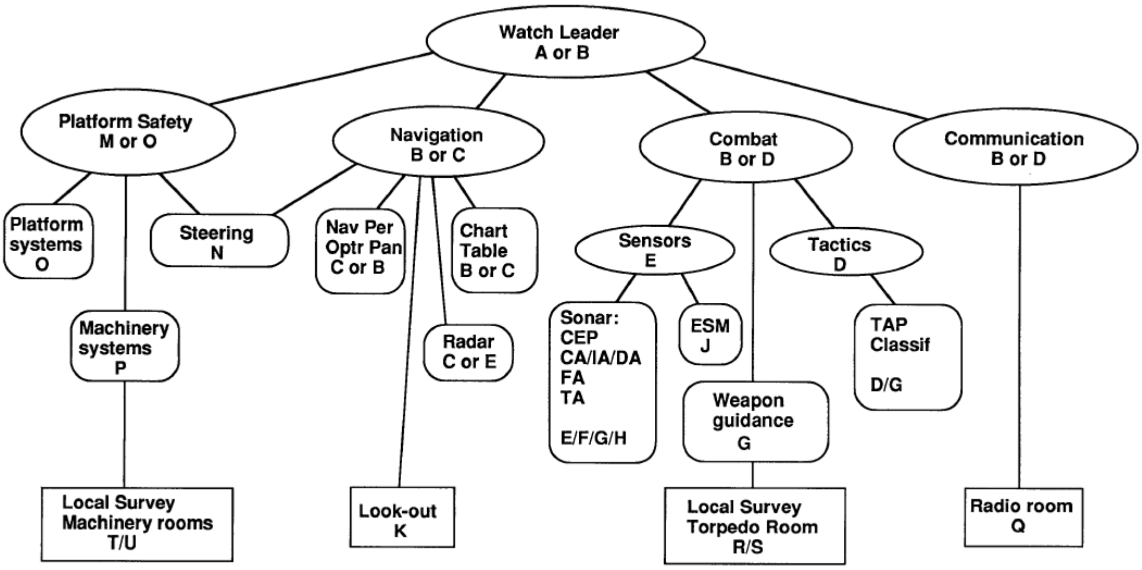

Figure B.1: Operational hierarchy and associated roles to fulfill the submarines mission

LIST OF DUTY STATIONS - MORAY 1800 (pf)H [SUBMERGED OPERATION --------------------] [SURFACED OPERATION ----------------------]

Code	Duty role	Duty station	1 Attack/ Threat	2 Patrol/Pot Threat	3 Operational Transit	4 Peacetime Transit	5 Narrow Waters	6 Surfaced Transit	7 Foreign Harbour	8 Own Base
A	Watch Leader	Centr. Contr. Room	1							
B	Duty Off.	CCR: Nav Table/Optr Cons/Periscope	1	1	1	1	1	1	1	1
C	Ass. Duty Off.	CCR: Nav Table/Optr Cons/Periscope	1	* 1	* 1	* 1	1	1		
D	CS Team Leader	CCR: CS display 1	1	1	1	for B or C	for C	for C		
E	CS Operator	CCR: CS display 2	1	1	1	1	1			
F	CS Operator	CCR: CS display 3	1	1	1					
G	CS Operator	CCR: CS display 4	1	1						
H	CS Operator	CCR: CS display 5 (Option)	[1]	[1]						
J	ESM operator	CCR - ESM display	# 1	# 1	for B or C					
K	Look - out	Bridge					1	1		
L	Guard	Deck							1	1
M	Subm. Oper. Off.	Central Control Room	1	1	1	* 1	1			
N	Steering Operator	CCR - Steering Control Panel	1	1	1	1	1	1		
O	Platf. Syst. Operator	CCR - Central Contr. Panel	1	1	1	1	1	1	1	1
P	Mach. Syst. Operator	Man. Room - Engine Control Panel	1	1	1	1	1	1	1	
Q	Comm's Operator	Radioroom - Comm. panel	# 1	# 1	# 1	# 1	1	1	1	
R	Launching Syst. Operator	Torpedoroom	1							
S	Launching Syst. Operator	Torpedoroom	1							
T	Local Machinery Surveyor	MMR/ER/Aux ER/(AIP Eng Room)	1	1	1	1	1	1	1	
U	Local Machinery Surveyor	Engine Room	1	* 1	* 1	* 1	1	1		
		Total	15	10	9	6	11	9	6	3
		Extra during snorting (*)		2	1	3				
		Extra at periscope depth (#)	2	2	2	1				
		Maximum	17	14	12	10	11	9	6	3

Figure B.2: List of duty roles and duty stations during all possible operational states

MANNING MORAY 1800 (pf)H MATRIX for PATROL/POTENTIAL THREAT - 2 DIVISIONS

A to U = duty stations
a = 1st watch / b = 2nd watch / (r) = roulation
# = extra at periscope depth / * = extra during snorting

Nr	Branch Name	On Duty:	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	REM
		2 0		2	* 2	2	2	2	2		# 2			2	2	2	2	# 2			2	* 2	REM
	OPERATIONS		A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	
1	Commanding Off	1																					
2	Executive Off			a																			
3	Navigations Off			b																			
4	Sonar Off					a																	
5	Sewaco Off					b																	
6	CPO Sonar	1			* a	(r)																	
7	PO Sonar	1					(r)	(r)	(r)		# a												
8	Sonar Operator						a																
9	Sonar Operator						b																
10	Sonar Operator							a															
11	Sonar Operator							b															
	(Sonar Operator)									[a]													
	(Sonar Operator)									[b]													
	COMMUNICATIONS		A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	
12	PO Communications	1													(r)			(r)					
13	Radio Operator	1													(r)			# a					
14	Radio Operator	1													(r)			# b					
	WEAPONS		A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	
15	CPO Weapon Electr	1			* b	(r)																	
16	PO Weapon Electr	1					(r)	(r)	(r)		# b												
17	Weapon Electr Eng								a														
18	Weapon Electr Eng								b														
19	PO Weapon Eng														a								
20	Weapon Eng														b								
	ENGINEERING		A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	
21	Mech Eng Off	1												(r)									
22	CPO Mech Eng													a									
23	PO Mech Eng																a						
24	Mech Eng	1															(r)					* a	
25	Mech Eng	1														(r)						* b	
26	Mech Eng																				b		
27	CPO Elec Eng													b									
28	PO Elec Eng																b						
29	Elec Eng															a							
30	Elec Eng															b							
31	Elec Eng																				a		
	LOGISTICS		A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	
32	Chief Cook	1																					
33	Steward	1																					
34	Logistics/Med Serv	1																					
	TOTAL	3 4																					

14 : off duty

Figure B.3: Manning Matrix MORAY for "Patrol/Potential Threat"-state

Table B.1: Manning matrix concept design for "Patrol/Potential Threat"-state

A to T = duty stations
a = 1st watch / b = 2nd watch
(r) = roulation / # = extra at periscope depth / [] optional

Nr	Branch Name			2			2	2	2	2		#2				2	2	2	2		#2			
	OPERATIONS		A	B	C		D	E	F	G	H	J	K	L		M	N	O	P		Q		R	S
1	Commanding Off	1																						
2	Executive Off			a																				
3	Navigations Off			b																				
4	Sonar Off						a																	
5	Sewaco Off						b																	
6	CPO Sonar	1					(r)																	
7	PO Sonar	1						(r)	(r)	(r)		#a												
8	Sonar Operator							a																
9	Sonar Operator							b																
10	Sonar Operator								a															
11	Sonar Operator								b															
	(Sonar Operator)									[a]														
	(Sonar Operator)									[b]														
	COMMUNICATIONS																							
12	PO Communications	1															(r)				(r)			
13	Radio Operator	1															(r)				#a			
14	Radio Operator	1															(r)				#b			
	WEAPONS																							
15	CPO Weapon Electr	1					(r)																	
16	PO Weapon Electr	1						(r)	(r)	(r)		#b												
17	Weapon Electr Eng									a														
18	Weapon Electr Eng									b														
19	PO Weapon Eng																a							
20	Weapon Eng																b							
	ENGINEERING																							
21	Mech Eng Off	1														(r)								
22	CPO Mech Eng															a								
23	PO Mech Eng																		a					
24	Mech Eng																							
25	Mech Eng	1																(r)	(r)					
26	CPO Elec Eng															b								
27	PO Elec Eng																		b					
28	Elec Eng																	a						
29	Elec Eng																	b						
30	Elec Eng																							
	LOGISTICS																							
31	Chief Cook	1																						
32	Steward	1																						
33	Logistics/Med. Serv.	1																						
	TOTAL OFF DUTY	**13**																						

Table B.2: Manning matrix for "Patrol/Potential Threat"-state when using manning philosophy based on an entirely battery powered submarine design

A to T = duty stations
a = 1st watch / b = 2nd watch
(r) = roulation / # = extra at periscope depth / [] optional

Nr	Branch Name			2			2	2	2	2		#2				2	2		#2					2
	OPERATIONS		A	B	C		D	E	F	G	H	J	K	L		M,O,P	N		Q		R	S		T
1	Commanding Off	1																						
2	Executive Off			a																				
3	Navigations Off			b																				
4	Sonar Off						a																	
5	Sewaco/Mech Eng Off						b																	
6	CPO Sonar	1					(r)																	
7	PO Sonar	1						(r)	(r)	(r)		#a												
8	Sonar Operator							a																
9	Sonar Operator							b																
10	Sonar Operator								a															
11	Sonar Operator								b															
	(Sonar Operator)									[a]														
	(Sonar Operator)									[b]														
	COMMUNICATIONS																							
12	PO Communications	1															(r)		(r)					
13	Radio Operator	1															(r)		#a					
14	Radio Operator	1															(r)		#b					
	WEAPONS																							
15	CPO Weapon Electr	1					(r)																	
16	PO Weapon Electr	1						(r)	(r)	(r)		#b												
17	Weapon Electr Eng									a														
18	Weapon Electr Eng									b														
19	PO Weapon Eng																a							
20	Weapon Eng																b							
	ENGINEERING																							
21	CPO Mech Eng	1														(r)								
22	PO Mech Eng	1														(r)								
23	Elec Eng															a			a					
24	Elec Eng															b								
	LOGISTICS																							
25	Chief Cook	1																						
26	Steward	1																						
27	Logistics/Med. Serv.	1																						
	TOTAL OFF DUTY	**13**																						

B.2 Maintenance reduction estimation

The maintenance reduction estimation is based on the original maintenance analysis of the MORAY design. The essential maintenance estimation, scheduled maintenance estimation and the maintenance requirements per department will be discussed in this appendix.

The essential maintenance requirements of the MORAY design and the estimated essential maintenance of the concept design are shown in table B.3. The service maintenance is reduced by 90 hours due to absence of diesel generators in the concept design. This reduction does also include diesel generator support systems. The corrective maintenance for the concept propulsion plant is estimated to be a quarter of the original corrective maintenance of the original propulsion plant. This estimation is based on the reduction from four main systems (one electro motor and three diesel generators) to one main system (only the electro motor). In the original maintenance estimation, the required corrective maintenance of the platform and control systems and miscellaneous mechanical equipment are estimated as respectively 30% and 60% of the corrective maintenance of the propulsion plant. This estimation is also used for the concept design. The maintenance requirements of the weapons, electronics and computers will not be influenced by the implementation of the concept power plant. The logistic delay times and administration time is also kept constant.

Table B.3: Essential maintenance estimation during a seven-week mission in hours

Code		MORAY	Concept
	Service maintenance		
2.1.1.1	Diesel generators	90	-
2.1.1.2	Miscellaneous platform systems	90	90
2.1.1.3	Electronics/weapons/computers	170	170
	Total servicing maintenance	**350**	**260**
	Corrective maintenance		
2.1.2.1	Propulsion plant	60	15
2.1.2.2	Platform and control systems	20	4.5
2.1.2.3	Miscellaneous mechanical equipment	40	9
2.1.2.4	Weapons/electronics/computers	60	60
2.1.2.5	Logistic delay times/administration	15	15
	Total corrective maintenance	**195**	**103.5**
	Total essential maintenance	**545**	**363.5**

Table B.4 shows the scheduled maintenance of the MORAY design and the estimated scheduled maintenance of the concept design.

Table B.4: Scheduled maintenance estimation during a seven-week mission in hours

Code		MORAY	Concept
2.2.1	Mechanical systems	390	97.5
2.2.2	Electrical systems	195	48.75
2.2.3	Electronic systems	350	350
2.2.4	Miscellaneous	120	120
	Total scheduled maintenance	**1055**	**616.25**

The scheduled maintenance for mechanical systems is estimated a quarter of the original. This is based on the estimation that the three diesel generators and their support systems are responsible for 75% of the scheduled mechanical maintenance in the original design. The scheduled maintenance for electrical systems reduced 75% as well, which is based on the aforementioned argumentation. The scheduled maintenance requirements for electronic systems, which are mainly weapon, sensor and computer systems, is not expected to change.

The maintenance activities need to be carried out by qualified personal. In table B.5 essential and scheduled maintenance activities are divided per department. Mechanical engineering and electrical engineering is performed by the engineering department. Electronics engineering is performed by the weapons department.

Table B.5: Maintenance requirements per department in hours for a seven-week mission

Code	MORAY	Concept
Mechanical engineering		
2.1.1.1	90	0
2.1.1.2	90	90
2.1.2.1/2/3/5	135	43.5
2.2.1	390	97.5
2.2.4 (half)	60	60
Total	**765**	**291**
Electrical engineering		
2.2.2	195	48.75
2.2.4 (half)	60	60
Total	**255**	**108.75**
Electronics engineering		
2.1.1.3	170	170
2.1.2.4	60	60
2.2.3	350	350
Total	**580**	**580**

Appendix C

Electrical distribution system

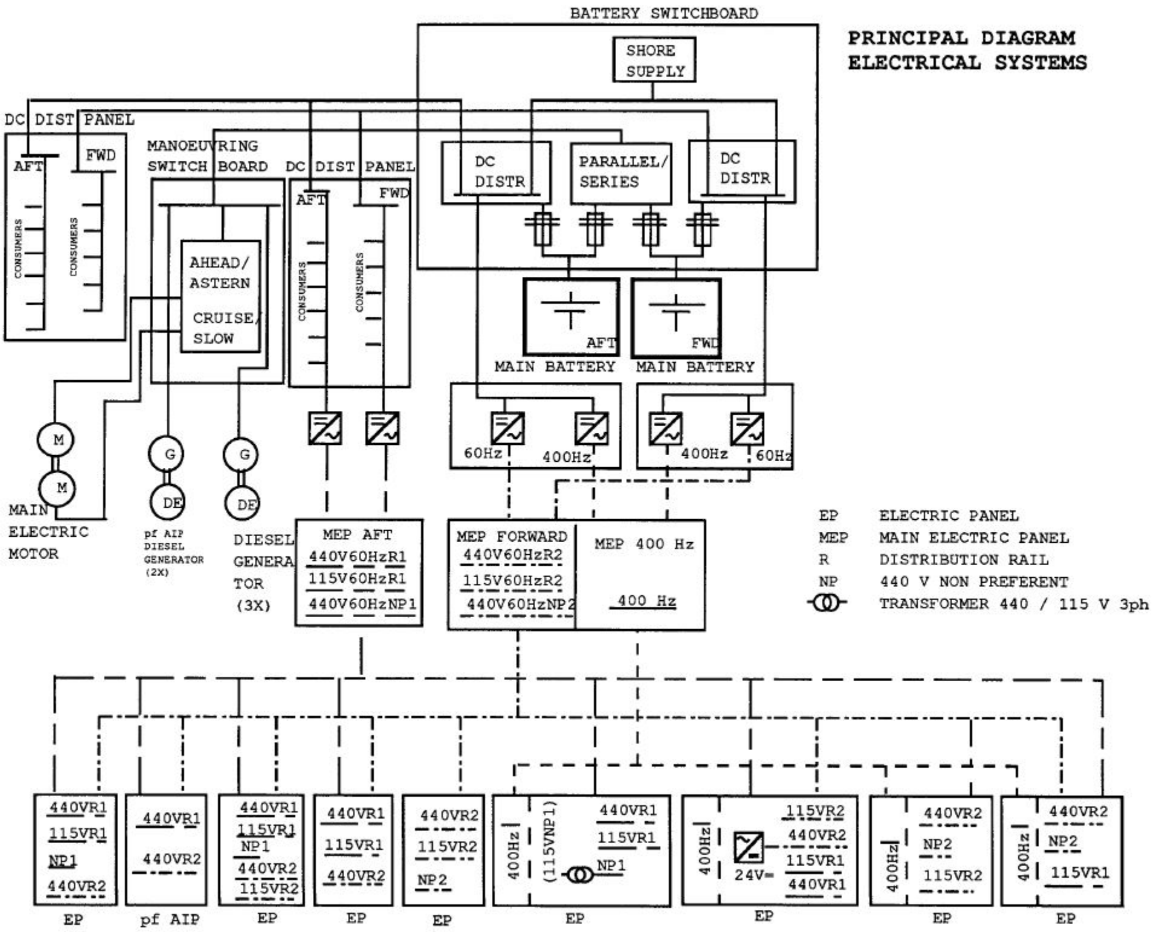

Figure C.1: Principal diagram of the electrical system of the MORAY

Appendix D

Calculations of CO_2 absorption and O_2 generation systems

The design requirements used of the CO_2 absorption system and the O_2 generation system are given in table D.1. For the concept design a submerged period of 600 hours is taken as first estimation. For the crew size, a margin of one crew member is applied. The calculations of the CO_2 absorption system are given in appendix D.1. The calculations of the O_2 are given in appendix D.2.

Table D.1: Design requirements CO_2 absorption system and O_2 generation system

	MORAY	Concept	
Submerged periods	3x 25, 1x 160	1x 600	[h]
Crew size	35	34	
Maximum number of crew	42	41	
Inboard volume in	1000	1000	[m^3]
CO_2 produced per person	25	25	[l/h]
CO_2 % prior to submerged condition	0,5%	0,5%	
Maximum CO_2 level	1.5%	1.5%	
O_2 absorbed per person	28	28	[l/h]
O_2 level prior to submerged condition	20.5%	20.5%	
Minimum O_2 level	18.5%	18.5%	

D.1 CO_2 absorption

The data of the CO_2 absorption unit, which is used for this calculations, is shown in table D.2. This data is of the CO_2 scrubber system originally used in the MORAY design.

Table D.2: Data CO_2 absorption unit

Number of CO_2 absorption units	2	
Number of chalkholders per unit	6	
Air flow per unit	60	[m^3]
Absorption capacity chalkholder	400	[l]
Weight chalkholder	4,5	[kg]
Volume chalkholder	4	[l]

Equation D.1 is used to calculate the time interval in hours for raising the CO_2 level up to the limit of 1.5 %. This is without the use of a scrubber system. In this equation, V is the inboard volume, pct_{start} is the CO_2 percentage prior to submerged condition, pct_{limit} is the maximum CO_2 percentage, p_{CO_2} is the CO_2 production per person in litres/person/hour and n_{crew} is the crew size.

$$T_{CO_2} = \frac{V \cdot \frac{pct_{limit} - pct_{start}}{100}}{p_{CO_2} \cdot n_{crew}} \tag{D.1}$$

The absorption capacity in cubic meters can be calculated with equation D.2. In this equation n_{units} is the number of absorption units, n_{chalk} is the number of chalkholders per absorption unit and $C_{abs_{chalk}}$ is the absorption capacity of a chalkholder in cubic meters.

$$C_{abs_{system}} = n_{units} \cdot n_{chalk} \cdot C_{abs_{chalk}} \tag{D.2}$$

The capacity of the CO_2 absorption system can be checked with the use of equation D.3. In this equation the surplus capacity in m^3/h is calculated. $\dot{V}_{air}$ is the air flow in m^3/h per unit and n_{max} is the maximum number of crew.

$$\dot{V}_{surplus} = n_{units} \cdot \dot{V}_{air} \cdot \frac{pct_{limit}}{100} - p_{CO_2} \cdot n_{max} \tag{D.3}$$

The operation time in hours of the chalkholders can be calculated with equation D.4. After this time, the chalkholders are saturated and must be replaced.

$$T_{operation} = \frac{Abs_{system}}{n_{crew} \cdot p_{CO_2}} \tag{D.4}$$

The required number of loadings of chalkholders per submerged period can be calculated with equation D.5.

$$n_{req} = \frac{T_{sub} - T_{CO_2}}{T_{operation}} \tag{D.5}$$

The required number of chalkholders is calculated with the use of equation D.1 to D.5 and data of table D.1 and D.2. The results of the calculations are shown in table D.3.

Table D.3: Results of the CO_2 absorption system calculations

	MORAY	Concept	
T_{CO_2}	11.43	11.76	[h]
$C_{abs_{system}}$	4.8	4.8	[m^3]
$\dot{V}_{surplus}$	0.75	0.78	[m^3/h]
$T_operatiom$	5.5	5.6	[h]
n_{req}	3x 3, 1x 27	1x 105	
Total required chalkholders	432	1260	
Weight of chalkholders	1944	5670	[kg]
Volume of chalkholders	1728	5040	[l]

The data of regenerable CO_2 scrubbers of TP group is given in table D.4. The data in table D.4 is given for a range of CO_2 removal rates. The CO_2 removal rate is used to estimate the size, weight and power requirements of the scrubber. The maximum required CO_2 removal rate is taken equal to the maximum CO_2 production rate, which is calculated with equation D.6.

$$R_{CO_{2max}} = n_{max} \cdot p_{CO_2} \tag{D.6}$$

Table D.4: Data regenrable CO_2 scrubber [45]

CO_2 removal rate	1 - 15	[kg/h]
Size of unit (volume)	1 - 5	[m^3]
Weight	800 - 2500	[kg]
Power usage	2 - 30	[kW]

Linear interpolation based on the maximum required CO_2 removal rate is used to determine the volume and weight requirements. The power requirements are based on the CO_2 production with a normal crew size, calculated with equation D.7.

$$R_{CO_2} = n_{crew} \cdot p_{CO_2} \tag{D.7}$$

Again, linear interpolation is used to estimate the power requirements. The estimated data of the regenerable CO_2 scrubber is given in table D.5. This data is used for the comparison between a regenerator scrubber system including required battery capacity and a chalkholder scrubber system. These results are shown in section 5.5.4.

Table D.5: Used data regenerable CO_2 scrubber

Maximum CO_2 removal rate	1.93	[m^3/h]
CO_2 removal rate	1.57	[m^3/h]
Size of unit	1.27	[m^3]
Weight	913	[kg]
Power usage	2.13	[kW]

D.2 O_2 generation

The data of the O_2 supply unit is given in table D.2. This data is the original data used in the MORAY class design.

Table D.6: Data O_2 generation system

Number of O_2 supply units	2	
O_2 candles per unit	1	
O_2 production per candle	3.4	[m^3]
Weight oxygen candle	12.5	[kg]
Volume oxygen candle	8.5	[l]

Equation D.8 can be used to calculate the interval in hours for dropping the O_2 level to the limit of 18.5%. This is without the use of oxygen candles. In this equation is V the inboard volume, ptc_{limit} the minimum required oxygen level, pct_{start} the oxygen level prior to submerged operation, O_{abs} the oxygen absorbed in liters/hours/person and n_{crew} is the number of crew.

$$T_{O_2} = \frac{V \cdot \frac{ptc_{limit} - pct_{start}}{100}}{Abs \cdot n_{crew}} \tag{D.8}$$

With use of equation D.9 the operating time between the using of two candles can be calculated. In this equation C_{candle} is the capacity of an oxygen candle in cubic meters.

$$T_{operation} = \frac{C_{candle}}{n_{crew} \cdot O_{abs}} \tag{D.9}$$

The number of oxygen candles required per submerged period can be calculated with the use of equation D.10

$$n_{req} = \frac{T_{sub} - T_{O_2}}{T_{operation}} \tag{D.10}$$

The required number of oxygen candles is calculated with the use of equation D.8 to D.10 and table D.1 and D.6. The results of the calculations are shown in table D.7.

Table D.7: Results O_2 generation system

	MORAY	Concept	
T_{O_2}	20.4	21.0	[h]
$T_{operation}$	3.5	3.6	[h]
n_{req}	3x 2, 1x 40	1x 163	
Total required candles	46	163	
Weight of candles	575	2037.5	[kg]
Volume of candles	391	1385.5	[l]

Appendix E

Transverse sections concept design

E.1 Concept design

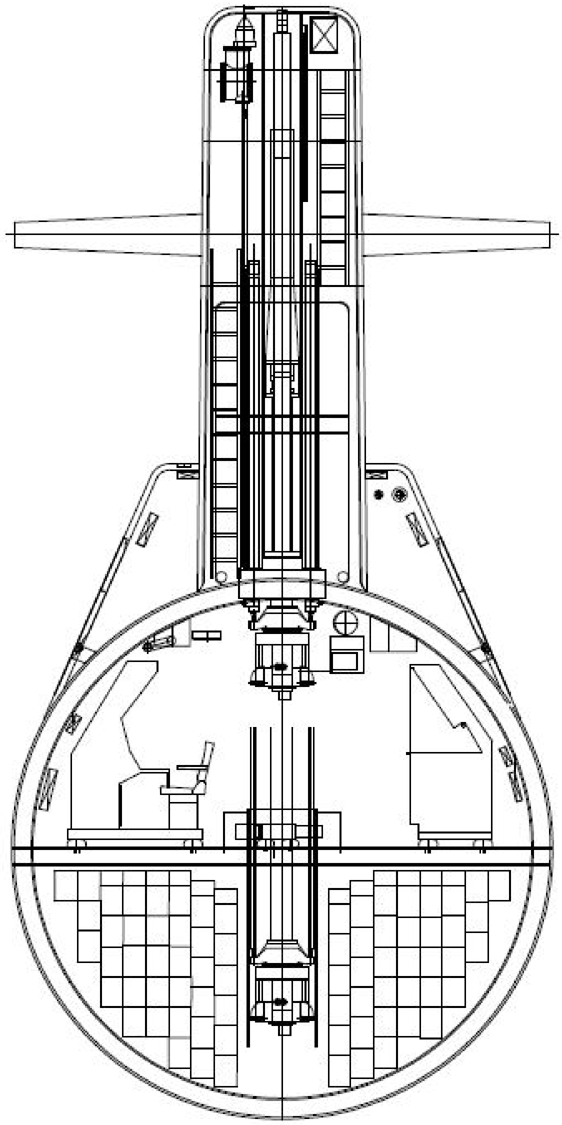

Figure E.1: Transverse section view at location of the sail

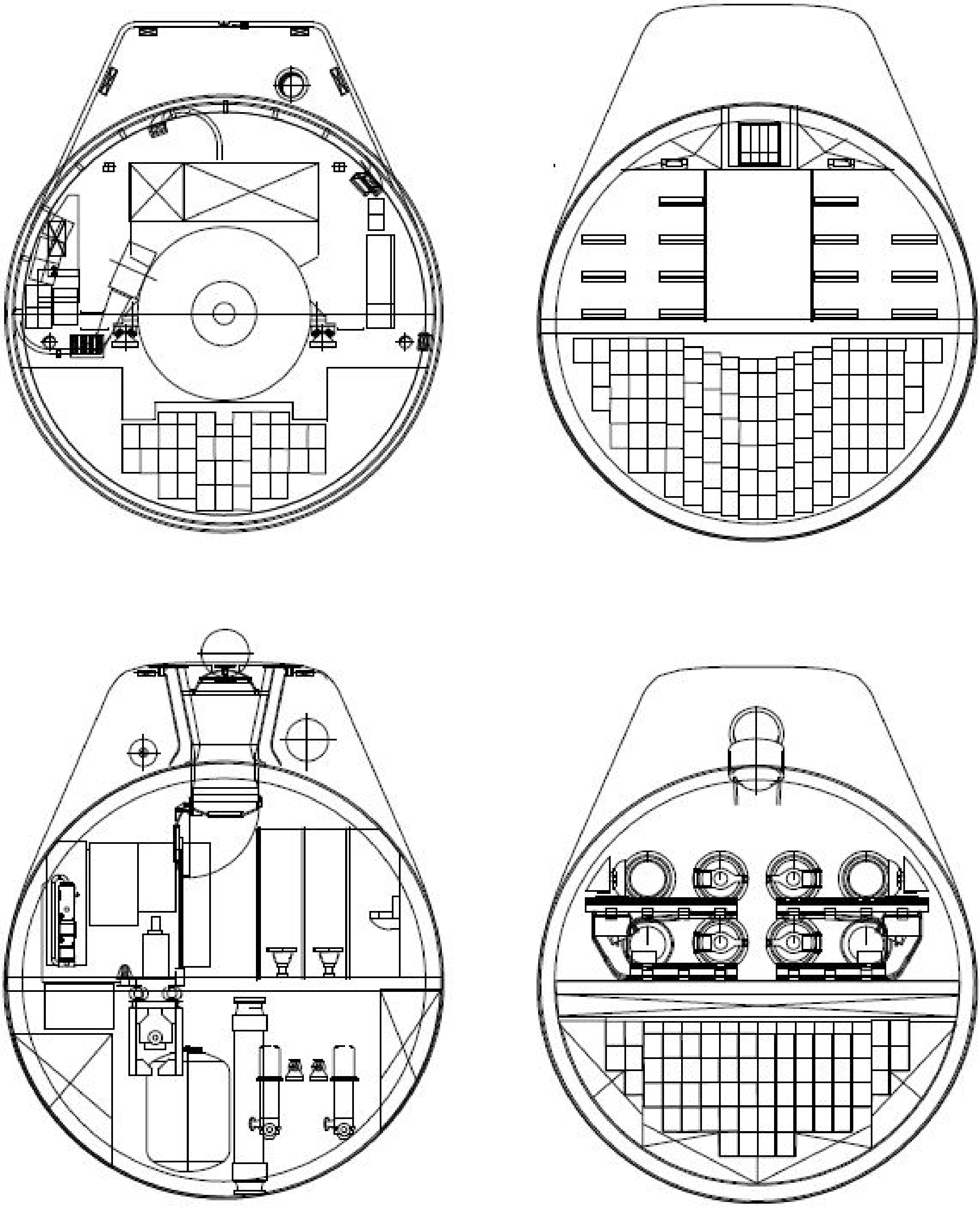

Figure E.2: Transverse section view at location of the MEM, rating cabins, auxiliary room and torpedo room

E.2 Modular lithium-ion section

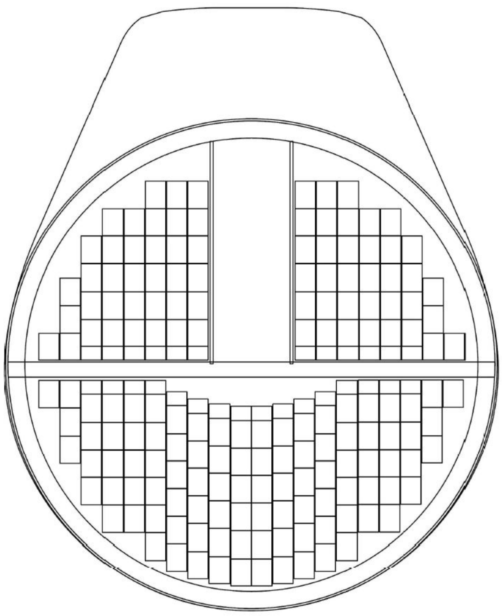

Figure E.3: Transverse view of modular lithium-ion section

Appendix F

Lithium-ion battery vent gas composition

Table F.1: Vent gas composition for a pouch LIB cell [8]

	% vol at 100% SOC
Carbon dioxide	30.00%
Carbon monoxide	22.90%
Hydrogen	27.70%
Methane	6.39%
Ethylene	2.19%
Ethane	1.16%
Propylene	4.52%
Propane	0.26%
Isobutane	0.20%
n-Butane	0.56%
Butenes	1.58%
Isopentane	0.07%
n-Pentane	0.73%
Hexanes	2.32%
Benzene	0.11%
Toluene	0.02%
Ethyl-benzene	0.00%