“DESIGNING AND PERFORMANCE OPTIMISATION OF SUSTAINABLE AIR INDEPENDENT PROPULSION (AIP) SYSTEM FOR EXTENDED ENDURANCE OF SUBMARINES”

A thesis submitted to the
University of Petroleum and Energy Studies

For the award of
Doctor of Philosophy
in
Power Engineering

BY

Cdr. R Raajiv

Jun 2020

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Research and Development
School of Engineering
University of Petroleum and Energy Studies
Dehradun-248007; Uttarakhand

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DECLARATION

I declare that the thesis entitled **“Designing and Performance Optimisation of Sustainable Air Independent Propulsion (AIP) system for extended endurance of Submarines”** has been prepared by me under the guidance of Dr. Jitendra K Pandey, Professor of Chemistry, University of Petroleum and Energy Studies, Dehradun and Cdr (Dr). R. Vijaya Kumar, Naval Constructor Officer. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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ABSTRACT

Submarines has become an integral part of every Navy be it bigger or smaller in size. The navies around the world operate submarines in almost every ocean of the earth. These war machines have improvised with advent of technology and time and has emerged to be more lethal and potent with increased stealth and fire capability. Depending upon the economic strength and defence expenditure the variant of submarine propulsion capability differs between a nuclear or a conventional diesel electric submarine. Diesel electric submarines plays a variety of roles offering littoral protection as well as distant reach capability. Advancement in submarine detection techniques from air through long range maritime reconnaissance aircraft and with advent of high precision periscope radars and advanced infrared photographic cameras fitted onboard aircraft cause severe menace to conventional submarines operating at surface and periscope depth.

Fig1. Notional submarine Operating oceanic regions

Nuclear submarines are massive in built and requires heavy financial indulgence in construction, maintenance and operation of the vessel. Improvements in design and technology has brought in a sea change in the sustainability and operating capability of conventional submarines. Conventional submarines are better suited to operate near the coast in a brown water littoral environment.

With the advent of fuel cells, the idea of using fuel cells for underwater propulsion is often a heavily debated topic. Fuel cell is often considered as a first choice mainly because of its inherent stability in operation robust constriction. Proton Exchange Membranes (PEM) is the most widely used fuel cell AIP option exploited onboard submarine. The research on Air Independent Propulsion in the present decade has mainly focused on bettering the power extraction from fuel cell and exploring other types of fuel cells other than PEM. DRDO, India is presently researching on PAFC for fitment onboard the Scorpene class submarines.

Presently the submarine manufactures around the world has been marketing this functionality of this system as a “Plug and play model” in addition to the diesel electric system onboard. This research aims to integrate Commercial Off The Shelf (COTS) fuel cell system to the existing submarine and to determine realistic endurance of the system.

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Nothing in this world exists without the grace of Almighty hence "**Ella Pugazhumm Iraivannukke** (in Tamil language)" – which translates into "All Glory to God".

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I would like to dedicate this work to my beloved wife Major Raje RR (retd) who is the wind beneath my wings. She had been my pillar of strength and constantly supported through thick and thin in our life. Her patience, understanding and perseverance to motivate me throughout had ensured successful completion of this research work.

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LIST OF ACRONYMS

ABBREVIATION	DETAILS
AIP	Air Independent Propulsion
CCD	Closed Cycle Diesel
MESMA	Module Et Sous Marine Autonome
SE	Stirling Engine
FC	Fuel Cell
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
SOFC	Solid Oxide Fuel Cell
MCFC	Molten Carbonate Fuel Cell
SM	Submarine
CHP	Combined Heat Power
LRMPA	Long Range Maritime Patrol Aircraft
DRDO	Defence Research and Development Organisation
NMRL	Naval Materials Research laboratory
MDL	Mazagaon Dockyard Limited
SSN	Submersible Ship Nuclear
SSBN	Submersible Ship Ballistic Missile Nuclear
NATO	North Atlantic Treaty Organization
INS	Indian Naval Ship
HMS	Her Majesty's Ship
USN	United States Navy
LH	Liquid Hydrogen
MH	Metal Hydrides
LOX	Liquid Oxygen
IR	Indiscretion Ratio
SHP	Shaft Horse Power
KW	Kilo Watt
SUBD	Submerged Displacement
L	Length
D	Diameter
OEM	Original Equipment Manufacturer

ABBREVIATION	DETAILS
MCDM	Multi Criteria Decision Making
FDM	Forced Decision Matrix
MAUT	Multi-Attribute Utility Theory
SWC	Sample Weighted Coefficient
AWC	Attributed Weighted Coefficient
TW	Total Weight
TWC	Total Weighted Coefficient
TOPSIS	Technique of Order Preference by similarity to Ideal Solution
MAVT	Multi Attribute Variabe Theory
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
WPM	Weighted Product Model
WSM	Weighted Sum Model
PAPRIKA	Potentially All Pairwise Rankings of all Possible Alternatives
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje(Multicriteria Optimization and Compromise Solution)
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
BWM	Best Worst Method
ELECTRE	Eimination Et Choix Traduisant la REalité (ELimination Et Choice Translating REality).
LAB	Lead Acid Battery
NAS	Sodium Sulphide
LI	Lithium Ion
LAIS	Lithium Aluminium Iron Sulphide
NC	Nickel Cadmium
DoD	Department of Defence
MARPOL	Marine Pollution
PLC	Programmable Logic Circuits
NG	Naval Group
DCNS	Direction des Constructions Navales

ABBREVIATION	DETAILS
TKMS	ThyssenKrupp Marine Systems
HDW	Howaldtswerke-Deutsche Werft
MR	Methanol Reformer
NABH4	Sodium Borohydride
BOP	Balance of Plant
DC	Direct Current
IMO	International Maritime Organisation
SGA	Simple Genetic Algorithm
AIS	Artificial Immune System
PSO	Particle Swarm Optimisation
EG	Error Graph

CHAPTER 1
INTRODUCTION

This chapter highlights the concept of Air Independent Propulsion (AIP) and its importance in the modern era of conventional submarines. In addition, this chapter includes research progress, software simulation, implementation of tools and field work undertaken. A summary of individual chapters to provide a gist of information is appended towards the end of Chapter.

1.1. OVERVIEW

A conventional diesel submarine as the name suggests utilises a diesel engine for generation of power through combustion. These diesel engines are exploited onboard the submarines in two different configurations viz., Surface and at Periscopic Depth (PD). The operation of diesels at PD is known as snorting where in the fresh air required for combustion of diesels is sucked onboard through a snort mast. The exhaust of the diesel is expelled outside the submarine as per the regime of operation. The advancement in the area of Maritime Patrol Aircraft (MPA) has made operation of conventional submarines extremely difficult in surface as well as PD. The Infra-Red cameras and thermal imaging and optical image stabilization cameras onboard aircraft has the ability to pick submarines at greater distances. With increase in need to operate submarines in a littoral water with enhanced stealth has made induction of an AIP system a necessity. Considerable amount of research has been undertaken in developing these systems. However, the design data on these systems are extremely scarce in open source. The advent of nuclear propulsion and the high associated cost has expedited the research and materialization of AIP systems onboard conventional platforms. Four different types of AIP systems are widely utilised by majority of the navies. Closed Cycle Diesels (CCD), Module Et Sous Marine Autonome(MESMA),Stirling Engine (SE) and Fuel Cells are the known AIP systems exploited onboard diesel submarines. The research is formulated as a techno-managerial research with identification of optimal AIP system using Multi Criteria Decision Making (MCDM) techniques and Weighted Decision Analysis.

The present endurance of the AIP system is dependent on the amount of fuel stored onboard. Taking into account the safe storage option for handling of hydrogen onboard various storage options are identified and assessed as part of this research. The safest and most efficient storage option is proposed for incorporation onboard. The storage options are analysed taking into account the possibility of replenishment at sea (Present AIP systems cater only for harbour replenishment). Due to the limitation of stored power AIP can be only used as an auxiliary support power source and cannot be considered as main power source which means it can only coexist as a hybrid (Lead Acid Battery + AIP) system.

1.2. Motivation

AIP is a necessity for a submerged platform for maintaining stealth, especially in enemy waters. In order to increase the operational ability, submerged endurance, it is extremely important that the conventional diesel submarines be equipped with an AIP system. The technology is to be considered as an essential option similar to other systems which have evolved all along as part if modernisation of diesel submarines. Majority of the world navies (Except US Navy and British Navy) have migrated to exploitation of AIP system for their submarines. The motivation towards undertaking research in this particular field is appended below: -

(a) Limited access to research materials & data in this field, makes it difficult for comparative analysis and improvement. Due to the nature of the project there is very little data available on open source. The present research aims towards considering AIP technology as any other powering source used in everyday scenario. This concept enables to integrate the Commercially Off The Shelf (COTS) technology onboard submerged platforms.

(b) Cost of technology is extremely high and requires precise simulations and calculations for integration of technology onboard a submerged platform.

(c) Efficient storage of fuel onboard as the capability of AIP system depends solely on the fuel availability onboard and thus determines the endurance of the system.

(d) Due to the higher fuel consumption rate by AIP fitted platforms viz., CCD & MESMA restricts their loiter speeds to 2~6 kts predominantly and sprint speeds upto 12 knots for a very short duration. Further these AIP systems involves rotating machinery which adds to the deterioration of overall stealth. Hence there is a need to identify a balanced AIP system without comprising the stealth feature of the submerged vessel.

(e) Understanding of complex project management techniques involving Multi Criteria Decision Making (MCDM) methodologies like FDM and TOPSIS to segregate the efficient technology amongst complex options available in real time scenarios.

1.3. Problem statement

The importance of an AIP system is elucidated in the preceding para 1.2. and it is inferred that induction of AIP system in future will become inevitable in order to operate conventional submarines in littoral waters. Enhanced stealth, increased underwater endurance, ease of operation, improved maintenance envelope is considered towards formulation of the problem statement "Design and performance optimisation of Air Independent Propulsion (AIP) system for extended endurance of submarines".

The problem statement entails selection of optimal AIP system amongst the existing AIP systems (using Forced Decision Matrix (FDM)) and implement a

Multi Criteria Decision Making (MCDM) technique viz., Technique of Order Preference by similarity to Ideal Solution (TOPSIS). Simulations of the submarine of definite length has been modelled using MATLAB and Paramarine software.

1.4. Objectives

The Objectives of the research are appended below: -

(a) To investigate the various parameters in order to achieve an optimized model of Air Independent propulsion (AIP) system for future fitment onboard Submerged Marine Vehicles.

(b) To analyse the effect of insertion of AIP plug onboard existing platforms.

(c) To recommend Co-generation systems to increase the overall efficiency of the Air Independent propulsion systems.

(d) Based on the afore research findings, it is proposed to have an optimised AIP system utilising fuel cell for hybrid submarine with extended endurance.

1.5. Research Methodology and Progress of work.

(a) Literature review comprising of technical notes and industrial experiences from marine industry was undertaken. Majority of work has been taken from open source material.

(b) Technical discussions with industrial experts, Marine engineers & technicians, foreign OEMs veteran submariners and Battery and Diesel Manufacturers were done in an extensive basis, Keeping in mind the need for a sustainable and reliable future proof system. critical parameters governing the exploitation of the system were identified.

(c) Based on the above parameters, a tool implementing project management technique towards identification of suitable Air Independent Propulsion (AIP) was formulated based on Forced Decision Matrix (FDM) methodology. Fuel Cell System was identified as the best suitable technology for implementation on submarines.

(d) Various Speed profiles of propulsion during transit, Patrol and Sprint speeds were formulated with graphical analysis and calculation of indiscretion rate for an AIP submarine.

(e) A MATLAB tool was designed to obtain an initial estimation regarding a Diesel electric submarine incorporating an AIP system. The results were exported to a MS Excel spread sheet for record keeping and further analysis.

(f) MATLAB program to assess the stability of the AIP Plug vis-à-vis the length, speed and endurance (based on no of days of AIP operation) is formulated.

(g) PEM fuel cell was modelled in MATLAB-SIMULINK and Simple Genetic Algorithm was utilised to optimise the results.

(h) In order to achieve a higher standard of efficiency a co-generation technique towards utilisation of waste heat towards preheating of the fuel cell system is proposed.

(i) Further, keeping in account the sustainability of the AIP plug, MIL grade commercial fuel cell based on power output has been considered to infuse a COTS technology into a military platform. Thus, increasing the ease of operation towards maintenance and spare supportability.

1.5.1 Source of data

(a) Open source

(b) Data sheets from OEMs

1.5.2 Tools Utilised: -

(a) MATLAB-Simulink 2017A

(b) MCDM Technique – FDM

(c) MCDM Technique – TOPSIS

(d) Paramarine

(e) Power Stage Designer Tool – M/s Texas Instruments version 4.0

(f) Simple Genetic Algorithm (SGA) implementation using MATLAB-SIMULINK model

1.6. Chapter wise Summary

This thesis is structured into seven chapters. A summary of individual chapters is depicted below: -

Chapter 1 gives us an introduction about the thesis. Overview, motivation behind the research work, objectives, research methodology and progress of work are mentioned briefly. Extensive software simulations have been coded, modeled using software programs viz., MATLAB-Simulink and Paramarine. The research is undertaken in a Techno-managerial methodology where in extensive simulations, modeling and calculations vis-à-vis MCDM a sub-discipline of operational research is also utilised as part of research.

Chapter 2 consists of literature survey. A total of 300 Plus references have been referred in connection with the technology and MCDM techniques. The papers were referred to portray the growth of propulsion technologies for submarines since its inception and the various advancements in the storage technologies. In addition, it also brings out the advantages and disadvantages of each of AIP technologies available in the present scenario.

Chapter 3 depicts the implementation of Forced Decision Matrix in order to select an optimal AIP system amongst four existing technologies viz., Closed Cycle Diesel (CCD), Module et Sous Marine Autonome (MESMA), Stirling Engine (SE) and Fuel Cell. It includes formulation of common critical parameters in order to evaluate a particular system. The FDM is an offset of Pugh selection Matrix often utilised in engineering for making decisions about designs.

Chapter 4 represents the usage of Multi Criteria Decision Making (MCDM) technique viz., Technique of Order Preference by similarity to Ideal Solution (TOPSIS) to filter out the best possible Fuel cell option for fitment onboard a submarine. Four different options of fuel cells used onboard surface naval vessels viz., Polymer Electrolyte Membrane (PEMFC), Phosphoric Acid (PAFC), Solid Oxide (SOFC), Molten Carbonate (MCFC) are compared using TOPSIS. The detailed formulation of the methodology along with the methods of calculations are described in this chapter. The results are depicted in a graphical model.

Chapter 5 extensively covers the simulations, coding and subsequent modeling of the AIP system using software tools viz., MATLAB -Simulink, Paramarine and Power Stage Designer Tool – M/s Texas Instruments version 4.0. The initial sizing of the Submarine was coded into a MATLAB file and the results were extrapolated to an M/s Excel Format for visual appreciation of the processed data.

Chapter 6 illustrates the optimisation of PEMFC using Simple Genetic Algorithm (SGA). A MATLAB -Simulink model of PEM fuel cell is designed and the SGA is infused into the sub-blocks of the Simulink model using MATLAB codes. Computation of error graph is generated in real time while running the program and the results are displayed in Graphical format.

Chapter 7 depicts the conclusion of the research work and the scope of future work on the subject. The importance of the research work and its importance for future is highlighted in this chapter.

Chapter Summary

Induction of an Air Independent Propulsion (AIP) system is a need of hour. Especially with majority of world Navies migrating to AIP Platforms and technologically advanced submerged platforms lurking in our nation’s water it is extremely essential that a comprehensive study about the topic is to be undertaken. This chapter illustrates the overview, motivation, problem statement and research methodology implemented in this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1. **Introduction** The history of fitment of Modernised AIP onboard submarines started in the early 1980's with Sweden refitting its submarines with a Stirling engine thus venturing its quest into the oceans depth with advanced propulsion system which enabled its submarines to stay under water for an appreciable amount of time as compared to the conventional submarines of that era[1]. The system was developed by the engineers from M/s Kockums and refitted onboard Gotland class submarines [1].

The closed cycle diesel engines were never pursued since the time of "cigarette lighter" boats which was widely known as an impending threat to the lives of men onboard. This Propulsion has never been explored ever since [2]. The closed cycle steam turbines which works on the principle of steam generation to generate power has been single handedly managed by France under the name MESMA. MESMA stands for its French abbreviation -Module D'Energie Sous-Marine Autonome [3]. This type of AIP propulsion is fitted only onboard the French submarines or on its export variants. There is a setback trade off in the system as even though the output power produced is much higher than any of its counterpart AIP systems the MESMA is considered as an "oxygen guzzler" and because of which the system overall efficiency reduces drastically.

Considerable research has been undertaken in different areas of submerged propulsion especially in the area of underwater propulsion systems. Since the power calculations of a submarine is secretive it is very rare that the concepts are available in the open source literature.

The majority of AIP research is focused into Fuel cells for reasons galore: -

(a) Absence of moving parts

(b) Easier to maintain as compared to other AIP technologies

(c) Lesser noise and heat signature

Low temperature fuel cell is often the most sought after technology for incorporation into an air independent propulsion system onboard submarines mainly because of their enhanced stealth due to noiseless components and the absence of exhaust pollutants [4]. The comparison of the air independent propulsion onboard submarines has been brought out by Cmdr. Lus et.al., [5]. The design and subsequent retro fitment of a AIP system consists of series of complex calculation which involves sizing, arrangement and power calculations of the system and the components[6]. A new flexible arrangement of systems and subsystems is rigorously pursued as a topic of interest around the world to add flexibility and complexity of the submarine design [7].

The initial study and design of system and components plays a pivot role in overall construction of submarine. Usage of Parameter optimization [8], [9][10] aids and genetic algorithms [11], [12]has improved the quality of design in a much better manner. The modelling of powering system is extremely important for platform implementation as it differs drastically from stationery model and requires parameter verification onboard a moving platform [13]. The AIP technology designated for a particular class of project (submarine) must take into account the safety, performance, efficiency and reliability of the system during the design stage of the submarine [14].

A similar type of parameter study was undertaken by M/s Artic Energies to assess the powering solutions of AUVs and Submersibles [15]. The concept was later adopted and were taken as reference for incorporation on a study to assess feasibility of AIP technology onboard submarines. Though, Kumm had contributed extensively towards feasibility of AIP onboard submarines[16], [17], the studies on unmanned underwater vehicles and studies on fuel cell incorporation onboard submarines [18][19][20][21] do not provide the much details on the nuances of the technology in detail. The efficiency of the fuel cell employed in an air independent system is extremely low [22] in the range of 20 to 40 %. The system must also cater for expulsion of exhaust gases [23][24] from submerged depth if the AIP system utilized onboard is different from fuel cells. Fuel cells disperses water as a byproduct from its operation. The technology governing AIP and associated is often a well-guarded secret in most of the nations and very little or scare information is available in open literature. First installation of a proton exchange membrane AIP system on a Russian Whiskey class diesel electric submarine in 1981 was reported by a visiting US team [14] in1993. Speculations concerning installation of an advanced AIP system on a Russian research submarine Beluga was also contemplated during early nineties[25].

Hydrodynamic studies carried on a Type 2400 class (also known as Victoria/Upholder Class) submarines indicate a power requirement of 50KW for propulsion speeds of 4-5knots [26]. Incorporation of AIP technology is not restricted to a newer class of submarine but also to an existing diesel electric submarine. For instance, Australia, had carried out studies for incorporating an AIP Plug to its existing Colin class submarines [27][28][29][30]. The endurance of an AIP system is based on the area coverage and sustainability at the area for a prolonged duration. From calculations it has been ascertained that for a submarine with a displacement of 2200 tons fitted with an 250KW AIP can sustain at a speed of 6 Knots[31]. The calculations are mostly done for a vessel to sustain at low speeds however further studies have been carried out for higher speeds to calculate the “sprint endurance” a vital factor of the submarine when facing an imminent threat [32][33][34][35]. Safety is paramount onboard a submarine and every installation onboard go through a series of stringent safety norms before the final nod onboard.

Oxygen and hydrogen being critical ingredients in an AIP system some amount of safety as well as experience in handling such systems are pre-requisites for smooth operation of the system. Swedish and German Navies have gained the much-sought experience of operating liquid oxygen within the safety margin from the Nacken and U- 1 vessels [36]. Earliest incorporation of fuel cell onboard a submersible or submarines dates back to late sixties [37]. Though there are many variants of fuel cells [38]–[40] available in the market, not all can be utilized onboard for power generation and more over for an air independent propulsion [21]. Even though alkaline fuel cell was used by Germans towards proving the air independent propulsion onboard Type 205 submarine in 1987, however the fuel cell was ditched in favor of PEM fuel cell [41]. The main reason for preference of PEM over other fuel cell type is primarily because of its low operating temperature [32].

Hydrogen storage onboard is characterized by the methodology of storage exercised by the designer. Adequate precautions are to be catered towards ensuring the shock proof cylinders used for storing hydrogen in gaseous state [42][43]–[47]. A study conducted by Newport news shipbuilding indicated that there is an expense of electrical energy when liquid hydrogen is used as fuel for the AIP system and thus adding to the overall decrease in the system efficiency [48]. Hydrogen storage in form of metal hydrides is one of the earliest and currently employed technology for storage of hydrogen onboard submarines [41]. The researchers have claimed hydrogen storage density as high as 6% in metal hydrides and the research in hydrogen storage is growing at an exponential rate[49], [50]. Storage density of 2% is being utilised by metal hydrides on type 205 vessel[14] . An innovative concept of utilising the oxygen cylinders to store the exhaust gases was explored using a Closed Cycle Diesel (CCD) technology [51]. A high precision piping is a requisite for LOX pipelines and are generally kept away from the contact area of the crew. An AIP design model is formulated based on the existing base models of conventional diesel electric submarines. Fuel power system are costly and requires heavy investment for installation and research, hence simulation of systems for marine and underwater systems prove to be a much better option in order to delineate an optimal system for installation and use [10][52][53][54]. Often Exergy analysis [55] of systems highlights the parameter optimization possible with a given system before its actual installation onboard [56]–[58]. Fuel cells have been considered as an option for propulsion of submersibles [59], [60][61]. MATLAB, LabVIEW, Ansys Fluent software are often used to simulate the Fuel cell system [62]–[70][71]–[74]. Studies determine the requirements of fuel and oxidants to achieve the wattage essential for the propulsion of the submerged vessel [75]. A newer version of Solid Oxide Fuel Cell (SOFC) is rapidly gaining momentum and is currently being researched all around the world as an alternate option of PEM fuel cell onboard Submarines [76]–[78]

2.2. Multi Criteria Decision Making (MCDM) Techniques

Forced Decision Matrix (FDM) technique has been utilized in this thesis to determine the best suited AIP system for submarines. Critical factors towards differentiation of AIP systems with respect to each other are enlisted under parameter identification. FDM enables us to prioritise the best option in a logical manner. The FDM is structured on the Decision Matrix analysis, a management technique which is a tool employed for undertaking Multiple Criteria Decision Analysis (MCDA)[79]–[81]. The tool is utilised towards selection of best AIP options on similar lines of a business decision making methodologies based on subjective data. Decision matrices are often employed when there are multiple alternatives and multiple interlink factors governing each alternative[82].

Forced decision matrix[80] is powerful for analyzing factors when there are more than one alternate solutions. It is understood from the table that the fuel cell has the maximum Total Weighted Coefficient and emerges as the best solution amongst other AIP systems[83]. Though Stirling engines have been installed onboard conventional boats and have performed consistently over the years, the technology however has reached its maturity and has very minimal scope for extraordinary improvement unlike the case of fuel cell AIP systems[84], [85]. Fuel cells may initially draw high investment costs but will be beneficial in the longer run. Lakeman et al [35]have investigated the AIP variants and have concluded that fuel cell technology emerges out the best option for stealthier conventional submarines to operate in the brown waters. FDM methodology can be considered as an important precursor solution towards project implementation. When tasked to choose between compelling technologies with close resemblance to each other the management tool like FDM is highly useful. The paired comparison utilised in the FDM methodology forces to arrive at a decision of one over the other in a paired decision matrix comparison. Further studies such as Techno economic analysis of the narrowed down project can be undertaken in future prior installation, based on the above FDM methodology.

TOPSIS – Technique for Order Preference by Similarity to Ideal Solution was invented by Hwang and Yoon in 1981[86]. Yakup Celikbelik et.al have elaborated the processes involved in the decision-making techniques[87]. TOPSIS considers two alternatives viz., Ideal alternative which has the best attribute and negative ideal attribute which has the worst attribute[88]. The MCDM technique selects the alternative which is closer to the ideal condition and farthest from the negative parameter. Four types of fuel cells which have been tested and implemented onboard commercial and military surface vessels were considered for installation onboard an underwater platform.

Evolutionary Algorithms – Simple Genetic Algorithm (SGA) is an optimisation technique based on principles of natural selection[89]. Genetic Algorithm (GA) is part of Evolutionary algorithm developed by John Holland in university of Michigan. Genetic algorithm is used for faster computational purpose and undergoes a process of recombination and mutation in order to arrive at a result. The process is inspired by the Charles Darwin's theory of natural selection[90].

A synergy of a hybrid propulsion system encompassing traditional powering system coupled with an alternative powering source fuel cell is the most sought-after technology in the field of marine propulsion [91]. These systems offer immense advantage in terms of stealth, efficiency and prevents noxious emissions. Directives towards emission control were proposed by International Maritime Organization (IMO) which includes adaptation of a hybrid electric propulsion onboard [92]. In order to realise true potential of hybrid systems it is essential that the parameters governing them is to be optimized. The Optimised parameters enables to achieve higher efficiency rate in an actual propulsion plant. The various types of Air Independent Propulsion (AIP) system are being considered for installation and further exploitation all around the world [5], [93]. However due to the maturity in technology and the need for higher efficiency at lower operating temperatures and high-power density targets PEMFC are considered a strong contender for marine vessels. In addition, Molten carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) systems are installed on various commercial and military ocean-going surface vessels [57] however adaptability for submarine use will take a long time due to its high temperature operation and necessity to expel byproducts outboard. Simulation Modeling of PEM fuel cell and its associated components has made great progress over the years with research studies prediction of parameters pertaining to, steady state mathematical and dynamic behavior of fuel cell are being undertaken all over the world [94]–[98]. Variation of computational evolutionary techniques are utilized in Genetic algorithms and its offsets. These algorithms are used for parameter predictions of various fuel cell models [99]–[101]. The health of the FC stack is ascertained on the basis of excess oxygen ratio in the fuel cell. Accurate adjustment of excess oxygen ratio enables high efficiency rates from the PEM fuel cell [102].

V-I characteristics of fuel cells has been reported in number of publications. The electrochemical model formulated by general steady state characteristics of PEM fuel cell was reported by Mann et.al [96]. An accurate model of fuel cell was presented by Correra et.al by means of physical and empirical formulas [94]. A similar model comprising of physical and empirical values was utilized by Pukrushpan et.al for V-I characteristics [103].

2.3. History of Submarine developments

The history of operation of submarines dates back to the early sixteenth century A.D. where the vessels were hand operated for propulsion [104]. Since then there has been a massive outgrowth in propulsion system of the submarines. Over the last fifty years, super navies of the world have been operating their nuclear-powered platforms across the oceans [105], [106].

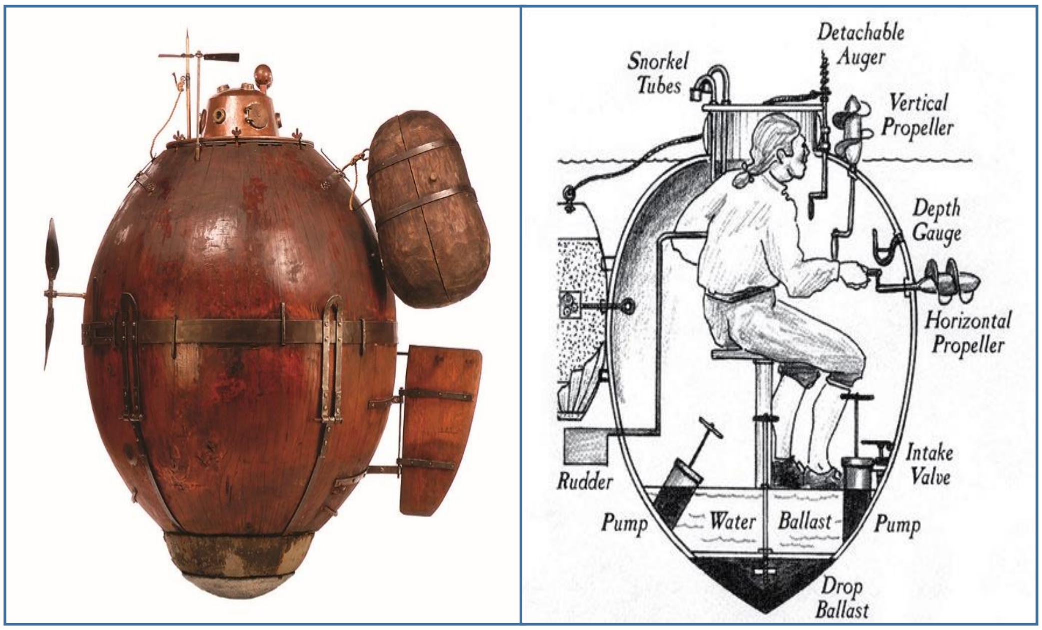


Fig 2.1 (a) Turtle submarine[107] (b) Single man driven submarine[108]

The origin of submarine construction dates back to the 17Th century where a single manned submarine named ‘Turtle’[109] was designed by David Bushnell for countering the English blockade at New York. The design was not successful and it did not achieve the desired results. However, the earliest submerged vessel propelled by oars was constructed in the sixteenth century by a Dutch Cornelius von Drebbel[110]. These boats were mainly propelled using human power and lack any propulsion components and were plagued by external pressure and human fatigue. Fulton’s vessel[111] had many interesting features viz., ellipsoid hull structure, buoyancy tanks, compressed air storage etc. which were considered as forerunner to modern submarine construction. These designs and inventions were immensely plagued by stringent cashflow as the public and military failed to realise the potent of these underwater submerged weapons.

During the mid-1800's a brilliant Bavarian named Wilhelm Bauer [112] invented a series of hand power submarines with varying design concepts (Brandtaucher and Seeteufel submarine)[113].

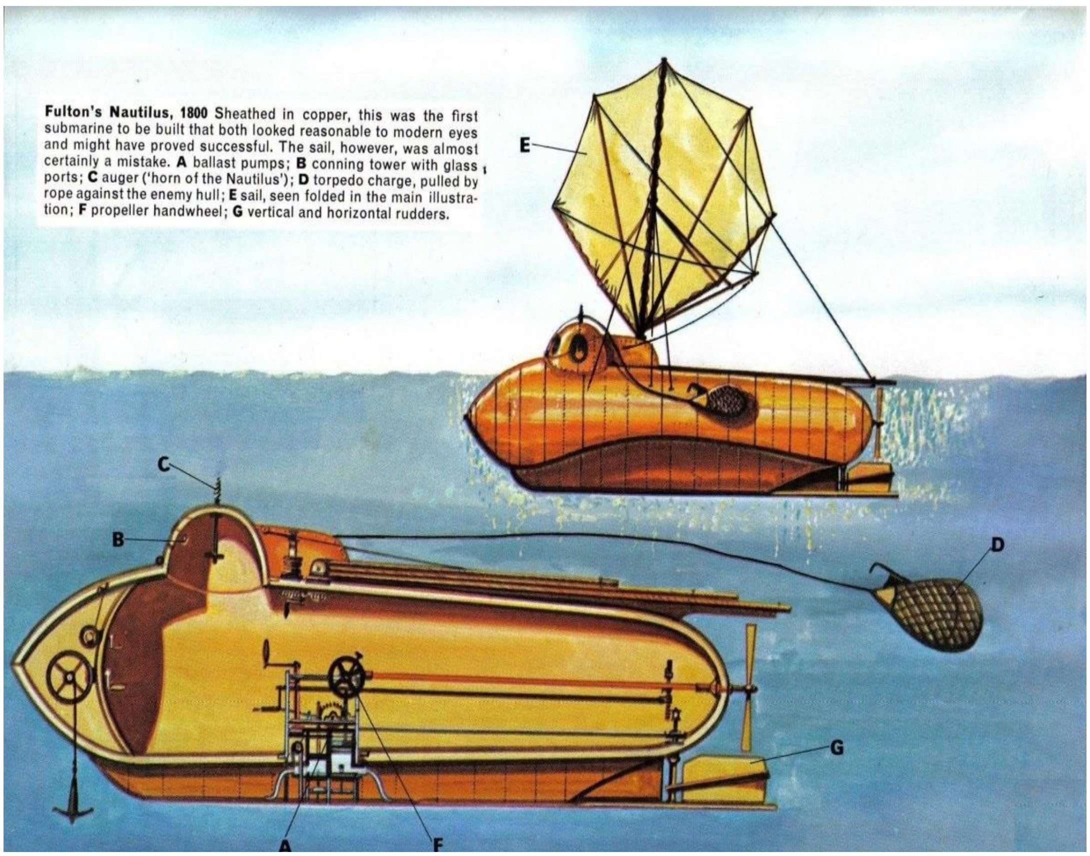


Fig 2.2. Fulton's Nautilus submarine[114]

Though the public demonstration of the "Brandtaucher" was severely scared by crack in hull and entrapment of the crew in the harbour of Kiel [115]. It demonstrated the first of its kind live submarine escape undertaken from a disabled submarine.

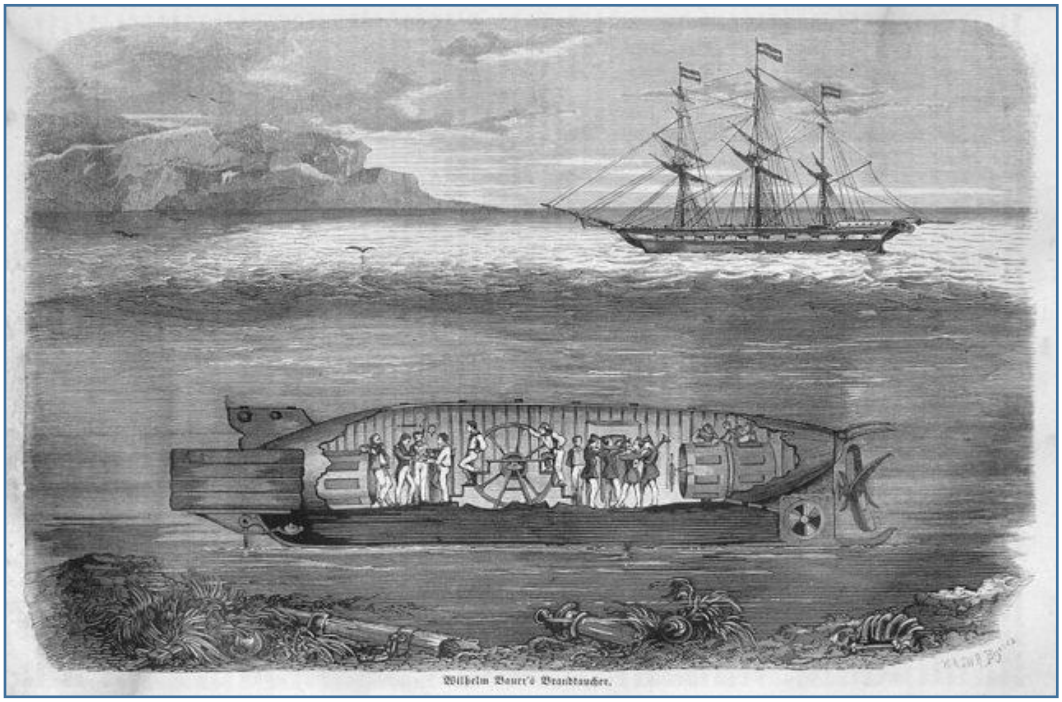


Fig 2.3. Wilhelm Bauer's – "Brandtaucher- the incendiary diver"[116]

2.4. Submarine Propulsion using Stored Power

The idea of utilisation of lead acid battery installation onboard submarine was originated from an invention of Plante[117]. With rapid advancements in technology and the need for weaponization and endurability of underwater vehicles the French had built its first submarine Gymnote[118]–[120] with storage batteries a first of kind electric propulsion amongst submerged vehicles. This submarine design incorporated 540 alkaline cells consisting of Zinc and Copper oxide electrodes with Potassium hydroxide electrolyte arranged in a parallel and series combination in order to achieve various speed profiles. During the same time another French Submarine named Morse[104] was launched and was fitted with a 284HP electric motor with an endurance range of 90 Nm at low speeds.

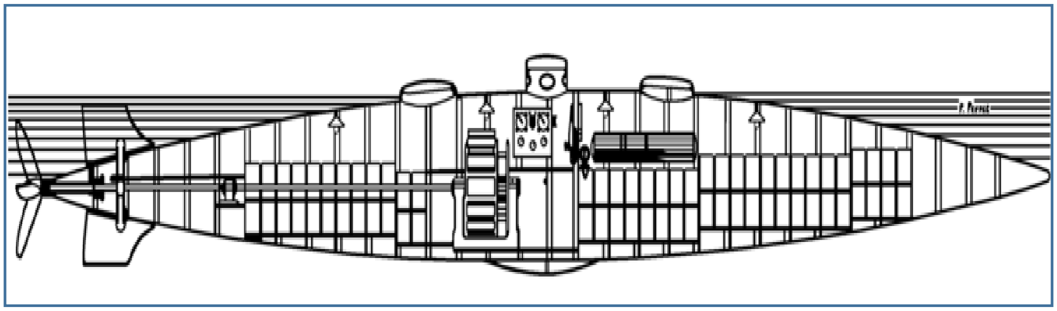


Fig 2.4. French Submarine - Gymnote[121]

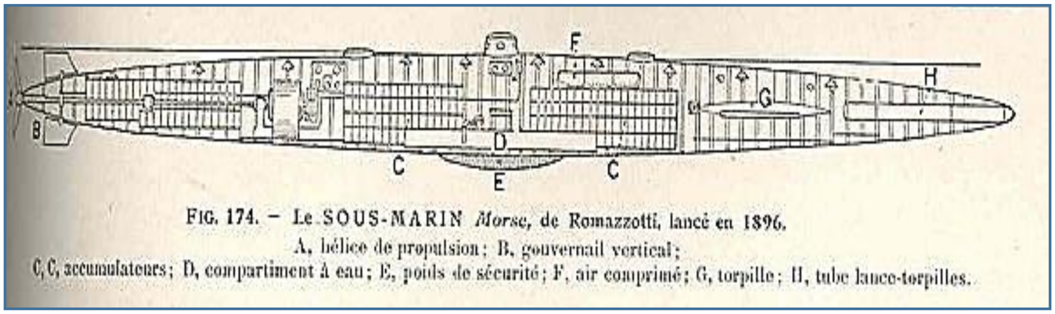


Fig 2.5. French Submarine – Morse (Image Courtesy: *Freshwater and Marine Image Bank)*

The submarine design saw a sea change when the first of its kind double hull submarine Narval [122] was launched in 1899. The submarine was steam powered whilst on surface and under submerged conditions the power was drawn from its storage batteries. Narwal submarine[123][124] paved way for a series of sub designs which later incorporated a diesel engine in place of a steam engine.

Fig 2.6. French Submarine – Narval[125]

2.5. Development of submarine propulsion during the Early 19TH Century

The United States Navy too conducted a series of underwater design platforms and had jumped into submarine production with the launch of its own class of submarines known as the Plunger or Adder class[126][127]. During the same era, submarines built by John Philip Holland was launched as Holland class[128]. Though the submarines were plagued with design issues, the propulsion on surface was achieved by means of an Otto-cycle gas engine[129][130]. Steam propulsion greatly increased the range of these vessels[131]–[133].

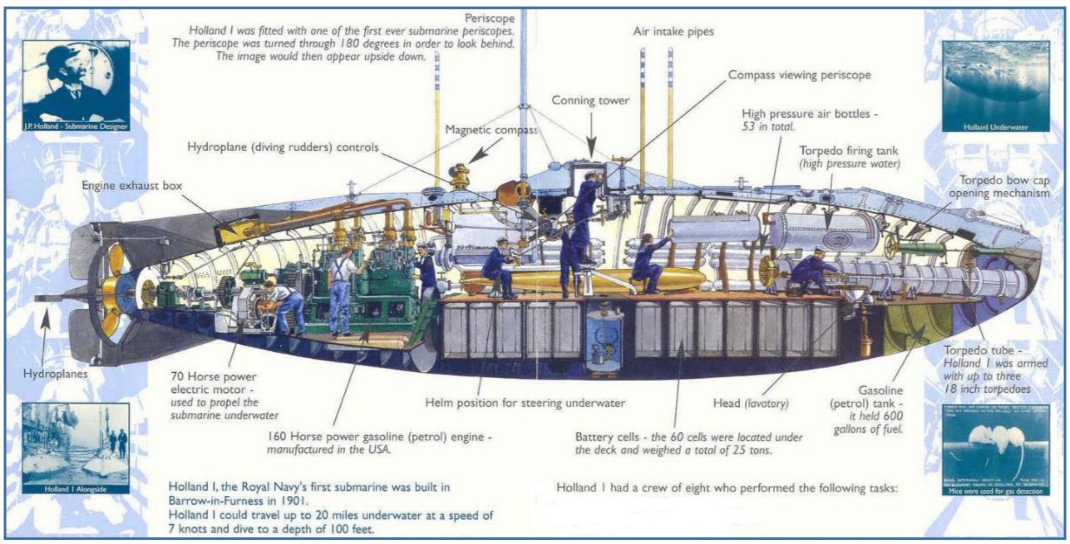


Fig 2.7. Royal Navy Submarine – Holland (1901-1913) by Holland Torpedo Boat Company of America[134]

In 1903, in order to attract attention of the German Army a private builder launched a new submarine Forel in Kiel Germany[135]–[137]. The submarine was bought by the Imperial Russian Navy (IRN) and was in service till 1910 (was rendered out of action due to a diving accident).

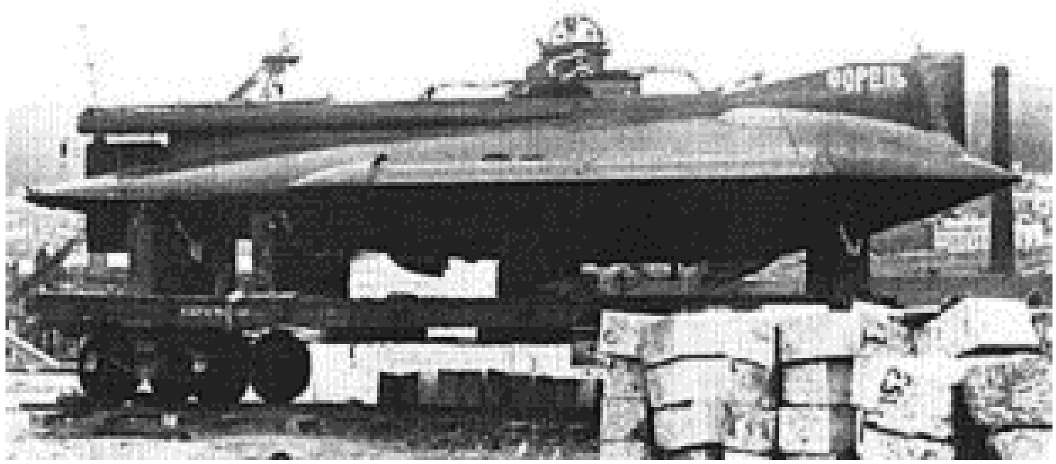


Fig 2.8. German constructed Submarine for IRN– Forel (Image courtesy: Wikimedia)

The Germans had swung into the submarine construction with launch of three Karp class submarines[138]–[140] for the Imperial Russian Navy. These submarine utilised kerosene as fuel for propulsion and had twin hull structure encompassing 7 ballast tanks for buoyancy and weight management. The first installation of diesel engines on a conventional submarine was on a German submarine U-19 class (2 MAN 8-cyclinder 8 stroke diesels)[141][142]–[144]. U-boats played a devastating role in both the World Wars (I &II). This period saw a surge in submarine design with respect to the hull form detection sensors both above and below water. The submarine U-boat (U-XXI) saw a modified snorkel masts [145]–[147][148]with a maximum speed of 17.5 knots and a creep speeds under submerged conditions.

The German submarine had come with a revolutionary design for propulsion known as Walter turbine propulsion plant[2], [149], [150]. This design implemented combustion of hydrogen peroxide [131], [151], [152]to produce steam which in turn had driven the turbines under submerged condition. Walter propulsion plant was fitted onboard V-80 submarine[153], [154] and could achieve a submerged speed of 20 Knots and endurance of 5.5hrs. The post war period saw the British Navy building two submarines imbibing the hydrogen peroxide propulsion system on an experimental basis[155]–[157]. However, these sorts of submarine propulsion lost its interest due to the advancement in the field of nuclear submarines[158]–[161].

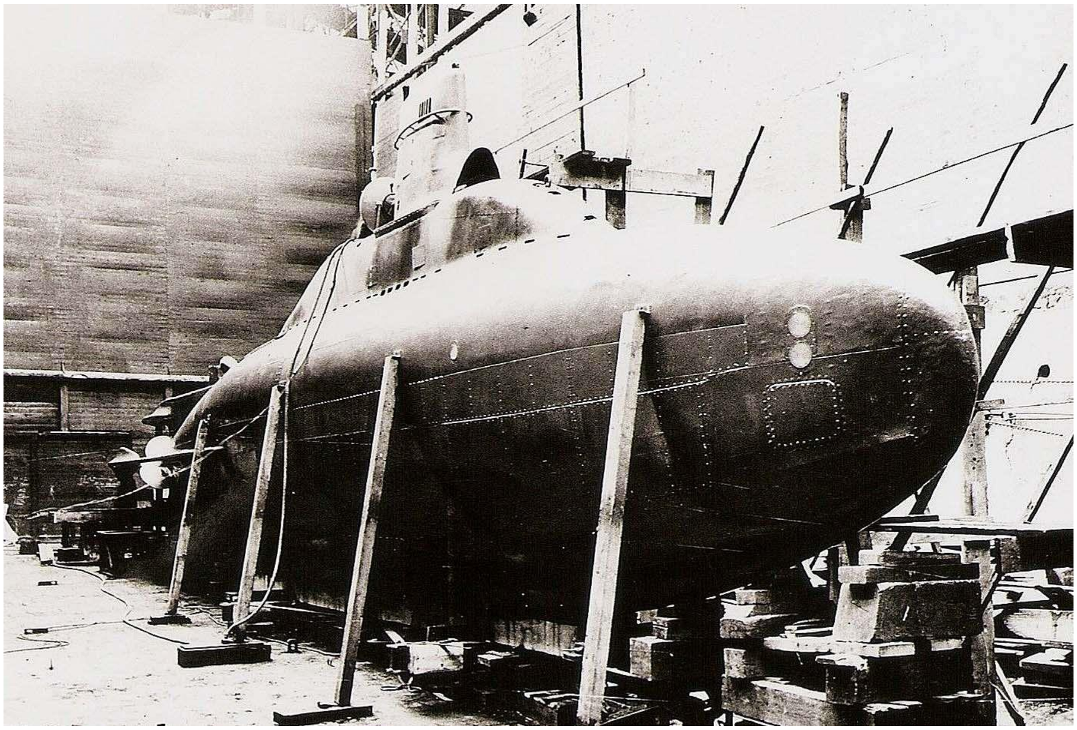


Fig2.9. V-80 Submarine – Walter turbine [162]

2.6. Dieso and Diesel Electric propulsion systems of conventional submarines

Earlier versions of submarine propulsion were realised through the mechanical coupling between the engine and the propeller. Though this can be justified as the submerged duration of these era submarines were comparatively much lesser than the modern-day submarines. The diesels were run during transit at the surface and the additional power was derived from the storage batteries. In late 1920's the US Navy proposed a better propulsive method were in electric motors were utilised for propulsion and thus reducing the diesel running hours and increasing the overall efficiency of the underwater propulsion system[163]. This new methodology gave lot of flexibility and maintenance envelope to the diesel and propulsion systems. These concept of diesel-electric propulsion were only exploited by US Navy till early 1945.

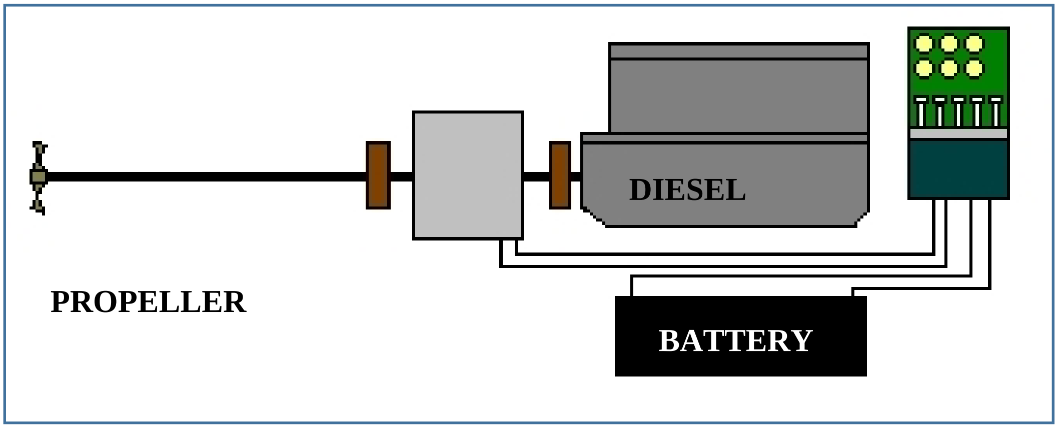


Fig 2.10. Direct drive diesel propulsion for submarines[164]

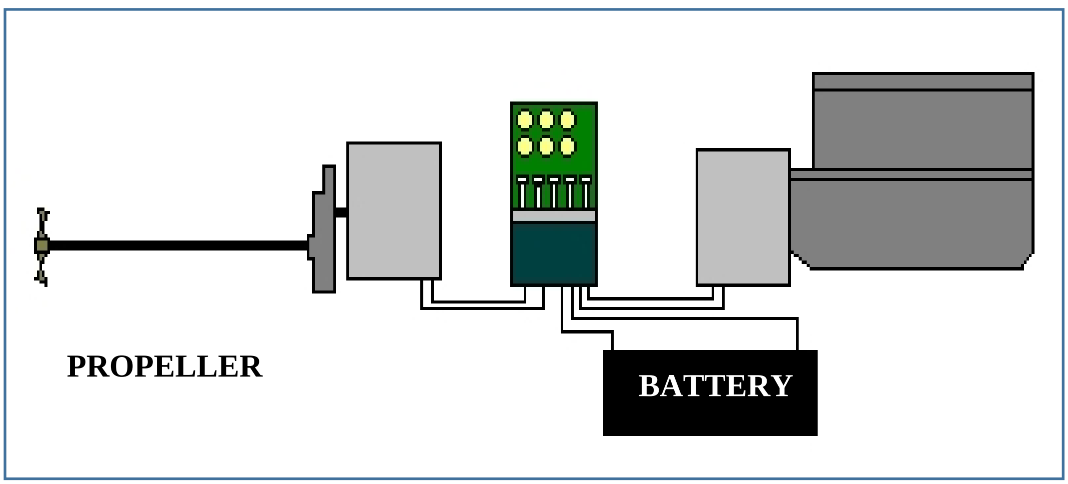


Fig2.11. Diesel-Electric propulsion for submarines[164]

In order to achieve better speed profiles and a higher operational exploitation diesel electric propulsion was pursued as the most ideal propulsion methodology for conventional diesel submarines. Diesels were coupled to an alternator which in turns coverts the mechanical energy (from diesels) to electrical energy[165]. The alternating current produced from the alternators is converted to Direct Current (DC) which in turn can be utilised for propulsion or for charging the battery groups.

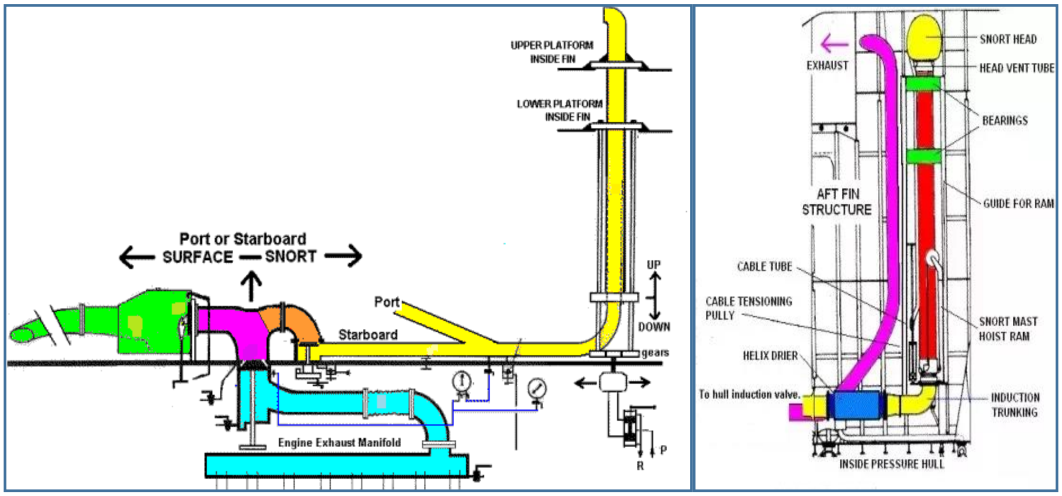


Fig 2.12 (a) Diesel exhaust system of submarine[166] (b) Snorkel Mast and snorkel exhaust[167]

2.7. Advent of thought process for an Air Independent Propulsion system

The hydrogen peroxide propulsion[168], [169] system was considered to be forerunner to the modern Air Independent Propulsion (AIP) system. The hydrogen peroxide was stored in the lower part of the hull in flexible plastic tanks and were fed to the combustion chamber through a turbo pump. Expulsion of CO_2 was a major hurdle in this design and it had severely restricted the submerged depth of the submarine.

These submarines were categorized as “open cycle systems” and created an oxygen environment by decomposition of hydrogen peroxide in presence of a catalyst for combustion of the diesel fuel in order to produce steam. The steam evolved was utilised to drive the turbines. The US Navy had experimented with hydrogen peroxide on a midget submarine X1[120], [170], [171] and had later abandoned due to explosion onboard. These systems were highly volatile and were always considered a threat due to the uncontrollable catastrophe it brings in case of an accident[172]. HMS Sidon [173]–[175]and Russian Submarine Kursk[176]–[180] are considered victims of Hydrogen peroxide systems.

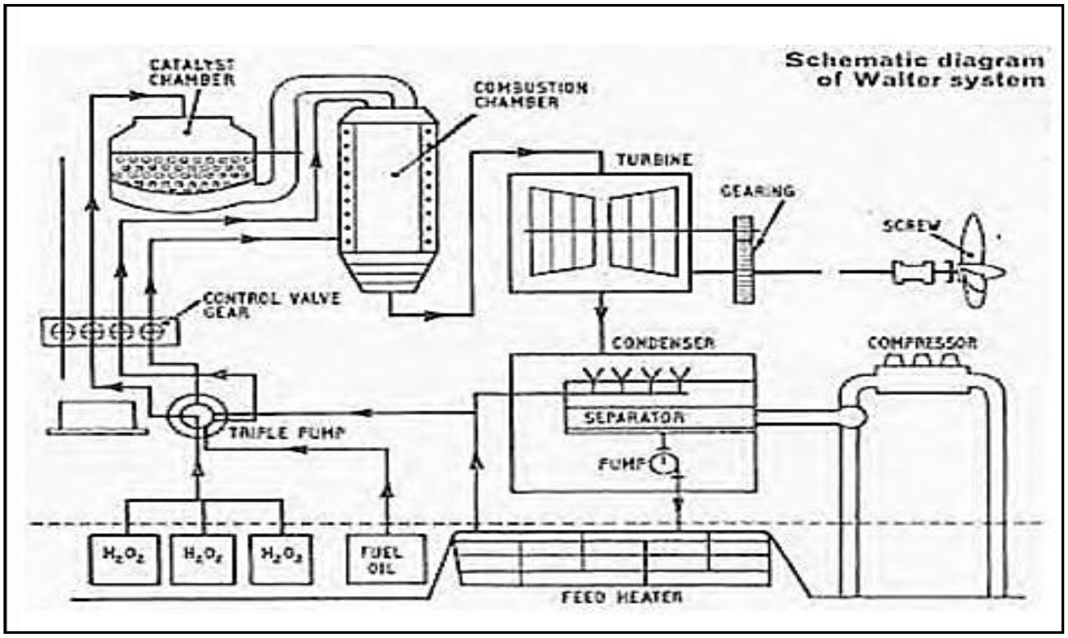


Fig 2.13. Schematic diagram of Walter system[181]

The US Navy experimented with submarine designs on a large scale prior and post the world wars. In order to optimise the design of diesel submarine the US Navy had launched a Greater Underwater Propulsion Power (GUPP'Y') to achieve greater endurance maneuverability and speed of submarines[182]–[187].

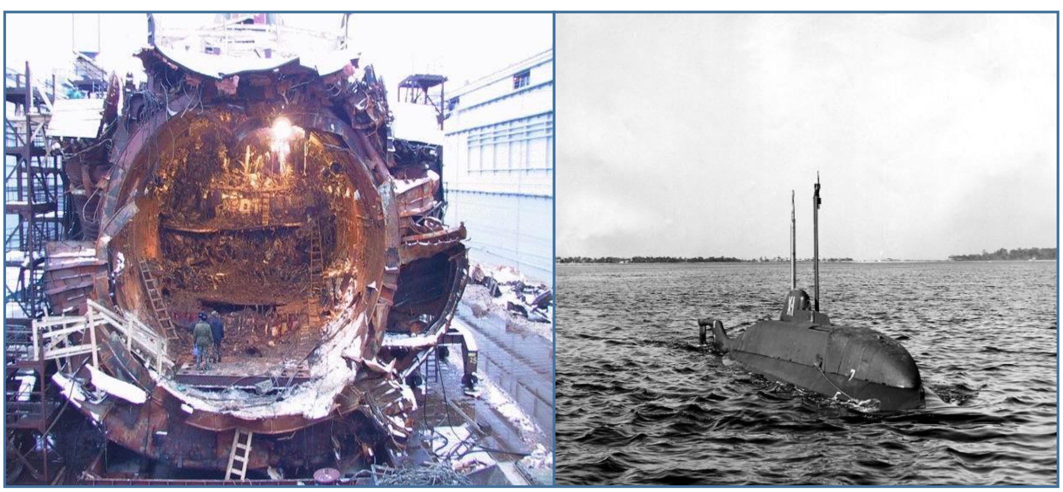


Fig 2.14 (a) Recovered Kursk submarine [188](b) X-1 Midget submarine[189]

The research in to diesel electric submarines had taken a back seat with launch of its first nuclear submarine USS Nautilus in 1958[190]–[195]. Understanding the need and combined with resourcefulness and economic independence of the country US Navy had structured its underwater strength only with nuclear submarines. The cold war period[196]–[202] saw tremendous growth towards design and development of nuclear submarines by USA and Soviet Union. Nuclear submarines were built in small numbers and were operated by the Royal[156], [203]–[205] and the French Navy[206]. In addition to these nations at present China [207]–[209]and India[210], [211] are the other nation which are currently operating nuclear submarines.

2.8. Air Independent Propulsion system

Air independent Propulsion(AIP) is a technology which allows a conventional submarine to remain submerged in its area of operation for a predominantly longer period of time without surfacing to regenerate its power by running its diesels[212]. During normal operations a conventional submarine will have to plane to Periscopic Depth (PD) at frequent intervals and have to run its diesels to replenish the diminished battery capacity. Due to the vast developments in the aerial sensors a submarine at snorkeling depth running its diesel engines becomes a most vulnerable source for detection.

An AIP system negates the necessity of a submarine to stay at periscope depth in an enemy area and the power for propulsion and other hotel loads are catered by the AIP system.

AIP has been a major contributor to the enhancement of stealth onboard submarines. The concept of AIP was originally incorporated onboard a vessel named Ictineo-II by an engineer Narcis Monturiol I Estradiol of Spain in 18 centuries[213] . It was the first chemical reactive submarine which incorporated the AIP technology. The advancement in the AIP technology had slowed due to the advent of nuclear powered platforms[214]. However, the AIP technology has recently picked up heavy momentum due to numerous stealth advantages the technology offers.

The concept of snorkel had been borrowed by the Germans from a captured Dutch submarine. Snorkel mast conceptually remains as a retractable mast intended to provide fresh atmospheric air intended for combustion of diesel engines. These masts are raised by submarines at periscopic depth for fresh air intake and the exhaust from the diesel compartment are thrown out by mean of an exhaust tunnel line running generally through the sail of the submarine. Over the years tremendous modifications to the snorkel mast has been undertaken around the world. However, it still remains an Achilles's heel in submarine design as it restricts the speed of submarines (around 6~8 Knots) and poses a threat of detection whilst running diesels. Earlier snorkel masts posed problems varying from ingress of sea water from the snorkel mast as well as abrupt building up of vacuum inside the submarine causing extreme discomfort of ears of the submarine crew. Improvements in snorkel design has led to inclusion of addition sensors, float valve and other safety mechanisms to prevent abrupt ingress of sea water into the diesel engine through the snorkel mast. It can be rightly said that as long as conventional diesel submarines are dependent on running diesel engines at periscopic depth so long shall the snorkel masts be onboard.

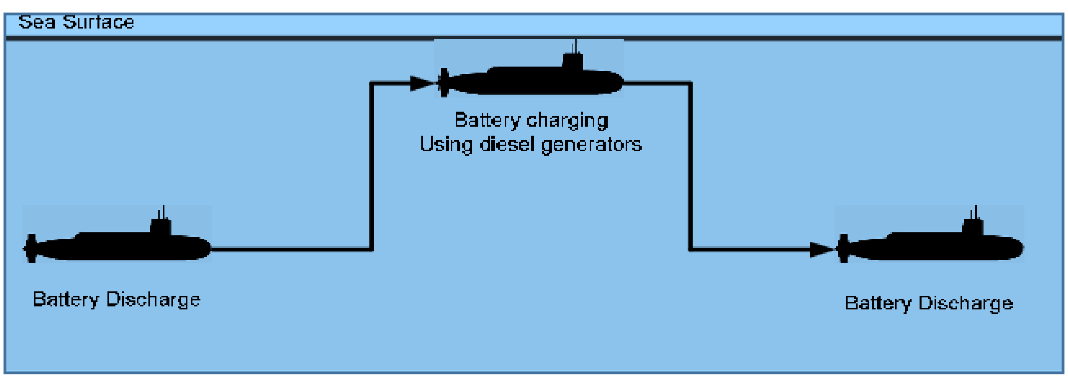


Fig 2.15 Operating profile of a conventional Diesel Electric submarine[215]

In a normal scenario of operation, a conventional diesel electric submarine will run its diesels at periscope depth once the battery capacity from harbour has diminished to a promulgated capacity (usually close to 50% of the theoretical capacity). The cycle of charging and subsequent discharging determines the indiscretion rate of class of submarine.

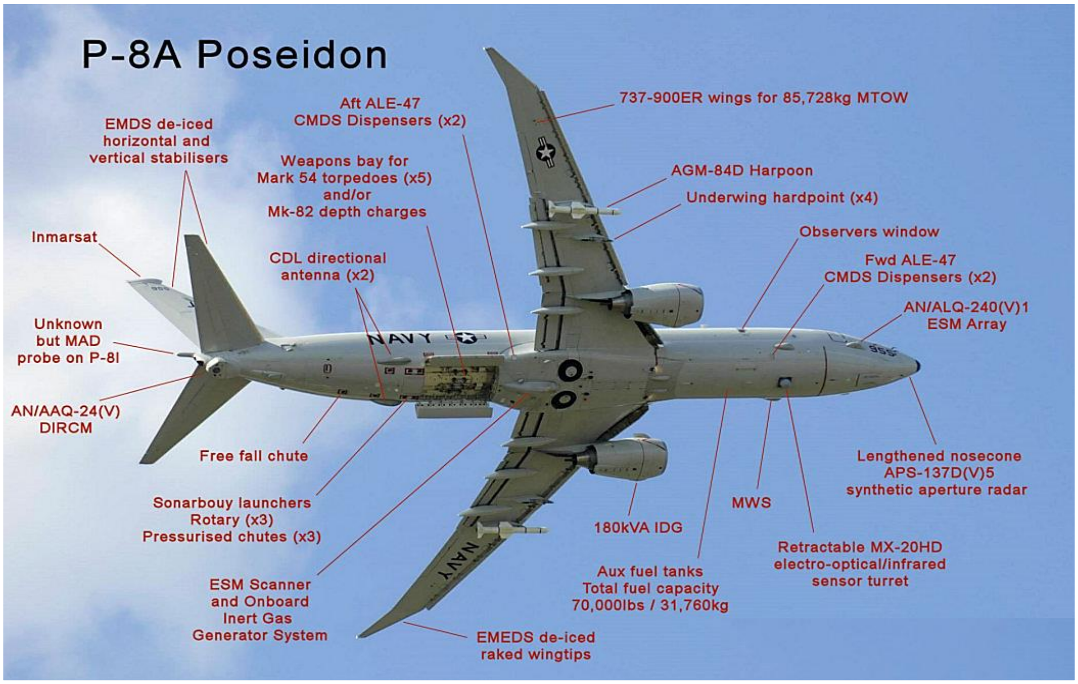


Fig 2.16 P-8A Long Range Maritime Patrol Aircraft [216].

When compared with a conventional diesel electric submarine with an AIP fitted submarine, the latter will predominantly be operated at submerged depths except for its need to surface for intelligence gathering. Advent of high precision thermal and infrared sensors have resulted in potential sightings of submarines by Long Range Maritime Patrol Aircrafts (LRMPA). These air vehicles severely restrict operation of submarines especially during running its diesels on Periscopic depth.

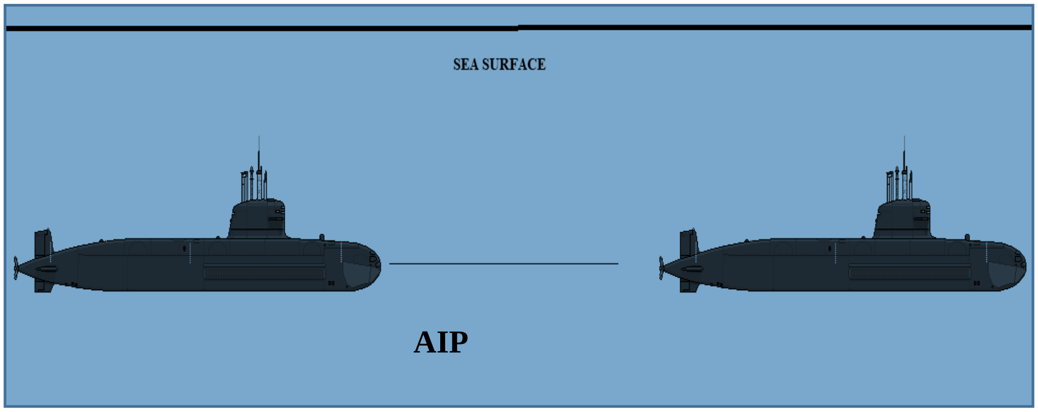


Fig 2.17 Operating profile of a conventional diesel submarine fitted with AIP [215]

Submarines fitted with AIP systems avoid running its diesel in enemy area and exploits the propulsive power and auxiliary power requirements from the AIP systems. The present AIP systems provide a submerged endurance ranging from 2~3 weeks. These systems are limited in endurance by the amount of liquid oxygen onboard.

Though the underwater nuclear platforms enhanced the longer deployment schedules there was always an increasing need to augment stealth features in an underwater vessel[217]. Nuclear platforms have always been considered as "noisy" compared to their diesel electric counterparts [218]. In the twenty first century, multi-function, multi-role theatre specific underwater stealth combat platform is considered a bigger potent than a nuclear platform. These vessels pose unimaginable threat to the nuclear platforms due to their enhanced stealth propulsion features[219].

2.9. Brief History on history of Indian submarine Arm

Indian Navy kick started its submarine arm program with acquisition of 08 Foxtrot class submarines from Russia. The first of the submarine INS Kalvari was commissioned into Navy in 1967. With experienced gained from the Russian boats and the need for a larger underwater Navy, India had signed an agreement with

Germany for purchase of 209 class SSK submarines. Two of them were built in Kiel, Germany and the other two submarines was built by M/s Mazagaon Dockyard Limited (MDL). These boats were commissioned between 1986-94. India had leased a Charlie class nuclear submarine from Russia in 1988.

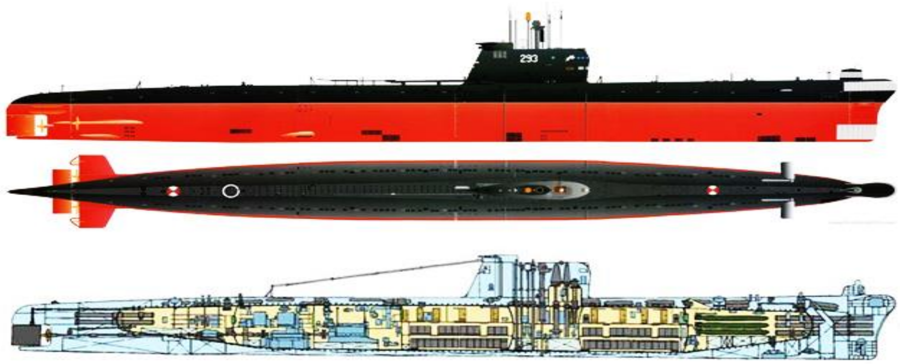


Fig 2.18. Foxtrot class Submarine[220]

The submarine was predominantly manned by Russian crew and had limited the Indian crew from entering the Missile and reactor compartment. These restrictions caused termination of lease within three years however, it provided valuable insight about operation of nuclear submarines to the Indian Navy. The Navy had further signed a contract with Russia towards acquisition of 10 Kilo class submarines which were delivered to India between 1986 -2000.

India has signed its second lease contract for acquisition of Akula class (SSN) nuclear submarine for a period of 10 years in 2012. In addition, the submarine building project of India was kick started in nineties towards building of SSBN nuclear submarines. The first of SSBN INS Arihant was built and commissioned into Navy in 2017. In order to augment the ailing and older conventional diesel India had signed a contract with France for building of 06 Conventional diesel electric submarines under transfer of technology being built in India by M/s Mazagaon Dockyard Limited (MDL). First of class submarine INS Kalvari was commissioned into navy on 14 Dec 17. With increase in need of higher endurance and enhanced stealth India had entrusted Defence Research Development Organization (DRDO) with development of first Air Independent Propulsion (AIP) system. Naval Materials Research laboratory (NMRL) in collaboration with myriad of OEMs viz., M/s Naval Group (NG), M/s Larsen and Toubro (L&T) and M/s Rolta has been working towards realisation of a working land-based platform. The model will be retrofitted into the existing submarine design or shall be ready towards integration into a new submarine design.

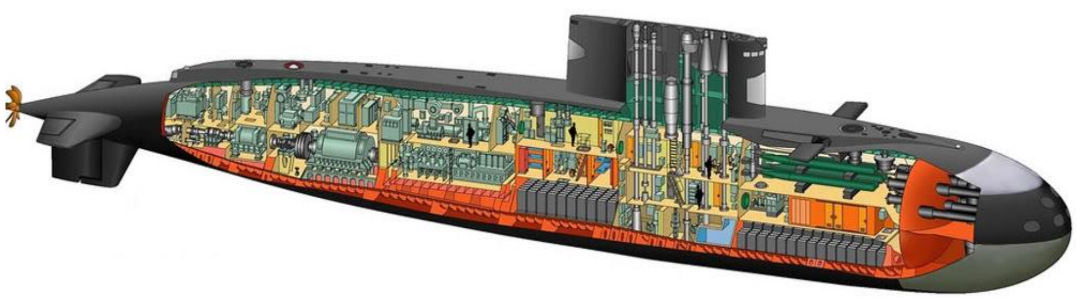


Fig 2.19. 877 EKM – Kilo Class Submarine [221]

2.10. Types of extant AIP systems

The various AIP technologies includes Viz., concentrated hydrogen peroxides, closed cycle diesel engines, closed cycle steam turbines, Stirling engines and Fuel cells these are enlisted in table 1[5]. Amongst various AIP technologies available around the world the fuel cells have captured the attention the most and has been undergoing extensive research. The current fuel cell systems are installed onboard submarines as add on system to the existing diesel propulsion machinery so as to extend the operating envelope of the submarine with enhanced stealth features [32]. Presently very few countries have successfully integrated their fuel cell technology into their underwater vessels[222]. However, the technology has just crossed its nascent stages and is presently in its developmental stages where in the efficiency of the systems involved onboard is the being constantly reviewed by engineers all around the world. The submarine manufactures around the world has been marketing this functionality of this system as a “Plug and play model” in addition to the diesel electric system fitted onboard [223].

The AIP technologies are broadly classified into four main groups: -

Group	AIP Technology
Group-I	Closed cycle Diesel Engines
Group-II	Closed Cycle Steam Turbines
Group-III	Stirling Cycle Engines
Group -IV	Fuel Cells

Table 2.1. Types of Extant Air Independent Technologies

2.10.1 Group-I: Closed Cycle Diesel Engine

Closed cycle Diesel engine comprised of a technology where in the conventional diesel engines were utilised on surface and a separate diesel engine employing combustion of liquid oxygen was used at sub surface for propulsion. The technology was heavily experimented and adopted by the Russian Navy in its Quebec class submarines until late 1970’s after which it had died a natural death owing to its high failure rate and loss of life [2]. This technology was first experimented by the German engineers during the World War II. The technology had gained a minimalistic momentum during the late eighties when an AIP system was installed on Ex-U 1 submarine formerly known by the name Klasse 205 U-Boat [224].

The closed cycle means ability to run diesels without coming up to surface or snorkel depth. The concept of closed cycle diesels was first exploited by a German firm (M/s Walter). The oxygen fed to the diesels were realised through decomposition of Hydrogen Test Peroxide (HTP). The World war caused a stoppage in realisation of this technology. However, the Royal Navy had acquired the CCD technology and the Type XVIIB -U Boat of German origin was commissioned into Royal Navy as HMS Meteorite.

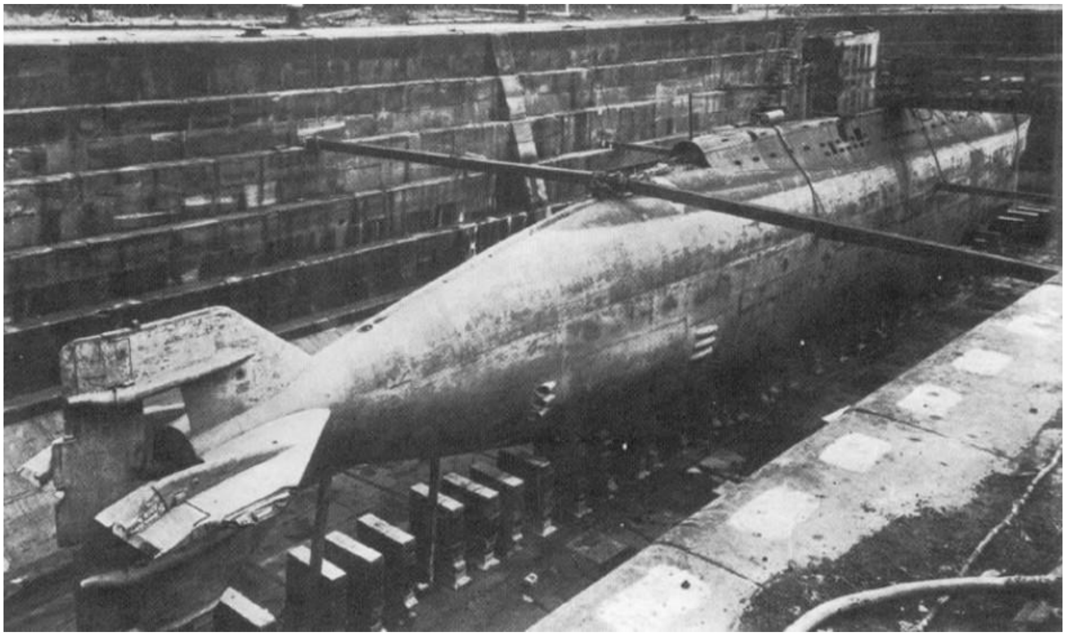


Fig 2.20. Walter Hydrogen Test Peroxide (HTP) submarine [225]

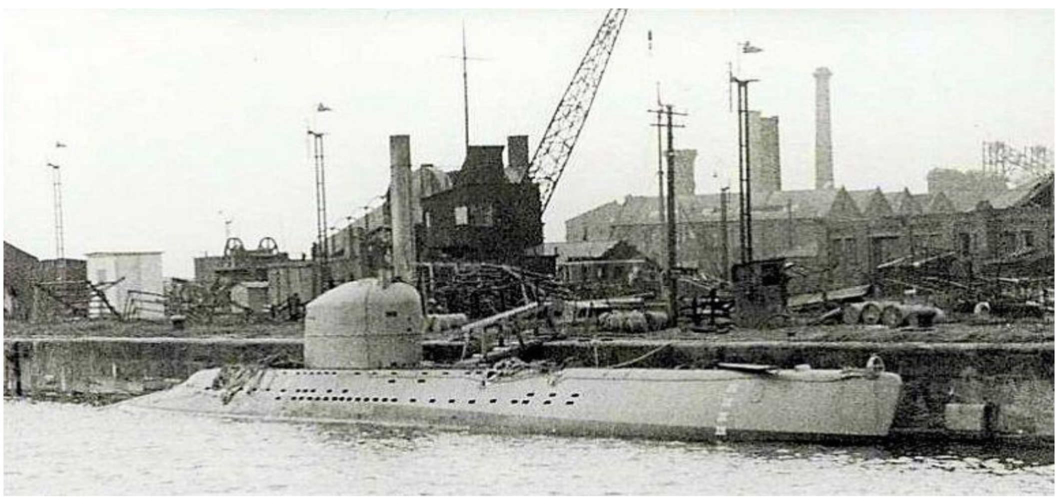


Fig 2.21. Closed Cycle Diesel Engine – HMS Meteorite [226]

Russia had also pursued its interest in AIP technology with first of class AIP submarine (project 617) utilising German Walter- Hydrogen Peroxide system. Further, AIP submarines were constructed under Project 615 also known as QUEBEC class submarines. These vessels stored liquid oxygen onboard and was used to run the third diesel in submerged mode. However due to high failure rate and frequent minor explosions on diesels these boats were nicknamed “Zippos”. After decades, in 1980’s Whiskey class submarine incorporated a modified design of storage of Liquid Oxygen (LOX) and Liquid hydrogen (LH) at cryogenic temperatures of -165^{o}C and -252^{o}C respectively. As a technology demonstrator AIP endurance of 3-4 weeks at speeds of 2-2.5 knots was established by the Whiskey class Submarine. However, the model was not put into production for reasons unknown.

Fig 2.22. Closed Cycle Diesel Engine – Russian Quebec class Submarine Project 615 [227]

Fig 2.23. Closed Cycle Diesel Engine – Russian Whiskey class submarine Project 617EH [225]

Closed cycle Diesel engines employs a technology where in the submarine utilizes its conventional diesel engine on the surface and a separate diesel engine for submerged condition [228].This Specialised diesel engine employed combustion of liquid oxygen for its sub-surface operations[228]. However, operation of diesel engine under submerged conditions will be slightly trickier due to two distinct facts – maintaining the thermodynamic efficiency of the engine and dispensation of exhaust against the water pressure at dived depth [5], [218], [229]. The closed cycle diesel engine AIP system is the cheapest among the existing AIP options however the system poses an inherent disadvantage of compromised stealth due to its heavy moving parts. The Overall thermodynamic efficiency of CCD AIP system is 30%. The closed cycle diesel was actively worked upon by an engineer named S.A. Basilevskiy prior the world war under Project REDO. Prototype of this plant was installed onboard Russian ‘M’ class or Malyukta class submarines.

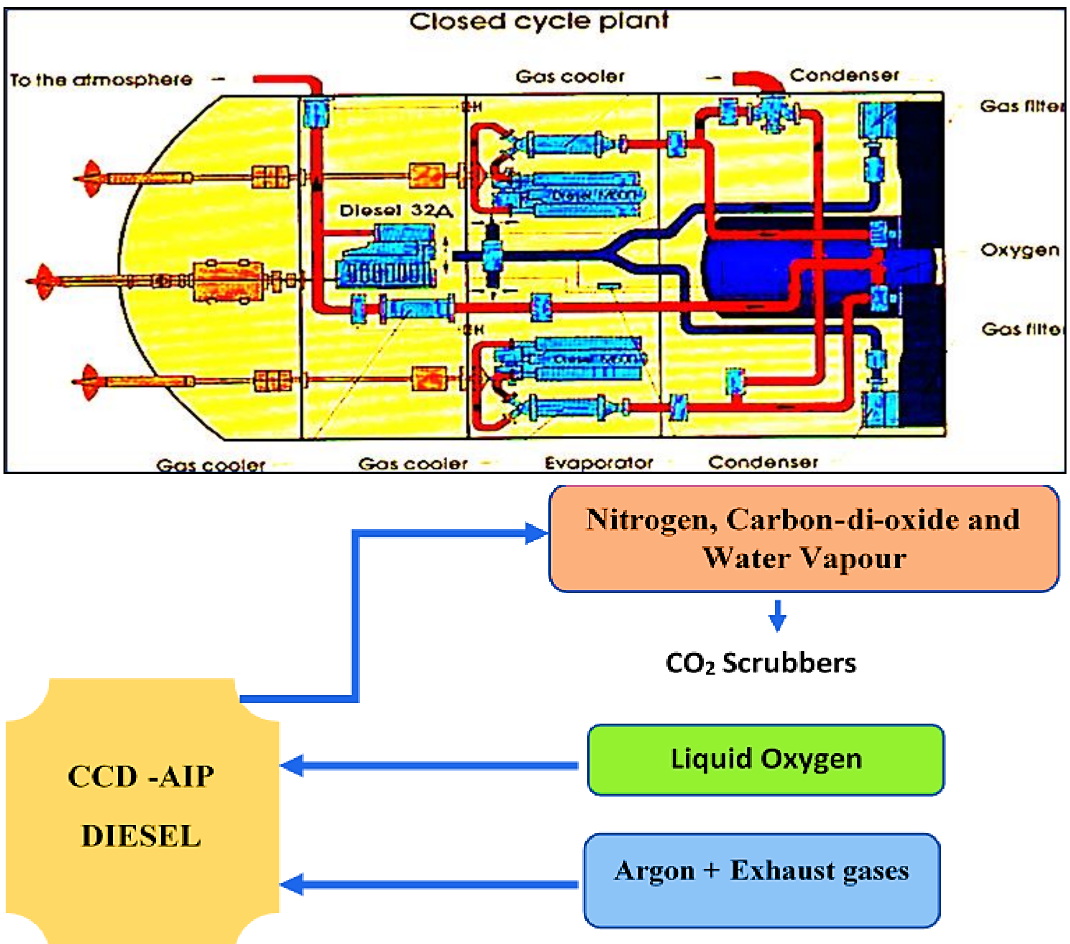


Fig 2.24. Schematic diagram of Closed Cycle Diesel Engine of erstwhile Quebec class Submarine [230]

Sl. No	Country	Remarks	year
(a)	Klein U-boat, Germany	Midget Submarine	World War II
(b)	Quebec Class Submarines, USSR	Severe loss of lives, Nicknamed the “Cigarette Lighters”	1953- 1956
(c)	Type 205, Germany	Nordseewerke shipyard used this submarine for experimental fitment of closed cycle diesel engine propulsion system. Production abandoned.	In 1993

Table 2.2. Employability of Closed Cycle Diesel Engine Technology around the world.

The Major reasons towards research and development of Submerged Air Independent diesel engines are: -

(a) Utilisation of onboard fuel – means that the increase in plug length off AIP system can be effectively modelled for storing fuel as per the design requirements.

(b) Incorporation of additional engine – reduces new maintenance costs and crew training.

(c) Flexibility of switching the same engine to operate under surface, sub surface and submerged condition can be exercised.

The diesel engines used for air independent propulsion are often categorised in unison, however they are distinctively different in operation. Closed Cycle Diesel (CCD) where the exhaust is expelled out of the submarines using scrubbers. Recycle Diesel (RCD) where in the exhaust is recycled and is fed back to the engine. The third variant is a Semi-Closed Cycle Diesel (SCCD) where in the exhaust gases is scrubbed and then expelled outside.

2.10.2 Group-II: Closed Cycle Steam Turbine -MESMA

Closed cycle steam turbine technology has been extensively researched and put to production only by a single nation successfully viz., France. The technology is known by its French acronym “MESMA” which stands Module D’Energie Sous Marine Autonome [3] . This technology is closed associated and are often referred to as unconventional nuclear reactor as steam being the main end product in both the cases. Combustion of ethanol in presence of oxygen causes generation of steam which in turn powers the turbine for generation of power[93]. It is pertinent to mention that the MESMA technology possess the least efficiency amongst the four prevalent AIP technologies in the world [231]. The submarines which has incorporated MESMA onboard is listed in table 3. The French technology was implemented onboard the Agosta-90B (Hamza) class submarines. The AIP plug consists of 09-meter-long AIP plug enabling a submerged endurance of two weeks (Theoretical claim).

Fig 2.25. PNS HAMZA – Agosta 90B (Image Courtesy: Wikimedia)

The concept of power generation is in close resemblance to a nuclear propelled submarine where in steam turbine coupled to a rotary generator is utilised for generation of power. The oxygen is stored in liquid form at a cryogenic temperature of – 185^0C. A cryogenic pump is used to transfer the liquid oxygen during this the pressure of oxygen is raised 60 bar from its storage pressure ranging between 2 to 10 bars. The transported oxygen is heated to change into gaseous state. The generated steam is sent to the turbine and then to a condenser. Alternating current is produced from the alternator coupled to the turbine. The rectifier assembly transforms it to Direct current which is utilised for propulsive power or towards charging of storage batteries. Ethanol is used as the main fuel. The exhaust carbon di-oxide (CO_2) generated is required to be expelled outside by additional means (This adds to the overall power consumption). Additional considerations and simulations were undertaken to store the by-products (CO2 & Water) inside the submarine and expelled as per situation. However, condensation of carbon-di-oxide was only possible at temperature of 15^0C and required additional equipment circuitry if the seawater temperature was higher outside. These circuitries add to the parasitic load of the submarine. the total power of the MESMA-AIP system is estimated to be around 200KW.

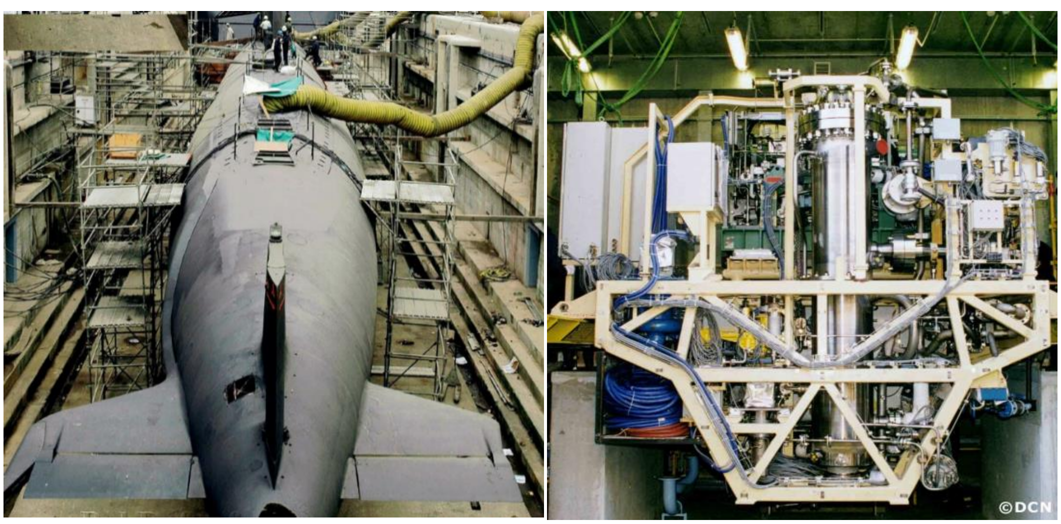


Fig 2.26. (a) PNS Hamza in drydock [232] (b) Modular construction of MESMA-AIP system[233]

Closed cycle steam turbine technology exploits the mechanical energy of the turbine coupled with an alternator to derive electrical energy. The system is based on Rankine cycle. It is pertinent to mention that the MESMA technology possess the least efficiency ($\leq 25\%$) amongst the four prevalent AIP technologies in the world [224]. In the current scenario, France is the only country which holds monopoly in Closed Cycle Steam Turbine technology

The trials of the MESMA plug was intended for incorporation into the AM -2000 submarine program (1992). As per the derived calculations the diameter of the plug is 6.2 m and the length are 10 m. The endurance (range) of a MESMA system is calculated by amount of the fuel (liquid oxygen) carried.

$$Endurance = \frac{usable\ volume\ of\ oxygen\ in\ m3}{Power\ of\ MESMA(KW) * Consumption\ of\ oxygen\ (\frac{litres}{KWh})}$$

The major drawbacks of MESMA system is that it is considered to be the least efficient as the consumption of oxygen compared to other AIP system is high. Due to the presence of significant moving parts the external radiated noise id relatively higher. MESMA being a steam system calls for a detailed maintenance regime.

Sl. No	**Country**	**Remarks**	**year**
(a)	Agosta 90-B - Pakistan	MESMA AIP plug installed, in service	Late 2000's
(b)	Scorpene - Chile, Malaysia, Brazil	Requires an additional 8.3 metres Technological plug to be inserted. Cost of each plug is 50- 60 Million USD. **Presently option is still under deliberation.**	2000- till present

Table2. 3. Closed Cycle Steam Turbine Technology

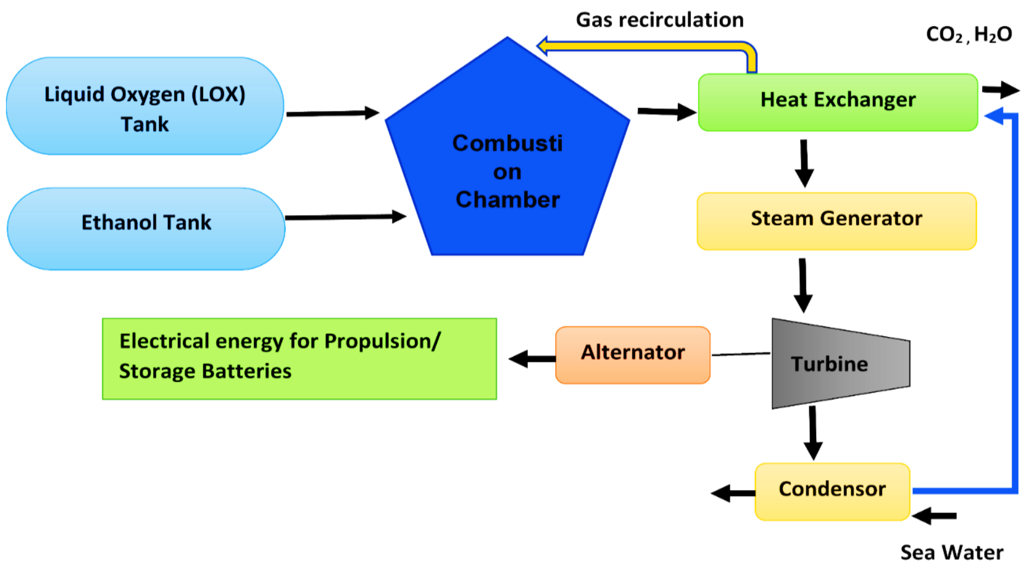


Fig 2.27. Schematic diagram of Closed Cycle steam turbine- MESMA- Module et Sous Marine Autonome (MESMA)

Fig 2.28. Air Independent Propulsion (AIP) Plug~9m- MESMA- Module et Sous Marine Autonome (MESMA) [234]

2.10.3 Group-III: Stirling Engine

Reverend Robert Stirling invented a heat engine operating in a closed operating cycle in 1816. Stirling Engines generates power by combustion of liquid oxygen with diesel fuel oil in a pressurised combustion chamber [41], [235]. This energy is either used for propulsion or for charging the submarine's battery bank. The exhaust gas generated from the combustion is required to be scrubbed and diffused into the seawater medium to retain stealth [93][21]. The Swedish Japanese and Chinese navies predominantly utilise Stirling engine technology onboard their submarines. The list of countries which have incorporated the Stirling air independent propulsion onboard their submarines is appended below in table 4. Stirling engines are based on a double acting principle, a piston moving back and forth between a hot and cold zone coupled to a rotary shaft and in turn to a generator. Running of diesel engines even at periscopic depth produces lot of heat dissipation inside the engine compartments which is eventually cooled by the onboard air conditioning systems. A Stirling engine running underwater will produce heat as an additional by product whilst in operation underwater and will require separate air conditioning arrangement and will add on to the parasitic hotel load of the submarine.

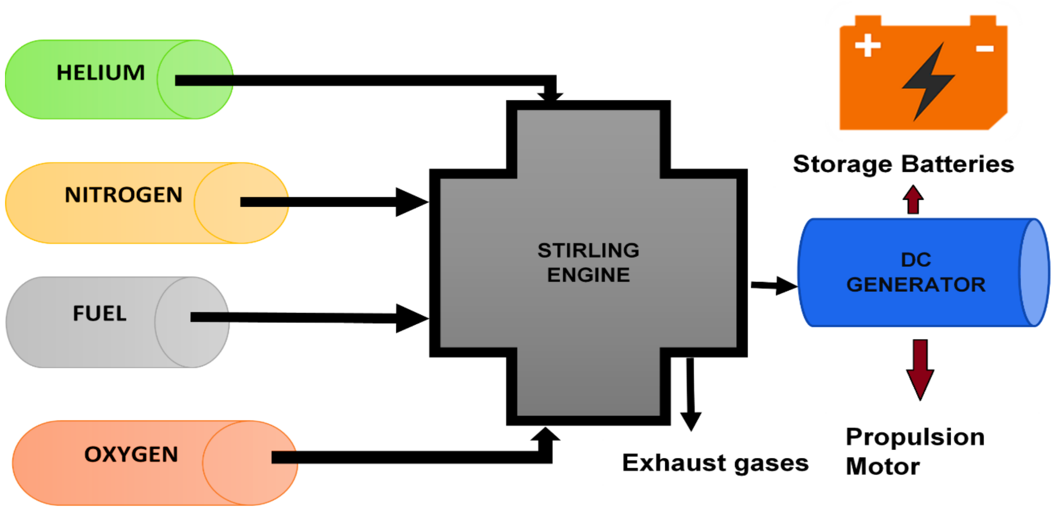


Fig 2.29. Schematic diagram of Sterling Engine AIP system

Stirling engines generate power by combustion of liquid oxygen with diesel fuel oil. The system is based on Stirling Cycle. The source of energy is extracted from the working fluid which is permanently contained as part of the system. The engine is run using the heat extracted from the working fluid. Then the extracted energy is used either to recharge batteries or for direct propulsive load of the submarine[236]. The resultant exhaust gases are thrown overboard the submarine by means of scrubbers. The Major advantage the system could offer is utilisation of diesel as its main fuel source hence reduces the complexity during refueling operations.

Fig 2.30. Stirling Engine AIP system [237]

The Stirling process can be explained as two pistons operating simultaneously with one piston operating in hot region and another piston operating in cold region. The working gas is enclosed between the piston and is alternated between the heating and cooling zones. The mechanical work is provided to the shaft which generally in case of submarines is coupled to an alternator which produces the alternating current. A 75 KW engine designated as V4-275 R were developed by M/s Kokums who is the system integrator for Swedish Navy.Field trials towards exploitation of Stirling engines were undertaken by the Swedish navy in 1985. A commercialized version of Stirling engine was fitted onboard a French diver lock out submarine SAGA-I. Two V4-275R Stirling engine of 100KW each were fitted onboard the French submarine. This submarine consists of two LOX tanks giving a storage capacity of 12000KWh. These systems are inherently bulkier and poses reduction in stealth when compared with the silent fuel cell AIP systems. The diving depth of the submarine will be restricted due to the interlock with the dispensation of exhaust gases overboard due to the running of the engine. Due to the flexibility, reduction in retrofit systems and cheaper operational costs feature as the Unique Selling Point (USP) for Stirling AIP system. The biggest advantage of the system is the ability of the system to utilize the onboard fuel. Though this technology avoids the need for additional fuel storage space, the storage volume is indirectly occupied by inclusion of a large Internal combustion diesel engine.

Initial trials were carried out using the 4-95 Stirling module developed for installation onboard diver lockout vehicle. The combustion or operating pressure of these systems was 30 bar to cater for offshore diving depths up to 300m. the power output of the module was 20KW. The Stirling engine designated for submarine integration was known as V4-275. The term V 4-275 represents 4 cylinders and a swept volume of 275 cm^3.

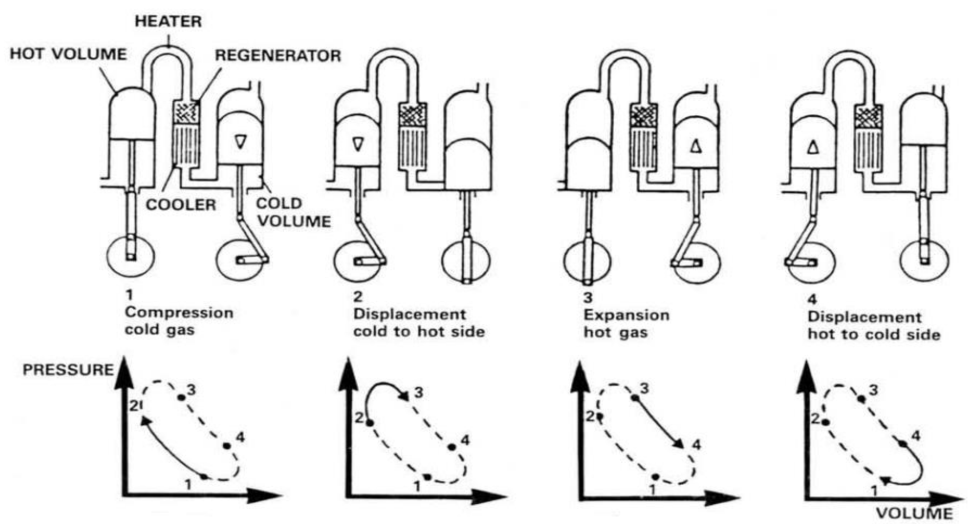


Fig 2.31. 4-Stage Stirling process [41]

Sl. No	Country	Remarks	year
(a)	Gotland Class, Sweden	First submarine to be fitted with an auxiliary diesel engine employing Stirling engine	1996- till present
(b)	Vaster Gotland Sweden	Employs a Stirling AIP plug	1987 - till present
(c)	Sodermanland Class Submarine, Sweden	Fitted with 02 Stirling class engines	1989 – till present
(d)	Archer Class, Royal Singapore Navy	Fitted with 02 Stirling Engines	2011- till present
(e)	Soryu Class, Japan	Fitted with 04 AIP Stirling engines	2009 – till present
(f)	Asashio Submarine, japan	Converted into AIP test Bed in 2002	2002 – till present
(g)	Yuan Class, China	Latest AIP Submarine	2015 – till present
(h)	Qing Class, China	World largest conventional submarine fitted with AIP	2012 – till present
(i)	A 26 Submarine, Sweden	Stirling engine is the main propulsion source	Under development

Table 2.4. Stirling Engine On-board Submarines around world.

2.10.4 Group-IV Fuel Cell

Fuel Cells are emerging as the widely preferred and most seeking flag bearer of the AIP technologies around the world [84]. The primary interest in this technology is due to the wide spread research in its field in the commercial sector. Employment of fuel cells onboard submarines started way back in early 80's and is still progressing ahead with a rapid pace solely owing to the rapidly paced research activities in area of fuel cells. The use of fuel cells onboard submarine was first introduced by the Germany [84]. The German Submarines utilised PEM fuel cell onboard their Submarines. Presently India is pursuing its indigenisation programme of developing an Air Independent Propulsion System utilising Phosphoric Acid Fuel Cell (PAFC) [212]. The project is being steered by National Materials Research Laboratory (NMRL), Ambernath a lab of DRDO.

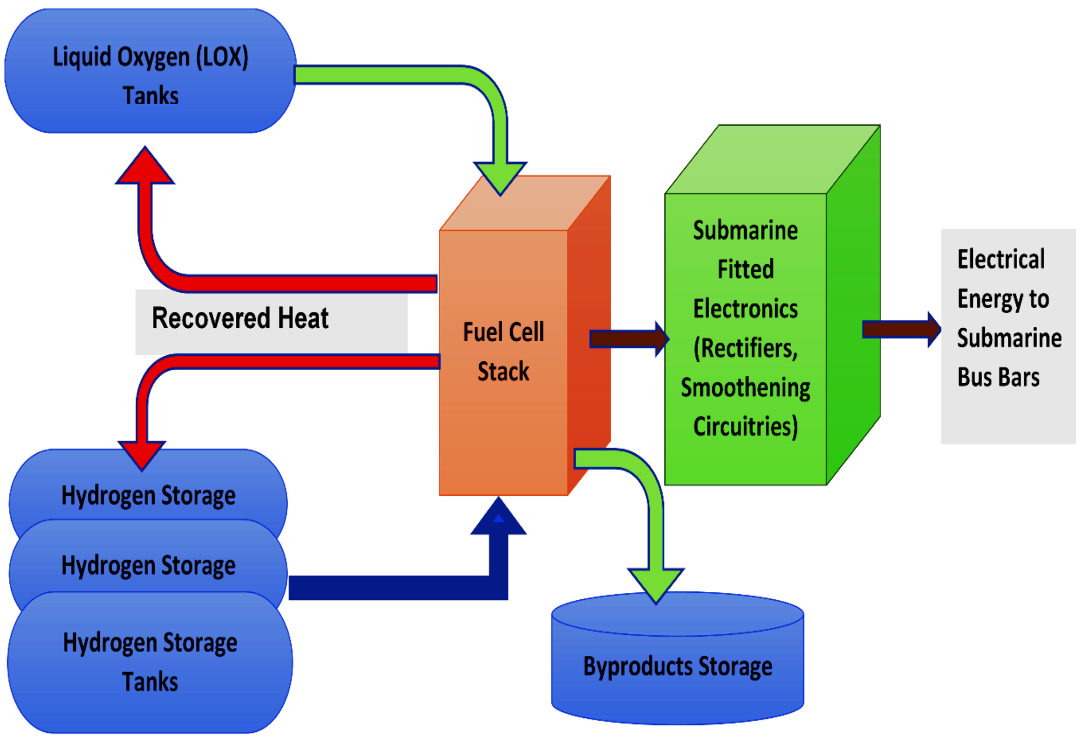


Fig 2.32. Schematic diagram of Fuel cell AIP system

A Proton Exchange Membrane (PEM) fuel cell of M/s Siemens is currently being exploited onboard German Type 212 Submarine[35]. Trial reports of the German U32 submarine have indicated that the vessel had undertaken a voyage of 1600 nautical mile using only its AIP system in April 2016. With greater stealth capability, ease of operation and redundancy in terms of distributed power generation (multiple stacks connected in series to realise the total power in order to avoid complete loss of system due to failure of single stack).

Naval Materials Research Laboratory (NMRL) a premier organisation of DRDO, India was tasked with undertaking research for fuel cell integration due to their ongoing research works in the pertinent field. The Project was broadly classified into three major phases

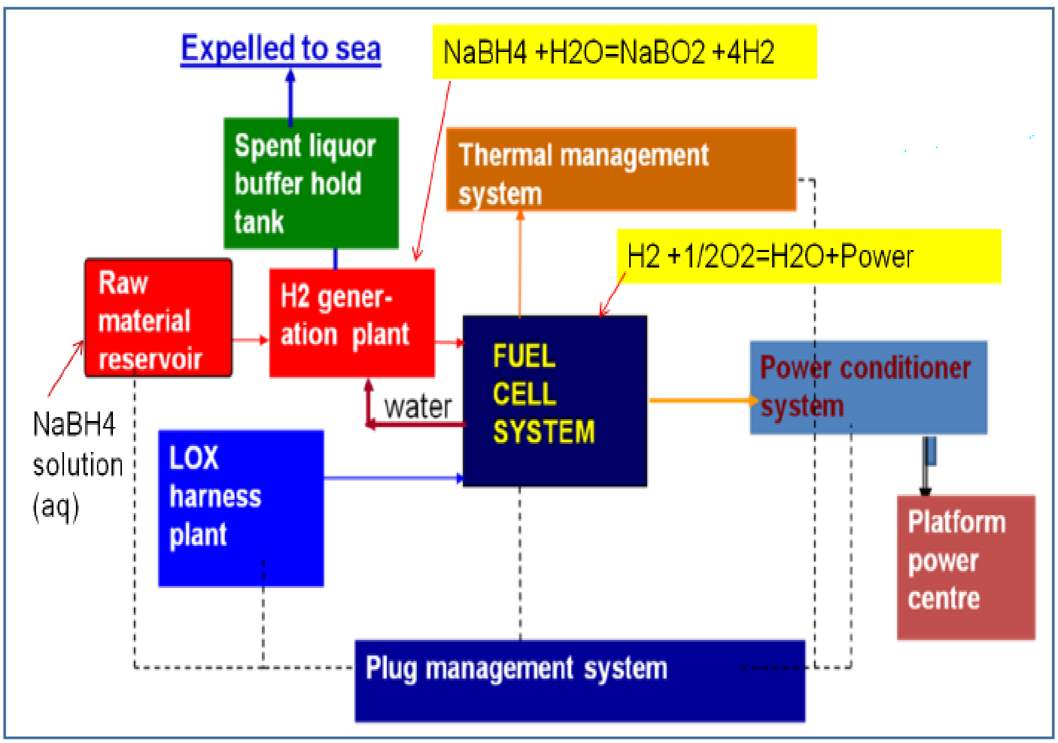


Fig 2.33: Schematic representation of Chemical reaction of NMRL AIP system[238].

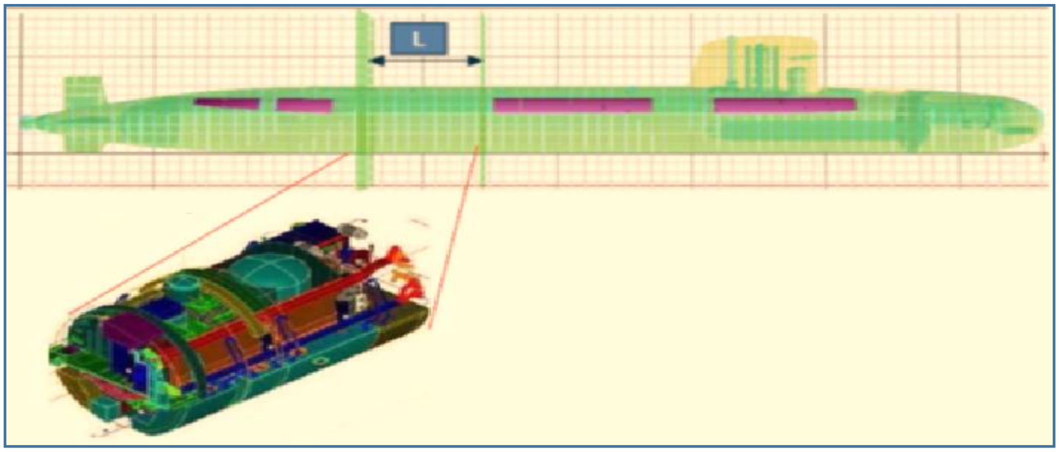


Fig 2.34: Fitment of AIP plug will entail increase in overall length (L) of the submarine[238].

The first being proof of Concept (POC) established on a Land Based Prototype (LBP) and subsequently fitment of the equipment into an analogous submarine platform. The final phase entailed fitment of the proven equipment onboard the conventional diesel electric submarine of Indian Navy. As part of ongoing Research and Development works the final phases of the activity has been initiated. The project is called Marinised Engineered AIP Energy Module (MAREEM). The project is steered by NMRL with continual assistance and role from Defence and Civil agencies viz., NPOL, L&T, MDL, IOCL, THERMAX, TEXOL, CEEFES, C-DAC, RCI, ROLTA, Digitronics and Indian Institute of Petroleum[239].

The NMRL AIP model utilises a Phosphoric Acid Fuel Cell (PAFC) as against the Proton Exchange Membrane (PEM) utilised onboard submarines by other foreign nations. The main fuel sources for the PAFC is Hydrogen and Oxygen. The Hydrogen is obtained from hydrolysis of Sodium tetraborate ($NABH_4$) and Oxygen is obtained from Liquid Oxygen (LOX) tanks. The chemical reaction produces DC power which in turn is fed to a DC_DC converter prior being fed to onboard batteries for topping up. The Schematic of AIP plug is shown in fig 29.

Fig 2.35: Laboratory setup of the Land Based Prototype at NMRL, Ambernath[240]

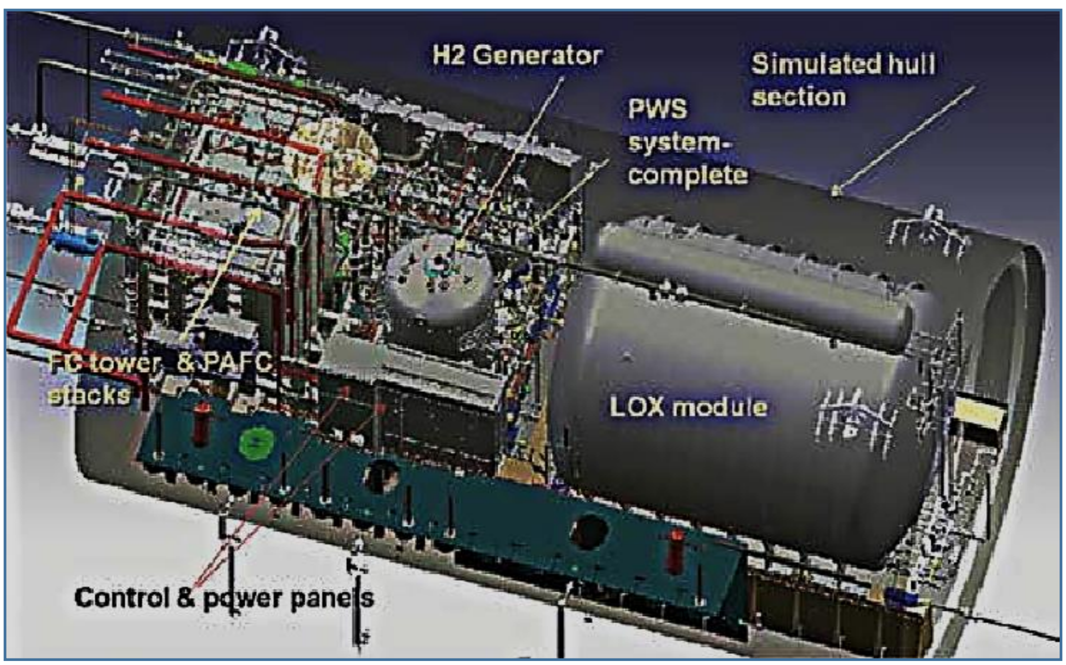


Fig 2.36: Simulated depiction of pipeline, tank & equipment arrangement of an AIP Plug [240]

Fig 2.37: Actual fitment of Liquid Oxygen tank inside the Submarine cut section[241].

Sl. No	**Country**	**Remarks**	**year**
(a)	Dolphin Class, Israel	Type-2 AIP Submarine, details unknown	2014- till present
(b)	Type 209 1400 Mod	120KW Siemens – 06 m AIP Plug	2005- till present
(c)	Type 212, Germany	U-31 employs 9 x (30-40 KW) cells = 270- 360KW output power Other variants utilizes 2x 120 Kw = 240 KW output cells.	2005 – till present
(d)	Type 214, Germany	Fitted with 02 BZM120 fuel cells (120 kW x 2)	2013- till present
(e)	Type 218, Germany	To be Fitted with 2 x 120KW fuel cells	Expected in 2020
(f)	S-80 class, Spain	Bio-ethanol processor to produce high purity hydrogen which in turn supplies the fuel cell module (300 KW)	Project delayed
(g)	Lada Class, Russia	02 Oxygen -Hydrogen fuel cells	2010- till date
(h)	Amur Class, Russia	Fuel Cells, No further information Available	No details available
(i)	Kalvari Class, India	Phosphoric Acid Fuel Cell (PAFC), indigenously developed by DRDO	AIP version not expected before 2024

Table 2.5. Fuel Cell – AIP System On-board Submarines around the world.

2.11. Hydrogen storage Options

The endurance of a Fuel Cell AIP system is directly proportional to the amount of fuel stored onboard. The various storage technologies available towards storage of Hydrogen and Oxygen for marine application is discussed in the subsequent paragraphs

2.11.1 Compressed Hydrogen

Compressed hydrogen gas cylinders have been in continual advancement due to the merit of usage of hydrogen in automotive applications. The US Department of Defence (DoD) supports considerable funds towards hydrogen storage. Presently compressed hydrogen at 700 bar pressure is stored in composite cylinders and is evaluated for a storage capacity of 11% weightage corresponding roughly to 2.5Kwh/Kg. As part of zero emission ships and towards MARPOL compliance most of the smaller passenger ferries and merchant vessels are migrating to compressed gas hydrogen storage and subsequent usage for propulsion. The greatest disadvantage posed by the compressed gas hydrogen system is the storage space occupied by the cylinders. In addition, the Air compressors during operation consume lot of power which adds to the overall decrease in efficiency of the system.

2.11.2 Cryogenic Storage of Hydrogen

Cryogenic storage of Hydrogen involves storage of hydrogen in liquid form. Though it offers an advantage of increased storage capacity when compared to compressed hydrogen gas, it is inferred that the sustainability of such a system for underwater applications is highly impractical due to the high-power requirement to store hydrogen at extreme low temperatures. In addition, extremely high standard of thermal insulated containers is required to prevent hydrogen containment and to avoid any leaks due to boil off.

2.11.3 Hydrogen Storage in Reversible Hydrides

Hydride storage is considered as the safest option for storage of hydrogen for marine applications. These hydride storages have often proven competitive an efficient option considering the volume and the additional power required towards sustainability of a liquid Hydrogen storage option. The hydrogen permeates into the hydride structure and hence has a limitation of dense packing inside the medium. The reactions during charging is exothermic and during discharging is endothermic, a heat exchanger and additional heating is required towards charging and discharging process of these metal hydrides. The Metal hydrides are packed into metallic containers and are stored at minimal pressures of 10~ 15 bars. Desorption of Hydrogen being an endothermic process will ensure minimal loss of hydrogen to surroundings in case of physical damage to storage cylinder and due to its inherent nature, the hydrogen leak will only reduce further (requires heat to release). The German 212 submarine utilises a metal hydride storage system for its AIP- Fuel Cell plant. These metallic cylinders are placed outside the pressure hull in a circular fashion. A total of 80 hydrides tanks are placed outside the pressure hull each weighing 4.4 Tonnes and with a storage of 1200 liters capable of delivering 1Mwh of energy per container. These tanks are designed to be maintenance free and are located in the lower region of the pressure hull.

2.11.4 Carbon Nanofibers

Nano storage of hydrogen is still in experimental stages. Though the laboratory test results provide a satisfactory and promising results it cannot be exactly extrapolated to meet the submarine’s energy demand at present status.

2.11.5 Reformation of fuels

Three types of reforming methods are researched for suitability at M/s HDW premises, Germany. The reformation fuels include the following: -

(a) Diesel ($C_{13.57}H_{27.14}$)
(b) Ethanol (C_2H_5OH)
(c) Methanol (CH_3OH)

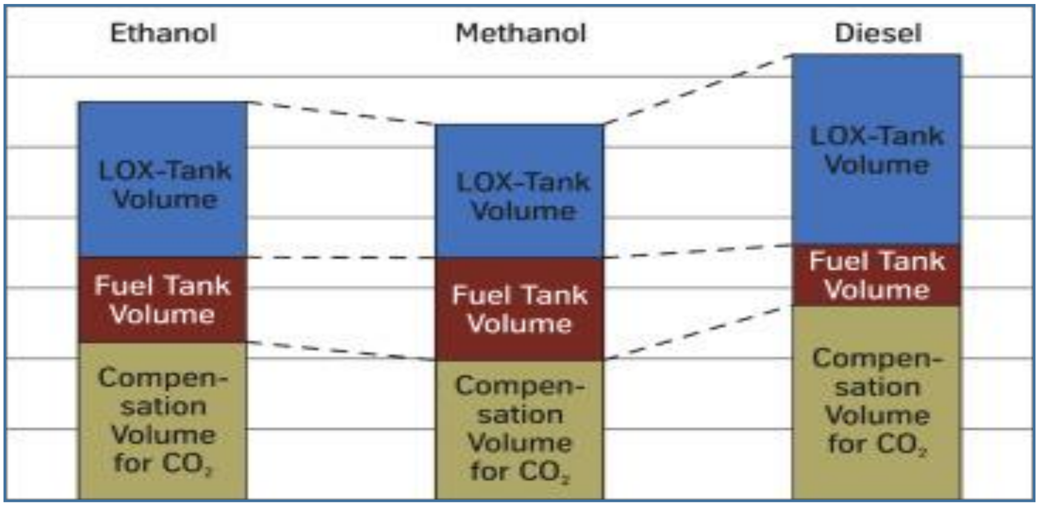


Fig 2.38: Graphical representation of Oxygen consumption and CO_2 compensation required during reformation of each fuel[242]

2.11.5.1 Ethanol Reformation

Th Spanish S-80 Program utilises the fuel cell system for its AIP system. The system is fed with Hydrogen reformed from bio Ethanol and oxygen stored in cryogenic form onboard. The byproduct viz., carbon di-oxide (CO_2) is expelled outboard by an integrated CO_2 dispensing system.

Fig 2.39: Land Based Setup of bio-Ethanol fed AIP system of S-80 Submarine[243]

2.11.5.2 Methanol reformation

The greatest advantage of utilisation of liquid fuel is its ability to be stored in tanks. Methanol and its variants are been widely used as a fuel in automotive and various land-based power and propulsion platforms. For submarine application the Methanol fuel is reformed to produce hydrogen. Unlike in a surface application wherein the atmospheric air is utilised for reformation, inside there is a requirement for dedicated oxygen feed for the reformation process. This requires additional storage of liquid oxygen for multi-process usage (reformation and operation of fuel cell). In addition, during the reformation process Carbon di oxide & Carbon monoxide is released as by product. Carbon-di-oxide is to be stored safely onboard or expelled outboard in a contained manner.

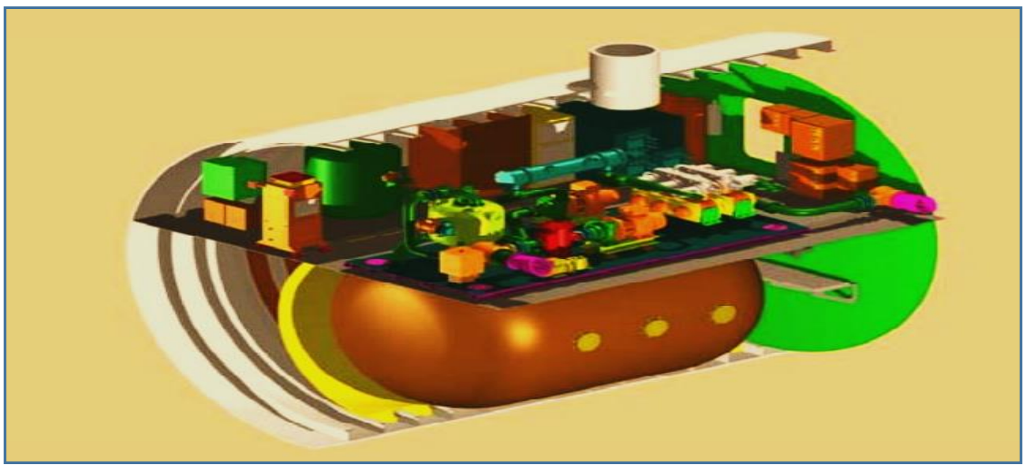


Fig 2.40: Graphical representation of Methanol reforming AIP Fuel cell plug of Spanish S-80 Program[244]

Methanol is stored at room temperature and is gradually expended with operation of fuel cell. Unlike the onboard fuel tanks which are compensated with seawater, the methanol tanks are not compensated upon usage hence these tanks are to be specially fabricated to adopt storage of methanol as fuel. Methanol reformer is presently under construction and evaluation by M/s Sener for Spanish S-80 Class submarine.

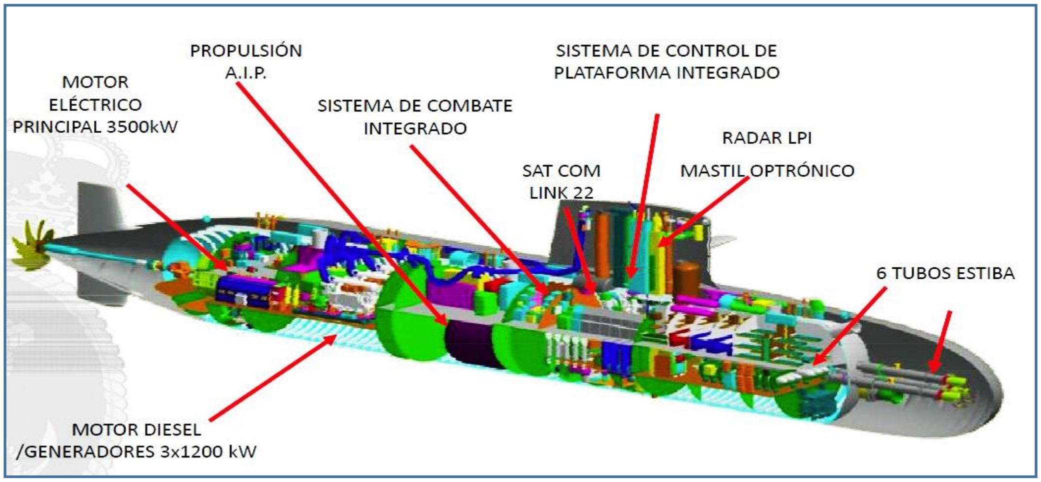


Fig 2.41: Spanish S-80 AIP Submarine [245]

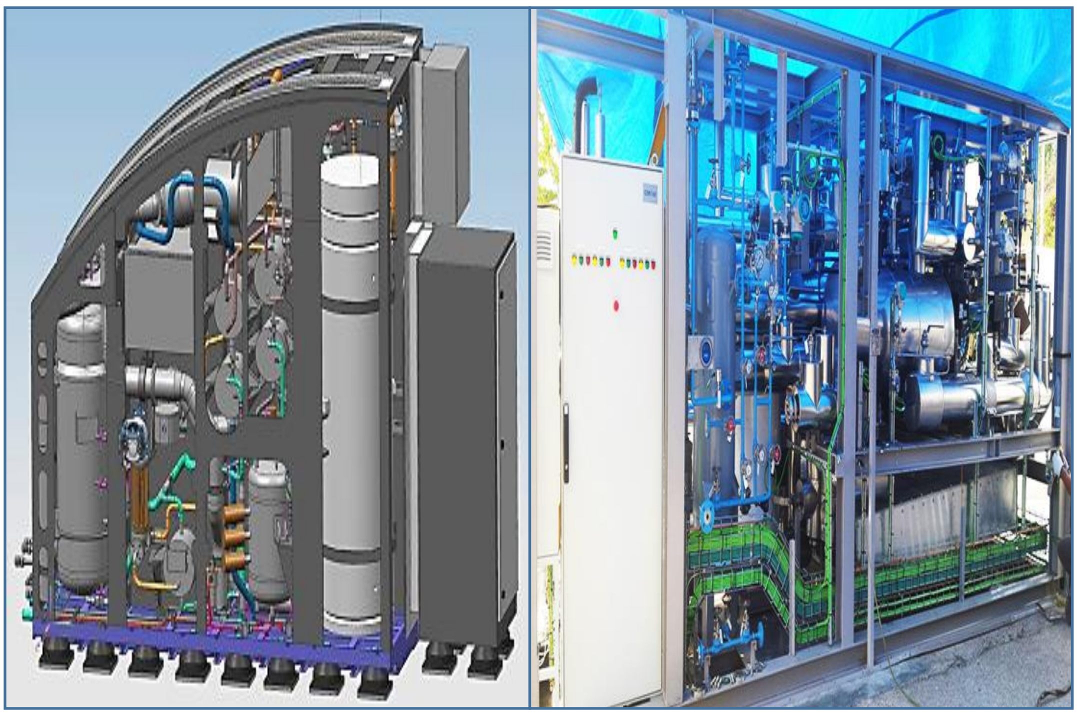


Fig 2.42 (Left to Right): (a) Methanol reformer AIP Fuel cell system for submarines[246] (b) Land Based platform developed by M/s Sener and M/s TKMS, Kiel Germany[247]

2.11.5.3 Diesel Reformation

Usage of diesel oil for AIP plant will emerge as the overall winner as it obviates the necessity for carrying additional fuel onboard. The distinct advantage of usage of diesel as fuel is its high volumetric and gravimetric energy densities. The following factors brings down the overall efficiency of the reformation process

(a) Overall conversion efficiency is 30~40% as compared to 50~60 % in methanol reformation.

(b) High Sulphur content will cause catalytic poisoning in fuel cells.

(c) In addition to carbon di-oxide harmful gases like carbon monoxide, Hydrogen sulphide are evolved and requires special extraction process.

The advantages of utilisation of diesel as main fuel include:

(a) High gravimetric and volumetric energy densities.
(b) Readily available
(c) Easy refueling

The main disadvantages include:

(a) Desulphurisation
(b) Requires high temperature and pressure
(c) Higher oxygen demand due to the reformation process
(d) Management of by products (storage onboard or expulsion outboard).

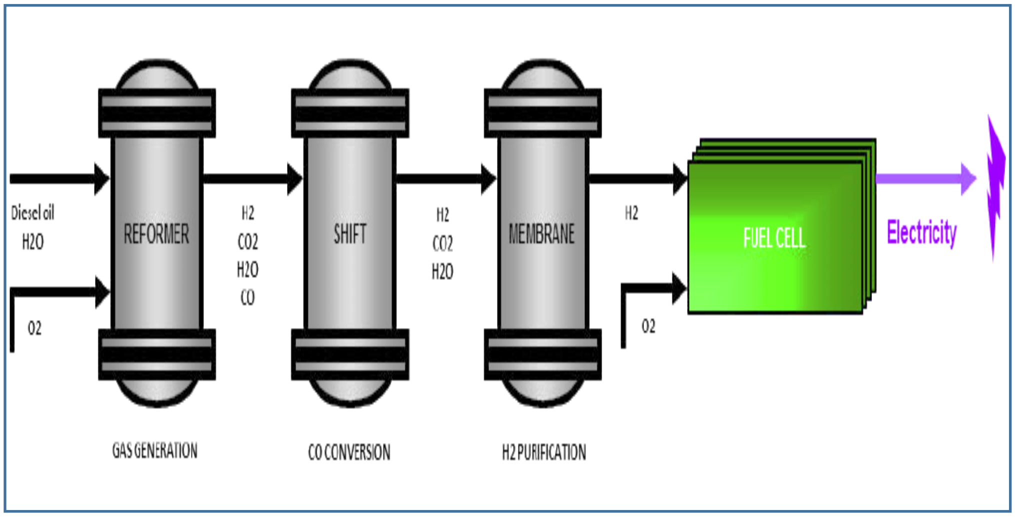


Fig 2.43: Graphical representation of Diesel Reforming process[248]

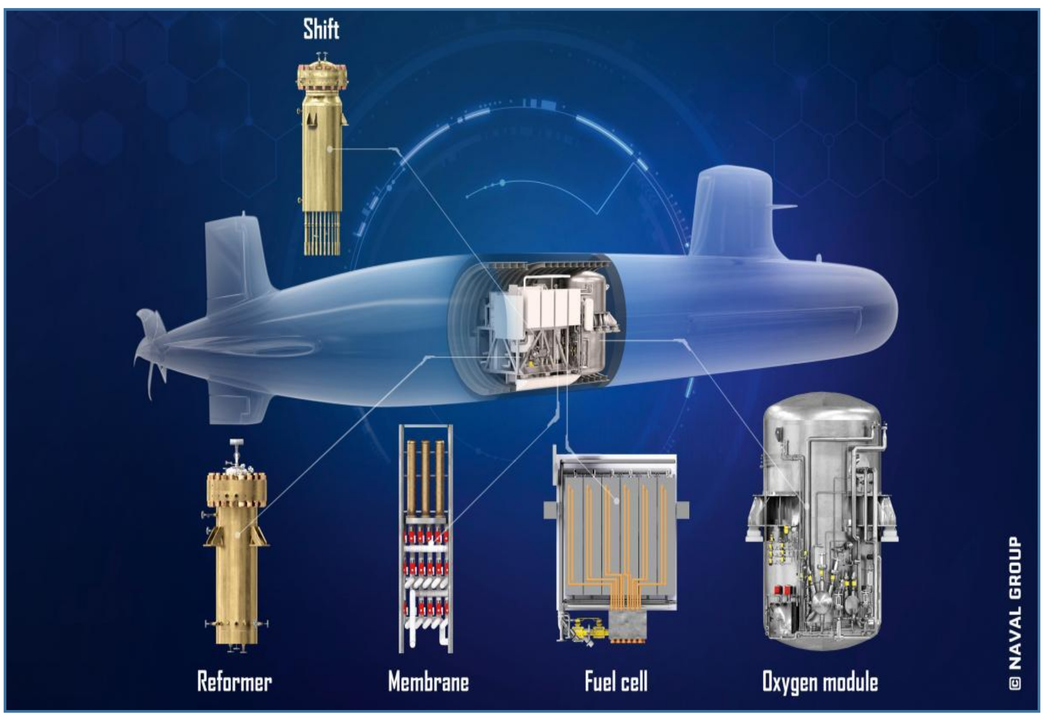


Fig 2.44: Graphical representation of sub components of Diesel Reformer system onboard a conventional diesel electric submarine[248][233]

Fig 2.45: laboratory setup of Diesel reforming AIP system of M/s DCNS, France [249]

Extensive 3-D modelling and simulation studies are undertaken to assess the suitability of fitment of components inside the cylindrical structure of the submarine. The laboratory or the land-based setup is often setup to establish the proof of concept of the particular equipment prior fitment onboard. However, the onboard fitment requires considerable study and modification to fit into submarine environment.

2.46: Top view of 3D-modelled Diesel Reforming system onboard submarine[249]

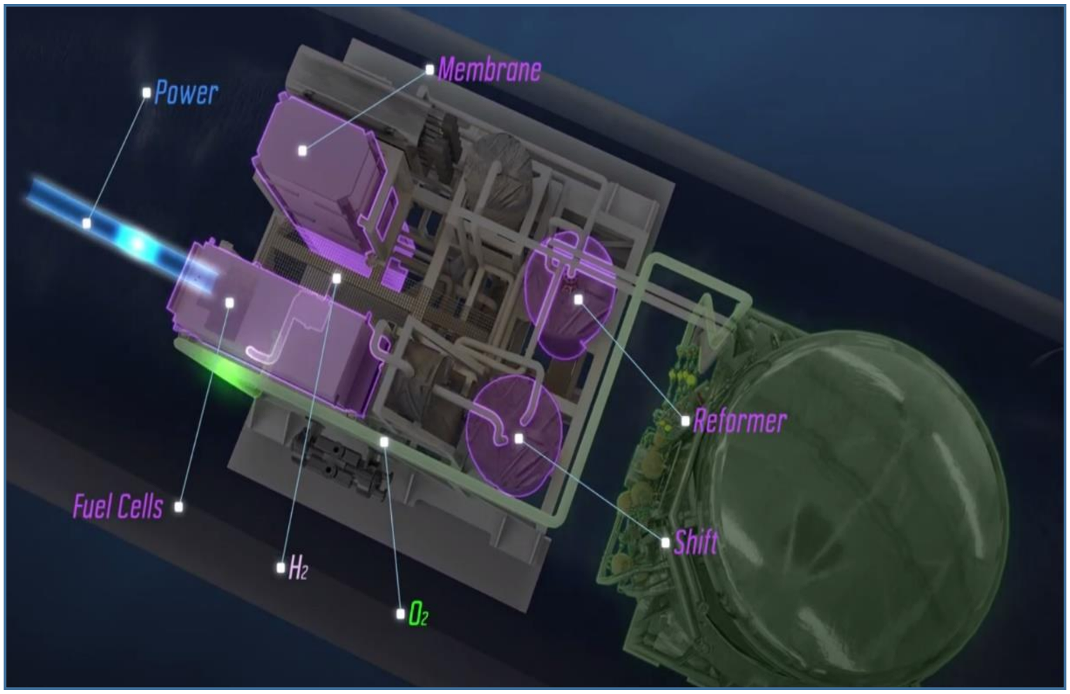


Fig 2.47: Top view of 3D-modelled AIP fuel cell system depicting O_2 & H_2 pipelines [249]

2.12. The Major advantages and disadvantages of four AIP system are tabulated below: -

Table 2.6. Advantages and disadvantages of various AIP systems

Closed Cycle Diesels (CCD)	
Advantages	**Disadvantages**
(a) Onboard fuel is utilised hence negating the need for additional storage space for fuel.	(a) Exhaust Gas Management – need for additional auxiliary equipment like CO_2 Scrubbers.
	(b) Reused Exhaust gases causes corrosion of components.
	(c) Noise due to rotating machinery
Module et Sous Marine Autonome (MESMA)-Closed Cycle Turbine	

Advantages	Disadvantages
(a) High Power Density	(a) Highest fuel Consumption amongst all AIP systems
	(b) Exhaust management toward expulsion of byproducts
	(c) High temperature causes corrosion of components
	(d) Steam turbine-rotating machinery generates noise- reduction in stealth
Stirling Engine (SE)	
Advantages	**Disadvantages**
(a) Onboard fuel is used	(a) Exhaust management of gases
(b) Reduced vibration compared to CCD and MESMA	(b) Need for additional storage space for Nitrogen and Helium in addition to Hydrogen and Liquid Oxygen.
(c) Wider Commercial and Military market	(c) High temperature causes corrosion of components
(d) Investment cost much lesser than Fuel Cell	(d) Rotating machinery generates noise.
Fuel Cell	
Advantages	**Disadvantages**
(a) Modular Robust System	High Investment cost
(b) No rotating components	
(c) By products are water and heat	
(d) Technological maturity- research undertaken at a faster pace	

Chapter Summary

This chapter illustrates the efficacy of an AIP system. A total of 300 Plus references have been referred in connection with the technology and MCDM techniques. The papers were referred to portray the growth of propulsion technologies for submarines since its inception and the various advancements in the storage technologies. In addition, it also brings out the advantages and disadvantages of each of AIP technologies available in the present scenario. The Literature survey has enabled to identify critical AIP systems its advantages, disadvantages and implementation onboard various platforms. Multi- Criteria Decision Making (MCDM) technique viz., Forced Decision Matrix and TOPSIS have been identified and has provided insight towards selection of systems and technology based on the platform requirements.

Chapter 3

3.1. Selection of AIP system

A project management decision tool viz., Forced Decision Matrix (FDM) is implemented in this paper towards identification of a suitable optimal Air Independent Propulsion (AIP) system for submerged vehicles. FDM is utilised in order to handle the trade-off from amongst multiple propulsion technologies. FDM is based on Multi-Attribute Utility Theory (MAUT) used extensively in decision analysis situations involving persuasive multiple alternatives. The efficiency and effectiveness of this methodology to tackle complex solutions is elaborated in this paper with appropriate calculations. A rational decision-making procedure is evolved using the FDM in order to select the best suited AIP technology for a submerged vehicle. It is inferred that FDM is an effective and potential tool towards identification of best suitable solution in a multi-option environment.

The World navies are undergoing a period of inevitable transformation wherein stealthier brown water patrolling has become the need of the hour. Air Independent propulsion (AIP) systems offer increased stealth and greater submerged endurance. These AIP sections are often referred as ‘plugs’ and can be catered for inclusion during the submarine design phase or retrofitted on an existing platform. The displacement of an average conventional submarine varies between 2500-3500 tonnes. The capability and exploitation of battery power on a conventional submarine is restricted to an average of 24 hours when operating at lower speeds (< 5 Knots) and necessitates snorkeling towards replenishment of batteries. At present, AIP technology is in its nascent stages and is often used only as supplementary powering source in addition to primary propulsive source onboard[93]. The current maximum submerged endurance of an AIP vessel is between 07 -14 days. In this paper, AIP systems have been classified into four main groups and the key parameters which determines the selection of technology have been reviewed comprehensively through implementation of Forced Decision Matrix (FDM) methodology. Identification of parameters and Calculation of co-efficient has been carried out. The advantages and disadvantages of each process are evaluated to select the best possible AIP solution.

In the present scenario, a significant amount of money and time is spent by nations all around the world in order to evolve a better Air Independent Propulsion technology which would be best suited for conventional diesel electric submarines. Conventional submarines are often considered stealthier than their nuclear counterparts. However, the only shortfall lies in their dependence to snorkel to recharge the batteries. A nuclear submarine edges the conventional submarine because of their exponential power availability for propulsion and its non-compromise on the bulkiness of the vessel and speed of transit. Even though the AIP systems are considered as an immaculate solution to bridge the gaps, there is a need to identify an idealistic AIP system for a conventional diesel electric submarine.

Most of the studies undertaken highlight the technological advantages of an AIP system, there exists very little literature available in open source towards implementation and adaptation of AIP system onboard. In this context the paper proposes FDM to evaluate the existing AIP technologies prevalent in the global scenario and aids in selection of an energy efficient system for induction onboard. Forced Decision Matrix (FDM) is a methodology which is based on the decision matrix analysis. It is a project management technique utilized in order to decipher the nuances of parameters and pitch it against each other to filter out the best amongst each parameter[81] structured in the similar way of a Business Decision model structure. All AIP systems installed onboard submarines usually employs a 'Plug Concept' where in the majority of the equipment and the control electronics are housed inside the submarine and only the hydrogen being hazardous in nature is stored outside the submarine in metal cylinders attached to the pressure hull of the submarine. Whilst taking into consideration the overall system efficiency it is important that the system availability and the associated costs involved be considered during system selection. The existing AIP technologies vis-à-vis their advantages and disadvantages in terms of stealth, efficiency and criticality has been brought out in this paper.

3.2. Types of Air Independent Propulsion (AIP) Systems

(a) Closed Cycle Diesel (CCD) Engines

(b) Closed Cycle Steam turbine -MESMA

(c) Stirling Engines

(d) Fuel Cells

Description of the individual AIP systems are covered in chapter 2.

3.3. Implementation of Forced Decision Matrix (FDM)

Forced Decision Matrix (FDM) has been utilized in this chapter to determine the best suited AIP system for submarines. Critical factors towards differentiation of AIP systems amongst each other are enlisted in the parameter identification (Table 5). Forced decision matrix enables us to prioritise the best option in a logical manner. The FDM is structured on the Decision Matrix analysis, a management technique which is employed for Multiple Criteria Decision Analysis (MCDA). This paper utilises the selection of all AIP options on similar lines of a business decision making methodologies based on subjective data. Decision matrix is often employed when there are multiple alternatives and multiple interlink factors governing each alternative.

3.4. Identification of Critical Parameters

The important parameters which governs the implementation of an AIP system onboard viz., Cost, stealth submerged endurance, operational exploitability, system down time, future expandability has been identified and is tabulated in table 1.

Table 3.1. Identification of Unique Parameters.

Parameter Selection		
SL. No	**Unique Identification Parameter**	**Value**
1.	Investment cost	1
2.	Technological Advancement/ Maturity	2
3.	Submerged Endurance	3
4.	Replenishment/routine maintenance/lay-off period	4
5.	Ease of operation	5
6.	Augmentation ability	6
7.	Stealth	7

3.5. Calculation of Attributed Weight Coefficient (AWC)

The calculation of the AWC is based on a matrix approach of pitting the unique parameters against each other in pair in order to determine the relative weightage. The most essential parameters for technology selection are enlisted in table 3.1. The calculation of AWC is undertaken utilising the weighted values of these parameters. The most important parameter is assigned the value “1” and the least is assigned “0”. The weights provided to different parameters are summed and divided with the total number of comparisons made in the matrix. For ease of understanding the first-row calculation of AWC is depicted in the following steps: -

(a) Summation of first row – (0+0+1+1+1+0) = 3.

(b) Attributed Weight Coefficient of 1st row depicting Investment cost = (Summation of first row /7) = 3/7.

(c) AWC = 3/7 = 0.4285 ≃ 0.43.

The same methodology is utilised for calculation of AWC values for other respective critical parameters as shown in table 2.

Table 3.2. Calculation of Attributed Weight Coefficient (AWC)

	1	2	3	4	5	6	7	AWC
1		**0**	**0**	**1**	**1**	**1**	**0**	**.43**
2	**1**		**0**	**0**	**0**	**1**	**1**	**.43**
3	**1**	**1**		**0**	**1**	**0**	**1**	**.57**
4	**0**	**0**	**0**		**1**	**0**	**0**	**.14**
5	**0**	**1**	**0**	**0**		**1**	**0**	**.29**
6	**0**	**0**	**1**	**1**	**0**		**1**	**.29**
7	**1**	**1**	**1**	**0**	**1**	**1**		**.71**

3.6. Determination of Sample Weight Coefficient (SWC)

To address the continual question to determine the best of the technology, seven critical parameters were identified common to the four existing AIP technologies and were compared against each other in pairs with respect to each parameter separately. The results of individual parameter comparison are formulated as a definitive matrix. The most important parameter is given a weightage of' '1' and least is assigned a value '0'. Finally, the individual parameter weightage is added and the sum is divided by the total number of comparisons from the matrix. SWC is calculated for each critical parameter as per the steps appended below

(a) Step1: -Summation of first row

(b) Step 2: - Sample Weight Coefficient of 1st row = (Summation of first row /4)

(c) Step 3: -Approximated decimal value of SWC for every AIP technology is calculated.

3.6.1 SWC for Investment Cost

Investment cost plays a vital role in the acquisition of the technology. This cost later transforms itself into operation and maintenance costs. The operation costs of fuel cells are much higher when compared to that of the CCD/Stirling engines. The major cost component of Fuel cell system is the storage system required for the liquid oxygen[250] as well as the hydrogen, the two essential components of the Fuel cell. Usage of methanol makes the MESMA a high-priced system next to Fuel cell[251]. The CCD/Stirling engines are relatively low priced when compared to their counterpart AIP systems as they utilize the Diesel oil of the conventional submarines to generate power[251]. The Sample Weight Coefficient calculated for investment cost parameter is tabulated in Table 3.3.

Table 3.3. Calculation of SWC: Investment Cost

	CCD	MESMA	STIRLING	FC	**SWC**
CCD		0	1	0	**0.25**
MESMA	1		1	0	**0.5**
STIRLING	0	0		0	**0**
FC	1	1	1		**0.75**

Table3. 4. Calculation of SWC: Technological Advancement/Maturity

	CCD	MESMA	STIRLING	FC	**SWC**
CCD		0	0	0	**0**
MESMA	1		0	0	**0.25**
STIRLING	1	1		0	**0.5**
FC	1	1	1		**0.75**

3.6.2 SWC for Technological advancement/maturity

Technological maturity will provide a clear advantage in choosing a technology which has been implemented onboard a vessel. Its performance characteristics can be assessed and a definitive opinion can be drawn on its output. These systems will have a low risk rate. Investments for further research towards betterment of such mature technologies will generally be dried up. the Soryu (Japan), Yuan (China) and Sodermanland (Sweden) class of submarines and are fitted with Stirling engines[33]. Technological advancements play a pivotal role towards acquisition and further aids in development and augmentation of the system. Ease of usage and replacement changes drastically when compared between a fuel cell AIP system with a CCD AIP system. It is learnt that the German 209s/214s export variant[252] fitted with fuel cells are providing a stiff competition to the MESMA and Stirling engine submarines. The Sample Weight Coefficient calculated for Technological Advancement/Maturity parameter is tabulated in Table 3.4.

3.6.3 SWC for Submerged Endurance

The submerged endurance of the AIP system is directly proportional to the amount of fuel that is present in the storage tanks[253]. The consumption of LOX plays a major role in determination of the endurance. MESMA is the largest consumer of LOX amongst the existing AIP systems and has a lowest efficiency rate of 25~30%[254]. The CCD systems when active in service had an efficiency rate of 30 ~ 35%[254]. The Stirling engines has an efficiency rate of 40% [254]. Due to comparative lesser consumption of oxygen results in an overall optimal sizing of a fuel cell AIP system. These Fuel cell systems have a high efficiency rate of over 70 %[255]. The Sample weight Coefficient calculated for submerged endurance parameter is tabulated in Table 3.5.

3.6.4 SWC for Replenishment/Maintenance/Lay off period

Replenishment of expended fuel plays a vital part for operation and exploitation of an AIP system. The fuel cell which mainly functions of Hydrogen and oxygen will require suitable infrastructural development for catering to its specific needs. Storage of H2/O2 are extremely complex in nature and a specialised local support team must be dedicated in order to the cater the needs of the submarine[256]. Replenishment of diesel oils utilized in CCD/Stirling engines are found to be less simple when compared to Liquid oxygen, hydrogen and ethanol used in fuel cell and MESMA Systems. The maintenance routines are far lesser in a fuel cell system when compared with MESMA, CCD or Stirling engine systems. The Sample weight Coefficient calculated for replenishment/maintenance/Lay off period parameter is tabulated in Table 3.6.

Table 3.5. Calculation of SWC: Submerged Endurance

	CCD	MESMA	STIRLING	FC	**SWC**
CCD		1	0	0	**0.25**
MESMA	0		0	0	**0**
STIRLING	1	1		0	**0.5**
FC	1	1	1		**0.75**

Table 3.6. Calculation of SWC: Replenishment/Lay-off period

	CCD	MESMA	STIRLING	FC	**SWC**
CCD		1	0	0	**0.25**
MESMA	0		1	0	**0.25**
STIRLING	0	0		1	**0.25**
FC	0	0	0		**0**

3.6.5 SWC for Ease of Operation

The Stirling engine, CCD and MESMA systems will be comparatively easier to operate from the crew's point of the view as the operation of these systems will not greatly vary from the operation of conventional diesel engines which are being operated on a daily basis[257]. Fuel Cell systems though will appear tough and sophisticated at the beginning, proper training with adequate exposure in operation of the system will enable the crew to exploit the system in an optimal manner. The Sample Weight Coefficient calculated for Ease of operation parameter is tabulated in Table 3.7.

Table3. 7. Calculation of SWC: Ease of Operation

	CCD	MESMA	STIRLING	FC	**SWC**
CCD		1	0	0	**0.25**
MESMA	0		1	0	**0.25**
STIRLING	0	0		1	**0.25**
FC	1	1	1		**0.5**

3.6.6 SWC for Augmentation Ability

The fuel cell system is widely researched all around the world and the research work will continue its growth exponentially in the forthcoming years. With huge investments being pumped in Fuel cell research coupled with outstanding efficiency rates compared to other AIP technologies, FC will be the best suited technology which stands a better future for any major augmentation/overhaul to an existing design. The biggest challenge faced by the Fuel cell system is its storage of hydrogen and oxygen fuels both onboard the submarine as well as in the yard. The Sample Weight Coefficient calculated for augmentation ability parameter is tabulated in Table 3.8.

Table 3.8. Calculation of SWC: Augmentation ability/Growth

	CCD	MESMA	STIRLING	FC	**SWC**
CCD		0	0	0	**0**
MESMA	0		0	0	**0**
STIRLING	1	1		0	**0.5**
FC	1	1	1		**0.75**

3.6.7 SWC for Stealth

Table3.9. Calculation of SWC: Stealth

	CCD	MESMA	STIRLING	FC	**SWC**
CCD		0	1	0	**0.25**
MESMA	0		0	0	**0**
STIRLING	1	1		0	**0.5**
FC	1	1	1		**0.75**

The stealth forms the most important parameter during acquisition of any major equipment which is going to be fitted onboard a submarine. The CCD, Stirling engines and the MESMA creates a large amount of vibrational noise due to the rotational noise created by the steam turbines. In addition, the carbon dioxide which is expelled as a by-product is expelled overboard through a muffler arrangement which still creates a disturbance in the ambient environment[258]. Fuel Cell is the quietest amongst all the AIP technologies and paves way for increasing the overall stealth of the conventional diesel electric submarine. The Sample weight Coefficient calculated for stealth parameter is tabulated in Table 3.9.

3.7. Calculation of Total Weight Co-efficient (TWC)

Determination of Total Weight Co-efficient enables us to zero in the most optimal AIP technology based on parameter optimization.

3.7.1 Total weight is determined by multiplication of Attributed Weight Co-efficient (AWC) of the individual parameter with the Sample Weight Co-efficient (SWC) of the individual AIP technology and is depicted in equation 1.

Total Weight (TW) = AWC * SWC

3.8. Results and Discussions

A Total Weight Coefficient (TWC) is calculated by summation of all individual Total weight (TW) of critical parameters. The results are tabulated in table 14. The results are based on the calculation of Total weight (TW) component of the particular AIP system. The calculations of CCD from table 14 is elaborated in the following steps:

(a) AWC values obtained for every critical parameter is substituted in row 1.

(b) SWC values obtained for every critical parameter is substituted in row 2.

(c) Total weight (TW)of CCD is obtained by product of AWC *SWC for every critical parameter. The values are substituted in row 3.

(d) Total Weighted Coefficient (TWC) is the summation of all the Total weights obtained for every critical parameter.

It is evident from the table 14 that Fuel cell outweighs the other AIP systems. The Project/system are ranked according to their overall scores.

Table 3.10. Calculation of Total Weight Co-efficient (TWC)

	ATT	1	2	3	4	5	6	7	TWC
CCD	**AWC**	**.43**	**.43**	**.57**	**.14**	**.29**	**.29**	**.71**	**0.53 (III)**
	SWC	**.25**	**0**	**.25**	**0.25**	**.25**	**0**	**.25**	
	TW	**.11**	**0**	**.14**	**0.04**	**.07**	**0**	**.18**	
MESMA	**AWC**	**.43**	**.43**	**.57**	**.14**	**.29**	**.29**	**.71**	**0.43 (IV)**
	SWC	**.5**	**.25**	**0**	**.25**	**.25**	**0**	**0**	
	TW	**.21**	**.11**	**0**	**.04**	**.07**	**0**	**0**	
STIRLING	**AWC**	**.43**	**.43**	**.57**	**.14**	**.29**	**.29**	**.71**	**1.0 (II)**
	SWC	**0**	**.25**	**.5**	**.25**	**.25**	**.5**	**.5**	
	TW	**0**	**.11**	**.29**	**.04**	**.07**	**.15**	**.34**	
FUEL CELL	**AWC**	**.43**	**.43**	**.57**	**.14**	**.29**	**.29**	**.71**	**1.82 (I)**
	SWC	**.75**	**.75**	**.75**	**0**	**0**	**.75**	**.75**	
	TW	**.32**	**.32**	**.42**	**0**	**0**	**.22**	**.53**	

Chapter Summary

This selection methodology utilises a project management technique (FDM) towards identification of optimal an AIP system for submarines. The analysis is focused on actual implementation whilst catering for long term parameters governing the installation of the system including operational limitation and supportability. Forced decision matrix[259] is powerful for analyzing factors when there are more than one alternate solutions. It is understood from the table that the fuel cell has the maximum Total Weighted Coefficient and emerges as the best solution amongst other AIP systems. Though Stirling engines have been installed onboard conventional boats and have performed consistently over the years, the technology however has reached its maturity and has very minimal scope for extraordinary improvement unlike the case of fuel cell AIP systems. Fuel cells may initially draw high investment costs but will be beneficial in the longer run. With increased need for stealthier conventional submarines to operate in the brown waters, fuel cell technology emerges out as a clear choice of AIP option for Conventional submarines. FDM methodology can be considered as an important precursor solution towards project implementation. Further studies such as Techno economic analysis of the narrowed down project can be undertaken in future prior installation, based on the above FDM methodology. The important disadvantages of a decision matrix include the following: -

(a) Arbitrary grouping of criteria options and more likelihood of an important criteria to be missed out.
(b) Values assigned are more on quantitative basis.
(c) Biasing can happen when faced with two important criteria.

Chapter 4

Selection of Optimal Fuel cell system for Air Independent Propulsion (AIP) of submarines using Multi- Criteria Decision Making (MCDM) methodology –

4.1 TOPSIS - Technique of Order Preference by similarity to Ideal Solution

The fuel cell is mainly defined by the type of electrolyte in it. Further, the electrolyte determines the chemical reaction, fuel intake and the expelled byproducts from the fuel cell. The following four types of fuel cells are found suitable for marine use [260][261]

(a) Proton Exchange Membrane (PEM)
(b) Phosphoric Acid Fuel Cell (PAFC)
(c) Molten Carbonate Fuel Cell (MCFC)
(d) Solid Oxide Fuel Cell (SOFC)

4.1.1 Proton Exchange Membrane Fuel Cell (PEMFC)

Oxygen and pure hydrogen are combined in order to produce electricity and water in presence of catalyst such as platinum. The expelled by product being water in turn catapults USP of the PEM fuel cell. The stack comprises of smaller modules which in turn are combined in a parallel-series combination to realise the required KW power. PEM fuel cells are widely utilised for civil and military purposes and in particular has a proven record in underwater applications [262](German submarines Type 209/212/214/216 & 218 uses various variants of PEM fuel Cells manufactured by M/s Siemens)[18]. The disadvantages of PEM fuel cell include catalyst poisoning due to the impurities in hydrogen. The other disadvantage includes storage of oxygen and hydrogen onboard but this remains as a common factor to be overcome with respect to any AIP system[263]. The distinct advantages of PEMFC are high power density, Low start up time, relatively lower operating temperatures as compared to other types of fuel cells and the expelled byproduct being water can be chosen to store onboard or drained outboard depending upon the situation of the underwater vessel thus contributing enhanced stealth during operation.

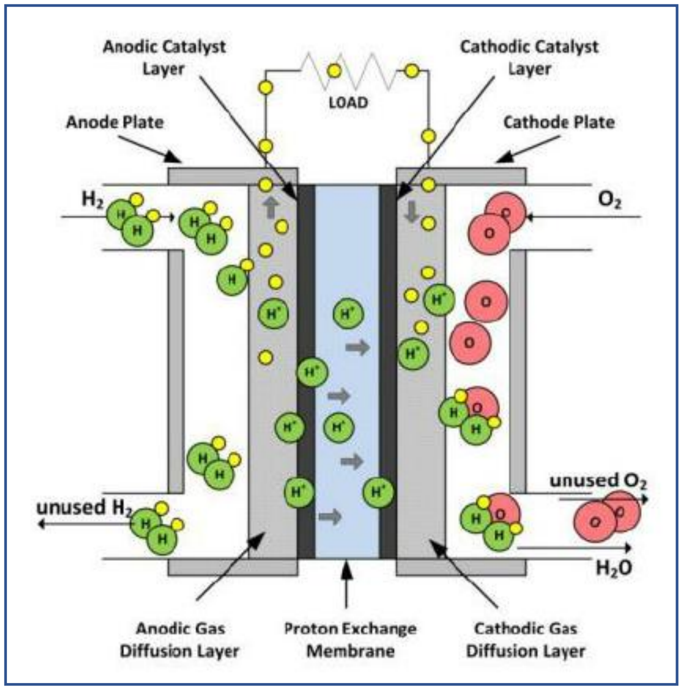


Fig 4.1: Pictorial representation of Proton Exchange Membrane (PEM) Fuel Cell

4.1.2 Phosphoric Acid Fuel Cell (PAFC)

The distinct feature of PAFC is phosphoric acid is utilised as an electrolyte saturated in silicon carbide matrix structure. Finely dispersed platinum is used as catalyst for the chemical reaction[263]. The operating temperature ranges are between 150- 200^0C. These temperatures are often found conducive for the expelled water to be converted to steam and be reutilized for Combined Heat Power (CHP) purposes. Correct utilisation of CHP can increase the overall efficiency of system to 70%. PAFCs are slightly better when compared with PEMFCs towards CO_2/CO tolerant. However, at low temperatures phosphoric acid is a poor ionic conductor. PAFCs are widely used in stationary power sources as well as in transportation buses. The Defence Research Development Organisation (DRDO) of India is developing an indigenous PAFC for retrofit onboard the Scorpene class and the follow-on submarine projects of India[238], [240], [264]–[267].

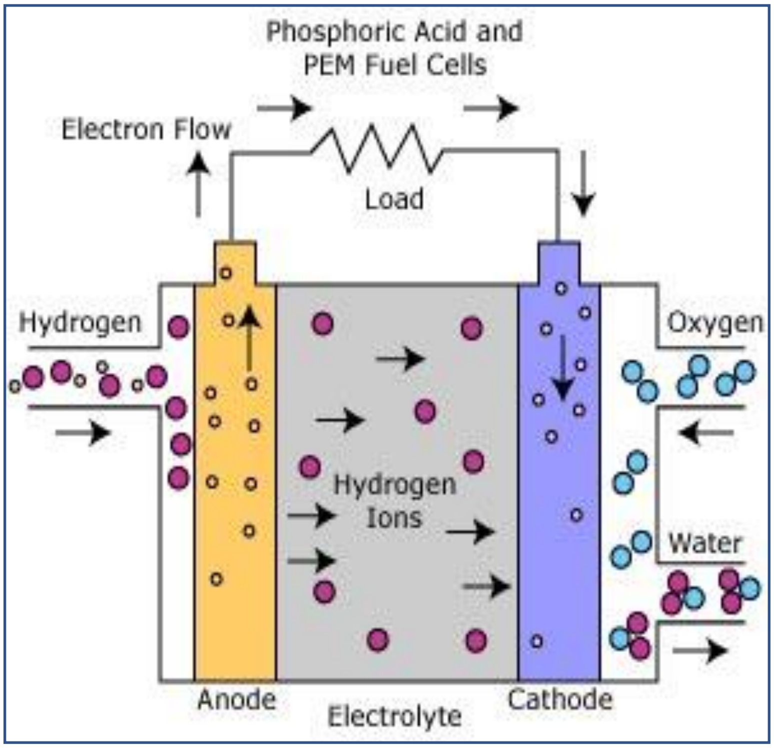


Fig 4.2: Pictorial representation of Phosphoric Acid Fuel Cell (PAFC)

4.1.3 Molten Carbonate Fuel Cell (MCFC)

These are high temperature fuel cells operating at temperatures greater than 600^0C[268]. electrolyte composing of porous, chemically inert ceramic lithium Aluminium oxide along with molten carbonate salt mixture is used in the fuel cell. In order to reduce the operation and maintenance costs non noble metals can be used as catalysts for these fuel cells. MCFCs greatly support CHP applications[269][270]. These fuel cell coupled with turbines can greatly increase the overall efficiency of the system. Due to the higher operating temperatures the lighter hydrocarbons and natural gas are gets converted into usable hydrogen within the fuel cell by a process known as internal reforming. These systems are prone to high corrosion and subsequent failure of components thus shortening the overall life of the fuel cell. The need to expel the CO_2 outboard pose a distinct disadvantage to the system, A coupled turbine for exploiting the reusable heat will cause diminished stealth capability due to rotating components in the system.

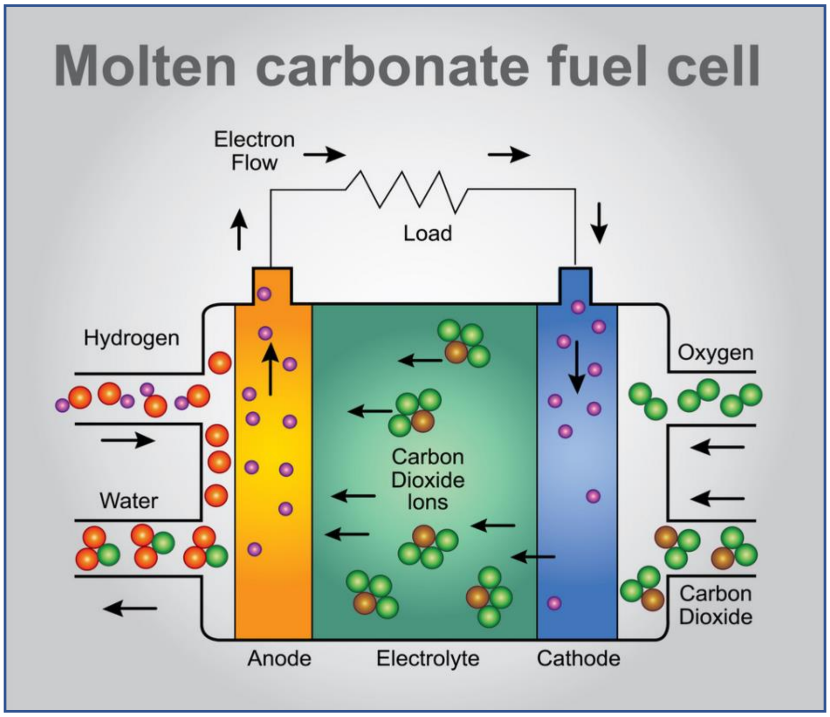


Fig 4.3: Pictorial representation of Molten Carbonate Fuel Cell (MCFC)

4.1.4 Solid Oxide Fuel Cell (SOFC)

Solid Oxide fuel cell uses a hard, non-porous ceramic compound as an electrolyte[271]. These fuel cells operate at extreme high temperatures of over 1000^0C provide a distinct advantage towards Combined Heat power (CHP) variants and thus increasing the overall efficiency of system[272]. High density fuels can be utilised for operation, However, the high operating temperature causes a corrosive environment and accentuated failure of system components thus making it extremely maintenance intensive. The excessive heat requires lot of thermal shielding of components thus increasing the overall cost of the system. Presently the fuel cell system is in experimental stages and are only exploited on marine surface platforms.

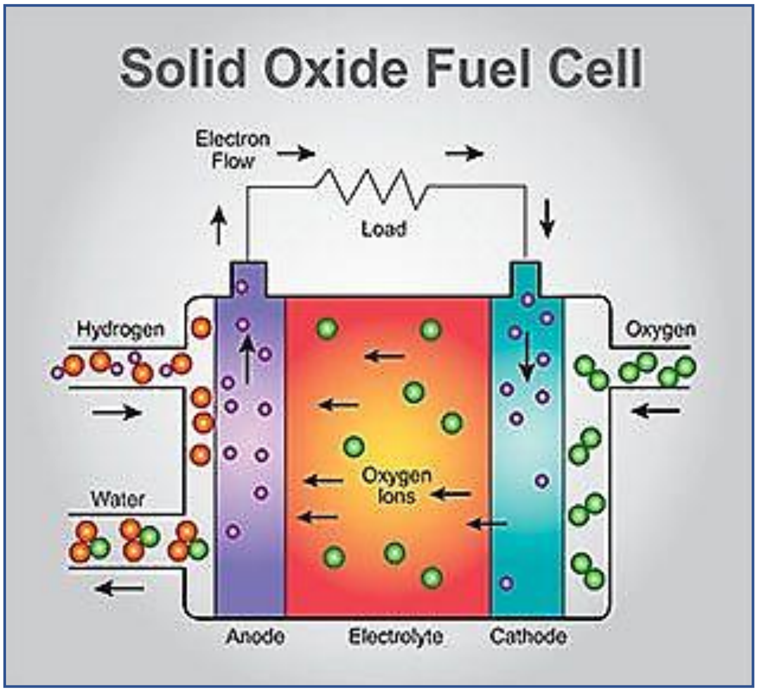


Fig 4.4: Pictorial representation of Solid Oxide Fuel Cell (SOFC)

4.2 Types of Multi -Criteria Decision Making (MCDM).

In order to determine the best suitable fuel cell option for an underwater submerged platform a MCDM approach has been undertaken. Evaluation of complex alternatives are resolved by a methodology known as Multi- Criteria Decision Making (MCDM) [273], [274], [283], [275]–[282] also known as Multiple Criteria Decision Analysis (MCDA) [284]–[292]. These methodologies are implemented in various fields of life viz., politics, groceries and energy alternatives. The results of this process can be interpreted in many ways and especially if the results do not point to a unique solution to the given problem, in such a case the resolver's preference towards identifying the particular solution also has to be taken into account. The various type of MCDM methods are as follows: -

(a) Multi Attribute Utility Theory (MAUT)[293]–[296]

(b) Multi Attribute Variable Theory (MAVT)

(c) Technique for the Order of Prioritisation by Similarity to Ideal Solutions (TOPSIS)[297]–[301]

(d) ELECTRE[302]–[309]

(e) PROMETHEE [309]–[316]

(f) VIKOR method [317]–[321]

(g) Analytical Hierarchy Process (AHP) [322]–[326]

(h) Analytical Network Process (ANP) [327]–[333]

(i) Best Worst Method (BWM) [334]–[337]

(j) Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) [338], [339][340]

(k) Potentially All Pairwise Rankings of all Possible Alternatives (PAPRIKA) [341]–[345]

(l) Weighted Product Model (WPM) [346]–[351]

(m) Weighted Sum Model (WSM) [352]–[358]

4.3 Implementation of TOPSIS

Identification of ideal fuel cell amongst the various types of fuel cells was realised using TOPSIS (Technique of Order Preference by similarity to Ideal Solution) - a Multi-Criteria Decision Making (MCDM) methodology. it is found that the methodology holds good towards choosing an optimal solution amongst close alternative solutions. The methodology was first proposed in 1981 by Hwang and Yoon. The proposal brought that the most suitable alternatives will be at the shortest distance from the positive alternative solution and farthest distant from negative ideal solution. The flowchart depiction of the TOPSIS procedure is depicted in Fig.1.

4.3.1 The important criteria which were identified towards formation of the decision matrix are: -

(a) Operating temperature - A low temperature fuel cell is apt towards installation onboard as it is cumbersome to install additional cooling equipment inside the limited space of the submarine. Additional ventilation will also be required inorder to maintain the ambient temperature inside the AIP compartment. Hence a low temperature fuel cell is a preferred option amongst fuel cell. The operating temperatures of fuel cells are PEMFC -100^{0}C, PAFC - 200^{0}C, MCFC-650^{0}C & SOFC- 1000^{0}C respectively.

(b) Startup time – A reduced start-up time is a preferred option as compared to longer start time in fuel cells as it will act as immediate backup when in times of need and shall not hinder immediate mission requirements.

(c) By products which are required to be expelled outboard – It is preferred that there should be no byproducts expelled from onboard due to the compromise in stealth. The byproduct of PEMFC is water and is preferred to be stored in onboard tanks. Whereas the other fuel cell expels carbon monoxide and CO_2 which necessitates the need for installation of scrubbers and other diffusing system for expulsion onboard.

(d) Suitability for installation on a marine platform – due to the modular construction of fuel cell combined with other factors viz., lesser auxiliary equipment for cooling and ventilation makes PEMFC a clear contender for installation onboard. It has been proven to be stable onboard German Submarines for almost 20 years.

(e) Maintenance Envelope – The maintenance of the fuel cell should be relatively simple and easy for the onboard crew to undertake. The modular construction and rack structure of PEMFC often simplifies the issue and has been comparatively simpler when compared to the maintenance of other fuel cells.

(f) Stack Efficiency – The efficiency of the stack plays a vital role towards understanding and assessing the sustainability of the fuel cell onboard though the efficiency of PEMFC and SOFC are 60%, SOFC loses the battle due to the extreme high temperature of operation and which in turn causes degradation of stacks.

The weightage of individual parameters is assigned on the basis of the importance and towards installation onboard.

4.3.2 Allocation of weights

The weight is allocated as per the relevance of each feature and the characteristic of the parameter towards installation under a submerged environment. Based on the data available from literature, it is inferred that all fuel cell except PEM fuel cell has long start time hence there is considerable delay or preparation time prior exploitation of fuel cell hence it has been considered as extremely vital hence start-up time has been allocated weightage of 0.35. The low operating temperature of PEM fuel cell is extremely conducive for submarine usage and can be cooled by onboard ventilation and hence it has been assigned a value of 0.15. The PEM fuel cell are often modular in rack format and hence the adaptability and installation onboard are much easier. The other parameters such as stack efficiency, maintenance and by-products are weighted as 0.1 and vary with importance as per the individual fuel cell option. The allocation of individual parameter weights are shown in the bottom portion of table 4.1

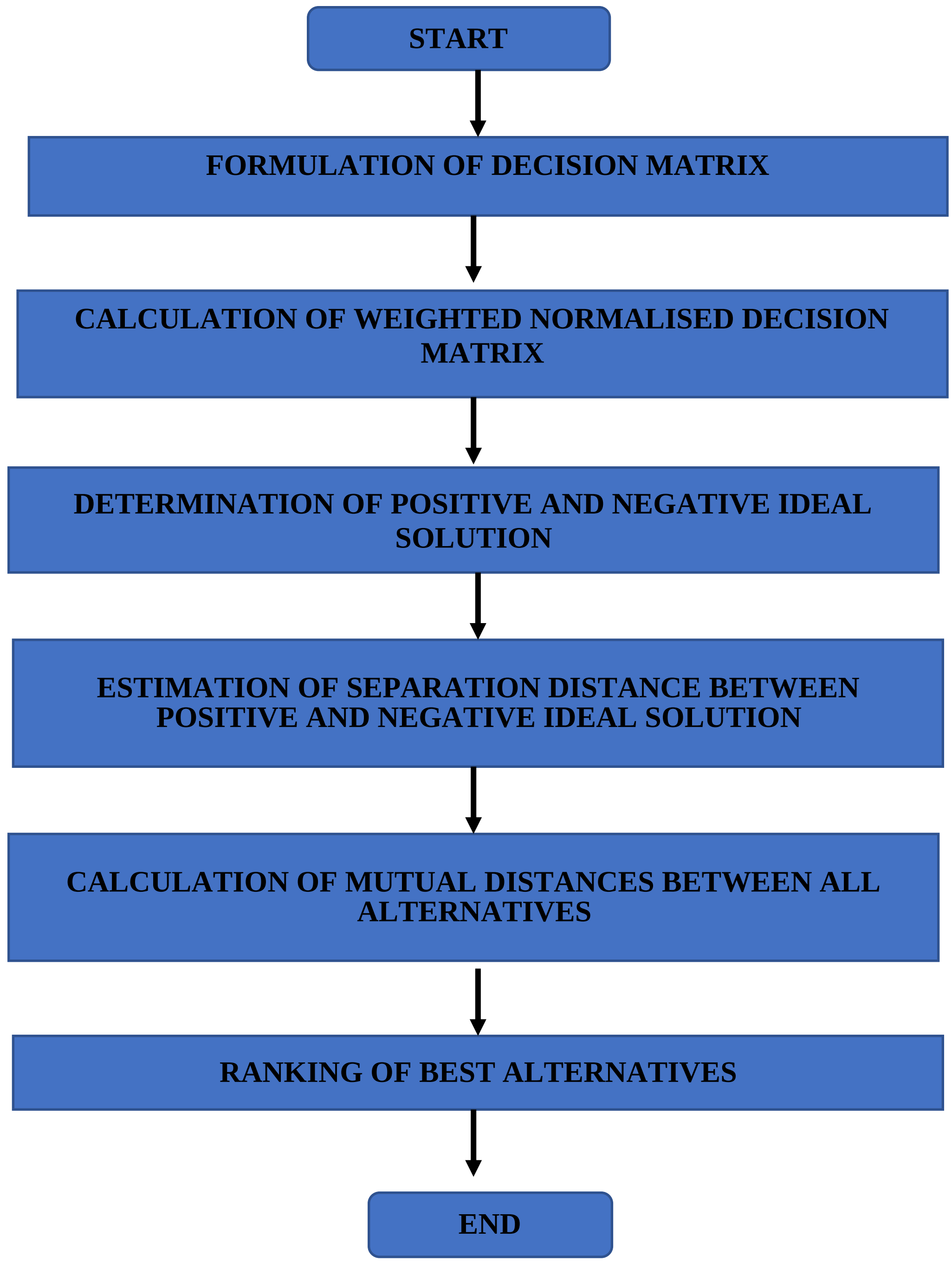


Fig 4.5. Flowchart of sequential steps in a TOPSIS methodology.

Step 1 :- Formulation of decision Matrix

$$DM = \begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{array}{c} L_1 \\ L_2 \\ \vdots \\ L_m \end{array} & \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{array} \qquad \textbf{(1)}$$

C_1, C_2,……….C_n refers to various criteria and L_1, L_2,……….L_n refers to the various alternative which are available.

Create an evaluation matrix consisting of m alternatives and n criteria, with the intersection of each alternative and criteria given as x_{ij}, we therefore have a matrix

$(x_{ij})_{m \times n}$.

TOPSIS assumes that we have m alternatives (options) and n attributes/criteria and we have the score of each option with respect to each criterion.

X_{ij} score of option i with respect to criteria j, hence we have a matrix $X = X_{ij}$ m * n matrix.

In the thesis m= 4 alternatives (fuel cells) and n = 6 attributes (criteria),

hence X_{ij} = 4 * 6 Matrix

Step 2: Calculation of Normalised Decision Matrix (NDM).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{J} x_{ij}^2}} \text{ , j = 1,2, 3………, J; i= 1,2, 3……………...n} \qquad \textbf{(2)}$$

NDM is realised through beneficial& non-beneficial criteria.

Step 3: Determination of Weighted Decision Matrix (WDM)

WDM is realised by multiplication of evaluation criteria weights W_i and Normalised Decision Matrix (NDM) $r_{ij.}$

$$v_{ij} = w_i * r_{ij} \text{ , j = 1,2, 3………, J; i= 1,2, 3……………...n} \qquad \textbf{(3)}$$

Step 4: Determine the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) where J refers to beneficial attributes and J' refers to non-beneficial attributes as shown in eqn 4 & 5.

$PIS = A^+ = \{ V_1^+, V_2^+, V_3^+ \ldots\ldots, V_n^+\}$, where $V_j^+ = \{$(maxi (V_{ij}) if j ε J) ;(mini V_{ij} if j ε J')} **(4)**

$NIS = A^- = \{ V_1^-, V_2^-, V_3^- \ldots\ldots, V_n^-\}$, where $V_j^- = \{$(mini (V_{ij}) if j ε J) ;(mini V_{ij} if j ε J')} **(5)**

	Alternatives with Quantitative Data							
		Factor 1	*Factor 2*	*Factor 3*	*Factor 4*	*Factor 5*	*Factor 6*	
	Options / Factors	**Operating Temp**	**Start-Up Time**	**Expelled Products**	**Suitability**	**Maintenance**	**Stack Efficiency**	**Rank**
Option 1	**PEMFC**	9	8	9	9	9	7	**1**
Option 2	**PAFC**	7	7	8	5	7	8	**2**
Option 3	**MCFC**	5	5	4	5	5	7	**3**
Option 4	**SOFC**	3	4	3	3	4	5	**4**
	Weights	**0.15**	**0.35**	**0.1**	**0.2**	**0.1**	**0.1**	**1**

Table 4.1. Selection of optimal Fuel cell for an underwater Platform using TOPSIS Methodology.

81	**64**	**81**	**81**	**81**	**49**
49	**49**	**64**	**25**	**49**	**64**
25	**25**	**16**	**25**	**25**	**49**
9	**16**	**9**	**9**	**16**	**25**
164	**154**	**170**	**140**	**171**	**187**

Table 4.2. Squaring of factor value

Normalised Data					
0.7028	0.6447	0.6903	0.7606	0.6882	0.5119
0.5466	0.5641	0.6136	0.4226	0.5353	0.5850
0.3904	0.4029	0.3068	0.4226	0.3824	0.5119
0.2343	0.3223	0.2301	0.2535	0.3059	0.3656

Table 4.3. Calculation of Normalised Data

Weighted Matrix					
0.15	0.35	0.1	0.2	0.1	0.1
0.15	0.35	0.1	0.2	0.1	0.1
0.15	0.35	0.1	0.2	0.1	0.1
0.15	0.35	0.1	0.2	0.1	0.1

Table 4.4. Calculation of Weighted Matrix

Weighted Normalised Data					
0.1054	0.2256	0.0690	0.1521	0.0688	0.0512
0.0820	0.1974	0.0614	0.0845	0.0535	0.0585
0.0586	0.1410	0.0307	0.0845	0.0382	0.0512
0.0351	0.1128	0.0230	0.0507	0.0306	0.0366

Table 4.5. Calculation of Weighted Normalised Data

Step 5: Calculation of separation distance between ideal and Non-Ideal solutions as shown in eqn 6 & 7.

$S^{+} = \sqrt{\sum_{j=1}^{n}(V_j^{+} - V_{ij})^2}$ where i= 1,……………,m **(6)**

$S^{-} = \sqrt{\sum_{j=1}^{n}(V_j^{-} - V_{ij})^2}$ where i= 1,……………,m **(7)**

The calculation of Positive and Negative matrix is part of the calculation of TOPSIS method. They are categorised as **High** for the following parameters namely operating temperature, Start-up time, efficiency and suitability Low for Expelled products and maintenance.

Step 6: relative closeness of all the alternative with respect to the most ideal solution is calculated as shown in eqn 8.

$C_i = \frac{S_i^{-}}{(S_i^{+} + S_i^{-})}, 0 \leq C_i \leq 1$ **(8)**

Step 7: Ranking the alternatives

Higher the value of C_i better is the chosen alternative.

Positive Matrix					
0.1054	0.2256	0.0230	0.1521	0.0306	0.0585

Table 4.6. Calculation of Positive Matrix

Si +
0.0603
0.1262
0.078
0.1038

Table 4.7. Calculation of Separation distance of ideal alternatives

Negative Matrix					
0.0351	0.1128	0.0690	0.0507	0.0688	0.0366

Table 4.8. Calculation of Negative Matrix

Si -
0.0284
0.0113
0.0054
0.0041

Table 4.9. Calculation of Separation distance of Non-ideal alternatives

Ci	Rank
0.3205	1
0.082	2
0.0645	3
0.0377	4

Table 4.10. Ranking of alternatives

Chapter Summary

Based on the data collected about implementation various types of fuel cells being utilised in marine environment, the suitability of incorporation onboard a submerged platform is assessed with respect to six governing factors common to each fuel cell. Four types of fuel cells viz., PEMFC, PAFC, SOFC and MCFC were considered and suitable weights vis-à-vis the governing factor was distributed. A Multi Criteria Decision Making (MCDM) methodology -TOPSIS was utilised to demonstrate the mathematical analysis of the most optimal fuel cell for installation onboard a submarine. The analysis of criteria amongst four different marine fuel cells by TOPSIS is tabulated in table 4.10. Based on the ranking. It is determined that Proton Exchange Membrane (PEM) fuel cell is the most suitable solution for implementation onboard underwater platform.

Chapter 5

Introduction

5.1 This Chapter covers the simulations, coding and subsequent modeling of the AIP system using software tools viz., MATLAB -Simulink, Paramarine and Power Stage Designer Tool – M/s Texas Instruments version 4.0. The initial sizing of the Submarine was coded into a MATLAB file and the results were extrapolated to an M/s Excel Format for visual appreciation of the processed data. Graphical analysis of six modern conventional submarines (Type 212, Type 214, MESMA (France), Stirling (Sweden), Yuan Class and Soryu Class) were undertaken for their power requirements. The simulation of 2000Tonne submarine fitted with Lead Acid Batteries (LABs) and with hybrid option (LAB + AIP) is undertaken with respect to propulsion and hotel load. Based on the above calculation the indiscretion rate of submarine is determined. A second MATLAB program codes were implemented in order to assess the buoyancy (Positive, Neutral or Negative) of the AIP Plug with respect to the fuel storage onboard. The fuel storage option for the AIP system has been extensively reviewed and the best possible option has been identified. In addition, for the purpose of power smoothening an inverted buck boost inverter has been modelled for the desired output voltage using the Power Stage Designer Tool – M/s Texas Instruments version 4.0. The feasibility of incorporation of COTS PEM fuel cell by two different OEMs viz., M/s Siemens (120KW x03 nos) and M/s Hydrogenics (30 Kw x 12 nos) were studied and found to be feasible for installation onboard. The size and weight requirements of these PEMFC modules are found to be suitable for incorporation inside an AIP plug. Detailed calculations, simulations, graphical analysis of data are included in this chapter.

5.2 Submarine Design flow chart

Design of the submarine is to commence with a baseline model which serves as a platform for principle of inclusions and exclusions in order to configure the right fit which meets the requirement of the customer. The design flowchart highlighted by Burcher and Rydill is shown in fig 5.1.

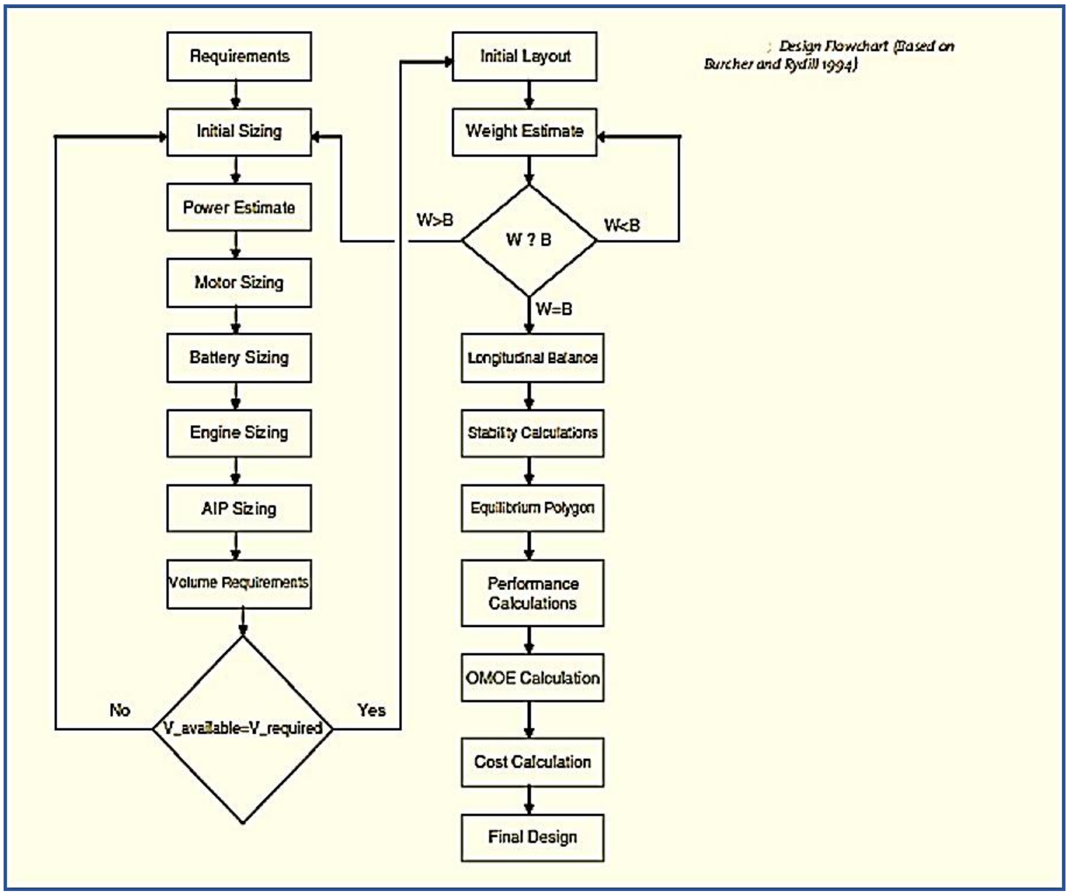


Fig 5.1. The design concept and its subsequent flow is elaborated by Burcher and Rydill[1]

[1] Burcher and Rydill in their Book titled “Concepts in submarine Design”.

The Preliminary power estimation of the submarine was calculated using Jackson's method and the parameters are tabulated in tables 5.1 and 5.2.

5.3 Concept of Parametric Survey

Parametric survey is undertaken towards understanding of hull form variation vis-à-vis change in dimensions. The Variation of parameters is plotted as graphs and is placed in Appendix.

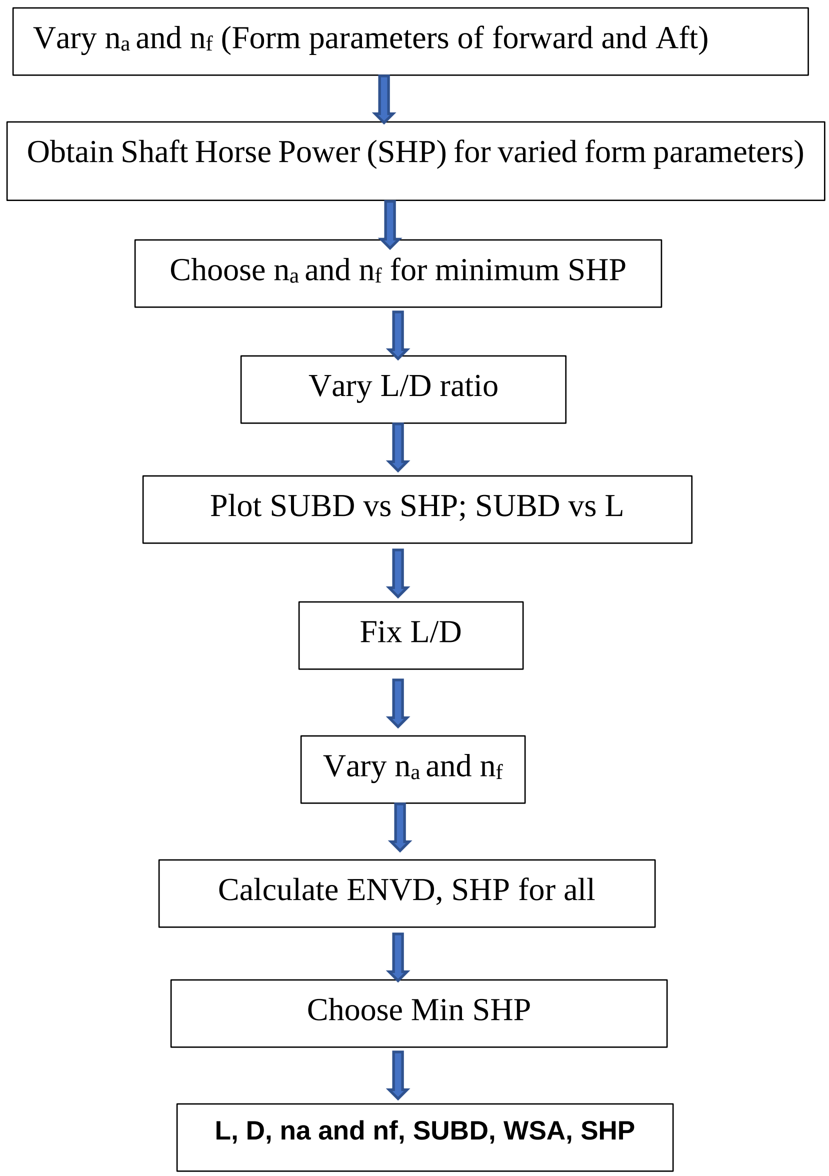


Fig 5.2: Flow chart depicting the process of parametric survey

The task now is to identify most efficient hull form that can ingeniously support the payload and meet the requirements of speed.

5.4 Parameters affecting Dimensions

The considerations required towards finalization of design are as follows: -

(a) Overall considerations:

- (i) Volume requirements
- (ii) Weight estimate
- (iii) Balance of weight and volume
- (iv) Resistance and powering
- (v) Cost considerations
- (vi) Stealth

(b) Length considerations:

- (i) Stack length requirement for equipment and spaces
- (ii) Area requirements (e.g. for accommodation spaces)

(c) Diameter considerations:

- (i) Number of decks
- (ii) Headroom requirement

Depending on the number of decks chosen the Length(L) for the Diameter (D) will be optimised. The diameter range was expected as 6-8 meters. Length-to-diameter ratios of existing designs vary from 8 to 12. A comparative analysis was undertaken vis-à-vis conventional submarines around the world and it is inferred that that the Length to Diameter ratios of submarines vary from 10.2 to 14 meters.

5.5 Estimation of Preliminary power

Governing Conditions: -

The variation in parameters was for:

(a) Operational parameters:

(i) Ability to accommodate all the weapons and sensors.

(ii) Sufficient space catering for equipment (including future provisions and crew.

(b) Geometrical parameters:

(i) Diameter: 6 to 10 m

(ii) L/D ratio (in Jackson's procedure): 8.5 to 12

(iii) Form Coefficients (in Jackson's procedure): 2 to 4.5 8

The variation in parameters and their effect has been formulated into a spread sheet format and graphical representation of the same has been realised. An AIP plug of the estimated power (360kW) has been studied. Two variant modules from COTS market has been taken into consideration for the study viz.,120 KW M/s Siemens PEMFC module and 120KW HyPM-R-120s of M/s Hydrogenics. A loiter speed of 4 to 6 knots is considered for operation of AIP system of the targeted submarine. The calculations were undertaken for a conventional submarine of 68 m in length and a diameter of 6.2 m in order to estimate the Power (KW) requirement of the submarine for various speed regimes (as shown in table 5.1). It is inferred that the maximum power requirement for a submarine of 68m is approximately is 3184.4 Kw at 20 knots speed and for 77.94 m length is 3200.64 KW.

5.6 Selected Dimensions of the Diesel Electric Submarine

A spread sheet analysis of increased length was calculated using Jackson's method (tabulated in 5.1 (a)& 5.1 (b)) to determine the Power (KW) requirement and the final dimensions are shown below.

(a) Length - 77.94 m (68+9.94)

(b) Diameter – 6.2m

(c) L/D – 12.57m

Table 5.1 : - Preliminary estimation of Power Using Jackson’s Method - Initial

PRELIMINARY POWER ESTIMATION- JACKSON`S METHOD									EHP vs speed in knots			SHP vs speed in knots		
	L(m)=	68	D=	6.2	WSA=	1159.903	L/D=	10.5	As=	1500	ft^2		k2 =	0.8952
	feet	223.04		20.336		12478.23	ft^2							
	speed (kt)	speed (m/s)	Rn	log Rn	Cf	EHP hull	PE (kW) hull	EHP append	EHP total	PE (kW)	SHP	PS (kW)	RT(kN)	
	1	0.5144	29493423	7.469725	0.002507	0.40568	0.302637	0.222672	0.628351	0.46875	0.766282	0.571647	0.911256	
	2	1.0288	58986847	7.770755	0.002252	3.023711	2.255689	1.781373	4.805084	3.584593	5.859859	4.371455	3.484247	
	3	1.5432	88480270	7.946846	0.002121	9.818985	7.324963	6.012135	15.83112	11.81002	19.30624	14.40246	7.652939	
patrol	4	2.0576	1.18E+08	8.071785	0.002034	22.6731	16.91413	14.25099	36.92409	27.54537	45.02938	33.59191	13.38714	
	5	2.572	1.47E+08	8.168695	0.001971	43.42084	32.39195	27.83396	71.2548	53.15608	86.8961	64.82449	20.66722	
	6	3.0864	1.77E+08	8.247876	0.001921	73.86452	55.10294	48.09708	121.9616	90.98336	148.7337	110.9553	29.4788	
	7	3.6008	2.06E+08	8.314823	0.001881	115.7818	86.37321	76.37638	192.1582	143.35	234.3392	174.8171	39.8106	
	8	4.1152	2.36E+08	8.372815	0.001847	170.9305	127.5141	114.0079	284.9384	212.564	347.4858	259.2244	51.65339	
	9	4.6296	2.65E+08	8.423968	0.001817	241.0521	179.8248	162.3276	403.3797	300.9213	491.9265	366.9771	64.99941	
	10	5.144	2.95E+08	8.469725	0.001792	327.8739	244.5939	222.6717	550.5456	410.707	671.397	500.8622	79.84195	
	11	5.6584	3.24E+08	8.511118	0.001769	433.1113	323.101	296.376	729.4872	544.1975	889.6186	663.6555	96.17515	
	12	6.1728	3.54E+08	8.548906	0.001749	558.4686	416.6176	384.7766	943.2452	703.6609	1150.299	858.1231	113.9938	
	13	6.6872	3.83E+08	8.583669	0.00173	705.6407	526.408	489.2096	1194.85	891.3584	1457.135	1087.022	133.2932	
	14	7.2016	4.13E+08	8.615853	0.001714	876.3139	653.7302	611.011	1487.325	1109.544	1813.811	1353.103	154.0692	
	15	7.716	4.42E+08	8.645816	0.001698	1072.166	799.8361	751.5169	1823.683	1360.468	2224.004	1659.107	176.3177	
	16	8.2304	4.72E+08	8.673845	0.001684	1294.869	965.9725	912.0631	2206.932	1646.372	2691.381	2007.77	200.0354	
	17	8.7448	5.01E+08	8.700174	0.001671	1546.087	1153.381	1093.986	2640.073	1969.494	3219.601	2401.822	225.2189	
	18	9.2592	5.31E+08	8.724998	0.001658	1827.478	1363.298	1298.621	3126.099	2332.07	3812.315	2843.987	251.8651	
	19	9.7736	5.6E+08	8.748479	0.001647	2140.694	1596.957	1527.305	3667.999	2736.327	4473.169	3336.984	279.9712	
max	20	10.288	5.9E+08	8.770755	0.001636	2487.382	1855.587	1781.373	4268.756	3184.492	5205.8	3883.526	309.5346	

Table 5.2: - Preliminary estimation of Power Using Jackson's Method -Final

PRELIMINARY POWER ESTIMATION- JACKSON`S METHOD									EHP vs speed in knots			SHP vs speed in knots		
	L(m)=	77.94	D=	6.2	WSA=	1391.647	L/D=	12.419	As=	1500	ft^2		k2=	0.8952
	feet	255.6432		20.336		14971.33	ft^2							
	speed (kt)	speed (m/s)	Rn	log Rn	Cf	EHP hull	PE(kW) hull	EHP append	EHP total	PE (kW)	SHP	PS (kW)	RT(kN)	
	1	0.5144	33804667.79	7.528977	0.002453	0.479756	0.3578981	0.22845319	0.708209341	0.528324168	0.863669928	0.644298	1.027068757	
	2	1.0288	67609335.58	7.830007	0.002207	3.580269	2.6708806	1.82762551	5.40789435	4.034289185	6.59499311	4.919865	3.921354185	
	3	1.5432	101414003.4	8.006098	0.002079	11.63401	8.6789752	6.16823608	17.80225107	13.2804793	21.71006228	16.19571	8.605805662	
patrol	4	2.0576	135218671.2	8.131037	0.001995	26.87615	20.049607	14.621004	41.49715304	30.95687617	50.60628419	37.75229	15.04513811	
	5	2.572	169023339	8.227947	0.001934	51.48707	38.409355	28.5566485	80.04371966	59.71261486	97.61429226	72.82026	23.21641324	
	6	3.0864	202828006.7	8.307128	0.001885	87.60919	65.356457	49.3458887	136.9550799	102.1684896	167.0183902	124.5957	33.1028025	
	7	3.6008	236632674.5	8.374075	0.001846	137.356	102.46761	78.3594436	215.7154873	160.9237535	263.0676674	196.2485	44.69111128	
	8	4.1152	270437342.3	8.432067	0.001813	202.818	151.30223	116.968032	319.7860366	238.5603833	389.9829715	290.9273	57.97054416	
	9	4.6296	304242010.1	8.483219	0.001784	286.0662	213.40538	166.542374	452.6085734	337.6459958	551.9616749	411.7634	72.93200185	
	10	5.144	338046677.9	8.528977	0.001759	389.1553	290.30988	228.453188	617.6085264	460.7359607	753.1811298	561.8731	89.567644	
	11	5.6584	371851345.7	8.570369	0.001737	514.1259	383.53789	304.071194	818.1970504	610.3749996	997.801281	744.3598	107.8705994	
	12	6.1728	405656013.5	8.608158	0.001718	663.0056	494.60217	394.767109	1057.7727	789.0984339	1289.966707	962.3152	127.8347644	
	13	6.6872	439460681.3	8.64292	0.0017	837.8111	625.00709	501.911654	1339.722769	999.4331858	1633.808255	1218.821	149.4546575	
	14	7.2016	473265349.1	8.675105	0.001683	1040.549	776.24944	626.875548	1667.424393	1243.898597	2033.444382	1516.95	172.7253106	
	15	7.716	507070016.9	8.705068	0.001668	1273.216	949.8191	771.02951	2044.245456	1525.00711	2492.982263	1859.765	197.6421864	
	16	8.2304	540874684.7	8.733097	0.001654	1537.801	1147.1996	935.744259	2473.545368	1845.264844	3016.518741	2250.323	224.2011135	
	17	8.7448	574679352.4	8.759426	0.001642	1836.285	1369.8688	1122.39051	2958.675719	2207.172087	3608.141121	2691.673	252.3982351	
	18	9.2592	608484020.2	8.784249	0.00163	2170.642	1619.2988	1332.33899	3502.980856	2613.223718	4271.927873	3186.858	282.2299679	
	19	9.7736	642288688	8.80773	0.001618	2542.838	1896.9571	1566.96042	4109.798372	3065.909585	5011.949234	3738.914	313.6929673	
max	20	10.288	676093355.8	8.830007	0.001608	2954.834	2204.3062	1827.62551	4782.459548	3567.714823	5832.267741	4350.872	346.7841002	

Table 5.3: -Empirical Data of coefficients

ΔCf=	0.0004
Cr=	0.000821
Aa*Cda=	4.535741
Cds=	0.014
hull eff=	1.238
prop eff=	0.65
RRE=	1.02
PC=	0.82

Table 5.4: - Calculation of AIP Plug parameters

AIP Design requirements			**Power requirements**		
Max Speed	6	Knots	Power Available	120 * 03 = 360	KW
Duration	20	days	Power available post losses	360 *0.9 = 324	KW
Hotel Load	150	KW			
AIP Plug Used	PEM Fuel Cell				
No of Plugs Used	03		Available Energy	360 *20*24=172800	KWh
Rated output	120	KW	Usable energy	172800 *0.9 = 155520	KWh

The total ship resistance coefficient may be expressed in the form:

C_{TS} = $C_{FS} + C_R + C_A$

C_{FS} = Frictional resistance coefficient

C_R = Residuary resistance coefficient (mainly due to viscous pressure drag)

C_A = Model to full scale correlation allowance.

Cf=0.075/($log10Rn$ - 2)^2

R_n = ((speed) * (length))/(Kinematic Viscocity)

$$\mathbf{C_R} = \frac{0.000789}{(L/_{D}-K2)}$$

A_a – Appendages area

C_{da} – Coefficient of Appendages

$Hull_{eff}$ – Hull Efficiency

$Prop_{eff}$ – Propeller Efficiency

P_c - Propulsive coefficient

R_{RE} – Relative rotative Efficiency

The Speed Vs Endurance of the diesel was calculated for the submarine of length 77.94 m and D=6.2 and the values are tabulated in table 5.5. Optimisation graph with respect to range vs Speed was undertaken and the same is shown in fig 5.4. The AIP endurance for 20 days was calculated taking into account the energy requirement and total load for every speed. The values are tabulated in Table 5.6 and the optimisation graph for the AIP endurance vs speed is shown in fig 5.5. The optimisation analysis indicate that at speeds of 5 & 6 knots (as shown in table 5.6) the sustainability of the AIP is at its maximum.

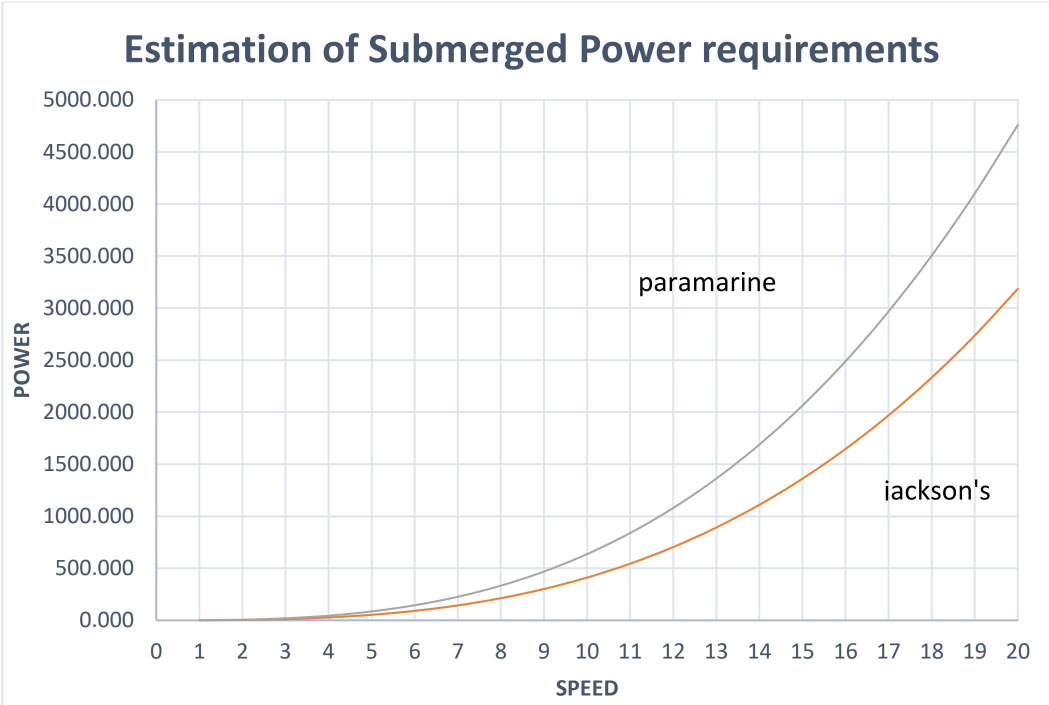


Fig 5.3: Estimation of submerged power requirements

5.7 Estimation of Volume and Length

For a diameter of 6.2m the size of plug can be calculated. By varying the size of the plug, the available volume of the plug can be calculated as shown in the table below. The determination of the plug being positively or negatively buoyant is determined using the second MATLAB program described in later part of the chapter.

Volume in m3	Π*3.1*3.1	Length
301	30.1754	9.975013
300	30.1754	9.941873
299	30.1754	9.908734
298	30.1754	9.875594
297	30.1754	9.842454
296	30.1754	9.809315
295	30.1754	9.776175

Table 5.5: - Calculation of AIP Plug volume and length

The speed Vs endurance range was calculated for the submarine of length =68 m and a diameter of 6.2 m. It is estimated that the max SHP at 20 knots is approximately 5205 KW as shown in table 5.5. Similarly, The Speed Vs Endurance for an AIP diesel submarine of Length = 77.94 m and Diameter D = 62 was calculated (as shown in Table 5.6). The Increase in the KW is attributed to the AIP component. The optimisation of the speed curves with and without AIPs are represented as graphical figures in 5.4 & 5.5.

The concept powering requirements for the platform were calculated using the method outlined by Burcher and Rydill (1994). This method used a series of simple equations that were able to be solved quickly to gain a preliminary predicted resistance for the submarine.

The form volume is the total volume within the overall submarine and was required to be calculated for the resistance prediction. Since the amount of additional free flood volume in the final configuration is uncertain at the concept stage, an allowance was made in the calculation which also accounted for external volumes in the bow, stern and sail. The free flood volume was approximated by adding a further 15% to the combined volume of the pressure hull and main ballast tanks. The equation used for the form volume is shown below: -

$$Form_{vol} = (PH_{vol} + MBT_{vol}) * 1.15$$

The comparative analysis of power requirement computed by two different methods namely Paramarine and Jackson's method is graphically represented in fig 5.3.

Speed vs endurance Diesel						
Sr No.	Speed	SHP	Transit	Total Load	Tsub	Range
	knots	kW	Hrs	KW	days	nm
1	1	0.644298	99.57230524	150.64	4.15	99.57231
2	2	4.919865	96.82425177	154.92	4.03	193.6485
3	3	16.19571	90.25503919	166.20	3.76	270.7651
4	4	37.75229	79.89250176	187.75	3.33	319.57
5	5	72.82026	67.31883296	222.82	2.80	336.5942
6	6	124.5957	54.62576056	274.60	2.28	327.7546
7	7	196.2485	43.32148983	346.25	1.81	303.2504
8	8	290.9273	34.01921385	440.93	1.42	272.1537
9	9	411.7634	26.7016323	561.76	1.11	240.3147
10	10	561.8731	21.07117058	711.87	0.88	210.7117
11	11	744.3598	16.77177434	894.36	0.70	184.4895
12	12	962.3152	13.4853866	1112.32	0.56	161.8246
13	13	1218.821	10.95833601	1368.82	0.46	142.4584
14	14	1516.95	8.998472913	1666.95	0.37	125.9786
15	15	1859.765	7.463560032	2009.76	0.31	111.9534
16	16	2250.323	6.249159018	2400.32	0.26	99.98654
17	17	2691.673	5.278580097	2841.67	0.22	89.73586
18	18	3186.858	4.495246466	3336.86	0.19	80.91444
19	19	3738.914	3.857117824	3888.91	0.16	73.28524
20	20	4350.872	3.332687729	4500.87	0.14	66.65375

Table 5.6: - Formulation of Speed Vs endurance using Diesels

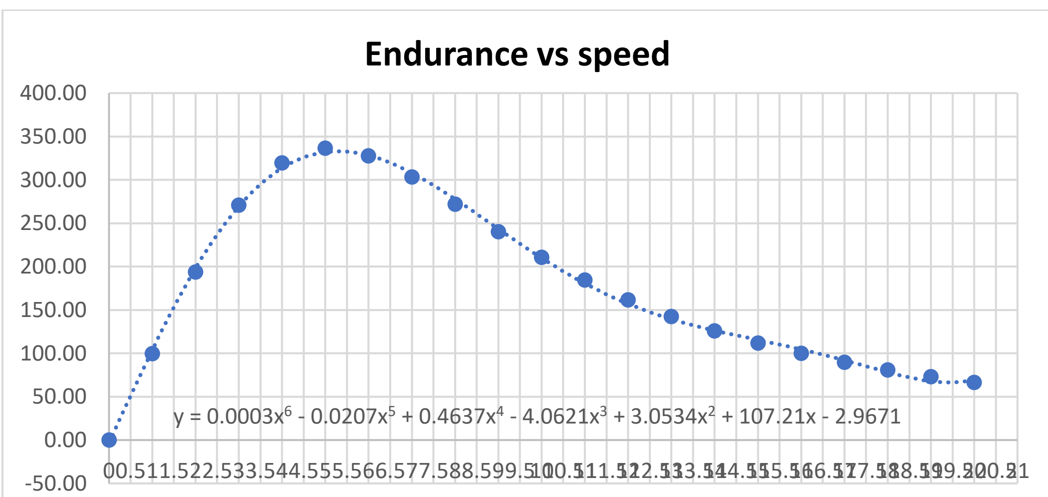


Fig 5.4: Graphical representation of Endurance Vs Speed

Speed vs endurance AIP						
Sr No.	Speed	SHP	Energy Reqt.	Designed Energy	Tsub	Range
	knots	kW	kWdays	kWdays	days	nm
1	1	150.64	3615.46	144000.00	39.83	955.89
2	2	154.92	3718.08	144000.00	38.73	1859.03
3	3	166.20	3988.70	144000.00	36.10	2599.35
4	4	187.75	4506.05	144000.00	31.96	3067.87
5	5	222.82	5347.69	144000.00	26.93	3231.30
6	6	274.60	6590.30	144000.00	21.85	3146.44
7	7	346.25	8309.96	144000.00	17.33	2911.20
8	8	440.93	10582.26	144000.00	13.61	2612.68
9	9	561.76	13482.32	144000.00	10.68	2307.02
10	10	711.87	17084.95	144000.00	8.43	2022.83
11	11	894.36	21464.63	144000.00	6.71	1771.10
12	12	1112.32	26695.56	144000.00	5.39	1553.52
13	13	1368.82	32851.70	144000.00	4.38	1367.60
14	14	1666.95	40006.79	144000.00	3.60	1209.39
15	15	2009.76	48234.35	144000.00	2.99	1074.75
16	16	2400.32	57607.75	144000.00	2.50	959.87
17	17	2841.67	68200.16	144000.00	2.11	861.46
18	18	3336.86	80084.60	144000.00	1.80	776.78
19	19	3888.91	93333.94	144000.00	1.54	703.54
20	20	4500.87	108020.92	144000.00	1.33	639.88

Table 5.7: - Formulation of Speed Vs endurance using AIP

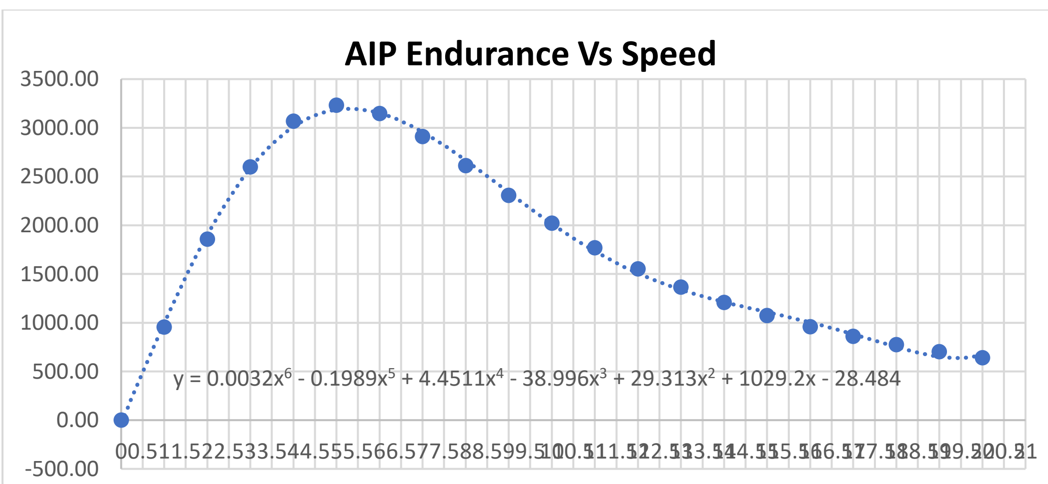


Fig 5.5: Graphical representation of AIP Endurance Vs Speed

The size of the main electric motor was governed by the maximum power required to be transmitted to the propulsor. This would normally be dictated by the maximum submerged speed (sprint speed).

$$Power_{eff} = K_p * (Form_{vol})^{0.64} * U^{2.9}$$

Burcher and Rydill recommended that the coefficient Kp assume a value of approximately 20 for an 'ideal' submarine shape which was typical of an 'Albacore' shaped submarine. As the design did not conform to this shape with a significant length of parallel mid-body, a value of 42 was determined to give a more accurate prediction for the hull form.

The power required to be transmitted by the propulsion motor will be greater than the effective power by factors of the hull efficiency((η_H) propulsor efficiency ((η_o) and the transmission efficiency ((η_s). The Required motor power was calculated using the equation

$$Power_{\ motor} = \frac{Power_{eff}}{\eta H \eta o \eta s}$$

As recommended in Burcher & Rydill the coefficients were taken as $\eta_{o*}\eta_{H\,=}$ 0.75 and $\eta s_{\,=}$ 0.98.

The predicted motor power required for the submarine as a function of submerged speed. This was the result of the powering prediction method outlined by Burcher and Rydill (1994). From these results a sprint speed was determined for the submarine to be 20 knots which required slightly more than 3MW of motor power. Also, the required motor powers at 4 knots and 11 knots were predicted to be 63kW and 715kW respectively.

5.8 Power requirements of conventional AIP submarines around the world are calculated in Table 5.8 and represented in fig 5.6.

Speed	Type 212	Type 214	Stirling (A 20)	Mesma (Agosta)	Soryu	Yuan
1	131.5208	127.9387	109.2873	125.3946	239.0859	199.6903
2	134.2438	130.6913	111.776	128.1571	243.8236	203.8858
3	141.6346	138.1627	118.531	135.6553	256.6832	215.2735
4	156.0273	152.7123	131.6855	150.257	281.7255	237.4497
5	179.7558	176.6994	153.3727	174.33	323.0115	274.0105
6	215.1541	212.4835	185.7256	210.2422	384.6021	328.552
7	264.5561	262.424	230.8775	260.3615	470.5582	404.6703
8	330.2958	328.8801	290.9615	327.0557	584.9407	505.9615
9	414.707	414.2114	368.1108	412.6925	731.8105	636.022
10	520.1239	520.7773	464.4586	519.64	915.2286	798.4476
11	648.8803	650.937	582.138	650.2658	1139.256	996.8347
12	803.3101	807.05	723.2821	806.9379	1407.953	1234.779

Table 5.8: -Formulation of Propulsion power of various Diesel submarines

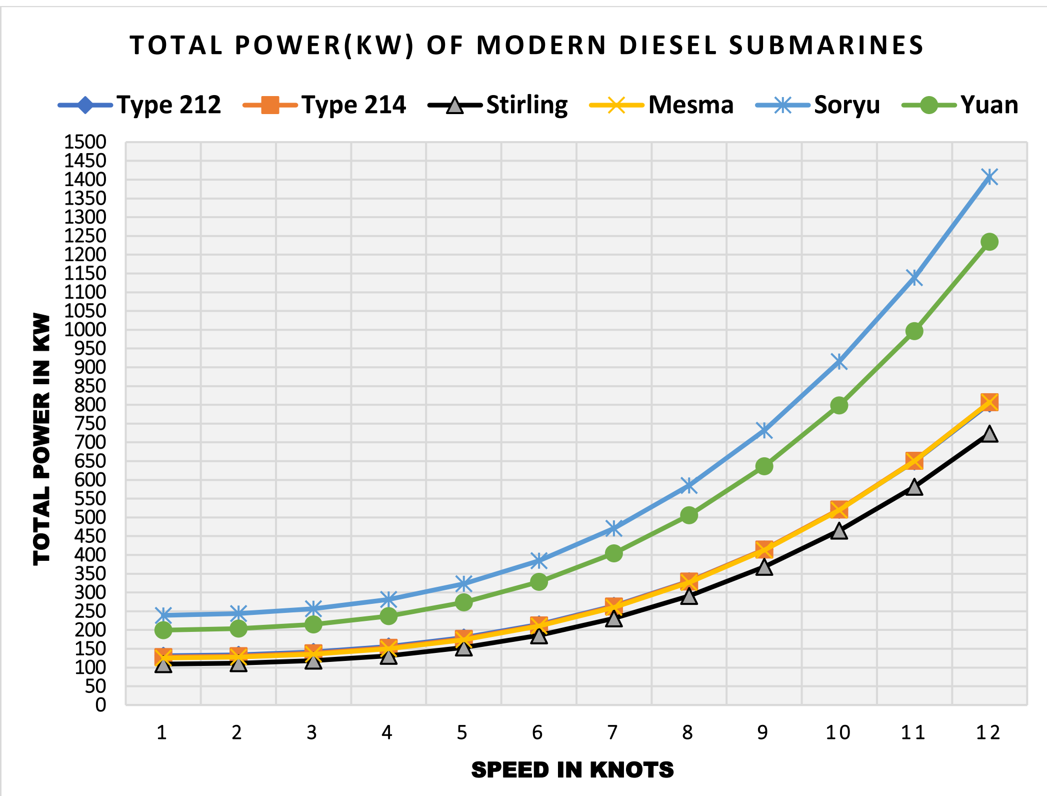


Fig 5.6: Graphical representation of Power requirements of Modern Diesel submarines for transit speeds

5.9 Determination of Propulsion Motor power

In order to determine the operating profile of the vessel the following speed regimes are formulated and it is calculated in a graphical format in fig 5.10.

Mode	**Snort Speed (knots)**	**Submerged Speed (knots)**	**Purpose**
Transit	6	8	Economical speed for long range transit to or from base port.
Patrol	4	4	Low speed patrol and loiter speed in enemy water.
AIP Patrol	-	4	Extended low speed transit or loiter speed in surveillance area.
Sprint	-	18	Highest sprint speed available to vessel when faced with an emergency situation.

Table 5.9: -Formulation of Speed Profile

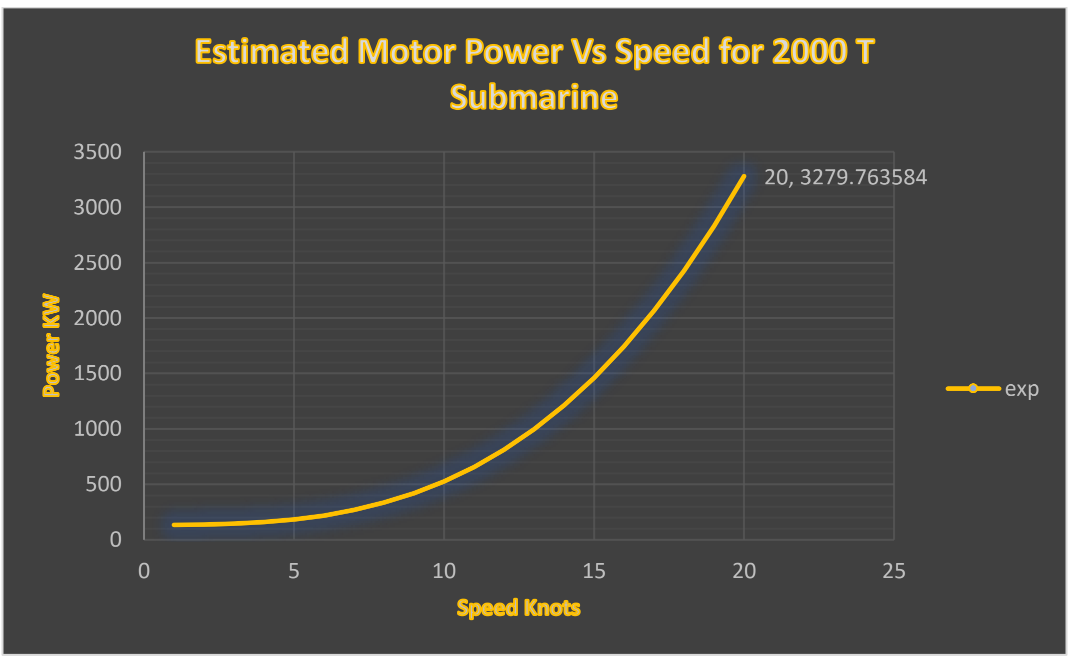


Fig 5.7: Graphical representation of predicted motor power Vs Speed

5.10 Lead Acid Battery (LAB) Capacity and Discharge Curves

Battery cell capacities for the initial calculations were based on figures published by Polish Naval Academy. A total of 420 cells requiring 10.5 MW for full charge were considered for the calculations. It is noted that the submarine batteries will not be fully discharged to 0% capacity during operations. The batteries are likely to be charged and discharged in a pattern as shown in fig 5.8 [359]. This shows that a typical charge and discharge pattern involves a cyclical manner with a periodic large charging event. This ensures nonlinear battery performance with memory, dependent on past operating history. Presently lead acid batteries are the primary powering source of diesel electric submarines around the world. Reports suggests the future Japanese submarines will be powered by Lithium based batteries. Research to achieve higher density batteries is pursued all around the world: -

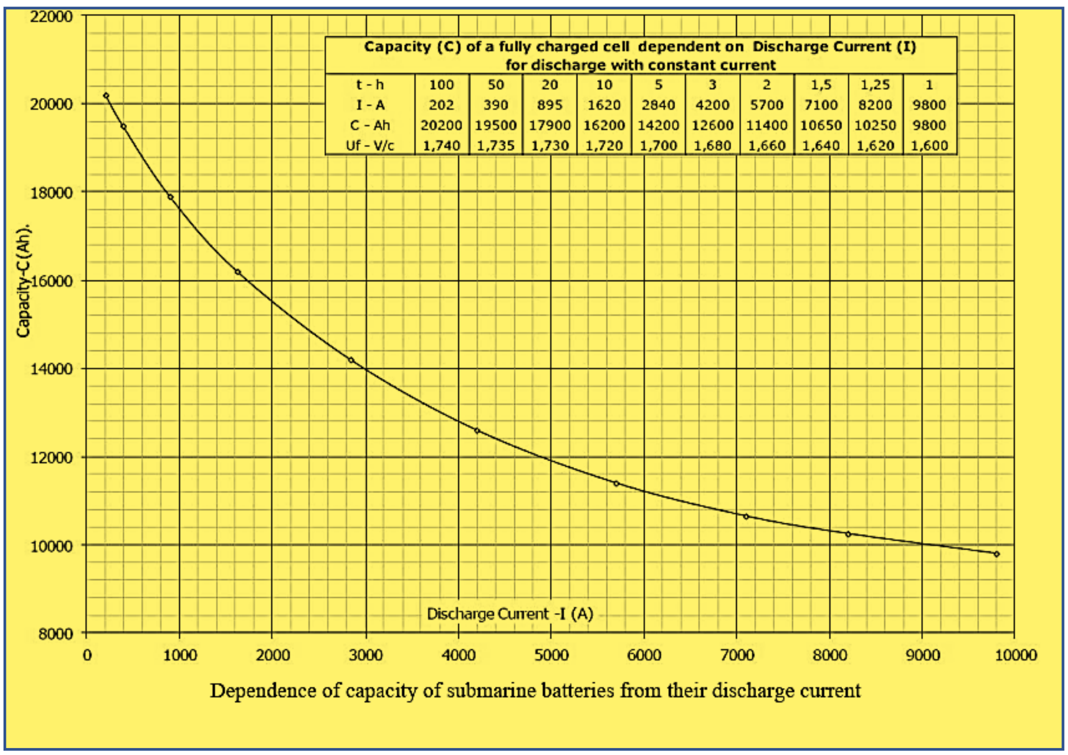
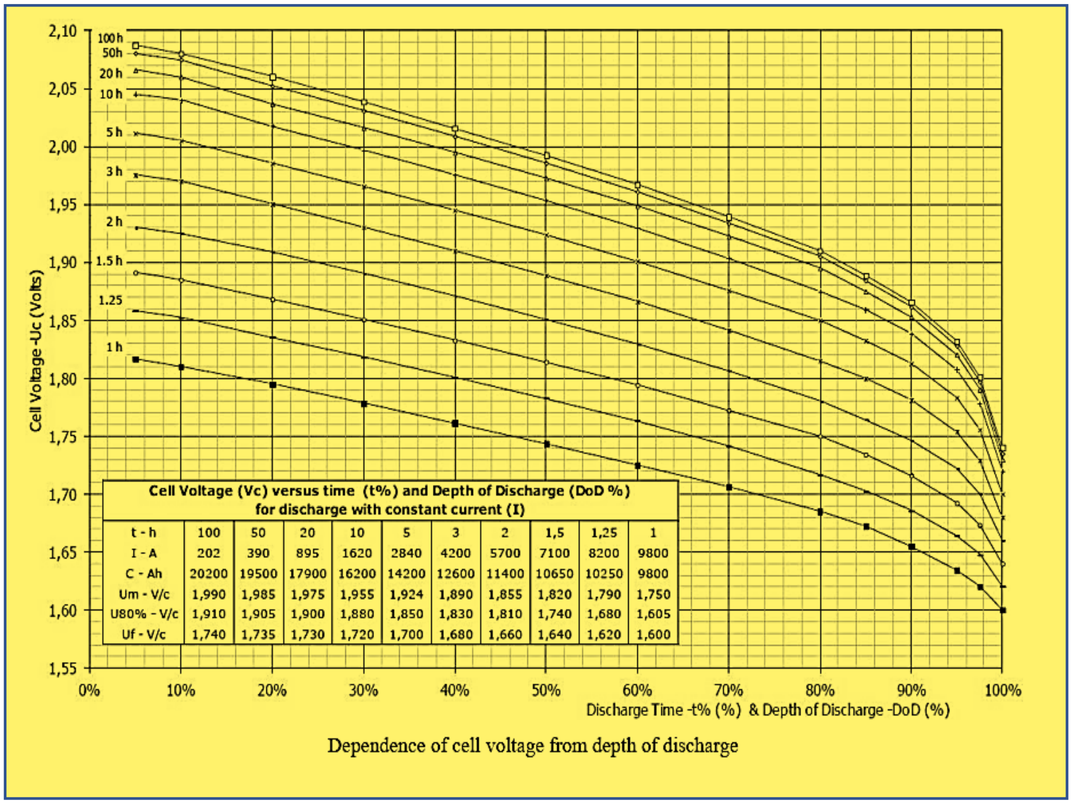


Fig 5.8: Graphical representation of lead acid battery capacity graph[360]

(a) Lithium Aluminium Iron Sulphide (LAIS)

(b) Lithium/Cobalt Batteries

(c) Silver/Zinc Batteries



Cell Voltage (Vc) versus time (t%) and Depth of Discharge (DoD %) for discharge with constant current (I)										
t - h	100	50	20	10	5	3	2	1,5	1,25	1
I - A	202	390	895	1620	2840	4200	5700	7100	8200	9800
C - Ah	20200	19500	17900	16200	14200	12600	11400	10650	10250	9800
Um - V/c	1,990	1,985	1,975	1,955	1,924	1,890	1,855	1,820	1,790	1,750
U80% - V/c	1,910	1,905	1,900	1,880	1,850	1,830	1,810	1,740	1,680	1,605
Uf - V/c	1,740	1,735	1,730	1,720	1,700	1,680	1,660	1,640	1,620	1,600

Fig 5.9: Graphical representation of lead acid battery Discharge time Vs Cell voltage[360]

5.11 Determination of Hotel Load

The hotel load is considered constant throughout the operations for the initial design although it is reduced for ultra-quiet or sustained submergence by switching off all non-essential equipment, and even limiting the operation of essential equipment [6].

The hotel load is assumed to remain constant at approximately 130kW under all operating circumstances of the submarine even during the operation of AIP for extended submerged periods of time.

At lower speeds such as when snorting and on patrol the hotel load is a considerable percentage of a submarine's total power requirement. From similar vessel research it was found that Spain's S-80A submarine hotel load has been calculated to be the nominal value of 110kW. In order to take a conservative approach to this, a hotel load of 150kW was assumed for the analysis.

The hotel load is a considerable percentage of the vessels total power requirement when at lower speeds such as when snorting, and on patrol. This is estimated at approximately 150kW [361] under 'normal operating circumstances". When the vessel is operating on AIP for extended submerged periods of time over 14 days extra power requirements are expected for atmosphere conditioning needs inside the submarine.

The first MATLAB program (sample output shown in fig 5.14) is written in order to assess and appreciate inclusion of various AIP systems as well as combination of storage options. The initial sizing program was written because the Paramarine software only supports Fuel cell AIP option. In order to appreciate the size and endurance the First MATLAB program encompassing three different storage options was written. The option chosen for the study is LAB batteries with capacity of 15000 Ah. The present submarines around the world except for Japanese Soryu class (Lithium-Ion) utilises lead acid batteries as the main storage option. This is primarily because of the high reliability and maturity of the technology over the last 100 years. The other batteries are either in their nascent stages for submerged environment and very less information about submarine usage is available in open source literature.

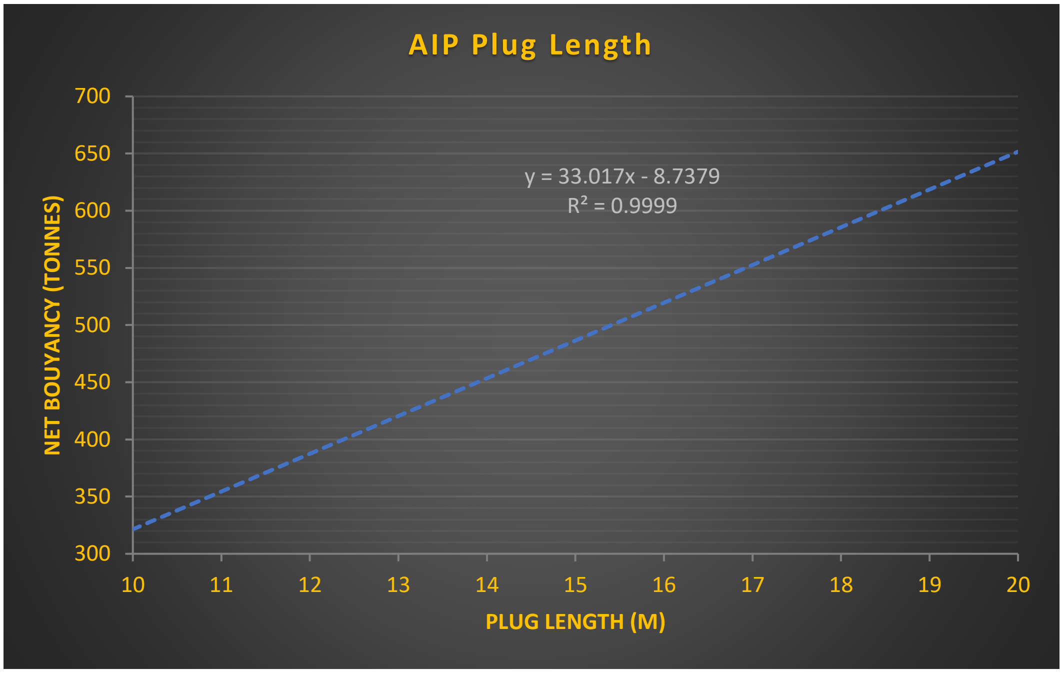


Fig 5.10: Estimation of Plug length Vis-à-vis Volume of plug.

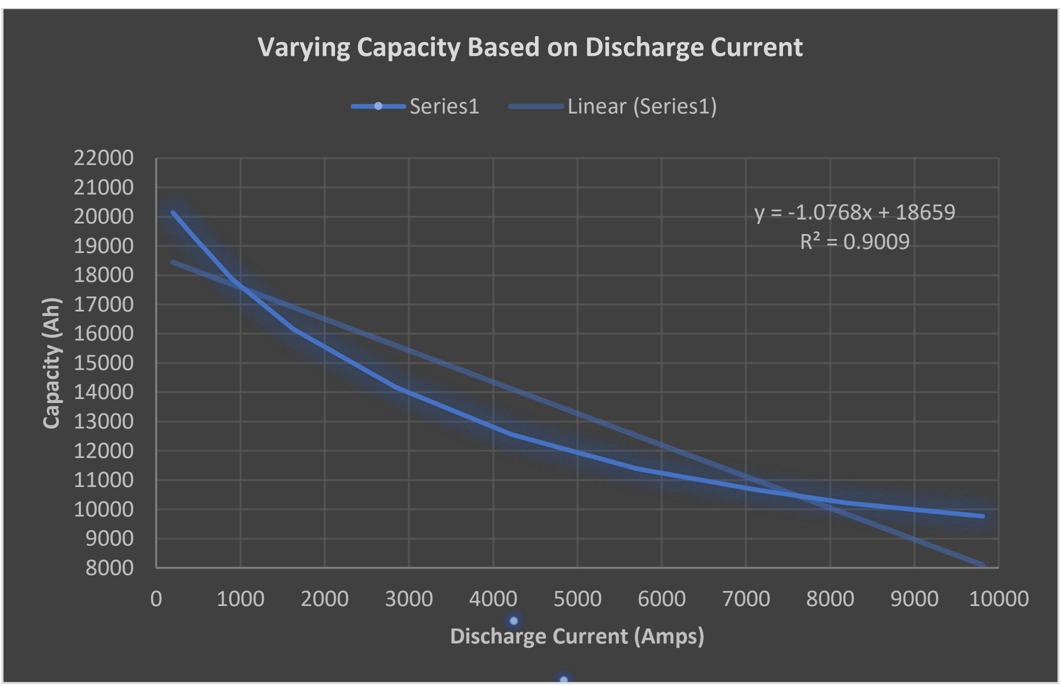


Fig 5.11: Varying battery capacity with varying discharge current

5.12 Sizing of Submarine using MATLAB program.

The estimation of size, volume and weight of submarines fitted with various AIP systems are formulated into codes using MATLAB. The values for initial sizing of submarine are obtained from various open-source theses[362]–[364]. The basic parameters of the systems are computed

(a) Submarine Parameters
(b) Envelope parameters
(c) Indiscretion parameters
(d) Storage options
(e) Types of AIP (six types)
(f) Fuel storage
(g) Endurance of AIP Plug
(h) Endurance of Battery
(i) Determination of Hotel load
(j) Determination of snort duration

Six different types of AIP plants installed, exploited onboard submarines and the two upcoming widely researched AIP systems viz., Closed Brayton cycle, Aluminium -oxygen semi fuel cell being utilised onboard UUVs are taken into account towards estimation of the AIP system. Though these systems are presently not exploited/considered for installation onboard submarines. The two technologies pose a potential contention to the existing AIP systems being exploited onboard submarines. In order to visually appreciate the output of MATLAB codes the results are exported to a MS-Excel sheet (a sample output of the result sheet is shown in Fig 5.12). Six different AIP systems with three different storage options Viz., Lead Acid Batteries (LABs), Lithium Aluminium Iron Sulphide (LAIS) and Nickel Cadmium. During the estimation it has been observed that Nickel cadmium battery has very low energy density and due to better available options, these batteries are not used onboard submarines. The excel output is categorized into 18 sheets. The results of the MATLAB sizing program are placed in Appendix B.

AIP SIZING PROGRAM OUTPUT(Plant:PEM/Battery:Lead Acid)					
INPUT DATA FOR AIP		**MARGINS**			
Total Ship Range (nm)	11500.00	Fixed Ballast (% NSC)	0.11		
Snort range @10 kts (nm)	6700.00	Variable Load(% NSC)	0.05		
Submerged @ 8 kts AIP (days)	25.00	Outboard Items (% Vph)	0.18		
Submerged creep @ 4 kts on battery (hours)	90.00	Res. Buoyancy(% Veb)	0.15		
Submerged burst @ 20 kts on battery (hours)	2.93	Freeflood Volume (% Veb)	0.06		
Submerged transit @ 13 kts on battery (hours)	14.14	**Envelope**			
Recharge time @ 4 kts (hours)	5.37	Length (m)	63.04		
SOA (m/s)	5.15	Diameter (m)	9.45		
Indiscretion Ratio	0.26	L/D	6.67		
Diving Depth (m)	274.32	Cpf	0.75		
CrewSize(m)	12.80	Cpa	0.64		
Torpedo Tubes	6.00	Cwsf	0.85		
Reloads (days)	22.00	Cwsa	0.75		
Mission Length (days)	60.00				
VOLUMES (m^3)		**WEIGHTS (ltons)**			
Weapons	213.50	Structure	795.15		
Mobility	1445.11	Mobility	1184.35		
Ship Support	412.44	Weapons	56.08		
C^3I	150.08	CI^3I	66.07		
Pressure Hull	2221.13	Ship Support	105.60		
Outboard	399.80	FixedBallast	303.39		
Everbuoyant	2620.93	Variable Load	132.14		
Main BallastTanks	379.10	Normal SurfCondition	2642.77		
Submerged	3000.03				
Freeflood	157.26				
Envelope	3171.33				
MOBILITY					
Battery Type	Lead Acid				
Number of Batteries	6.62				
Battery:Weight(lton	505.89				
Volume(m^3)	150.00				
Capacity(kW-hr @ 2hr rate)	10594.48				
Propulsive Coeff	0.86				
InstaliedSHP	3998.29				
Hotel Load (kW)	142.14				
Bunker Fuel(ltons)	6147.23				
AIP					
AIP Plant Size (kW)	359.88				
Type	PEM	Weight(ltons)	6.38	Volume(m^3)	3.50
Reformer	YES	Weight(ltons)	6.38	Volume(m^3)	4.32
Oxidant	LOX	Weight(ltons)	158.58	Volume(m^3)	293.49
Breath.LOX	NO	Weight(ltons)	4.06	Volume(m^3)	7.44
Fuel	METHANOL	Weight(ltons)	72.27	Volume(m^3)	91.72
Other	COMP WATER	Weight(ltons)	34.65	Volume(m^3)	247.51
Cosworth	YES	Weight(ltons)	0.59	Volume(m^3)	23.99
Totals		Weight(ltons)	282.90	Volume(m^3)	671.96

Fig 5.12: Sample output of MATLAB Sizing program of a PEM and LAB submarines

The first MATLAB program is intended to model a conventional diesel electric submarine with AIP component and to understand the change in length vis-à-vis the other parameters. The Sizing program can be utilised to calculate various parameters by changing the input parameters in the "**main**" program of the sizing program (as shown in fig 5.13). The Program can be modified to include a new battery version as fourth version which would give a spreadsheet analysis of 24 variants or the existing one of the battery modules can be replaced with the fresh version.

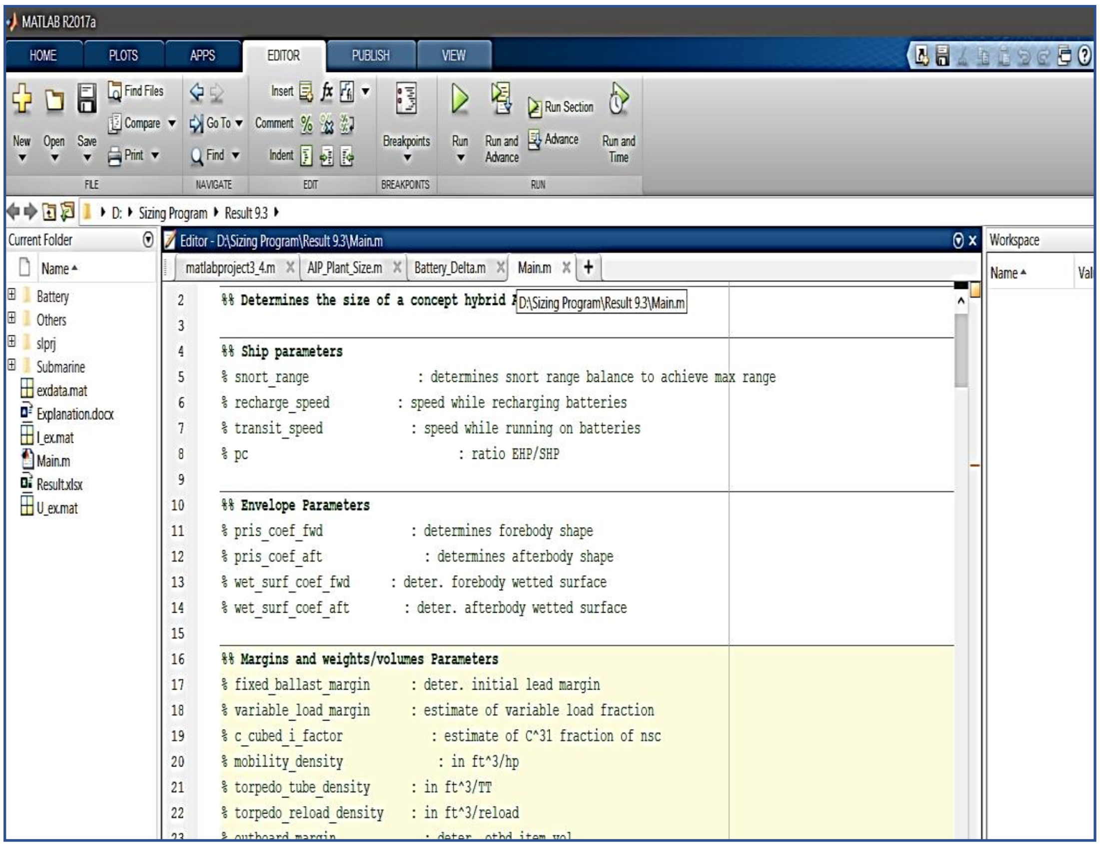


Fig 5.13: Screen Shot of the "main.m" MATLAB sizing program.

5.13 Reactants for fuel cell

Fuel cell reactants for the AIP system include hydrogen stored in tanks inside pressure hull as an aqueous mixture of sodium borohydride and liquid oxygen which is stored internally or externally to the pressure hull. Siemens BZM120 series were considered (03 nos) to provide 360kW of power which is enough to provide for the propulsion and hotel load at low operating speeds. The dimensions (as shown in table 5.13) of the module are well suited for installation onboard AIP plug.

5.14 PEM Fuel Cell calculations

(a) Determine the size of the fuel cell stack

(b) Based on the operating voltage the total number of cells

(c) From the voltage current density graph, the cell voltage is determined to 0.7V.

(d) The Maximum Operating voltage is assumed to be 385 V.

(e) Number of cells will be 550 (385/0.7)

(f) The total current from the stack when supplying the maximum power can now be calculated.

Power = Voltage * Current

P =300 KW

U * I = 550 * 0.7 ≈ 385

Max Power of Fuel cell ≈ 300KW

$$I = \frac{300 * 1000}{385}$$

I ≈ 779 A

The German type 212 and 214 submarines are fitted with BZM modules of M/s Siemens make PEM fuel cells. The first batch of Type 214 is fitted with 09 BZM 34 modules delivering an effective power of 306kW. The later batch of submarine are fitted with advanced BZM 120 modules consisting of 320 cells each and weighing about 900kg.

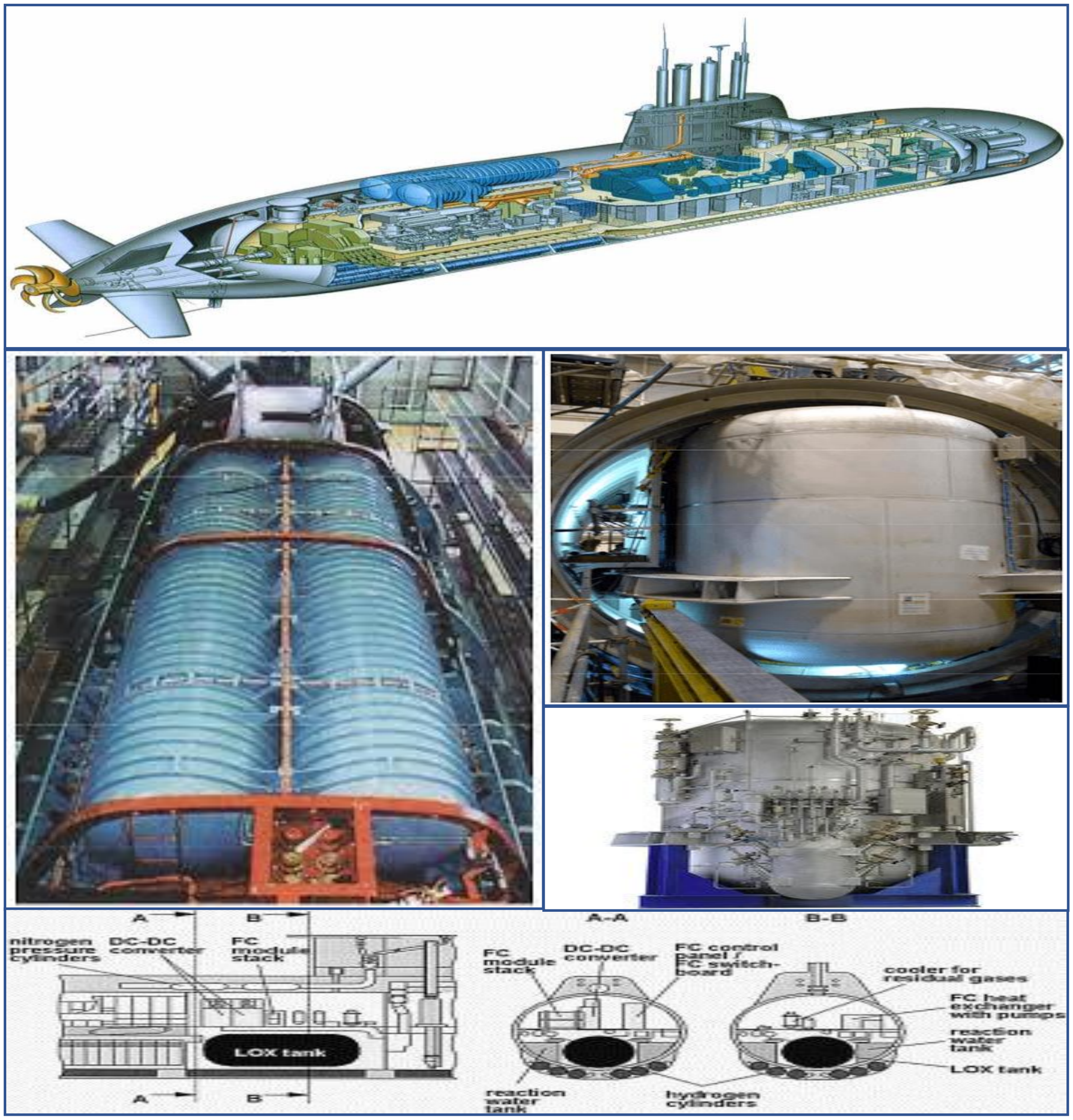


Fig. 5.14 (Clockwise from bottom) (a) Storage of Hydrogen and LOX tanks onboard submarines. (b) Elongated AIP fuel storage tanks for extended endurance of Submarines. (c) Schematic of Type 212 German diesel electric AIP submarine (d) LOX storage tanks inside the cylindrical Cut section of the submarine.(e) LOX storage tanks specifically designed for AIP submarines by M/s Air Liquide, France.

Table 5.10: - Technical specifications of Hydrogenic fuel cell variants

Technical Data	**HD 30**	**HD 50**	**CELERITY**	**HD 90**
Continuous Power (KW)	31	51	60	93
Dimensions(mm)	719x 406 x219	973 x 406x 261	800 x 375 x 980	1582 x 1085 x 346
Volume(L)	76	103	290	594
Mass (Kg)	72	110	275	360
Operating Current (A_{dc})	0 to 50	0 to 540	0 to 200	0 to 50060-
Operating Voltage (V_{dc})	60 to 120	108 to 220	300 to 640	180 to 360
Peak Efficiency ($\%_{LHV}$)	59	59	53	53
Expected Lifetime (h)	10000^{+}			

Table 5.11: - Technical specifications of M/s Siemens fuel cell variants

Technical Data	**BZM 34**	**BZM 120**
Rated Power (KW)	34	120
Voltage range(V)	50 to 55	208 to 243
Efficiency at rated load (%)	59	59
Operating Temperature (Deg C)	$80^{0}C$	
H_2 Pressure (bar abs)	2.3	
O_2 Pressure (bar abs)	2.6	
Dimensions(cm)	48 x 48 x 145	50 x 53 x 176
Weight (without module electronics) Kg	650	900

A comparative analysis of Fuel Cell modules installed onboard submarines is tabulated in table 5.11 The M/s Siemens made fuel cell modules and subsequent variants are installed onboard German and other nation submarines.

Table 5.12: - M/s Siemens Fuel cell modules onboard German submarines

Type	Power (Kw)	Country
BZ 34	34	German (212 A) and Italian Navy
BZ 120	120	German (209, 214, 216) and 209 Classes of Greece, Turkey, Republic of Korea & Portuguese Navy.
FCM NG 80,135 & 160	80,135,160	Advanced fuel cell modules of 80,135 & 160 KW are in various stages of trials/production for incorporation in future platforms.

5.15 Balance of Plant (Bop) components

The complete PEM fuel cell systems will encompass the following components: -

(a) Stacks

(b) Valves and Piping for inlet of fuel (Oxygen, Hydrogen)

(c) Various Sensors

  (ca) Gas Monitoring (inlet, outlet)

  (cb) Pressure

  (cc) Temperature

  (cd) Level

  (ce) Voltage

  (cf) Current

(d) Nitrogen Filled chamber (3.0 Bar abs) to prevent any accidental gas leakage.

(e) Associated electronic modules and PLC's for functioning of modules.

(f) Inboard and Outboard tanks for storage of fuel (oxygen & Hydrogen) depending upon the design of the submarine.

(g) Residual water storage and draining system.

(h) DC/DC converter for smoothening and feeder breakers for routing the supplies to the onboard consumers viz., Main storage batteries, propulsion and auxiliary load consumers (Design Specific). However, it is preferable to have a fuel cell connected to charge the batteries rather than supplying directly to the consumers in order to avoid any load fluctuations in the system.

5.16 Proposed Hydrogen storage system using Sodium Borohydride ($NaBH_4$)

The proposed system for storage of hydrogen onboard the proposed submarine is elaborated in the succeeding paragraphs. Hydrogen generation from hydrolysis of chemical hydrides is found to be advantageous as it enhances safety of handling hydrogen storage onboard. These hydrides seem to possess high energy density and volumetric capacity. The volumetric and gravimetric densities of hydrogen in various chemical hydrides is depicted in fig 5.15.

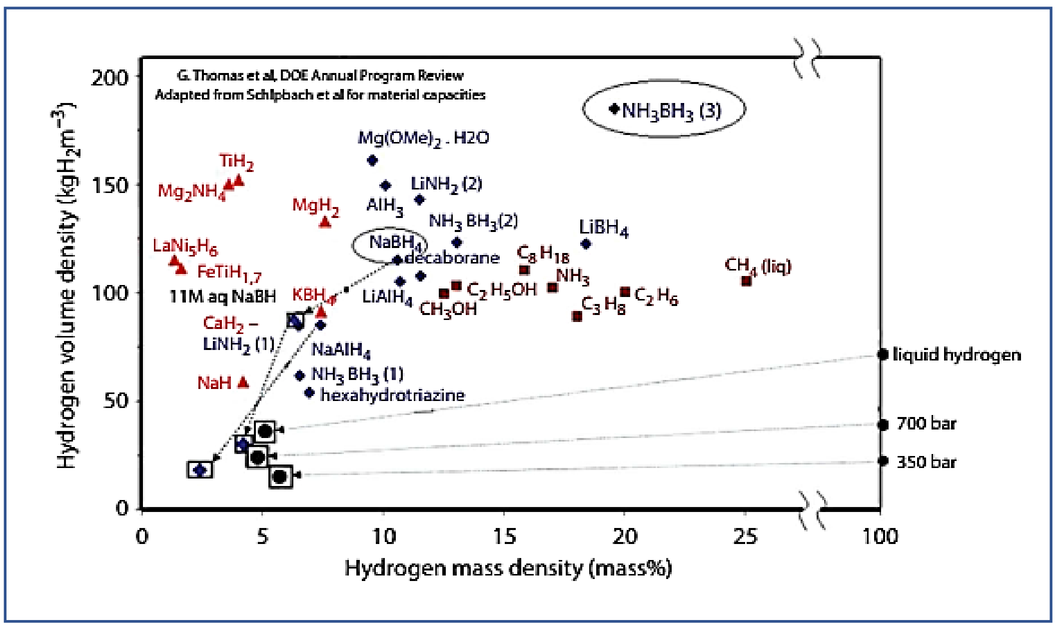


Fig 5.15: Volumetric and Gravimetric hydrogen densities in some selected hydrides [365]

The hydrolysis of chemical hydrides is an exothermic reaction, the chemical reaction of $NaBH_4$ is given below: -

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 + \Delta H$$
$$\Delta H = -217 kj/mol$$

The reaction happens at slow time approximately when 0.6ml/min, when 1.2 mmol Sodium borohydride is dissolved in about 10ml of distilled water [366]. Various catalysts are utilised to speed up the hydrolysis process. The catalysts includes noble metals like Pt, Pt-Ru, Pt-Pd, Ru, Rh, Pd etc. and transition metals such as Ni, Cu, Co & Fe-Ni alloys[366].

The volumetric efficiency of the hydrogen generation [365] is given by the equation below

$$Volumetric\ \eta = \frac{real\ H_2\ generation}{theoretical\ H_2\ generation} = \frac{V}{u * \frac{x}{38} * 4 * 22.4}$$

Where

V – rate of hydrogen generation in L/min

u- Solution flow rate g/min

x – $NaBH_4$ Concentration

When the conversion is 100% the hydrogen generation can also be defined as

$$V_h = (0.213\ W_s V_s d) * 11.2 = 2.39 W_s V_s d$$

Linear extrapolated values of hydrogen generation from $NaBH_4$ with addition of various catalysts.

Chemical Hydride	Catalyst used	Amount of catalyst(g)	H2 generation Rate (L/min)	H2 Generation rate per amount of catalysis (L/ min g)	Efficiency (%)	Reference
NaBH4	Pt/C(powder)	0.003	0.0224	7.467	94	[367], [368][365]
	Pt/C	0.1	2.3	23	97.4	
	Pt/C (Vulcan XC)	0.005	0.023	4.5	85	
	Pt/C (active carbon)	0.005	0.035	7	97.5	
	FeCl3/Ni foam	0.4	0.2	0.5	84.4	[369] [370]
	FeCl3	1.173	1.08	0.92	98	[371] [372]

Table 5.13: - Efficiency of hydrogen Generation using Metal Hydrides

The aqueous mixture of $NaBH_4$ is utilised as fuel towards hydrogen generation. These are stored in storage tanks which is present inside the AIP section (bottom portion). The amount of hydrogen (Kg) stored is given by

$$Weight\ of\ H_2 = Total\ Number\ of\ moles\ in\ Hydrogen\left(N_{H_2}\right) * Molecular\ Weight\ of\ Hydrogen\left(M_{H_2}\right)$$

$$Total\ Number\ of\ moles\ in\ Hydrogen\left(N_{H_2}\right) = \frac{(Cummulative\ Energy\ requirement)}{(\Delta H * \eta_{Total})}$$

$$\eta_{Total} = \eta_{Battery} * \eta_{\frac{DC}{DC}Converter} * \eta_{FC}$$

Cumulative weight of Hydrogen Storage system is given by

$$W_{H_2 Total\ system} = \frac{(Weight\ of\ H_2 * 100)}{Gravimetric\ storage\ of\ hydrogen\ in\ percentage\ (WT_{perc})}$$

Total hydrogen storage system volume in m^3 is given by

$$V_{H_2 Total\ System} = \frac{Cummulative\ Energy\ Requirement}{Volumetric\ energy\ density(E_{vol}) * \eta_{Total} * 1000}$$

So, for calculating the weight of a $NaBH_4$ storage system (($W_{NaBH_4 Total\ system}$)

$$Total\ System\ Weight\ of\ NaBH_4\ (W_{NaBH_4 Total\ system}) = W_{NaBH_4} + W_{H_2O} + W_{BOP}$$

Where

W_{NaBH_4} - Weight of Sodium Borohydride

W_{H_2O} - Weight of Water

W_{BOP} - Weight of Balance of Plant

The weight of Sodium Borohydride can be determined from the equation

$$W_{NaBH_4} = \frac{N_{H_2} * M_{NaBH_4} * 10^{-3}}{4}$$

M_{NaBH_4} - Molecular weight of $NaBH_4$ (g/mol)

$$W_{H_2O} = \frac{N_{H_2} * 2 * M_{H_2O} * 10^{-3}}{4}$$

From the above, the Total volume of Sodium Borohydride can be determined from the equation

$$Total\ System\ Volume\ of\ NaBH_4\ (V_{NaBH_4Total\ system}) = V_{NaBH_4} + V_{H_2O} + V_{BOP}$$

Where

V_{NaBH_4} - Volume of Sodium Borohydride

V_{H_2O} - Volume of distilled Water

V_{BOP} - Volume of Balance of Plant

Volume of Sodium Borohydride can be derived from the equation

$$V_{NaBH_4} = \frac{W_{NaBH_4}}{\rho_{NaBH_4}}$$

ρ_{NaBH_4} - Density of $NaBH_4$ (kg/m^3)

Volume of Distilled water

$$V_{H_2O} = \frac{W_{H_2O}}{\rho_{H_2O}}$$

ρ_{H_2O} - Density of water (Kg/m^3)

The density and hydrogen stored percentage will give the weight and volume in the case of Sodium Borohydride system.

5.17 Comparison of properties of Hydrogen with other fuels

A comparative study of the properties of hydrogen vis-à-vis fuels viz., Methanol and gasoline was undertaken. A graphical analysis of the same is depicted in the figure 5.16.. Properties of Hydrogen as compared with other fuels

Table 5.14: - Comparative Technical specifications of Hydrogen and other fuels

Property	Hydrogen	Methanol	Gasoline
Molecular Weight (g/mol)	2.016	32.04	107
Density (kg/m3) 20 Deg C and 1 atm	0.08375	791	751
Higher Heat-ing Value (MJ/kg)	142	22.9	47.3
Lower Heating value (MJ/Kg)	120	20.1	44

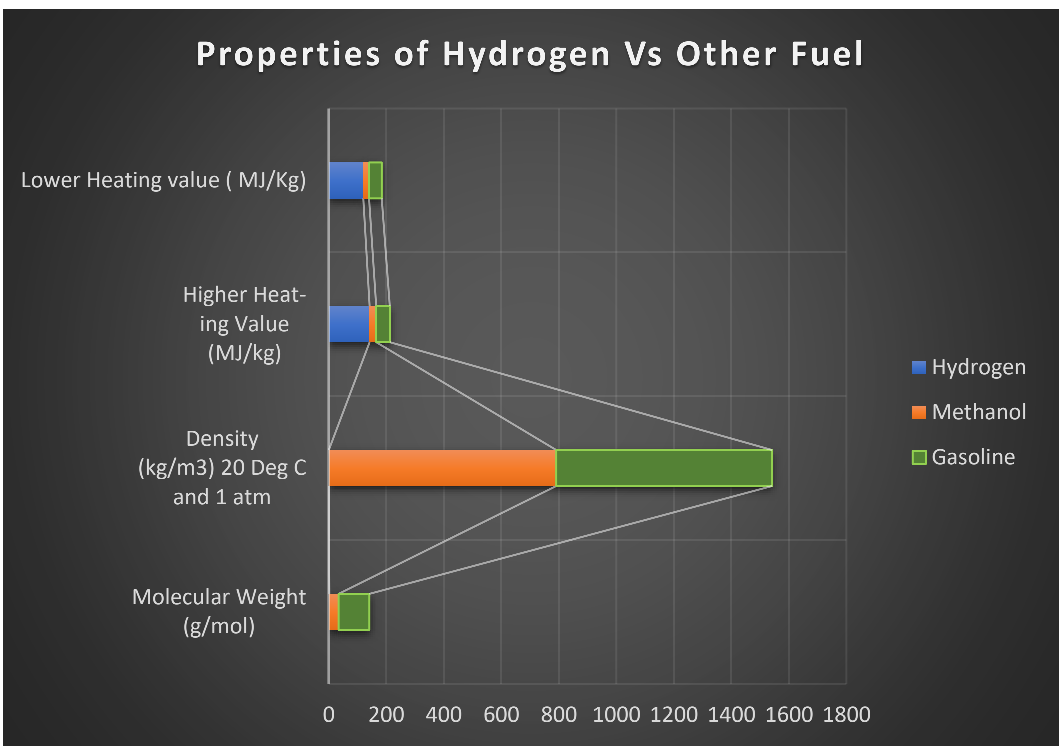


Fig 5.16: Properties of Hydrogen vis-à-vis other fuels

5.18 Proposed Cryogenic Oxygen Storage

The molecular mass of oxygen is 32 g/mole and density of liquid oxygen is 1141 kg/m^3. In the case of Polymer Electrolyte Membrane (PEM) Fuel Cell a molecule of oxygen reacts with almost half the volume of hydrogen. The total number of moles of oxygen $\left(N_{O_2}\right)$and corresponding weight of oxygen $\left(W_{O_2}\right)$ is given by the equation

$$Number\ of\ Oxygen\, moles\ \left(N_{O_2}\right) = \frac{N_{H_2}}{2}$$

$$Weight\ of\ Oxygen\ \left(W_{O_2}\right) = 2 * W_{H_2}$$

The weight of the liquid oxygen (compressed) system can be calculated using the equation.

$$Weight\ of\ Liquid\ Oxygen\, System = \left(\frac{N_{O_2} * M_{O_2}}{r_{grav}}\right) * 10^{-3}$$

Where

r_{grav} - gravimetric fraction

M_{O_2} - Molecular weight of Oxygen (g mol^{-1})

The liquid oxygen storage volume is expressed by the following equation

$$Volume\ of\ Liquid\ Oxygen\ storage\ system\, V_{LOX\ system} = \frac{N_{O_2} * M_{O_2}}{1000 * r_{vol} * \rho_{LOX}}$$

Where ρ_{LOX} = 1141kgm^{-3} (Density of liquid Oxygen)

5.19 System modelling for a 2000 T submarine

Based on the power consumption of various equipment over a 24-hour period is formulated and categorized under four different profile. The power consumption of overall load of submarines over 2,8,24-hour period has been calculated. With extensive survey of literature and understanding of practical implementation of AIP systems amongst world Diesel AIP submarines it is preferred to use sodium borohydride ($NaBH_4$) as a storage option for hydrogen storage and oxygen is stored in liquid form in specialised cryogenic tank. The fuel cell modules, pipelines, sensors add to the Balance of Plant (BoP) component. The load profiles of various loads are shown in fig 5.17

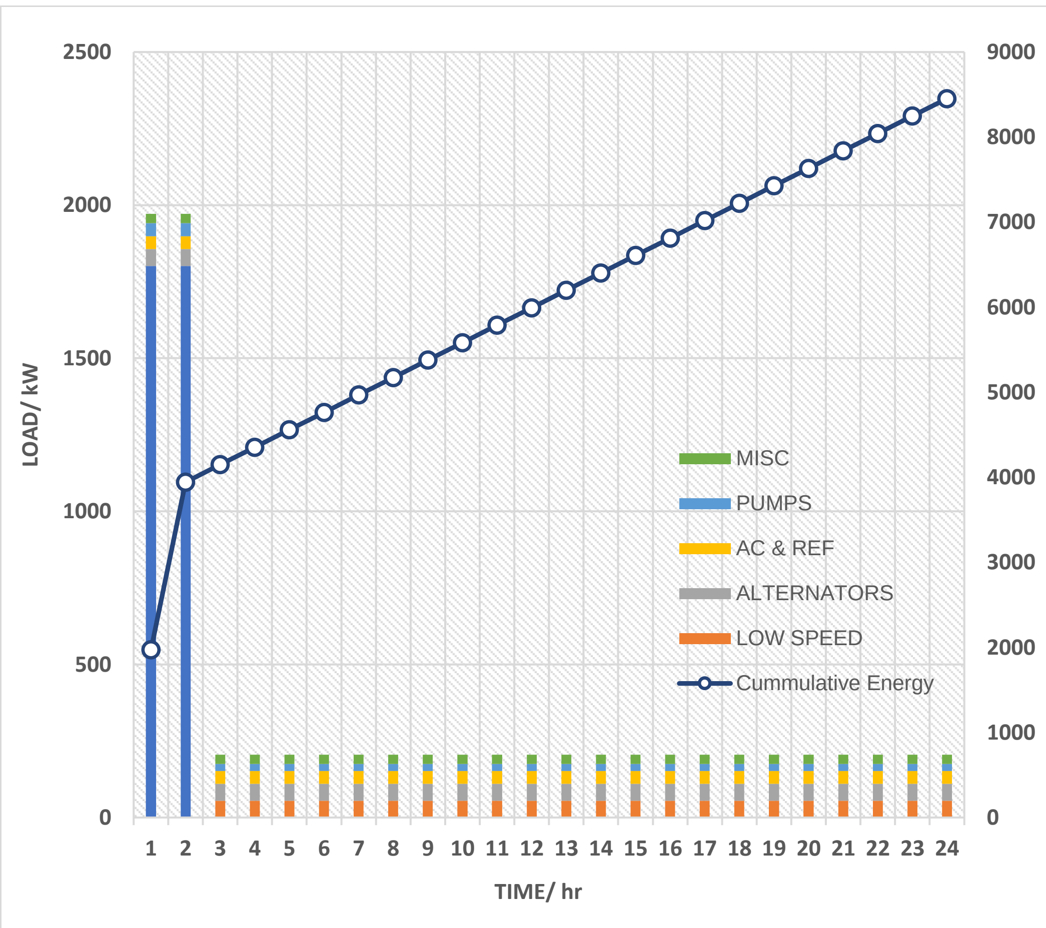


Fig 5.17: Computation of hotel load of 2000 T Submarine

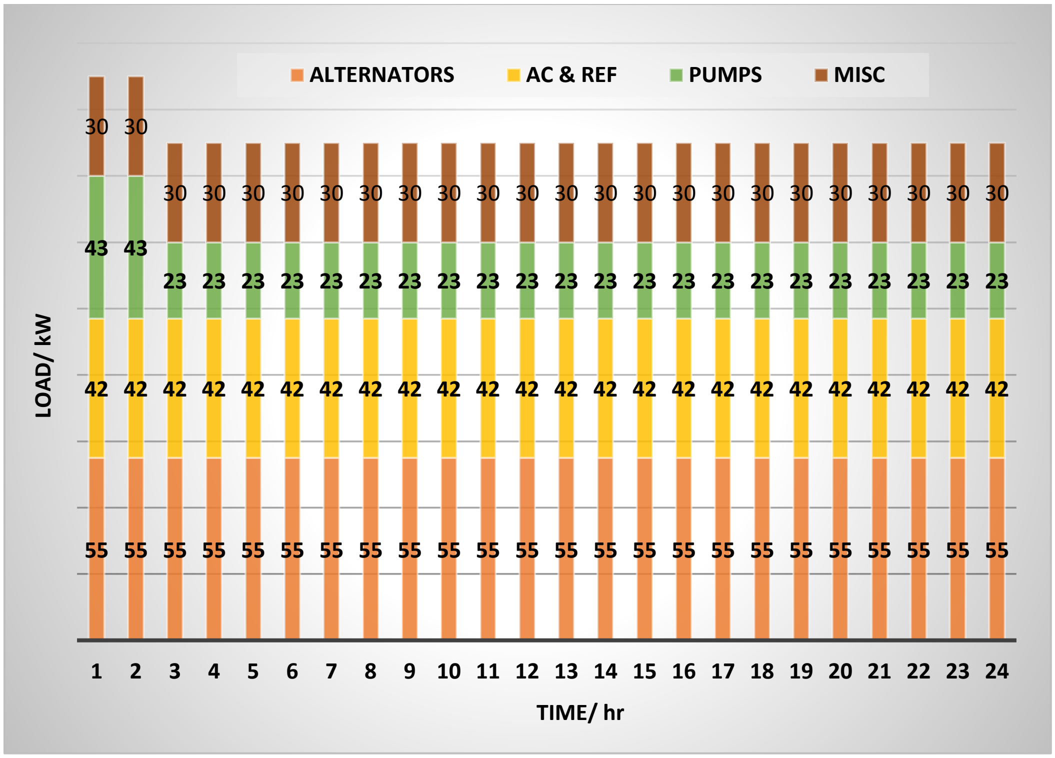


Fig 5.18: Graphical representation of Hotel load of 2000 tonne Diesel submarine

A detailed analysis of weight as well as volume requirements for a submarine system powered by Lead acid batteries (LABs), and PEMFC was modeled on M/s Excel spread sheet and the graphical analysis of weight and volume parameters of the system is shown in fig 5.19- 5.28. The system analysis has been undertaken taking into account two different storage categories of oxygen and hydrogen viz., gas cylinders for oxygen and hydrogen, Cryogenic storage of oxygen and storage of hydrogen in aqueous mixture of Sodium Borohydride. Further the weight and volume analysis of three combinations (a) Submarine powered only by Fuel Cell (FC) (b) Hybrid Option – submarine powered by Fuel Cell and LABs (c) Submarine Powered by LABs. The values from the spread sheet is shown in table 5.15- 5.19.

Table 5.15: - Calculations of cumulative energy requirements of 2000T submarine

Time	HIGH SPEED	LOW SPEED	ALTERNATORS	AC & REF	PUMPS	MISC	POWER EXPENDED	Cu. Energy
1	1801.42	0	55	42	43	30	1971.42	1971.420427
2	1801.42	0	55	42	43	30	1971.42	3942.840855
3		54.975	55	42	23	30	204.975	4147.815843
4		54.975	55	42	23	30	204.975	4352.790832
5		54.975	55	42	23	30	204.975	4557.765821
6		54.975	55	42	23	30	204.975	4762.740809
7		54.975	55	42	23	30	204.975	4967.715798
8		54.975	55	42	23	30	204.975	5172.690786
9		54.975	55	42	23	30	204.975	5377.665775
10		54.975	55	42	23	30	204.975	5582.640764
11		54.975	55	42	23	30	204.975	5787.615752
12		54.975	55	42	23	30	204.975	5992.590741
13		54.975	55	42	23	30	204.975	6197.56573
14		54.975	55	42	23	30	204.975	6402.540718
15		54.975	55	42	23	30	204.975	6607.515707
16		54.975	55	42	23	30	204.975	6812.490695
17		54.975	55	42	23	30	204.975	7017.465684
18		54.975	55	42	23	30	204.975	7222.440673
19		54.975	55	42	23	30	204.975	7427.415661
20		54.975	55	42	23	30	204.975	7632.39065
21		54.975	55	42	23	30	204.975	7837.365639
22		54.975	55	42	23	30	204.975	8042.340627
23		54.975	55	42	23	30	204.975	8247.315616
24		54.975	55	42	23	30	204.975	8452.290605
							8452.29	

Table 5.16: - Formulations of weight and volume of Sodium Borohydride and Liquid Oxygen (LOX) system

	FC	Fuel Sys	Oxidant sys	Total Energy (kWh)
MH/O2	7	260	145	193901
MH/LOx	7	326	80	242570
SBH/O2	7	103	302	403887
SBH/LOx	7	177	228	693875

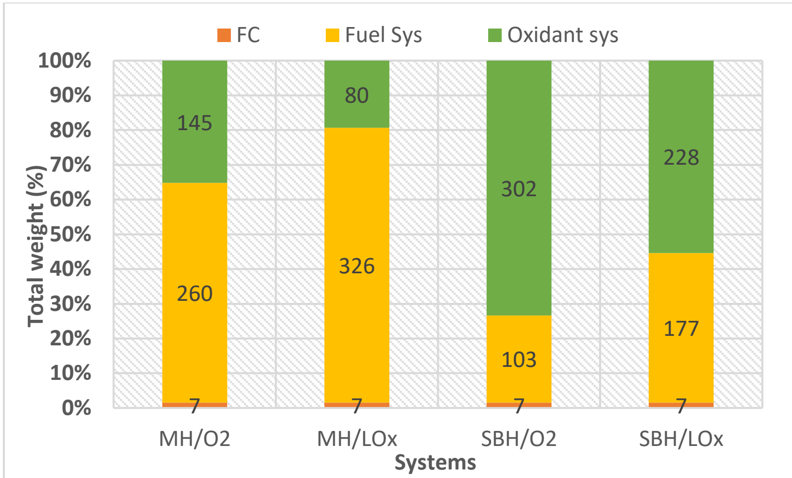


Fig 5.19: Weight Analysis of systems with different storage options of fuel

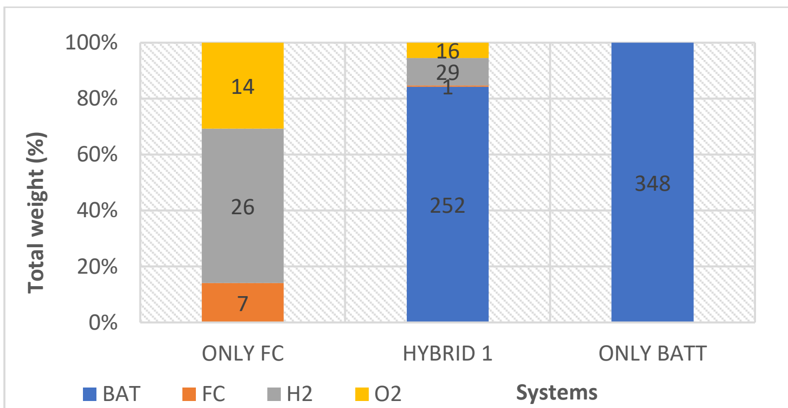


Fig 5.20: Weight analysis of systems utilising Hydrogen and Oxygen

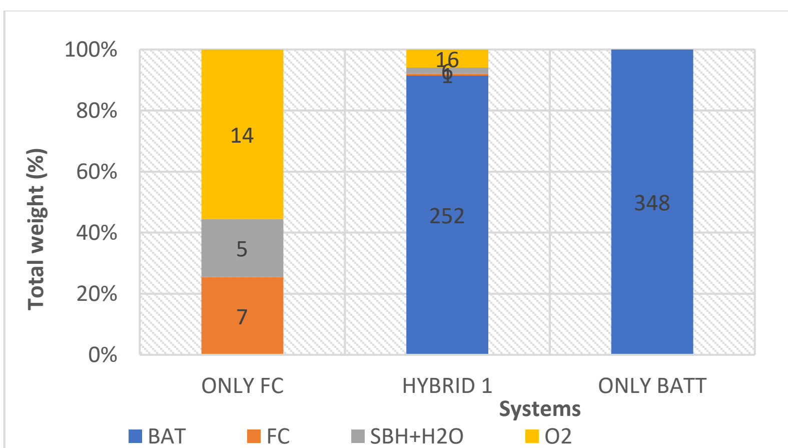


Fig 5.21: Weight analysis of systems using Sodium Borohydride and Oxygen

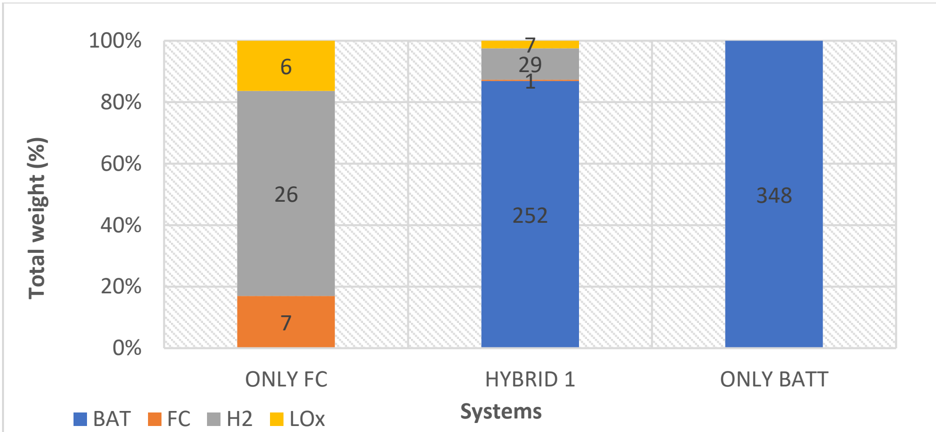


Fig 5.22: Weight analysis of systems using Metal hydrides and LOX

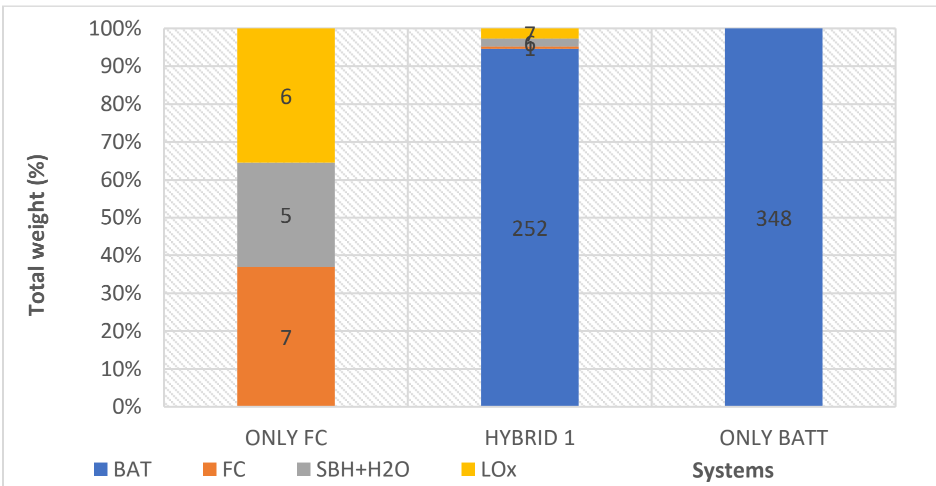


Fig 5.23: Weight analysis of systems using sodium borohydride and LOX

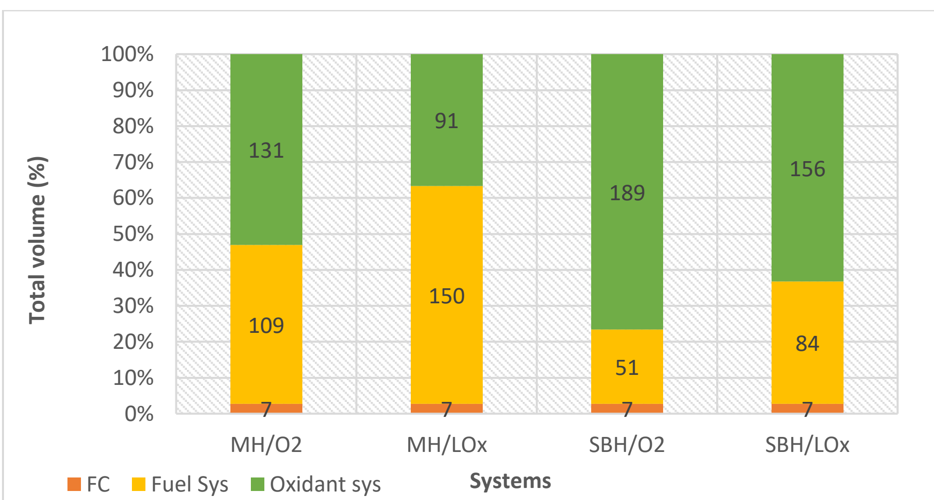


Fig 5.24: Volume Analysis of systems with different storage options of fuel

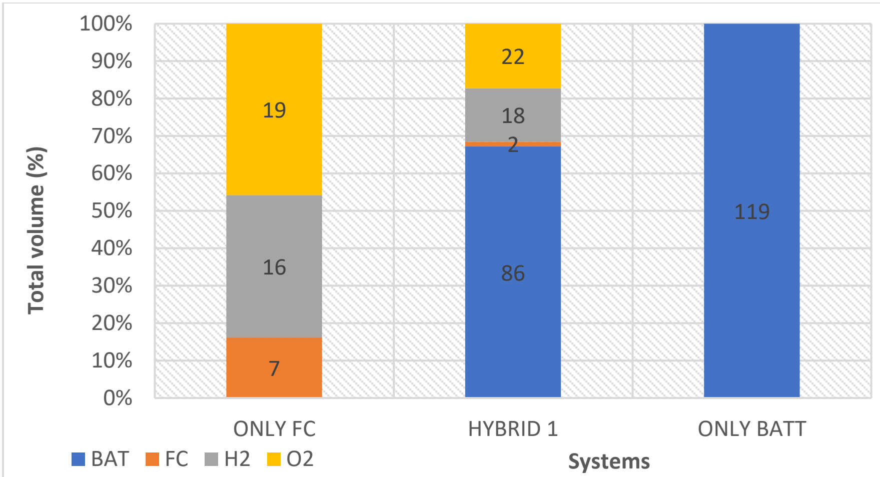


Fig 5.25: Volume analysis of systems utilising Hydrogen and Oxygen

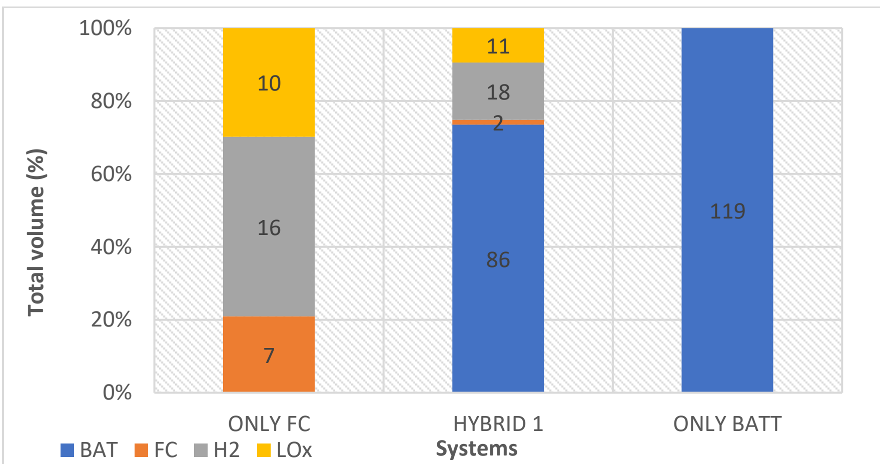


Fig 5.26: Volume analysis of systems utilising Hydrogen and LOX

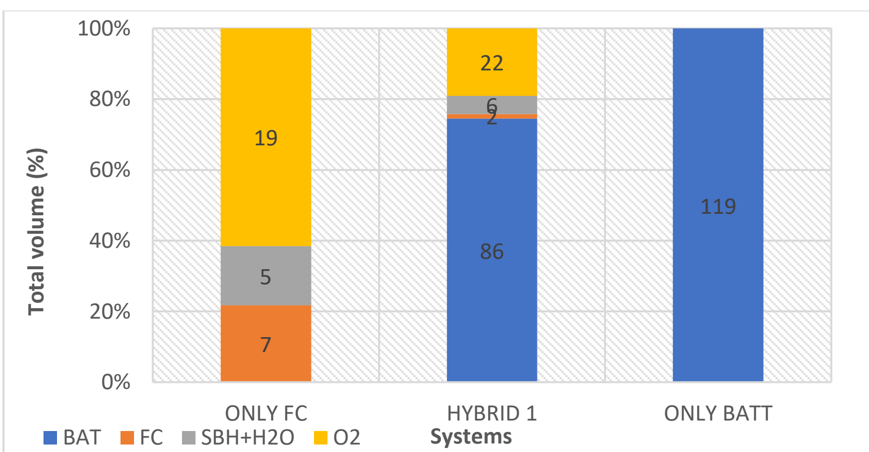


Fig 5.27: Volume analysis of systems utilising Sodium Borohydride and Oxygen

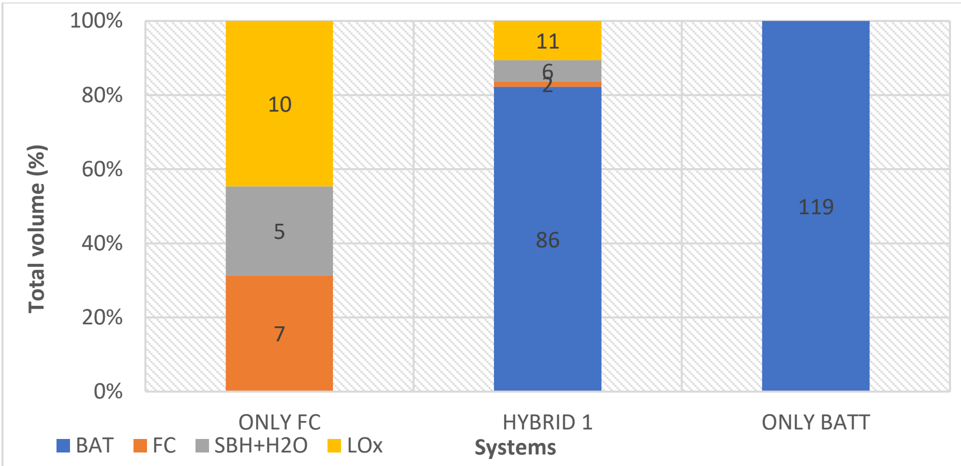


Fig 5.28: Volume analysis of systems utilising Sodium Borohydride and LOX

Table 5.17: - Weight Estimation of systems with various fuel storage options

Based on Daily requirements					
	Battery	**FC**	**H2**	**O2**	**TOTAL (tonnes)**
ONLY FC	0	7	26	14	47
HYBRID 1	252	1	29	16	299
ONLY BATT	348	0	0	0	348
	Battery	**FC**	**H2**	**LOx**	**TOTAL**
ONLY FC	0	7	26	6	39
HYBRID 1	252	1	29	7	290
ONLY BATT	348	0	0	0	348
	Battery	**FC**	**SBH+H2O**	**O2**	**TOTAL**
ONLY FC	0	7	5	14	26
HYBRID 1	252	1	6	16	276
ONLY BATT	348	0	0	0	348
	Battery	**FC**	**SBH+H2O**	**LOx**	**TOTAL**
ONLY FC	0	7	5	6	18
HYBRID 1	252	1	6	7	266
ONLY BATT	348	0	0	0	348

Table 5.18: - Volume estimation of Hydrogen and Oxygen Storage options

Volume				
	FC	Fuel Sys	Oxidant sys	Energy (kWh)
MH/O2	7	109	131	130962
MH/LOx	7	150	91	179720
SBH/O2	7	51	189	188769
SBH/LOx	7	84	156	309991

Table 5.19: - Volume Estimation of systems with various fuel storage options

	BAT	**FC**	**H2**	**O2**	**TOTAL (m^3)**
ONLY FC	0	6.798001	15.97183	19.21087	41.9807
HYBRID 1	85.87933	1.548308	18.26051	21.96369	127.6518
ONLY BATT	118.6631	0	0	0	118.6631
	BAT	FC	H2	LOX	TOTAL
ONLY FC	0	6.798001	15.97183	9.665818	32.43565
HYBRID 1	85.87933	1.548308	18.26051	11.05088	116.739
ONLY BATT	118.6631	0	0	0	118.6631
	BAT	FC	SBH+H2O	O2	TOTAL
ONLY FC	0	6.798001	5.197814	19.21087	31.20668
HYBRID 1	85.87933	1.548308	5.942635	21.96369	115.334
ONLY BATT	118.6631	0	0	0	118.6631
	BAT	FC	SBH+H2O	LOx	TOTAL
ONLY FC	0	6.798001	5.197814	9.665818	21.66163
HYBRID 1	85.87933	1.548308	5.942635	11.05088	104.4212
ONLY BATT	118.6631	0	0	0	118.6631

Based on the above analysis the sodium borohydride storage for hydrogen storage option and liquid oxygen as storage option for oxygen storage. These are considered the best as they enhance the safety margin as hydrogen is generated through hydrolysis of sodium borohydride. The controlled generation of hydrogen is considered the best option towards exploitation of a hydrogen source onboard.

5.20 Feasibility of installation of Commercially of The Shelf (COTS) Proton Exchange Membrane (PEM) fuel cell in a cylindrical cross-section.

The following approximations were inferred based on the computer simulations for varying diameter and length of the AIP Plug. The dimensional details of the cylindrical cross section is shown in fig 5.29.

Volume of Cylinder $V = \pi r^2 h$

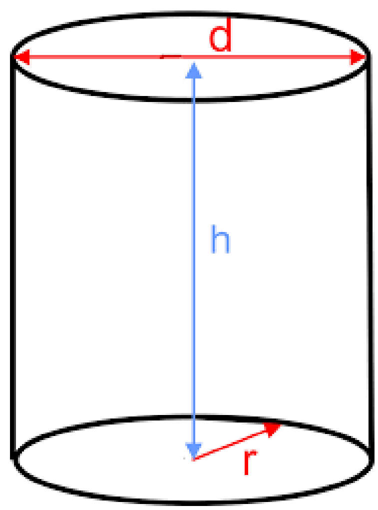


Fig 5.29: Volume of Cylinder

(a) Diameter of the circle (d) – 6.2 meter

(b) Radius of the circle (d/2) - 3.1 meter

(c) Height of the cylinder (h) - 9.94 meter

(d) Volume of Cylinder $V = \pi r^2 h$ = 3.14 * (3.1) ^2 * 9.94 ≈ 299.9434

(e) V ≈ 300 m^3

The Gravimetric power = [Output Power/ Fuel Cell mass] (KWh/Kg),

The Volumetric Power = [Output Power/ Fuel Cell Volume] (Kwh/m^3)

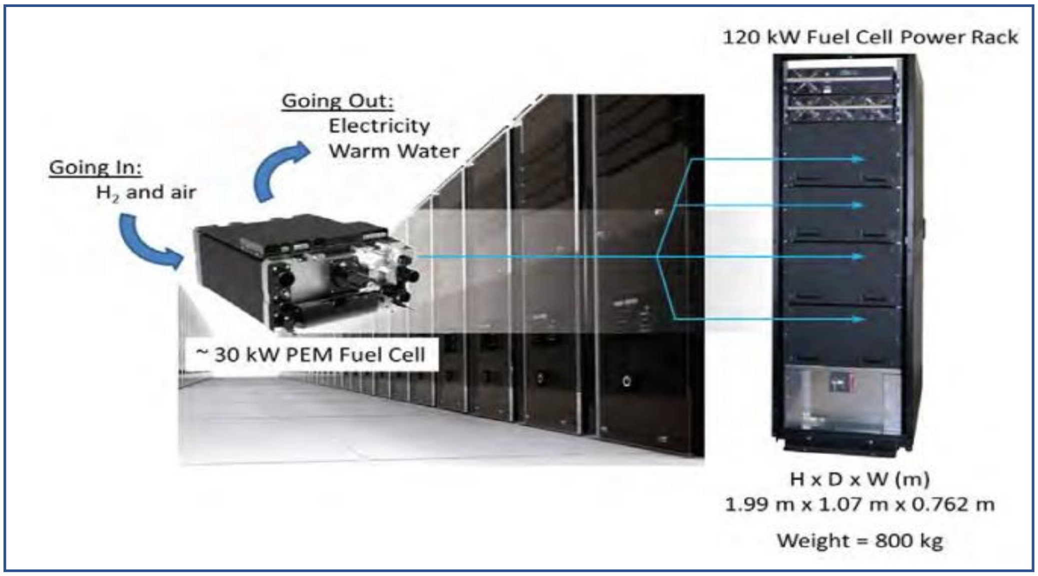


Fig 5.30: HyPM-R-120S PEM Fuel Cell Rack with Dimensional details

A single 120KW fuel cell power Rack comprises (fig 5.30.& 5.31) of 04 sub-modules of 30KW each. Each rack functions as an independent source delivering a combined output of 120 KW. The rack complies with IES 60079-10-1 code of 2015.

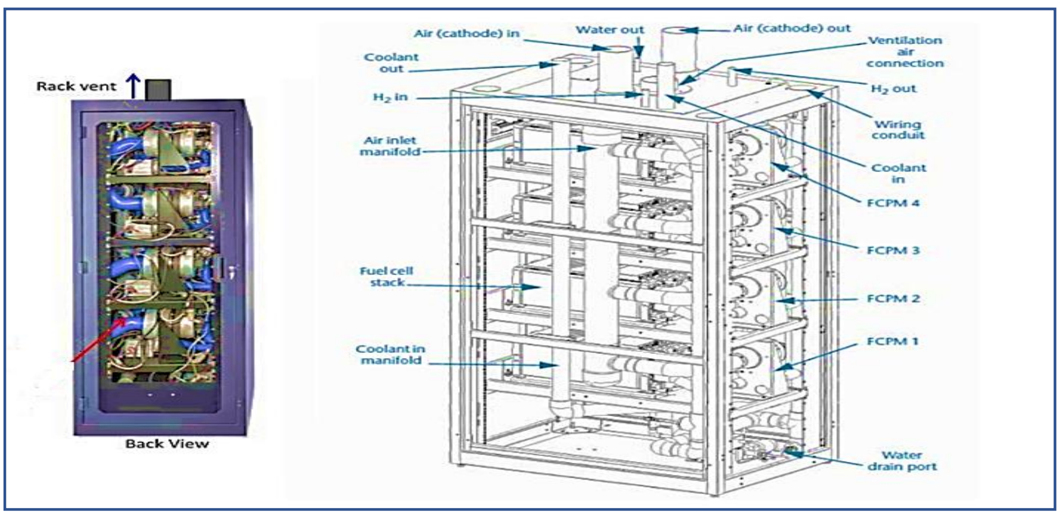


Fig 5.31: HyPM-R-120S Rear view of PEM Fuel Cell Rack

The hydrogen is generated on demand basis from hydrolysis of $NaBH_4$ stored in an aqueous mixture. The oxygen is supplied through the evaporator from the Liquid Oxygen (LOX) storage tank. The Output of the fuel cell is DC and is smoothened before it is fed into the main bus bar link for charging of battery groups.

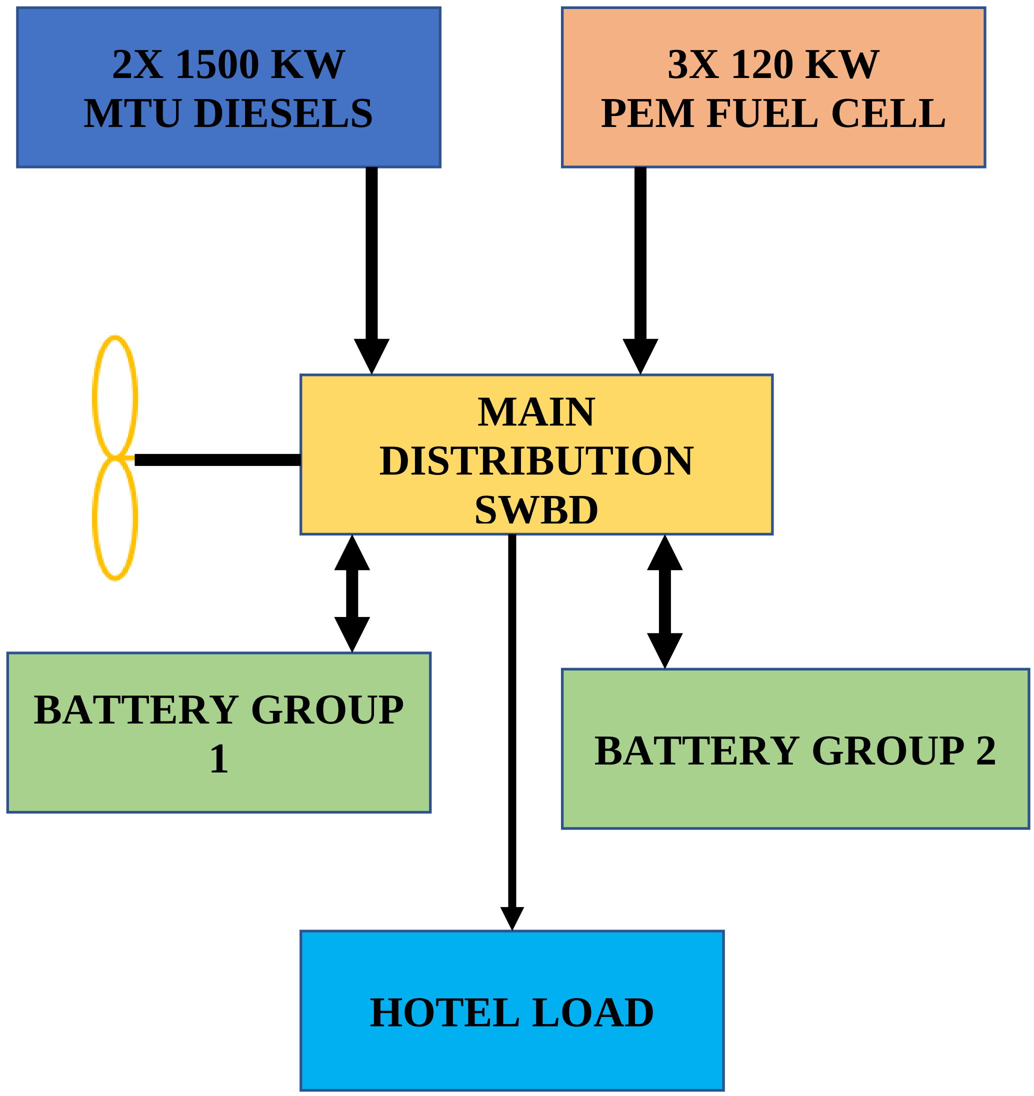


Fig 5.32: Schematic representation of Power generation and Distribution of an AIP submarine

5.21 Assessment of extraction of power through Fuel Cell and Batteries.

In order to infuse a better maintenance envelope and continuous availability of equipment under AIP mode it is proposed 3 racks of 120 Kw, comprising of 12 modules of 30KW each. The modules can be rotated whilst in operation or can be kept as onboard spares (OBS). The additional 02 modules will enhance the power of system to 360KW. The weight of single rack is approximately 800kg and total weight of 3 racks of 120Kw amounts to 2400Kg. The vertical height of the rack is approximately 2.5m taking into account the incoming and outgoing cable, fuel and cooling pipelines. The AIP Plug is designed to be reconfigurable compartment with all the equipment mounted on a cradle to avoid/reduce the noise generated by the individual equipment to be transferred to the hull. The LOX tank is vertically mounted towards the aft of the compartment with $NaBH_4$ tanks mounted in the lower most portion of the compartment carrying the aqueous mixture. The Fuel cell modules are located in the forward portion and are located in such a way so as to provide a clear operation and maintenance envelope to the crew members.

Based on the fuel consumption rates (oxygen and hydrogen) the plant weight and subsequently overall weight of the system was calculated. The numerical data as well as the graphical representation of the various AIP systems is appended below.

The average fuel consumption vis-à-vis the plant weight and its overall impact on the range and endurance is calculated in table 5.20 and depicted as a graphical representation in figure 5.33.

Determination of AIP plant size and weights.

Table 5.20: - Calculations of a Fuel Cell AIP System

Sizing Model for AIP Systems-Fuel Cell-Assumes 360 kW Power Required					
Time Deployed (Days)	Hours	Oxygen Usage Rate 0.60 Kg/kWh	Fuel Usage 0.41Kg/kWh (hydrogen)	Plant Weight 19Kg/KW	Total Weight
7	168	36.288	24.7968	6.84	67.9248
8	192	41.472	28.3392	6.84	76.6512
9	216	46.656	31.8816	6.84	85.3776
10	240	51.84	35.424	6.84	94.104
11	264	57.024	38.9664	6.84	102.8304
12	288	62.208	42.5088	6.84	111.5568
13	312	67.392	46.0512	6.84	120.2832
14	336	72.576	49.5936	6.84	129.0096
15	360	77.76	53.136	6.84	137.736
16	384	82.944	56.6784	6.84	146.4624
17	408	88.128	60.2208	6.84	155.1888
18	432	93.312	63.7632	6.84	163.9152
19	456	98.496	67.3056	6.84	172.6416
20	480	103.68	70.848	6.84	181.368
21	504	108.864	74.3904	6.84	190.0944

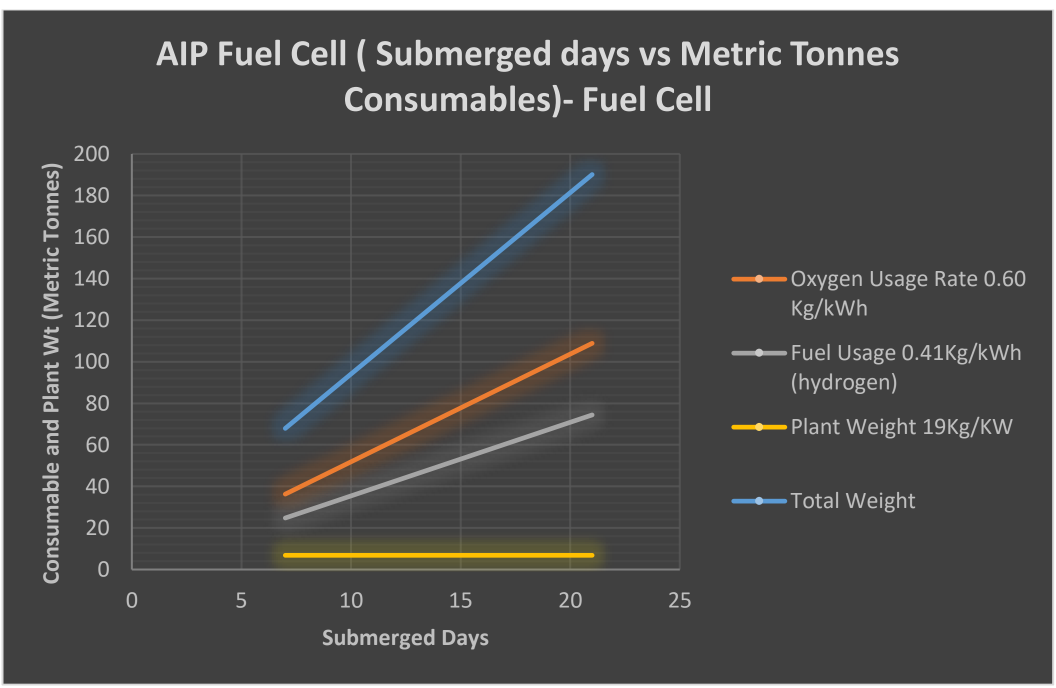


Fig 5.33: Graphical representation of fuel consumption of AIP fuel cell system

5.22 Determination of buoyancy of the AIP plug

A MATLAB program has been coded according to the user defined mission profile based on following factors

(a) No of Days in Patrol (Quiet) state
(b) Minimum speed to be maintained whilst in quiet state
(c) Cumulative sprint speed required during the patrol in days
(d) Maximum sprint speed
(e) Length of the submarine

The MATLAB codes are written so as to investigate and assess the buoyancy of the plug incorporating the AIP system of a 2000T submarine displacement. These values are variables but were fixed to allow a comparison to be made with different systems. The submarine propulsion system is formulated as an independent as well as a hybrid system with the AIP plant supporting the lead acid battery for submerged operations. Simulations were completed with differing profiles to assess the sensitivity of the plants to differing profiles.

The limiting factor on the endurance of the AIP plant is the amount of fuel and oxygen carried onboard. It is inferred that the limiting function is more pronounced with the storage capacity of oxygen onboard. The proposed plant option is carefully formulated taking into account easier recharging options at harbour and a possible option for replenishment of LOX at sea. The program is code in a flexible manner so as to incorporate a varied mission profile and endurance based on variance of speed and number of days. A sample output of the result obtained from the MATLAB program is shown in fig 5.35.

```
Input No Days in Patrol Quiet State: 14
Required Speed in Patrol Quiet State (Min Speed 2 kts): 4
Input No Days at Sprint Speed: .5
Required Sprint Speed (Top Speed 9 kts): 8
Input the length of the Submarine in meters: 77.94
Plug is neutral buoyancy

Total Endurance of CCD =   -1.3872

LOXCap = -4.9439e+03

Recharge = -98.8778

Indiscretion Ratio =    2.9700

Plug is neutral buoyancy

Total Endurance of SE =   -1.0531

LOXCap =   -4.7915e+03


Recharge = -95.8306

Indiscretion Ratio =    3.7917

Plug is neutral buoyancy

Total Endurance of FC Hydride =   -1.1999

LOXCap = -2.3231e+03

Recharge = -46.4624

Indiscretion Ratio =    1.6135

Plug is neutral buoyancy

Total Endurance of FCMR =   -1.7664

LOXCap = -4.4653e+03

Recharge = -89.3057

Indiscretion Ratio =    2.1066

Plug is neutral buoyancy

Total Endurance of MESMA =   -0.7227

LOXCap = -3.9961e+03

Recharge = -79.9229

Indiscretion Ratio =    4.6082
```

Fig 5.34: Sample output of the result obtained from Matlabproject 3_4

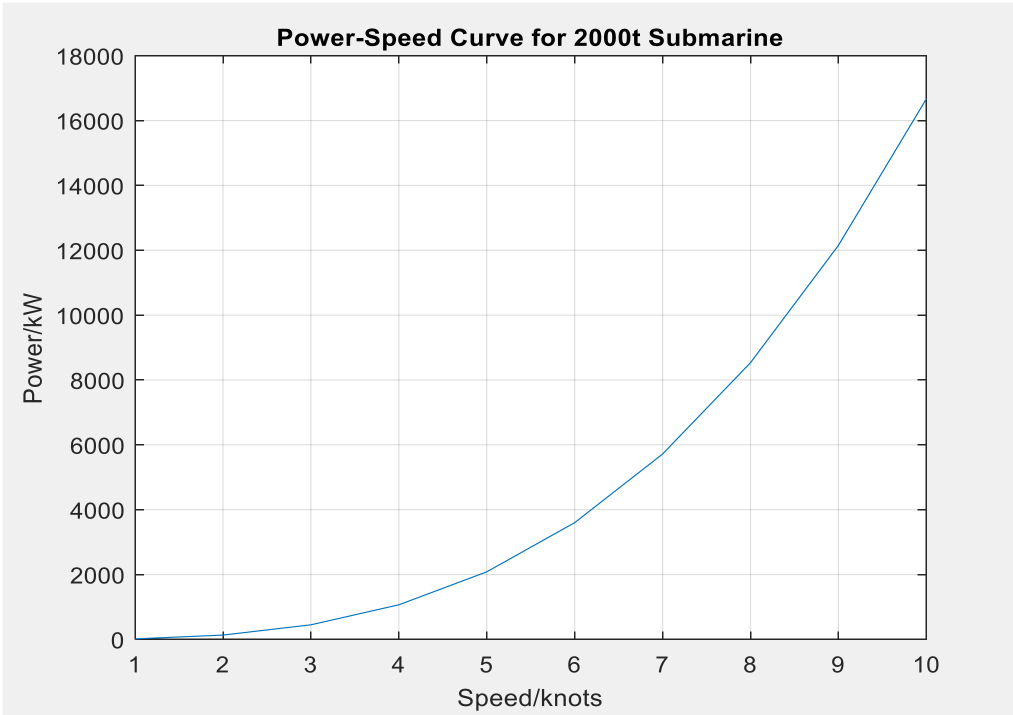


Fig 5.35: Power-Speed Curve of a 2000T submarine

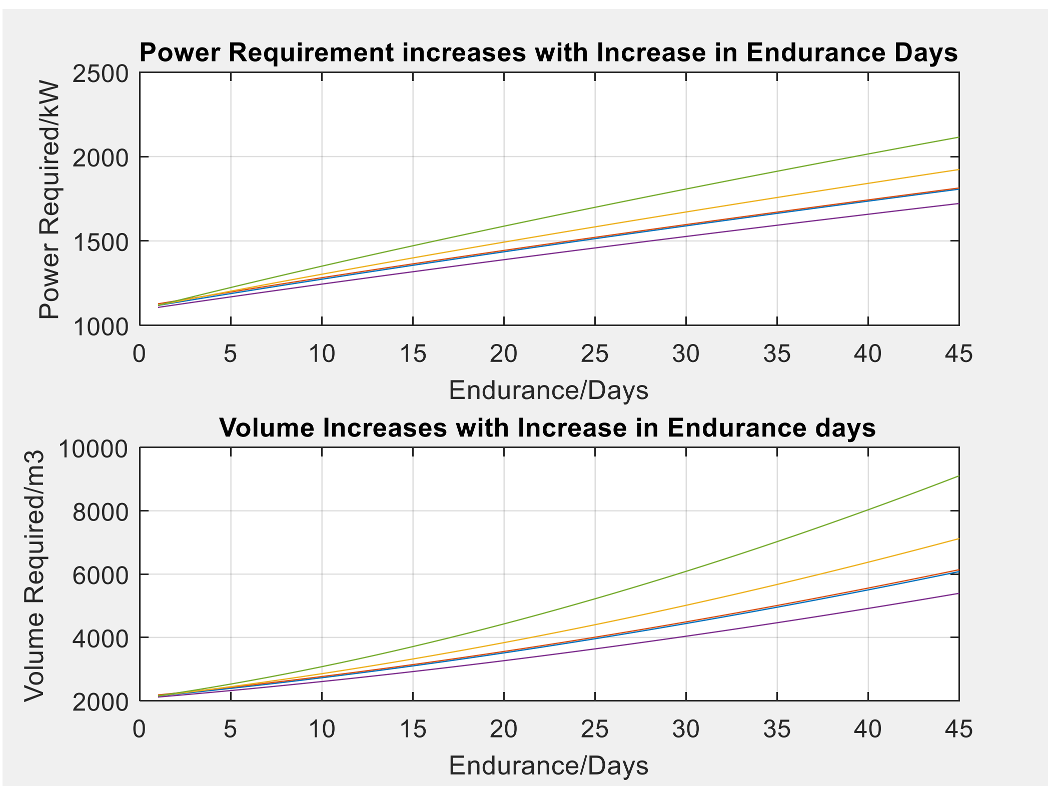


Fig 5.36: Endurance calculations vis-à-vis power and Volume

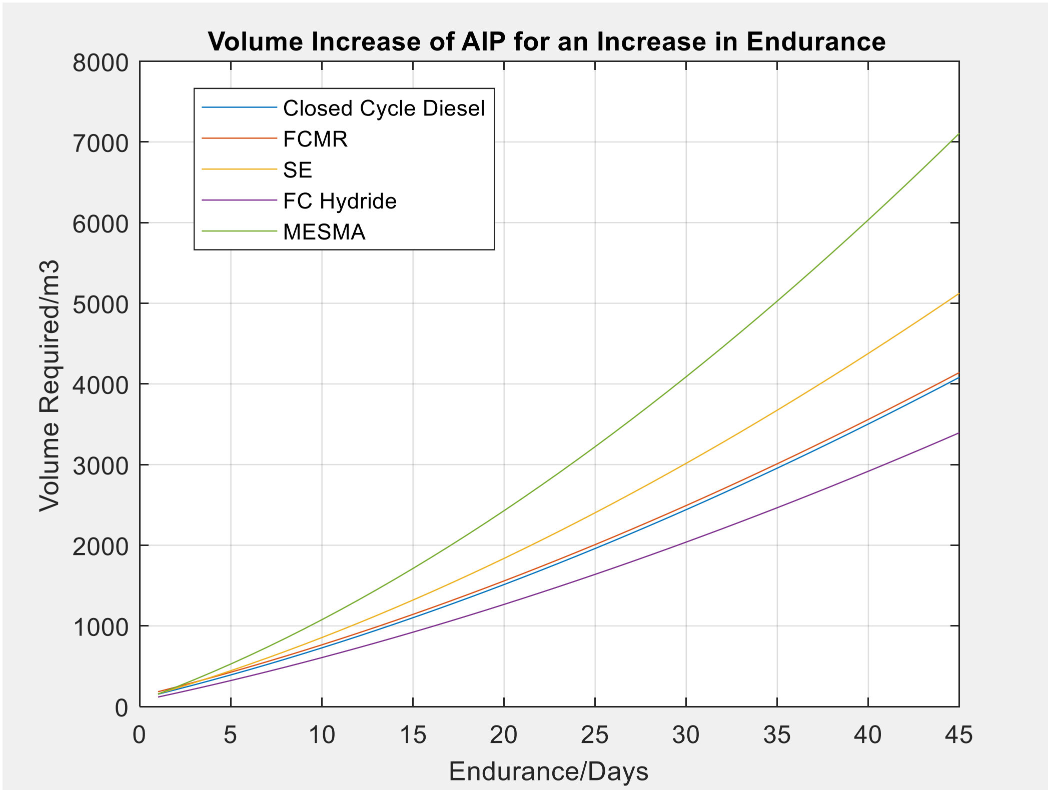


Fig 5.37: Endurance calculations of various AIP systems.

The graphical analysis of the second MATLAB program for a 2000 T submarine is represented in fig 5.35 -5.37. It is shown that the power and volume increase with increase in need of underwater endurance. This directly corresponds to the fact that the endurance of the AIP system is directly proportional to the amount of AIP fuel carried onboard. Further, in fig 5.38 it is seen that the volume requirement of the selected Fuel cell AIP system with hydride storage option has the least storage space when compared to the other AIP options.

5.23 Smoothening of Output voltage

The output of PEM fuel cell is DC voltage and in order to ensure uniform regulated output voltage being fed to the main busbars towards load consumption or towards topping up of charge of storage batteries. A DC-DC converter has been modeled taking into account the following characteristics

(a) Minimum voltage of busbar supplied by the onboard storage battery

(b) Maximum Voltage which the battery would be subjected whilst inducement of charge.

(c) Maximum current which the total Fuel cell packs can produce.

A variant of DC-DC converter is modeled using an open source software – Power Stage Designer Tool – M/s Texas Instruments version 4.0[373]. An inverting Buck-Boost Converter. The modelled variant and the component graph for minimum and maximum voltages are shown below.

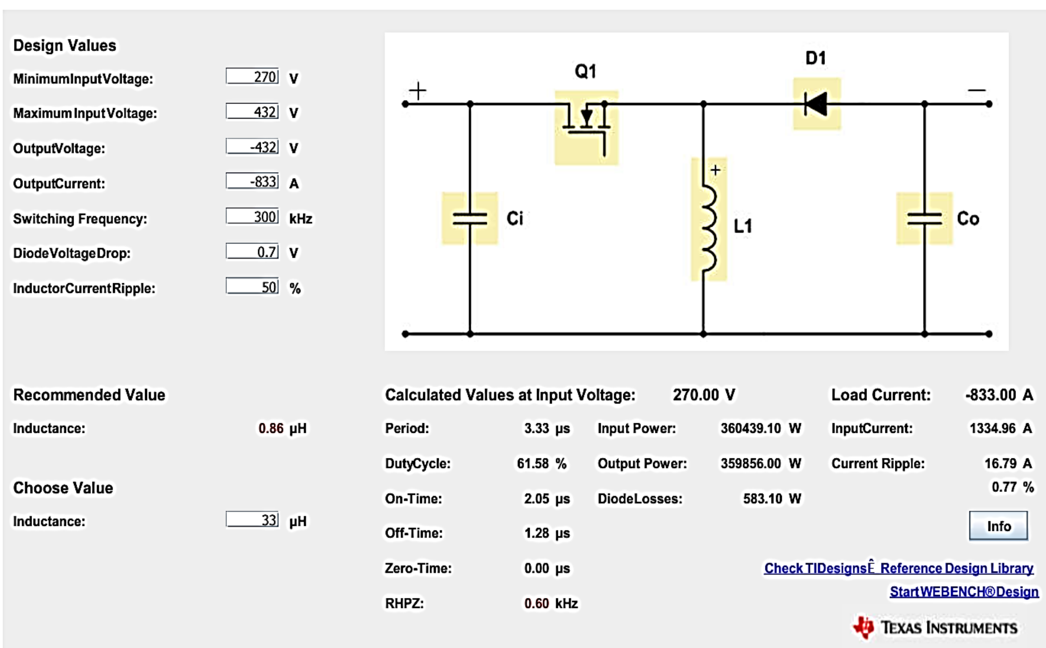


Fig 5.38: Modeling of Inverting Buck Boost Converter using Power Stage Designer Tool

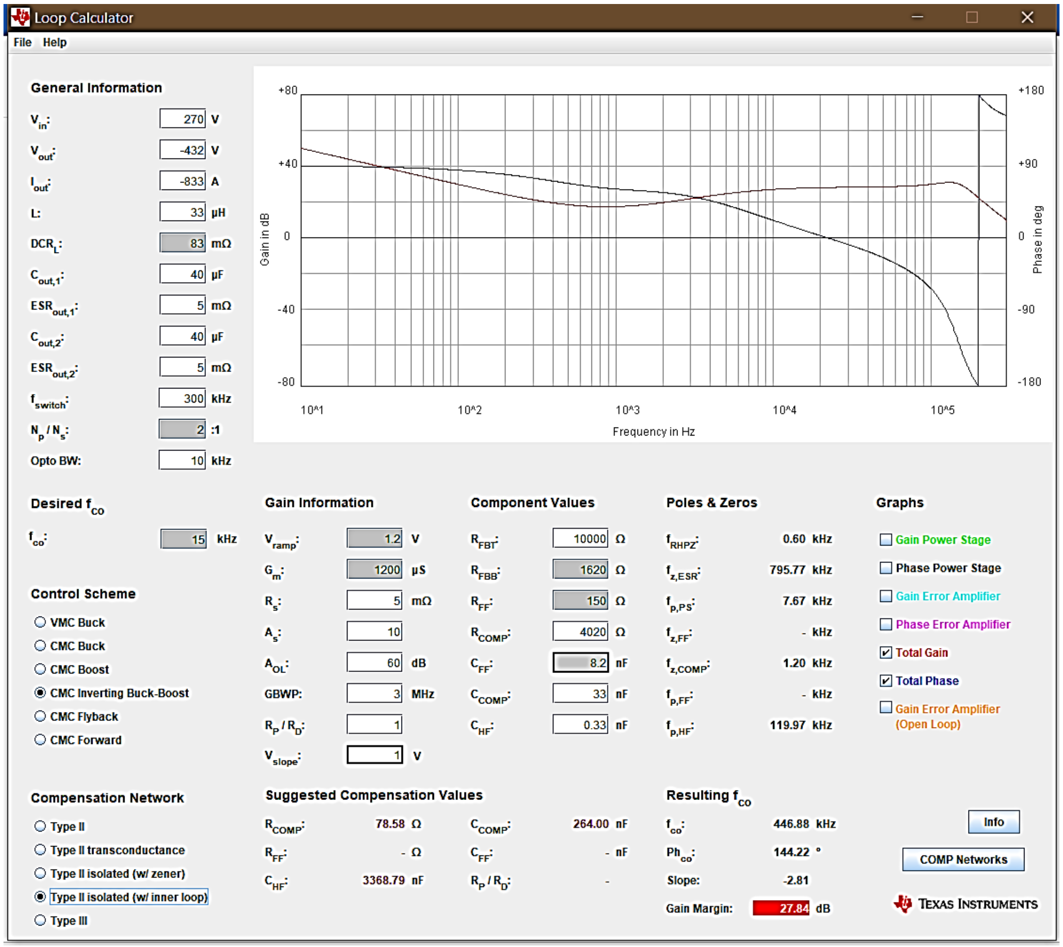


Fig 5.39: Loop calculation showing various component parameter values

Fig 5.40: Waveforms at FET Q1(V) – 270 Volts

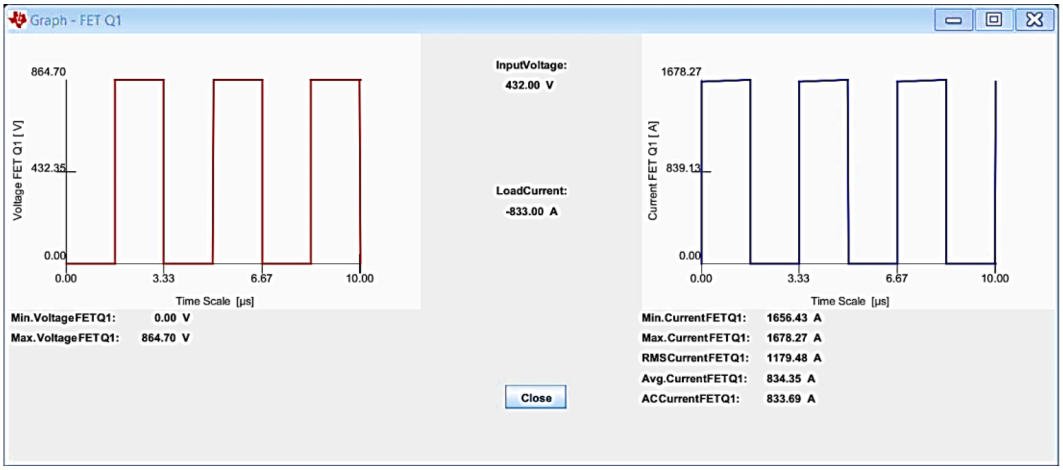


Fig 5.41: Waveforms at FET Q1(V) – 432 Volts

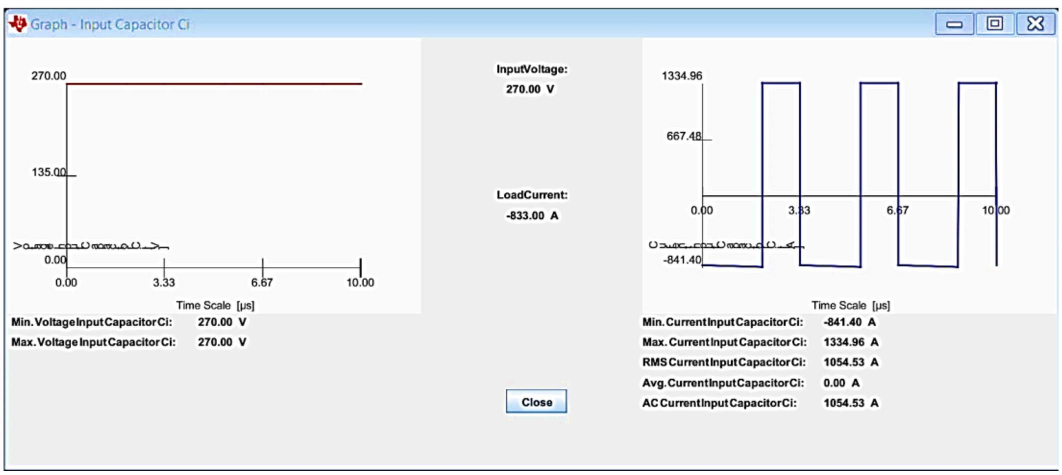


Fig 5.42: Waveforms at input capacitor – 270 Volts

Fig 5.43: Waveforms at input capacitor – 432 Volts

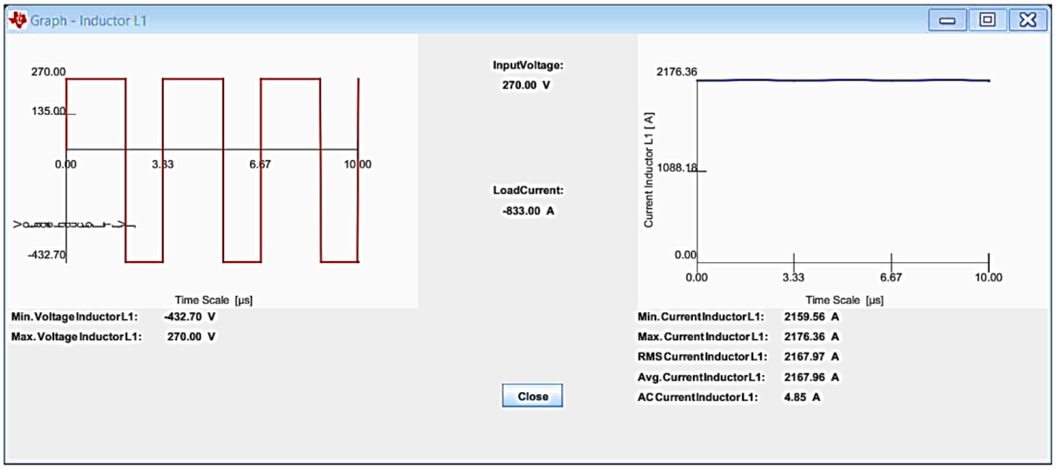


Fig 5.44: Waveforms at Inductor L1 – 270 Volts

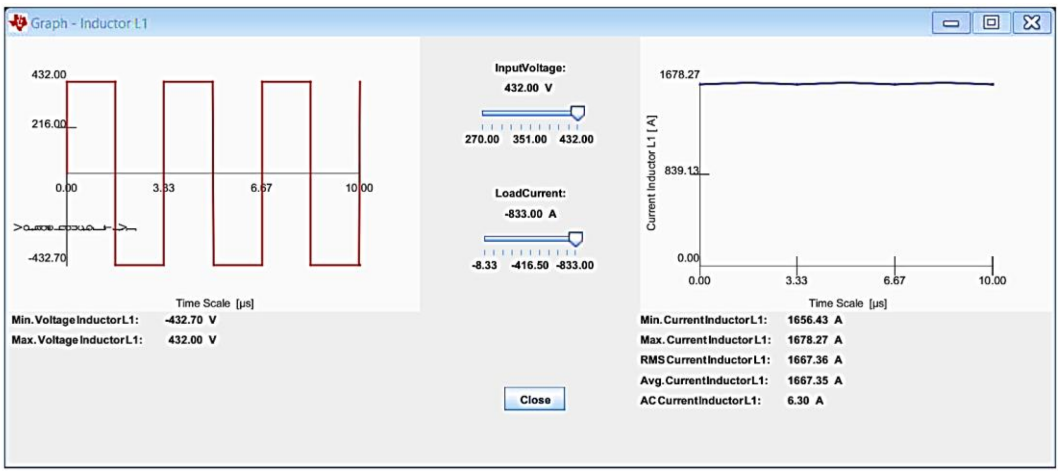


Fig 5.45 Waveforms at Inductor L1 – 432 Volts

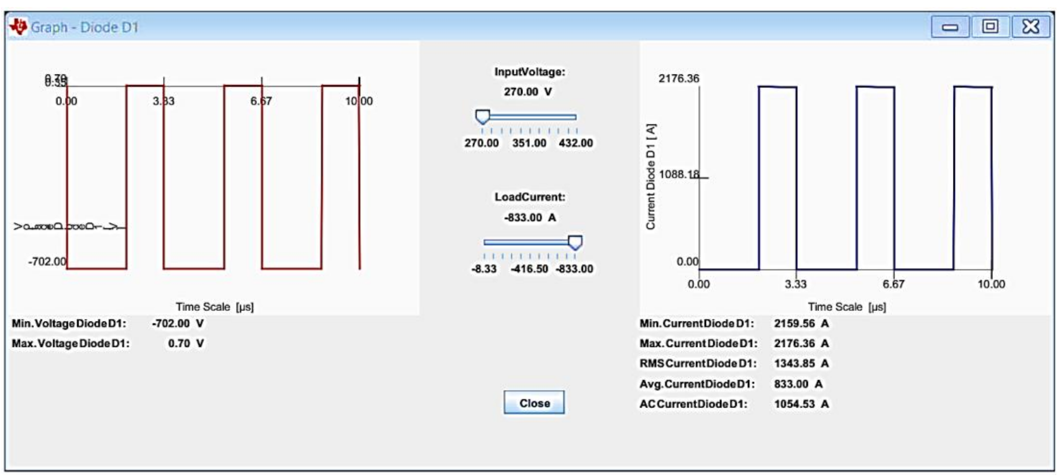


Fig 5.46: Waveforms at Diode L1 – 270 Volts

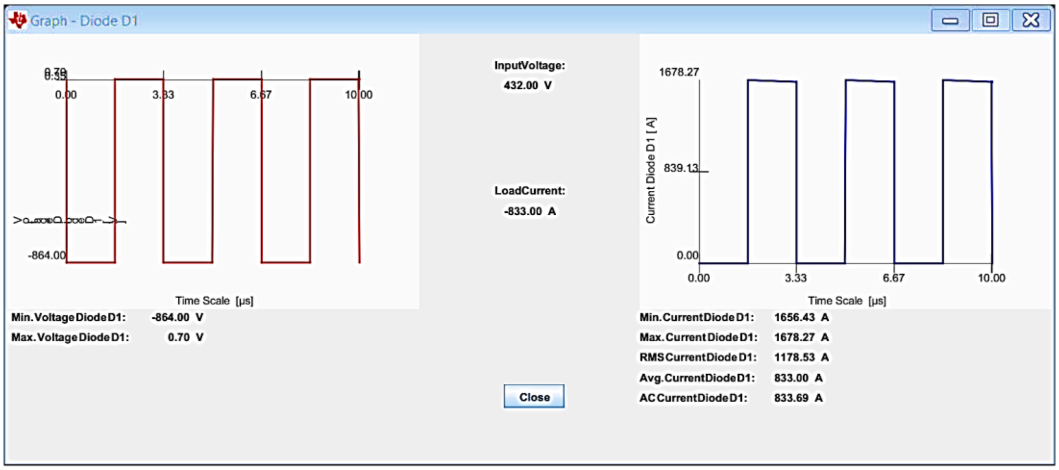


Fig 5.47: Waveforms at Diode L1 – 270 Volts

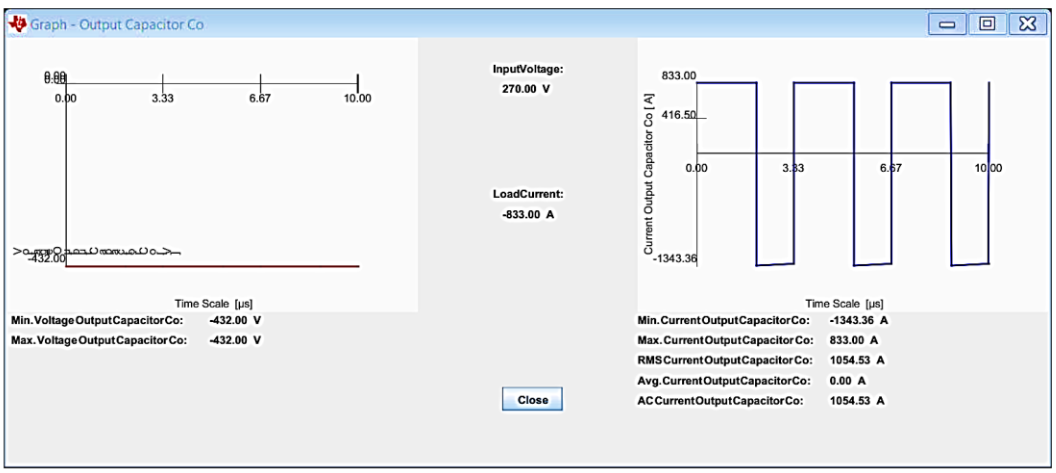


Fig 5.48: Waveforms at Output capacitor C_O – 270 Volts

Fig 5.49: Waveforms at Output capacitor C_O – 432 Volts

5.23.1 Advantages and Disadvantages of Buck -boost converters

(a) Advantages of Buck -Boost Converters

(i) Can undertake step-up or step-down functions

(ii) Low operating duty cycle.

(iii) High Efficiency

(iv) Comparatively cost efficient

(b) Dis-advantages of Buck-Boost Converters

(i) Larger filters give rise to EMI problems

(ii) Complex feedback loop , control system

5.24 Proposals towards replenishment of AIP fuels at harbour and Sea

The endurance of the AIP submarine is directly proportional to the amount of fuel stored onboard. The present AIP systems around the world is limited in endurance due based on the fuel consumption as well as the speed of operation and requires a considerable amount of time for replenishment at harbour (liquid oxygen replenishment by M/s Air liquid on German submarine shown in Fig 5.51 -52)

Fig 5.50 (Left to right): (a) Refueling of LOX onboard an AIP Submarine[249]. (b) LOX storage container of M/s Air Liquide, France for AIP Submarines[374].

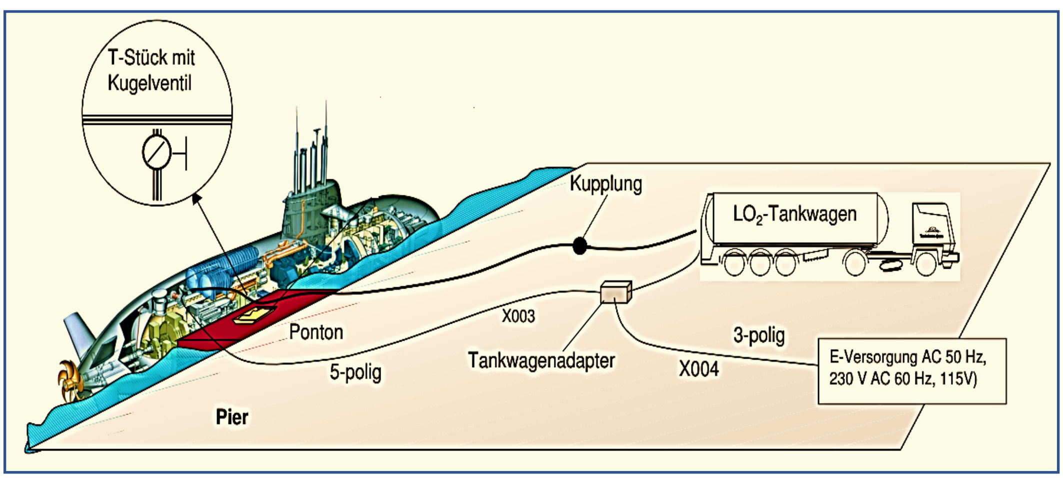


Fig 5.51: Refueling of LOX onboard an operational 212 A -AIP Submarine [375]
Storage of Hydrogen Onboard Submarines

The German Submarines predominantly utilises metal hydride cylinders for safe hydrogen storage onboard. These cylinders were stored around the pressure hull in the aft portion of the submarine (Hydride cylinders shown in fig 5.53-5.54).

Fig 5.52 (Top to bottom): (a) German Type 212 on syncrolift [376](b) German AIP Submarine with Metal hydride and LOX storage tanks on pressure hull[377].

It is proposed to have a dual loading point for sodium borohydride and liquid oxygen on the casing of the submarine. This will enable smooth replenishment of fuel in harbour and with this proposed modification the possibility of AIP fuel replenishment at sea can also be considered.

Fig 5.53 (Top to bottom): (a) Aft portion-Cut Section of German Type 212 on syncrolift showing Metal Hydride tanks around pressure hull during construction, Kiel , Germany [378] (b) Wholly booted Type 212A submarine [379] (c) Metal hydride cylinder being removed by crane for maintenance [33]

5.25 Endurance, Range and Indiscretion ratio of conventional diesel submarines without/with AIP.

Indiscretion ratio of the submarine is defined the ratio between the total time the submarine is running its diesels either at surface or at Periscopic Depth (PD) to the total time of operation of the submarine

$$IR = \frac{Battery\ Charging\ time}{(Snorting\ time + total\ Submerged\ duration)}$$

Ideally it is considered that IR values between 7 to 10% for submarine on patrol at 4 knots and between 20-30% for transit. Range estimation for the selected submarine indicates that the best speed of exploitation of the AIP submarine is at speed of 4-5 knots as shown in Fig 5.56. Endurance of the submarine with AIP plug at speeds between 3-4 knots amounts to 15 to 18 days as shown in fig 5.55

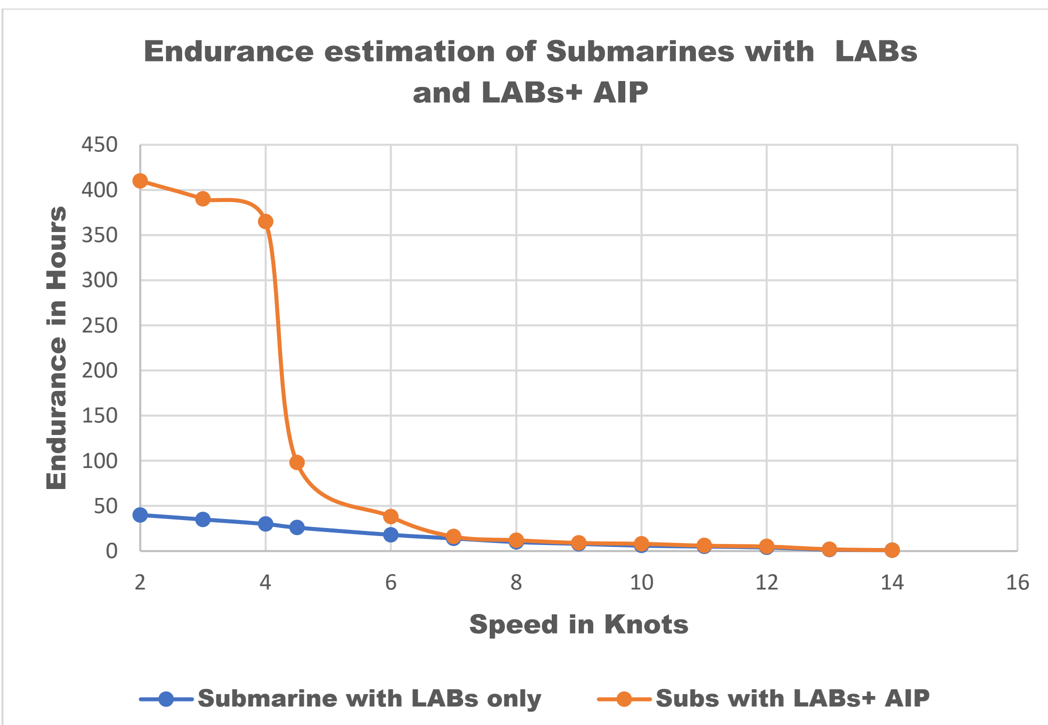


Fig 5.54: Endurance estimation of submarines with LABs and with AIP

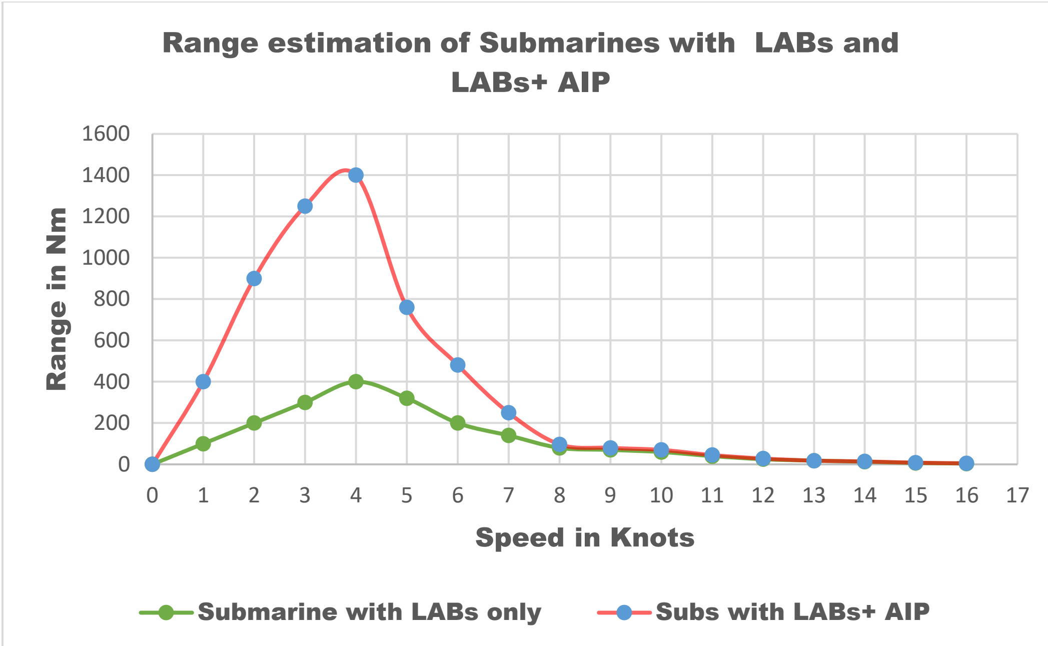


Fig 5.55: Range Estimation of Submarines with LABs and with AIP

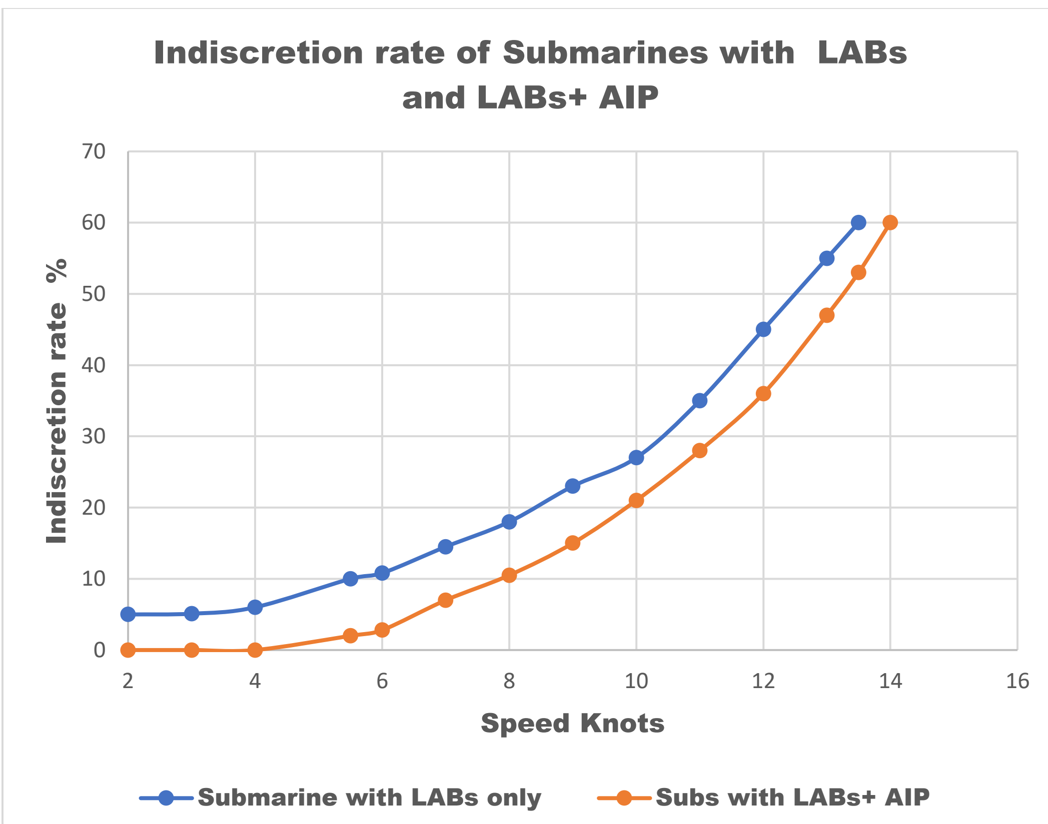


Fig 5.56: Indiscretion ratee of Submarines using LABs+ Diesels and AIP only

5.26 Co-generation concept in PEM Fuel cell.

Co-generation concept is much successful in fuel cell systems as they increase the overall efficiency of the fuel cell. The co-generation concept is highly successful in residential sector and is generally utilised to provide heating options to household. In the present case the operating temperature of PEM fuel cell is approximately 80-100^{0}C and the temperature does not provide much scope for energy extraction. The output of the PEM cell is water and heat. The expelled heated water is recirculated towards maintaining the operating temperature of the fuel cell system.

5.27 The final Specification of the diesel electric submarine with PEM fuel cell AIP Plug

Table 5.21: - Specification of a Fuel Cell AIP Submarine

Submarine Initial Length	68 m
Submarine Diameter D	6.2 m
Increase in Length (AIP Plug)	9.94m
Volume	299.9434 m^3
Final Submarine Length	77.94m
Final Sub Diameter	6.2 m
SHP	4350.872 KW
AIP	PEMFC
Hydrogen Storage	Sodium Borohydride
Oxygen Storage	Liquid Oxygen
DC-DC Conversion	Inverse Buck boost converter
Endurance of AIP	15 to 18 days @ speeds between 3.5-4 knots
COTS PEM fuel cell	M/s Siemens BZM 120
	M/s Hydrogenics 30KW rack module
Storage	Lead Acid batteries with 15000 Ah
No of cells	360

5.28 Discussion

(a) Preliminary estimation of power of submarine of length -77.94m and diameter D -6.2 m is calculated using Jackson's method and compared with the power estimation undertaken by Paramarine. It is understood that the Paramarine can only analyse Fuel cell as the only AIP option and other AIP cannot be estimated using the software. To obviate the above limitation, a MATLAB program (first) was written so as to analyse various other AIP option and their impact on the overall dimensions on the submarine length keeping a constant diameter. In addition, three battery models were analysed as storage options and the results were exported to a M/s Excel spread sheet for further analysis.

(b) The AIP section/Plug of 9.94m was added to the initial length of the submarine. The final length of the submarine is 77.94 m (68+9.94m) and Diameter 6.2m. Power estimation of the submarine with increased length has been undertaken and the range and endurance estimation for submarine was undertaken. It is established that the endurance of the submarine at speeds between 3.5 to5 knots is the maximum.

(c) Analysis of 2000T submarine with AIP system has been undertaken with four different variation of fuel storage options (gaseous hydrogen and oxygen, cryogenic oxygen (LOX), Hydrogen stored in metal hydrides and aqueous Sodium Borohydride ($NaBH_4$)). A spread sheet analysis of the entire load profile of the submarine along with storage options for hydrogen (sodium borohydride) and oxygen (Liquid oxygen) was undertaken and volume is computed to be 104.42 $m^{3.}$

(d) The buoyancy of the plug is analysed vis-à-vis length in order to determine whether the plug is buoyant positively, negative or neutrally. A MATAB program (second) is written to determine the buoyancy of the AIP system as well as to give a comparative analysis of the volume requirement of PEM fuel cell with sodium Borohydride option vis-à-vis other AIP options.

(e) In order to smoothen the output voltage being fed to the batteries. An inverse Buck boost DC-DC Converter was modeled using Power Stage Designed tool -M/s Texas Instruments Version 4.0. The converter is designed for a minimum input voltage of 232V and maximum input voltage of 432 V (gassing voltage) of Lead Acid Battery (M/s Hagen) of 15000 Ah Capacity.

(f) It has been observed that there is no major variation of hotel load. Minor variations (when the submarine is running at sprint speeds necessitating the need to run additional sea water cooling pumps) in hotel load is observed at higher speeds. Hence it is assumed that majority of AIP operating speeds are limited to speeds between 2.5 to 6 Knots and the sprint speed only through the AIP source is restricted to speed less than 9 knots. Hence no Major variations of load is observed.

(g) Two models of commercially available PEM fuel cell (M/s Hydrogenics PEMFC module – 4 x 30 Kw tower, M/s Siemens BZM – 120 Kw) was been analysed for suitability for fitment onboard submarines. Due to the increasing availability and induction of COTS items onboard marine platforms it is pertinent that the calculations and simulations made from the parameters obtained from the OEMs will enable to build confidence to retrofit a power source for Air independent propulsion onboard submarines.

Chapter Summary

Chapter 5 covers the simulations, coding and subsequent modeling of the AIP system using software tools viz., MATLAB -Simulink, Paramarine and Power Stage Designer Tool – M/s Texas Instruments version 4.0. The initial sizing of the Submarine was coded into a MATLAB file and the results were extrapolated to an M/s Excel Format for visual appreciation of the processed data. The simulation of 2000Tonne submarine fitted with Lead Acid Batteries (LABs) and with hybrid option (LABs+AIP) is undertaken with respect to propulsion and hotel load. Based on the above calculation the indiscretion rate of submarine is determined. A second MATLAB program codes were implemented in order to assess the buoyancy

(Positive, Neutral or Negative) of the AIP Plug with respect to the fuel storage onboard. The fuel storage option for the AIP system has been extensively reviewed and the best possible option has been identified. In addition, for the purpose of power smoothening an inverted buck boost inverter has been modelled for the desired output voltage using the Power Stage Designer Tool – M/s Texas Instruments version 4.0.

Chapter 6 Optimisation of PEM fuel Cell

6.1 Modelling and Optimisation of PEM Fuel Cell using Simple Genetic Algorithm (SGA)

A synergy of a hybrid propulsion system encompassing traditional powering system coupled with an alternative powering source fuel cell is the most sought-after technology in the field of marine propulsion [91]. These systems offer immense advantage in terms of stealth, efficiency and prevents noxious emissions. Directives towards emission control were proposed by International Maritime Organization (IMO) which includes adaptation of a hybrid electric propulsion onboard [380]. In order to realise true potential of hybrid systems it is essential that the parameters governing them is to be optimized. The Optimised parameters enables to achieve higher efficiency rate in an actual propulsion plant. Amongst underwater platforms, various types of Air Independent Propulsion (AIP) system are being considered for installation and further exploitation all around the world [5], [93]. However due to the maturity in technology and the need for higher efficiency at lower operating temperatures and high-power density targets PEMFC are considered a strong contender for marine vessels [103], [381]–[383]. In addition, Molten carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) systems are installed on various commercial and military ocean-going surface vessels [57]. Simulation modeling studies of PEM fuel cell has made great progress over the years with prediction of parameters pertaining to, steady state mathematical and dynamic behavior are being undertaken by researchers all over the world [94]–[96], [98],

[384]. Variation of computational evolutionary techniques are utilized in Genetic algorithms and its offsets. These algorithms are used for parameter predictions of various fuel cell models [99], [101], [385], [386]. The health of the FC stack is ascertained on the basis of excess oxygen ratio in the fuel cell. Accurate adjustment of excess oxygen ratio enables high efficiency rates from the PEM fuel cell[102], [387] .

6.2 Mathematical modeling of PEM Fuel Cell

Proton Exchange Membrane fuel cells emerges as top contenders for implementation onboard subsurface and submerged vehicle operations owing to their relatively low startup time and ease of operations [85]. The greatest advantage of the PEM fuel cell is that byproduct water can be stored onboard or pumped outboard depending on overall necessity of platform without making any major alterations to the draining systems onboard. [388]. The overall endurance of the propulsion system surmounts to the effective storage capacities of oxygen and hydrogen fuel tanks. Underwater vehicles prefer to operate without the presence of atmospheric air such type of powering solutions is known as Air Independent Propulsion (AIP). Though these systems possess low specific energy density and mandate recharging they provide the most invaluable power of stealth to an underwater platform [75]. PEM fuel cell is often the preferred option for submerged vehicles owing to its high gravimetric and volumetric power density with operating temperatures between 80- 100^{0}C [389]. The hydrogen and oxygen fuel are supplied to the anodic and cathodic nodal points of the fuel cell, the resultant electrochemical reaction inside the cell produces electricity. Based on the distribution network the produced electricity is utilized either for propulsion or stored as reserved power in batteries for utilization at a later stage. The output voltage of Cell is given by

$$\boldsymbol{V_s = n * (E_{nerst} - V_{act} - V_{ohmic} - V_{con})} \qquad \textbf{(1)}$$

'n' is the number of series connected cells to achieve the desired operating voltage range of the platform. Vs is the Stack Voltage(V), $V_{act,}$ V_{ohmic} & Vcon are the Activation, Ohmic and concentration Volatge drops respectively.The Nernst voltage of a single cell is given by eqn (2). PH_2 & PO_2 are the partial pressures of Hydrogen and Oxygen respectively.

$$\boldsymbol{E_{nerst} = 1.229 - 0.85 * 10^{-3} * (T - 298.15) + 4.3085 * 10^{-5} * T[\mathrm{l\,n}(PH_2 + 0.5\ln(PO_2))]} \qquad \textbf{(2)}$$

The voltage drop (V_{act}) at the surfaces of anode and cathode is depicted as a parametric expression in Eqn 3

$$\boldsymbol{V_{act} = \varepsilon_1 + \varepsilon_2 T + \varepsilon_3 * T * ln(Co_2) + \varepsilon_4 * T * \mathrm{l\,n}(i)} \qquad \textbf{(3)}$$

ε_1, ε_2, ε_3 & ε_4 are the parametric coefficients obtained from experimental data of a Ballard Mark IV PEM fuel cell Investigated by Amphlett et.al[384]As per Henry's Law, Co_2 is the the concentration of oxygen (mol cm^{-3}) at cathode end of fuel cell (Eqn 4) is given by

$$\boldsymbol{Co_2 = \frac{Po_2}{\left[5.08 * 10^6 exp^{-\frac{498}{T}}\right]}} \qquad \textbf{(4)}$$

The overall resistance drop (Eqn 5) contributing to the ohmic voltage drop is obtained from the summation of membrane resistance (R_M) and contact resistance R_C multiplied with current i.

$$\boldsymbol{V_{ohmic} = i.(R_M + R_C)} \tag{5}$$

The specific resistivity (ρ_M) of the membrane (Ωm), thickness of the membrane (l) and area(A) is utilized to calculate the membrane resistance of the fuel cell (Eqn 6)

$$\boldsymbol{R_M = \rho_M . \frac{l}{A}} \tag{6}$$

Nafion membranes is most commonly used in PEM fuel cell. λ is the water content of the membrane. The specific resistivity of Nafion membrane (Eqn 7) is given by:-

$$\boldsymbol{\rho_M = \frac{181.6\left[1+0.03\left(\frac{i}{A}\right)+0.062*\left(\frac{T}{303}\right)\left(\frac{i}{A}\right)^{2.5}\right]}{\left[\left[\lambda-0.634-3\left(\frac{i}{A}\right)\right]*exp\left[\left[\frac{4.18(T-303)}{T}\right]\right]\right]}} \tag{7}$$

Concentrations of oxygen and hydrogen are affected by means of mass transportation (Eqn 8) and is calculated using the current density (I/I_{max}) and parametric Co-efficient b. I is the actual current density of the cell (A/cm^2) and I_{max} – max current density(A/cm^2)

$$\boldsymbol{V_{con} = -bln\left[1-\left(\frac{I}{I_{max}}\right)\right]} \tag{8}$$

Modeling of PEM fuel cell were based on the governing equations is formulated by Amphlett et. al[384]. Optimisation of parameters were undertaken by utilization of Genetic Algorithm (GA) codes incorporated in MATLAB-SIMULINK MODEL (Fig.1.)

6.3 Parameter extraction and modeling of PEM fuel cell using Simple Genetic Algorithm

The voltage versus current (V-I) characteristic curve is often utilized to determine the FC performance. The current and voltage parameters form the basis for subsequent design and selection of other components including stack size and other underlying operating parameters. The V-I Curve can be generated from experimental data. These parameters are used as initial inputs to generate the experimental curve. A MATLAB-Simulink model (Fig.6.1) was developed to generate a Voltage-Current characteristic reference curve from the experimental data.

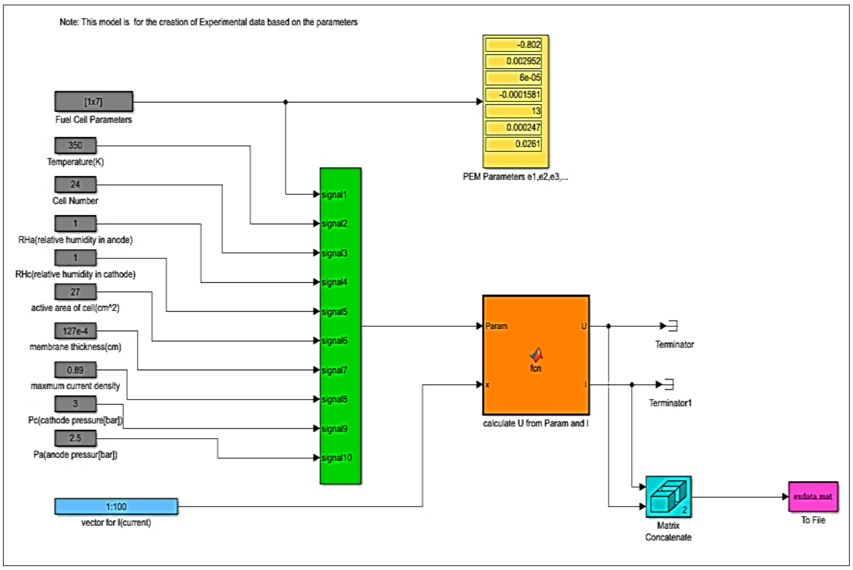


Fig. 6.1. Simulink model of PEM Fuel Cell – creation of Experimental graph

The V-I curve generated is compared with the linear characteristic curve and linear normalization of the data is depicted as a histo-bar subplot in the graph (Fig 6.2).

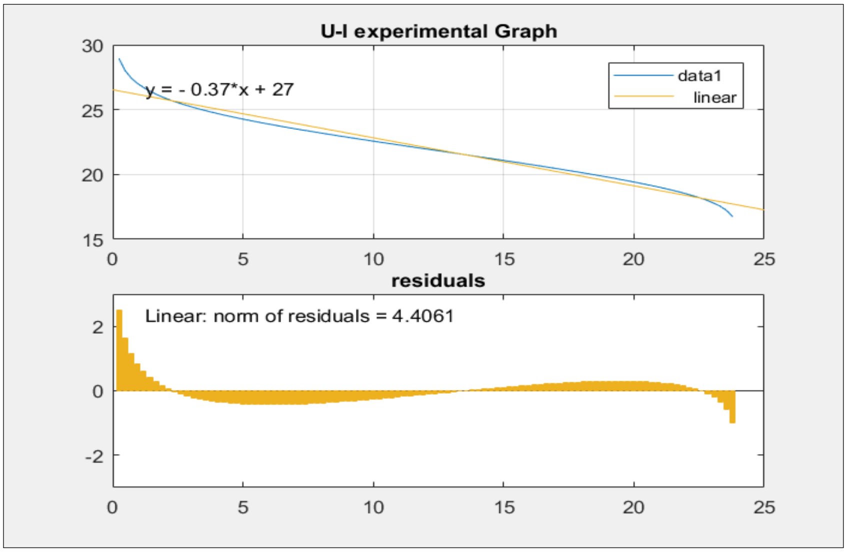


Fig. 6.2. V-I characteristic Curve derived from the experimental data obtained from the first Simulink Model

Table 6.1. Stack parameters

Parameters	Values
Number of cells	24
Stack Temperature T(K)	350
Effective area of the Cell $A(Cm^2)$	27
Cathode Pressure (bar)	03
Anode Pressure (bar)	2.5
Relative humidity at anode	1
Relative humidity at Cathode	1
Membrane Thickness	127 e-4

6.4 Utilisation of Simple Genetic Algorithm

Genetic algorithm is a complex metaheuristic process which forms part of the larger evolutionary algorithm group [89].

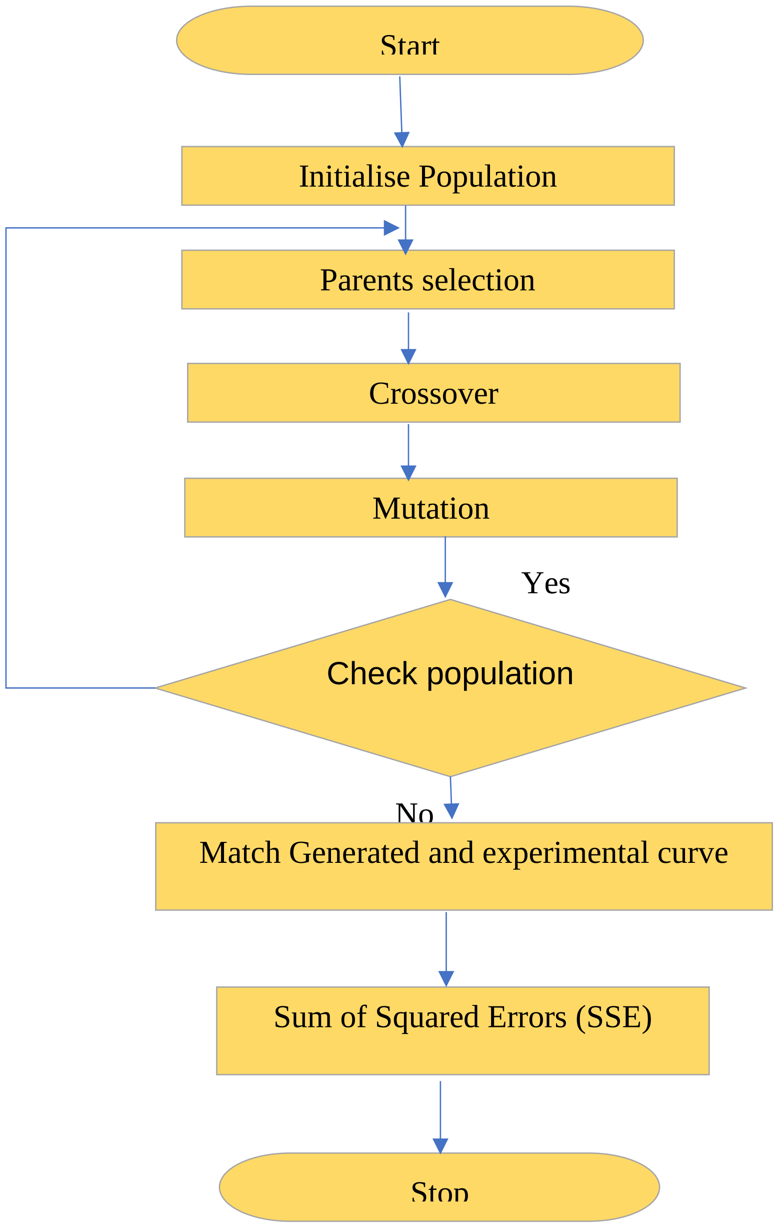


Fig. 6.3. Flowchart of genetic Algorithm process

These algorithms are most commonly used to process and quantify optimization problems heavily relying on the biological concepts of cross-over rates and mutation. The most common prerequisites to resolve a problem is twofold. First is genetic representation of the problem and the second lies in evaluation of fitness function. Post definition of initial steps the process is looped into an iterative process of cross-over and mutation. The pictorial representation of the genetic algorithm process is depicted in the flow chart Fig. 6.3.

6.4.1 Objective Function

The objective function can be derived from the voltages obtained from the experimental data and voltage obtained from the model. The parameters can be determined by utilizing the objective function for optimization to derive the squared error between the output voltage of the PEM stack and the experimental data obtained from actual fuel cell.

$$\min(\varepsilon 1, \varepsilon 2, \varepsilon 3, \varepsilon 4, b, Rc, \lambda)\left(y = \sum_{j=1}^{j}(Vexp - Vs)^{2}\right) \qquad (9)$$

6.4.2 Implementation of Genetic algorithm for optimization of parameters

A comprehensive MATLAB-SIMULINK model of a PEM fuel cell as shown in Fig.4 was modeled in order to optimize the FC parameters. The genetic algorithm was incorporated into the functional blocks of the Simulink Model. The upper and lower bounds of the parameters are given in Table 6.2.

Table 6.2. Upper and Lower bounds of the parameters

Parameters	ε_1	$\varepsilon 2$	$\varepsilon 3$	$\varepsilon 4$	λ	R_c	b
Upper bound	-0.944	0.005	$7.8*10^{-5}$	$-1.88*10^{-4}$	23	$8*10^{-4}$	0.5
Lower bound	-0.952	0.001	$7.4*10^{-5}$	$-1.98*10^{-4}$	14	$1*10^{-4}$	0.016

6.4.3 Optimisation technique

The steps involved during Optimisation of fuel cell parameters using Genetic Algorithm (GA) is appended in the following steps: -

6.4.3.1 Step 1: - Initialisation and generation of population

Chromosomes are pooled together to generate a population. These chromosomes consist of binary strings which represents the model parameters of the PEM fuel cell. Initialisation of GA operators viz., Population size, Number Cross-over rate and Mutation rate are undertaken in this process. Further the number of iterations and number of variables are defined in this step.

6.4.3.2 Step 2: - Selection of parents.

Post Initialisation of parameters, the program undertakes selection of parents. Roulette wheel selection method is used for selection of parameters. In this method the chromosomes are assigned virtual sectors in a virtual wheel and the sector value is proportional to the fitness function.so depending upon the number of genes in the chromosome the selection of largest or smallest sector is been undertaken. The selected parents are moved forward in the process to undergo crossover and mutation functions. The above process of parent selection is coded into a Simulink model as shown in Fig.6.4.

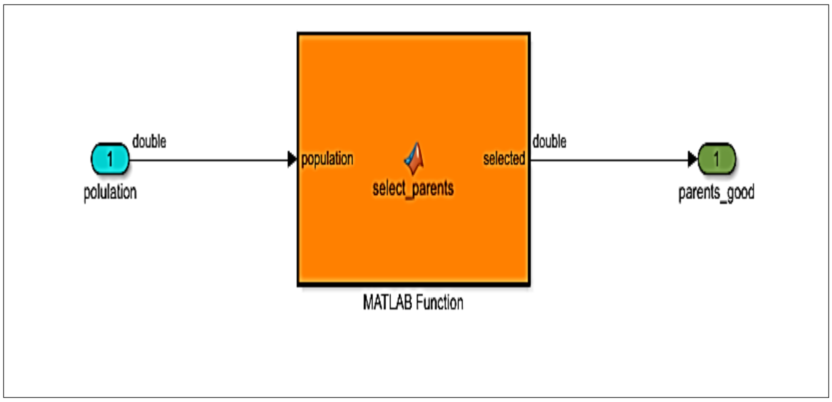


Fig. 6.4. Selection of parents

6.4.3.3 Step 3: - Crossover and Mutation rate operation

The process involves selection of genes from the parent chromosomes for combination to create a new offspring. Depending upon the combination and the gene pool originating from parents the new chromosome stands to possess better characteristic obtained from the parents. For enhancing efficiency of crossover, a multi-point crossover rate is chosen. The generated offspring undergoes mutation process in which one or more characteristics of the gene are altered. The mutation operator toggles the value of the gene from 1 or 0 based on the preset value of mutation probability. The entire procedure of crossover and mutation rates were coded in MATLAB and incorporated as a functional block in the Simulink model as shown in Fig 6.5.

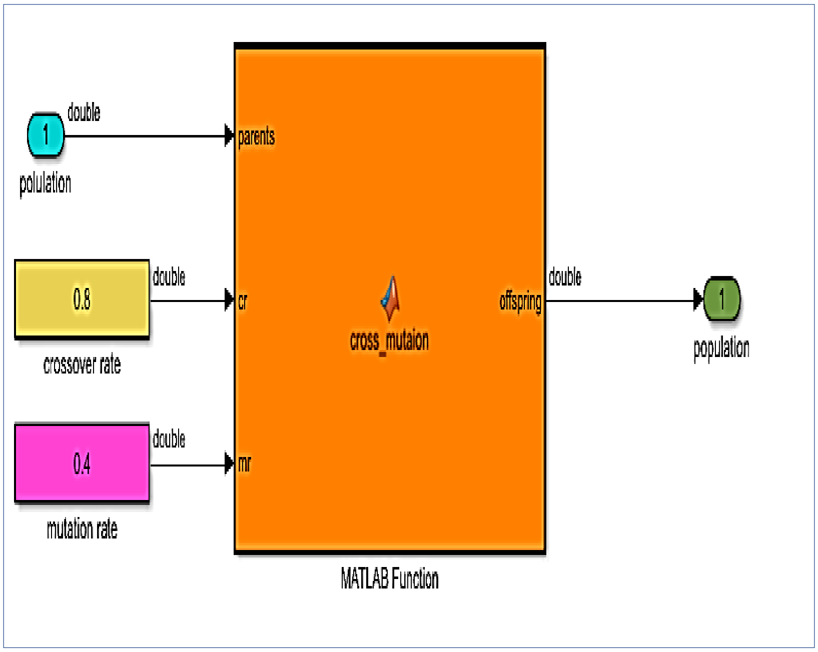


Fig. 6.5. Cross-Over and Mutation functions

6.4.3.4 Step 4: - Generation of new population

The old population is replaced with the current generated population with newer characteristic traits. The whole procedure is repeated till the termination criteria is achieved. The process of formulation of new population as shown in

Fig.6.6 and Fig.6.7 is undertaken using MATLAB codes infused into a functional block of Simulink.

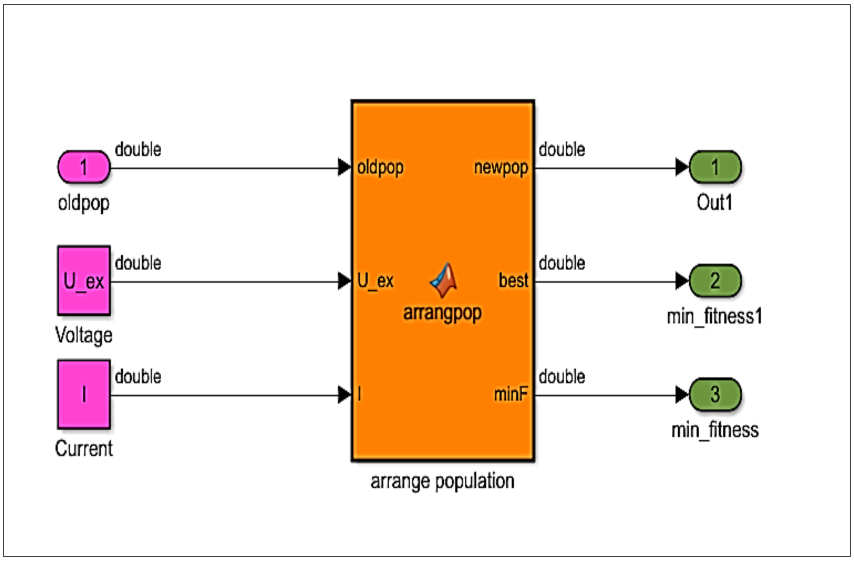


Fig. 6.6. Arrangement of population

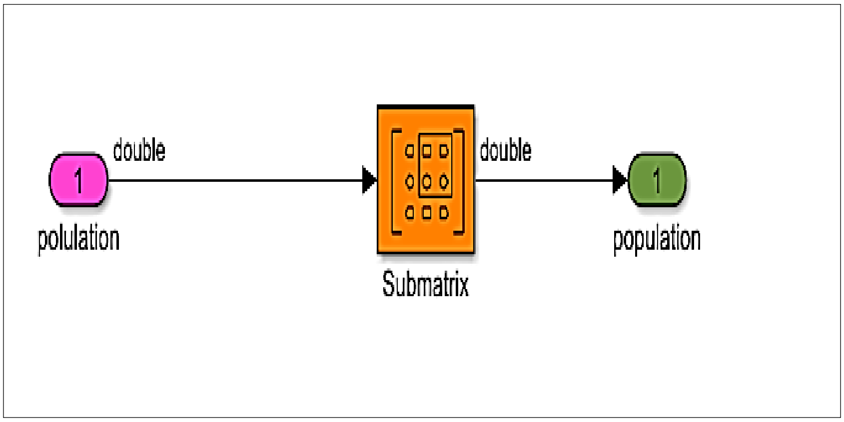


Fig. 6.7. Iterative matrix for refining of results

6.4.3.5 Step 5: - Iterative matrix

The iterative process is terminated upon achievement of desired criteria; else the process is reverted to step 2 and is continues till the termination criterion is met.

6.5 Simulink model of PEM fuel cell

A Simulink model of PEM fuel cell is modeled incorporating the entire Genetic Algorithm (GA) procedures in a sequential manner in the form of functional Simulink blocks as depicted in Fig.6.8.Table 6.3 shows the optimized parameters obtained post running of MATLAB-Simulink model.

Table 6.3. Optimised parameters

Parameters	ε_1	ε2	ε3	ε4	λ	R_c	b
Optimised	-0.9476	0.003	$7.4 * 10^{-5}$	-23.1	20	$3.32 * 10^{-4}$	0.037

6.6 Discussions

The outcome of the simulation is to generate a set of optimal parameters which would replicate the actual behavior of Fuel cell. In order to implement the influence of Genetic algorithm calculations modeling of PEM fuel cell was undertaken based on the generic equations governing the FC. A Simulink model was shown to generate a reference experimental graph. The purpose of this work was aimed at finding an optimal parameter setting for designing and operation of fuel cell. This work provides a visual appreciation of the Optimisation process through the Simulink block models. Optimisation provides flexibility towards computation of parameters in shorter time, cost effectiveness and provides baseline data for advanced techniques suitable towards fine tuning of the system.

The model parameters viz., $\varepsilon 1, \varepsilon 2, \varepsilon 3, \varepsilon 4, b, Rc, \lambda$ are extracted by the GA codes which forms part of the MATLAB-SIMULINK model. Minimisation of the values defined by the objective function defined in eqn (9) is executed. The upper and lower bounds of the parameters are defined in table 2. The data utilized for the proposed technique has been borrowed from the PEM fuel cell model [96] and are depicted in table 2. A dedicated MATLAB-Simulink program was developed for incorporation of Simple Genetic Algorithm (GA) technique. The simulations were performed using an INTEL(R) CORE (TM) i7-7700 HQ CPU @ 2.80 GHz,64-bit OS, X64-based processor.

In order to highlight the simplicity an efficiency of simple genetic algorithm a comparison of result obtained through optimisation using other evolutionary algorithms [390], [391] were undertaken and tabulated in table 4.

Table 6.4. Comparison of Optimised parameters

Parameters	ε_1	$\varepsilon 2$	$\varepsilon 3$	$\varepsilon 4$	λ	R_c	b
SGA	-0.9476	0.003	$7.4 * 10^{-5}$	$-1.91*10^{-4}$	20	$3.32*10^{-4}$	0.037
AIS	-0.951	0.003	$7.43*10^{-5}$	$-1.88*10^{-4}$	22.9	$1.02*10^{-4}$	0.032
PSO	-0.951	.003	7.6910^{-5}	$-1.95*10^{-4}$	22.3	$5.71*10^{-4}$	0.033

A comparison of the graphical simulations shown in Fig.9. shows that the V-I characteristic curves obtained from experimental and from simulations are exactly a match thus validating the proposed formulation. This method will serve as a bench mark for further simulation models.

An error graph has been obtained by calculating the difference between the experimental and the actual values shown in Fig.10. The Error values are calculated using the equation (9). MATLAB codes were written for infusing the error generation graph into the Simulink model Fig.9.The graph is plotted between the normalized value vis-à-vis the iteration number. The proposed method shows that that the error value shows considerable reduction and under similar conditions for actual and experimental data. The error graph proves the robustness of the method. PSO is a concept derived from the movement and communication patterns occurring amongst group of birds' insects and fishes. The swarm comprises of collection of movements viz., flying particles it forms the changing solutions. The possible solutions exist in search area. The movement towards target area forms the optimal solution. AIS is a branch of artificial Intelligence and are adaptive systems inspires by theoretical immunology and observes immune principles. Learning and memory the major characteristics of immune system forms the basis of problem solving in these AIS algorithms.

The Artificial Immune System (AIS) and Particle Swarm Optimisation technique optimisation values established in other research papers were cross compared with the values obtained from GA optimisation technique. The values are tabulated in table 4. These parametric values hold good only when a customer specific fuel cell is built from scratch by OEM. However, in case of a COTS fuel cell these will be provided by OEM which will govern the optimal efficiency of the fuel cell based on specific operating conditions as specified by the Manufacturer.

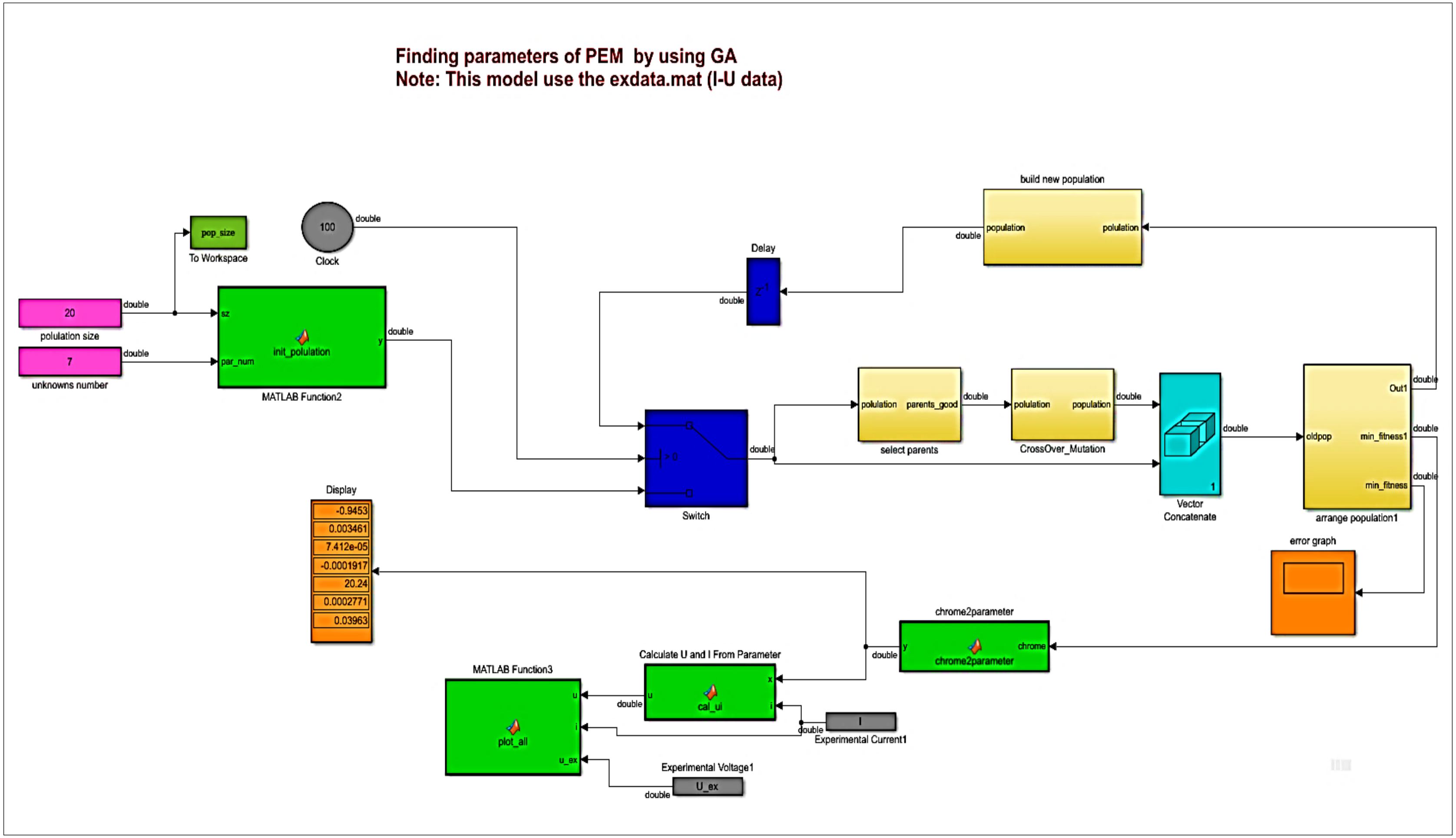


Fig. 6.8. Simulink model of PEM Fuel Cell – implementation of GA codes for generation of parameters

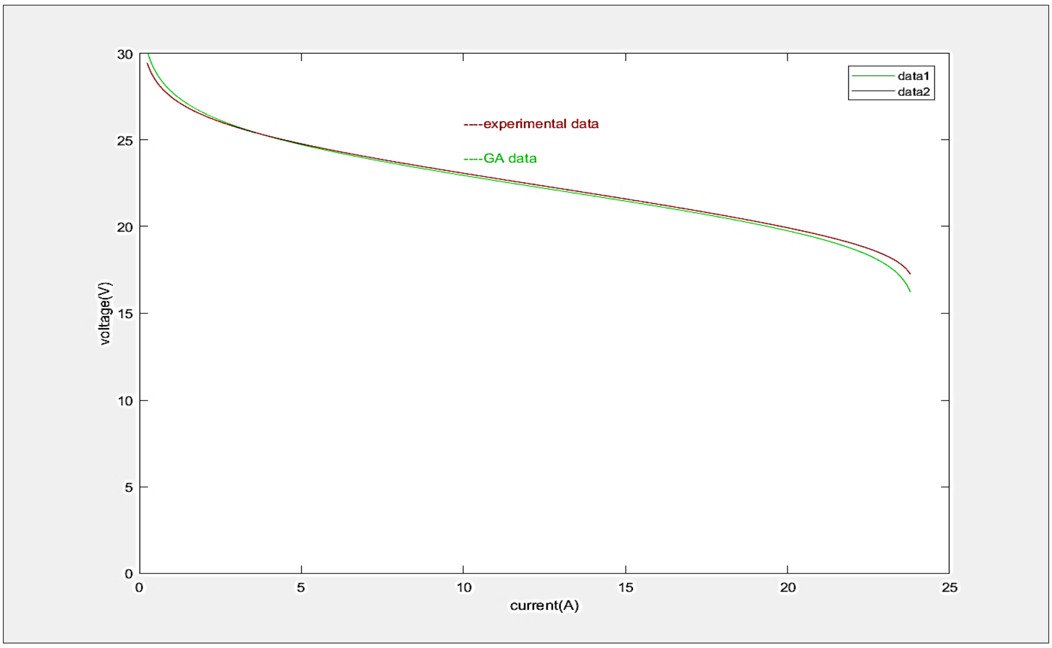


Fig. 6.9. V-I characteristic curve from Experimental and actual simulated data models

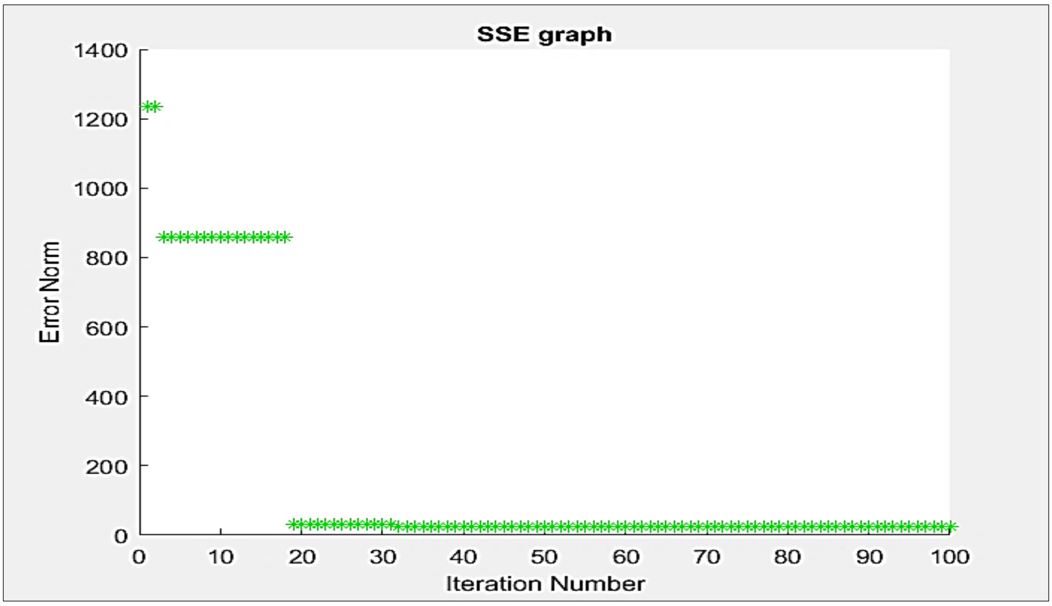


Fig. 6.10. Error Graph

Chapter Summary

A MATLAB-Simulink model of a PEM fuel cell models was developed in order to extract experimental as well as Optimised parameters. A simple Genetic Algorithm procedure is utilized for parameter Optimisation of a PEM fuel cell. The following $\varepsilon 1, \varepsilon 2, \varepsilon 3, \varepsilon 4, b, Rc, \lambda$ 07 parameters were derived from the simulation models. The results obtained from the procedure are displayed utilizing the traditional curve-fitting approach and the V-I characteristics obtained post optimisation agrees well with the experimental data. This new methodology of infusing the Genetic algorithm codes into a MATLAB - Simulink functional block model will help in better appreciation of the algorithm and the processes involved in modeling of a fuel cell. The Simulink model provides a cost-effective simulation strategy for design of a propulsion plant for marine platforms. Future studies can be undertaken keeping the optimised parameters as baseline values.

Chapter 7 Conclusion and Future perspectives

Conclusion

7.1 The focus of the present study has been to gain an understanding of implementation of an optimal Air Independent Propulsion (AIP) system onboard conventional submarine. The simulation modeling was undertaken using Paramarine and MATLAB-Simulink software to establish the baseline and optimisation of AIP system. The initial formulation of AIP data vis-à-vis combinations of AIP systems and storage options of batteries combinations were coded in MATLAB and the derived results were exported into a MS Excel format. A Multiple Criteria Decision Making (MCDM) or Multiple Criteria Decision Analysis (MCDA) tools viz., Forced Decision Matrix (FDM) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) were incorporated to identify the best suitable AIP system for installation onboard submarines. Therefore, as a first step in the direction of research exhaustive literature survey and field surveys were undertaken in Indian and Foreign shipyards and subsequently the research was transformed to field based on the concrete findings of the research. The research has taken into account all the generic specifications of conventional submarines (operational as on date as well as the models under construction). Based on the simulation studies and subsequent analysis of Original Equipment Manufactures' specifications and feasibility of installation on an actual field plug model the details are highlighted at the end of each chapters. The generic conclusions from this work are summarised below:

(a) A Multi Criteria Decision making (MCDM) infused project management approach is required to select and subsequently install an Air Independent Propulsion (AIP) system onboard an existing conventional diesel electric submarine or any futuristic design.

(b) The AIP system is to be used an energy top-up device to the existing storage batteries onboard submarines in comparison to the idea of utilisation of the system as an independent power source. The studies undertaken gives a distinct advantage of the former option and increase the overall efficiency of the system.

(c) Forced Decision Matrix (FDM) methodology was implemented in order to segregate the best possible AIP plug amongst four closely available AIP technologies (Closed Cycle Diesel (CCD) Engine, Module et Sous Marine Autonome (MESMA), Stirling Engine & Fuel Cells) suitable for fitment onboard a diesel electric submarine.

(d) A Multi Criteria Decision Making (MCDM) methodology - TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is utilised to achieve the best possible fuel cell implementation amongst the four options in a marine environment (Polymer Electrolyte Membrane (PEM), Phosphoric Acid Fuel Cell (PAFC), Solid Oxide Fuel Cell (SOFC) & Molten Carbonate Fuel Cell (MCFC)).

(e) Towards assessing the initial sizing of the submarine and the various AIP options the equations and governing parameters are coded into MATLAB. The results for various different combinations are exported to a MS-Excel file. Further Marine simulation software Paramarine was undertaken to assess the stability of the AIP plug.

(f) MATLAB- SIMULINK model of PEM fuel cell is modelled and the values are optimised using Simple Genetic Algorithm (SGA)

(g) The main outcome of the study is to identify the best possible AIP option amongst the existing alternatives by use of FDM (chapter 3). Amongst the existing marine grade Fuel Cells, the most optimal fuel cell which can be efficiently exploited was identified using a MCDM -technique-TOPSIS (chapter 4). Two MATLAB programs are presented to analyse the effects of insertion of AIP plug. The final AIP system is intended to be installed onboard a Submarine of length 68 m and Diameter of 6.2m. The length of the plug is calculated to be 9.94 m and hence the overall length of the submarine will be 77.94m with a diameter -6.2 m. The merits of the system are that the overall system stealth is enhanced and allows a submerged endurance of 14 to 18 days at loiter speed of 3.5- 4 knots. The major demerits include that the submarine will experience increased resistance due to the increase in length of the body. The loss in speed (high power consumed) is actually negligible when compared to the features which the AIP system offers.

7.2 Future Scope and Perspectives

It is observed that the following can be explored in the future research towards optimisation of the system: -

(a) The present studies concerning the auxiliary propulsion powering system are restricted in endurance mainly because of limitation in the storage capacity of fuel Viz., Oxygen and Hydrogen storage. A completely new concept of AIP exploitation based on batteries and super capacitor hybrid combinations can be studied upon.

(b) Higher and more efficient forms of diesel reforming will aid in absolving the requirement to carry Liquid Oxygen (LOX) and Hydrogen using various storage options.

(c) Implementation of high-power Stirling AIP engine in lieu of both diesel engine or a combination of conventional diesel engine with AIP Stirling Engine for snorting conditions can be studied. With German Type 212 A submarines employing only a single diesel engine for its normal operations, the concept of conventional diesel engine along with Stirling AIP will emerge as a game changer in the underwater scenario.

(d) Present study caters the widely prevalent lead acid batteries as the storage option. With the present limitation AIP cannot function as an independent power source but can only exist as an additional option. Other higher energy density batteries like Lithium, Sodium Sulphide and Zebra Batteries in conjunction with AIP plug can be studied to assess the overall increase in efficiency of the submarine.

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Appendix A

MATLAB Program for optimisation of parameters.

```
%% comment:
% main script is one to check the exactness of
GA
% Firstly  make predefined parameters. we use
this data as experimental data.
% Secondly, assume that we don't know the
parameters and find the parameters using the GA
method and MPP
clc;
close all;
clear all;
% make artificial experimental data
data=GetModel();% get model
I=data.Imax/100 : data.Imax/1000 :
data.Imax*0.99;% set the current variable vector
x=[-0.8020, 2.9521e-3 , 6e-5, -1.5812e-4 , 13 ,
2.47e-4, 0.0261];% parameter, epsilon1,..,
epsilon4,  lambda, Rc, b setting
U_ex=GetVfc(I,data,x);% calculate the voltage of
PEM
figure(1);
title('U-I relation graphics(default parameter
model)');
plot(I,U_ex);
[Umpp,Impp]=get_mpp(U_ex,I);% get voltage and
current of MPP
data.Umpp=Umpp;
data.Impp=Impp;
data.U_ex=U_ex;
data.I=I;
%%------------------------ Intialization -------
----------------------%%
maxIter=100; % maximum iteration number
ps=20; % popular size
cr=0.8; % crossover rate
mr=0.4; % mutation rate
nv=7; % numbers of variables
```

```
%% step 1 - generate population
pop=randi([0, 1023], ps, nv); % generate
population

    %% step2 - select parents with
probability=0.8

for iter=1:maxIter;
    pop=ArrangePop(pop,data);% arrange
population according to chrome's object function
value
    n=ceil(ps*0.8);% selected parents number
    pop=pop(1:n,:);
    parents=dec2bin(pop,10);
    %% step3- crossover with crossover rate,
mutation with mutation rate
    pair_list=randperm(n);
    cross=parents;

    for i=1:2:n-1
        for j=1:nv
            i1=(pair_list(i)-1)*nv+j;% chrome
number
            i2=(pair_list(i+1)-1)*nv+j;% chrome
number
            m=randperm(10,cr*10);% cr apply
            % cross over operating
            cross(i1,m)= parents(i2,m);
            cross(i2,m)= parents(i1,m);
            % mutation
            mi=randperm(10,mr*10);
            for kk=mi
                if(cross(i1,kk)=='1')
                    cross(i1,kk)='0';
                else
                    cross(i1,kk)='1';
                end
                if(cross(i2,kk)=='1')
                    cross(i2,kk)='0';
                else
                    cross(i2,kk)='1';
                end
            end
        end
    end
```

```
    child=bin2dec(cross);
    child=reshape(child,n,nv);
    pop=[pop ; child];

    %% check population

    % Get The Best Solution
    [pop,minF1]=ArrangePop(pop,data);
    best=pop(1,:);
    [dstParam,
minF]=ChromeToSolution(best,data);% unknown
parameters from chrome
    format long;
    %% match experimental curve and calculated
curve
    figure(1);
    hold off;
    plot(I,U_ex,'-r');
    hold on;
    Vfc=GetVfc(I,data,dstParam);% get fuel cell
voltage
    plot(I,Vfc,'g');
    text(10,15,'experimental data','color','r');
    text(10,20,'GA data','color','g');
    ylim([0,28]);
    %% SSE
    ErrorVector=U_ex-Vfc;
    sse=sum(ErrorVector.^2);
    figure(2);
    title('SSE graph');
    hold on;
    plot(iter,sse,'*r');
    xlim([0,maxIter]);
    drawnow;
end
% figure(1);
% title('U-I characteristic graph tracked by
Genetic Algorithm');
% hold on;
% grid on;
% plot(I,Vfc,'g');
% plot(I,U_ex,'r');
% plot(Impp,Umpp,'v');
figure(1);
hold on;
%diplay labe on the axis
```

```
xlabel('I (current-[A]');
ylabel('U (Stack Voltage-[V]');
title('Experimental graph and Tracking Graph of
GA');
display(sprintf('q1=%d q2=%d q3=%d q4=%d
lambda=%d Rc=%d b=%d',dstParam));
%(1),...
 %   dstParam(2), dstParam(3), dstParam(4),
dstParam(5), dstParam(6));


figure(2);
hold on;
xlabel('Iteration Number');
ylabel('Error Norm');
```

```
function [newpop, minF]=ArrangePop(oldpop,model)
%Arrange Population according to the rule from
low to high
    ps=size(oldpop,1);
    y=zeros(ps,1);
    for i=1:ps
        x=oldpop(i,:)/1024.*(model.ub-
model.lb)+model.lb;
        y(i)=ObjFun(x,model);
        %y(i)=ObjFum_MPP(x,model);
    end;
    [yy,I] =sort(y,'ascend');
    newpop=oldpop;
    for i=1:ps
        newpop(i,:)=oldpop(I(i),:);
    end
    minF=yy(1);
end
```

```
function [sse]=CheckPop(pop,data)
    figure(2);
    grid on;
    xlim([0,25]); ylim([0,30]);
    % Get The Best Solution
    [pop,minF1]=ArrangePop(pop,data);
    best=pop(1,:);
```

```
    [dstParam,
minF]=ChromeToSolution(best,data);
    format long;
    dstParam
    minF
    %% match experimental curve and calculated
curve
    i=data.I/data.A; U=data.U;
    hold off;
    plot(data.I,U,'r');
    hold on;
    Vfc=GetVfc(i,data,dstParam);
    plot(data.I,Vfc,'g');
    plot(data.impp*data.A, data.Umpp,'og')
     %% SSE
    ErrorVector=data.U-Vfc;
    sse=sum(ErrorVector.^2)
    figure(3);
    title('SSE graph');
    hold on;
    plot(data.curIter,sse,'*r');
    xlim([0,data.maxIter]);
    ylim([0,10e4]);
    drawnow;
end
```

```
function [x,minF]=ChromeToSolution(chrome,model)
% get real solution from chrome data
    x=chrome/1024.*(model.ub-model.lb)+model.lb;
    minF=ObjFun(x,model);
    %minF=ObjFun_MPP(x,model);
end
```

```
function [umpp,impp]=get_mpp(U,I)
%% return valtage umpp and impp of MPP from U-I
data
P=U.*I;
[Pmax,id]=max(P(:));
umpp=U(id);
impp=I(id);
end
```

```
function [model]=GetModel()
% ------------------------------ Input Data
Setup  ----------------------
model={};
model.T=350;% PEM Temperature 343.15~153.15 K
model.N=24;% cell numbers
Psat=2.95e-2*(model.T-273.15)-9.18e-5*(model.T-
273.15)^2+1.44e-7*(model.T-273.15)^3-2.18;
model.Psat=10^Psat;% saturation pressur of water
vapour [atm]
model.RHa=1;% relative humidity in anode
model.RHc=1;% relateiv humidity in cathode
model.A=27; % active area of cell [cm^2]
model.Pc=3;% or all value in range 1~5, cathode
pressure[bar]
model.Pa=2.5;%or all value in range 1~3, anode
pressure[bar]
%l is the thickness of the membrane(cm)
model.l=127e-4;
%model.Imax=0.86e4;% Maximum current density
Imax[A/cm^2]
model.ub=[-0.944,0.005,7.8e-5,-1.88e-4,23,8e-
4,0.5  ];
model.lb=[-0.952,0.001,7.4e-5,-1.98e-4,14,1e-
4,0.016];
model.Imax=0.89*model.A;% maximum current [A]
model.Impp=0;
model.Umpp=0;
model.I=[];
model.U_ex=[];
% [U,I]=get_testdata(1,model.Imax);
% model.I_ex=I;
% model.U_ex=U;
% [model.Umpp,model.Impp]=get_mpp(U,I);
```

```
function [Vfc]=GetVfc(I,model,x)
%% return voltage of pem , I: current [A],
% model: modelling structure
% x: fitness parameter variable
% x(1): epsilon1,x(2): epsilon 2, x(3): epsilon
3, x(4):epsilon4
% x(5): b, (
    q1=x(1);
```

```
    q2=x(2);
    q3=x(3);
    q4=x(4);
    lamda=x(5);
    Rc=x(6);
    b=x(7);


PO2=(model.RHc*model.Psat).*(1./(exp(4.192.*(I/m
odel.A)/model.T^1.334)*(model.RHc*model.Psat)/mo
del.Pc)-1);

PH2=0.5*(model.RHa*model.Psat).*(1./(exp(1.635.*
(I/model.A)/model.T^1.334)*(model.RHa*model.Psat
)/model.Pa)-1);

    %reversible voltage of Cell
    Enst=1.029-0.85e-3*(model.T-273.15)+4.3085e-
5*model.T*(log(PH2)+0.5*log(PO2));

    %consentration of dissolved oxygen(mol/cm3)
    CO2=PO2/(5.08e6*exp(-498/model.T));

    % voltage drop due to the activation of the
anode and cathode
    Vact=-
(q1+model.T*(q2+q3*log(CO2)+q4*log(I)));

    %roM is the specific resistivity of the
membrane ofr the electron flow(om*meter)

RoM=181.6*(1+0.03*(I/model.A)+0.062*(model.T/303
)^2*(I/model.A).^2.5)./(lamda-0.634-
3*(I./model.A))./exp(4.18*(model.T-
303)/model.T);

    %equivalent resistance of the membrane(om)
    RM=RoM*model.l/model.A;

    % the ohmic voltage(V)
    Vom=I.*(RM+Rc);

    % voltage drop(V) due to the mass transport
    Vcon=-b.*log(1-I/model.Imax);
```

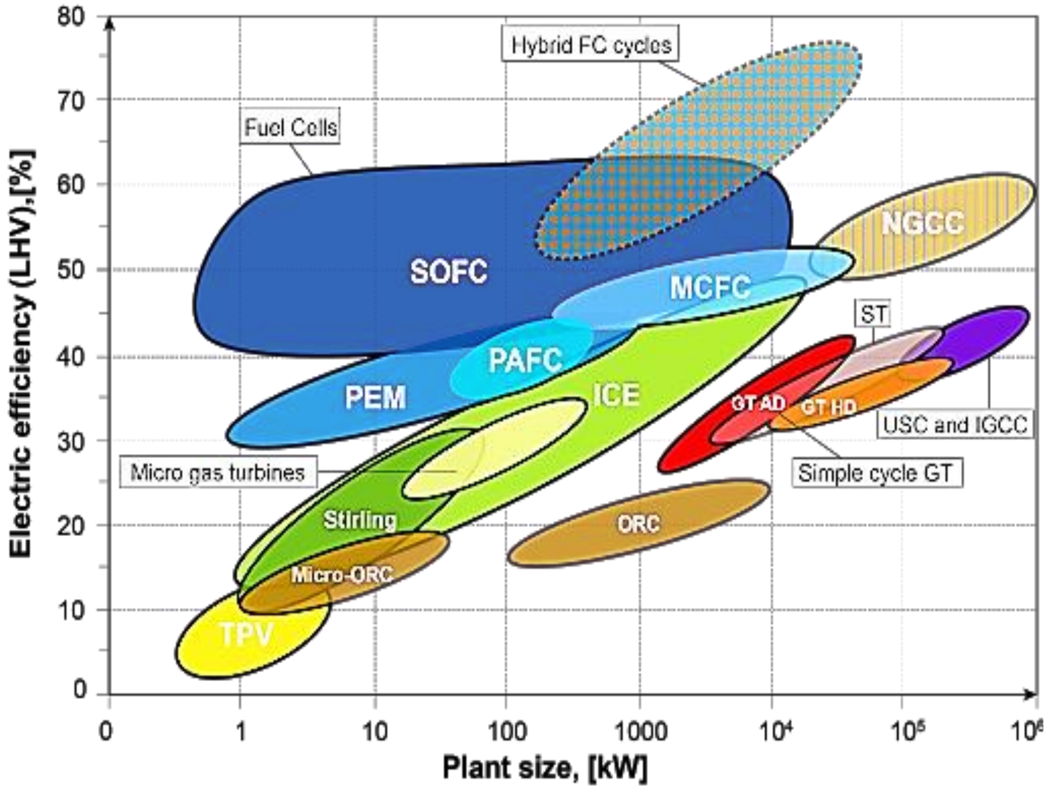
```
    Vfc=model.N*(Enst-Vact-Vom-Vcon);% total
voltage between anode and cathode

end
```

```
function y=ObjFun(x,model)

% calculate Object Function
Vfc=GetVfc(model.I,model,x);
ErrorVector=model.U_ex-Vfc;
y=sum(ErrorVector.^2);

end
```



	AFC	PEFC	PAFC	MCFC	SOFC
Temperature	low	<100°C →		Up to 1000°C	high
Catalyst	pure	Platinum ←		metal	less pure
Gas specification	clean	4-5,0 H_2 →		C_nH_m	less clean
Cell efficiency	low	40-50% →		50-60%	high
System complexity	low	Reforming System ←		Internal Ref.	high
Start-Up-Time	At once	Seconds →		Hours	high
Dynamic	high	←			low

Fig 1: Graphical representation of Plant size and critical parameters of Fuel cells

Fuel Cell Type	Polymer Electrolyte Membrane (PEMFC)	Alkaline (AFC)	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Fuel	H_2	H_2	H_2	H_2/CO/reformate	CO, H_2
Oxidizer	O_2, air	O_2, air	O_2, air	CO_2,O_2, air	O_2, air
Common Electrolyte	Hydrated Polymeric Ion Exchange Membranes	Mobilized or Immobilized Potassium Hydroxide in asbestos matrix	Immobilized Liquid Phosphoric Acid in SiC	Immobilized Liquid Molten Carbonate in $LiAlO_2$	Perovskites (Ceramics)
Operating Temperature	40 – 80 °C	65 – 220 °C	205 °C	650 °C	600 -1000 °C
Typical Stack Size	1kW-250kW	10-100kW	400W	300kW-3MW	1kW-2MW
Efficiency	60% (Transportation) 35% (Stationary)	60%	40%	50-60%	50-60%
Applications	-Backup power -Portable power -Distributed generation -Transportation -Specialty vehicle	-Military -Space	Distributed generation	-Electric utility -Distributed generation	-Auxiliary power -Electric utility -Distributed generation
Advantages	-Solid electrolyte reduce corrosion & electrolyte management problems -Low temperature -Quick start-up	-Cathode reaction faster in alkaline electrolyte, leads to high performance -Low cost component	-High temperature enable -Increase tolerance to full impurities	-High efficiency -Fuel flexibility -Can use variety of catalyst -Suitable for CHP	-High efficiency -Fuel flexibility -Can use variety of catalyst -Solid electrolyte -Suitable for CHP&CHHP -Hybrid/GT cycle
Challenges	-Expensive catalyst -Sensitive to fuel impurities	Electrolyte management	-Pt catalyst -Long start up time	-High temperature corrosion and breakdown of cell components -Long start up time -Low power density	High temperature corrosion and breakdown of cell components

Table 1: Advantages and Disadvantages of Fuel Cells

	L/D										
SUBD	7.5	8	8.5	9	9.5	10	10.25	10.5	11	11.5	12
2200	4402.943	4384.906	4371.78	4362.567	4356.511	4353.028	4352.105	4351.662	4352	4353.9	4357
2250	4448.808	4430.479	4417.136	4407.767	4401.6029	4398.051	4397.106	4396.649	4397	4398.9	4402
2300	4494.315	4475.697	4462.139	4452.614	4446.3423	4442.722	4441.756	4441.284	4441.7	4443.5	4446.7
2350	4539.476	4520.57	4506.798	4497.119	4490.7397	4487.052	4486.063	4485.577	4485.9	4487.8	4491
2400	4584.3	4565.108	4551.124	4541.29	4534.8048	4531.049	4530.039	4529.538	4529.9	4531.8	4535
2450	4628.796	4609.32	4595.125	4585.138	4578.5471	4574.724	4573.692	4573.177	4573.5	4575.4	4578.7

Table2 : Submerged Displacement (SUBD) Vs Shaft Horse Power (SHP)

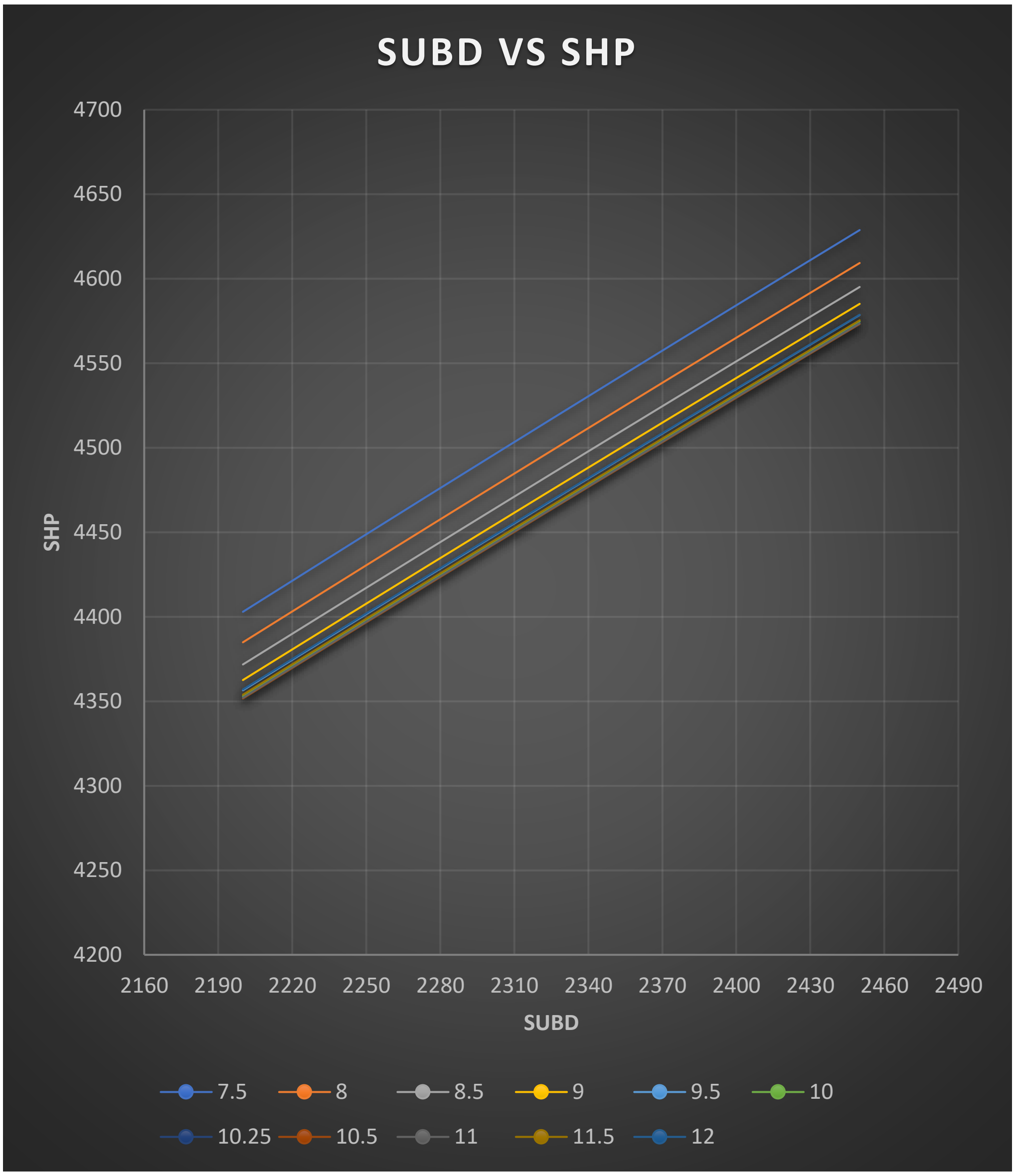


Fig 2: Graphical representation of Submerged Diameter (SUBD) Vs Shaft Horse Power (SHP)

	L/D										
SUBD	7.5	8	8.5	9	9.5	10	10.25	10.5	11	11.5	12
2200	60.01551	62.37205	64.68978	66.97059	69.216336	71.42878	72.52305	73.6096	75.76	77.882	79.977
2250	60.46677	62.84103	65.17619	67.47415	69.736779	71.96586	73.06835	74.16308	76.33	78.468	80.579
2300	60.91139	63.30312	65.65544	67.9703	70.249568	72.49504	73.60564	74.70841	76.891	79.045	81.171
2350	61.34962	63.75855	66.1278	68.45931	70.754978	73.01661	74.13519	75.2459	77.444	79.614	81.755
2400	61.78167	64.20757	66.5935	68.94143	71.253268	73.53083	74.65729	75.77582	77.99	80.174	82.331
2450	62.20777	64.65039	67.05278	69.41691	71.744686	74.03795	75.17218	76.29843	78.528	80.727	82.899

Table 3:- Submerged Displacement (SUBD) Vs Length (L)

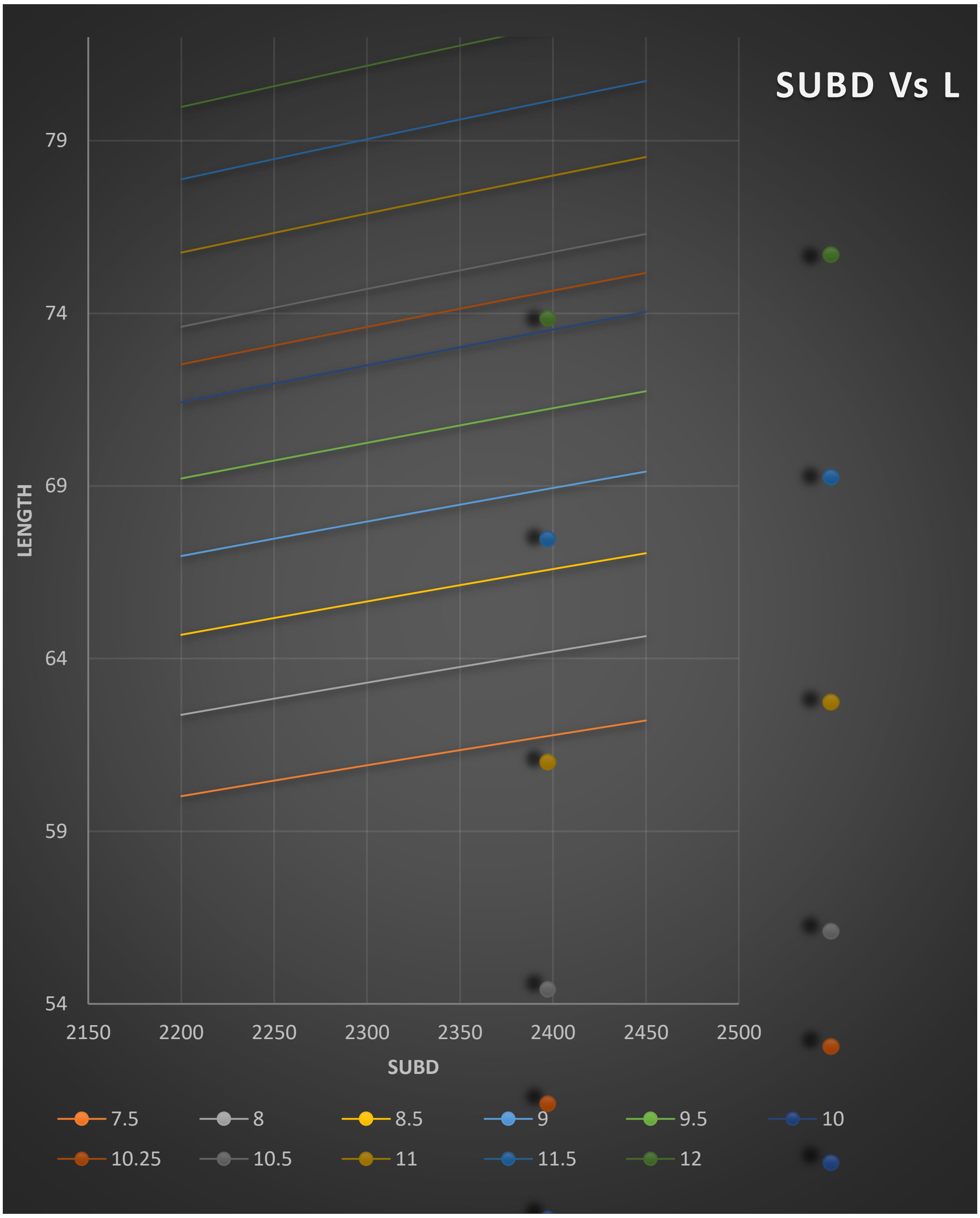


Fig 3: Graphical representation of Submerged Diameter (SUBD) Vs Length (L)

	L/D										
SUBD	7.5	8	8.5	9	9.5	10	10.25	10.5	11	11.5	12
2200	8.002067	7.796507	7.610563	7.441177	7.2859301	7.142878	7.075419	7.010438	6.8873	6.7724	6.6648
2250	8.062236	7.855129	7.667787	7.497128	7.3407136	7.196586	7.12862	7.06315	6.9391	6.8233	6.7149
2300	8.121519	7.91289	7.72417	7.552255	7.3946913	7.249504	7.181038	7.115087	6.9901	6.8735	6.7643
2350	8.179949	7.969819	7.779741	7.60659	7.4478924	7.301661	7.232702	7.166276	7.0404	6.9229	6.8129
2400	8.237556	8.025946	7.83453	7.660159	7.5003441	7.353083	7.283638	7.216745	7.09	6.9717	6.8609
2450	8.294369	8.081299	7.888563	7.71299	7.5520722	7.403795	7.333872	7.266517	7.1389	7.0198	6.9082

Table 4 : Submerged Displacement (SUBD) Vs Diameter (D)

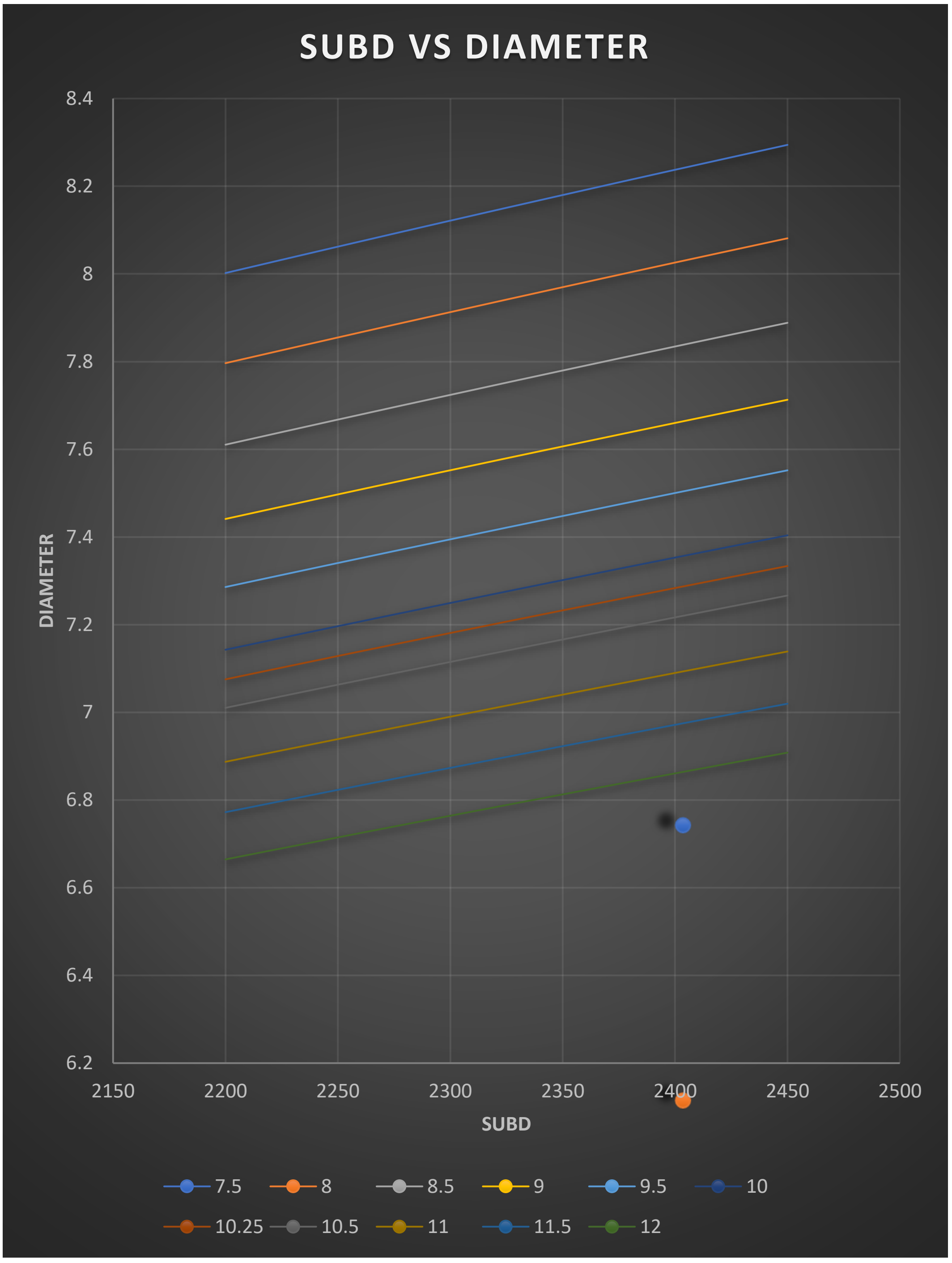


Fig 4: Graphical representation of Submerged Diameter (SUBD)Vs Diameter(D)

Estimation of motor power

Shaft Power = Effective Power / Propulsive Coefficient

P_C = 0.82

$$P_{prop} = \frac{\rho_s}{\eta_m}$$

$\eta_m - motor\ efficiency$

Effective power – 2204.3062 kw

Shaft power = (2204.3062/0.82) =2688.18kw.

Motor efficiency = 0.92

Power estimated = (Shaft power/Motor efficiency)

= 2688.18/0.92 = 2921.93 KW

Estimation of Parallel Mid -Body

According to Capt Jackson's Paper – Fundamentals of Submarine Concept Design the length of the submarine can be determined by the following

$$L = L_a + L_{pmb} + L_f$$

$$L_a = 3.6D$$

$$L_f = 2.4\ D$$

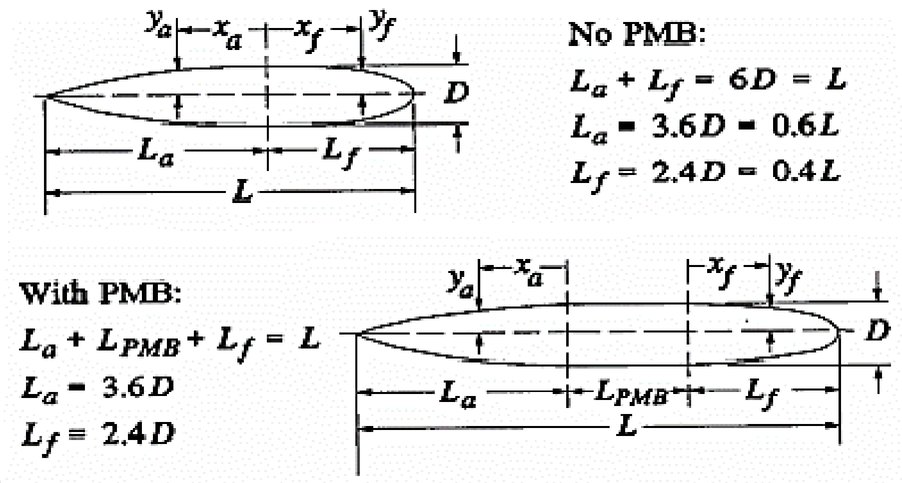


Fig 5: Graphical representation of geometry of submarine

Considering a constant D =6.2 m

L_a = 3.6 * 6.2 = 22.32m

L_f = 2.4 *6.2 = 14.38m

L_{pmb} = 40.94 m

Therefore L =22.32+14.38+40.94 = 77.94 m

Table 5: - Estimation of Power Using Paramarine

speed (kt)	effective_power (kW)	shaft_power (kW)	advance_ratio	shaft_speed (RPM)	open_water_efficiency (%)	wake_fraction	thrust_deduction	rotative_efficiency	shaft_torque (MNm)
0	0	0	0	0	0	0	0	0	0
1	0.513	0.6	0.875	5.889	64.772	0.249	0.063	1.079	0.001
2	3.762	4.324	0.895	11.511	65.93	0.249	0.063	1.079	0.004
3	12.115	13.796	0.906	17.058	66.551	0.249	0.063	1.079	0.008
4	27.817	31.477	0.913	22.561	66.969	0.249	0.063	1.079	0.013
5	53.045	59.747	0.919	28.032	67.282	0.249	0.063	1.079	0.02
6	89.93	100.922	0.923	33.479	67.529	0.249	0.063	1.079	0.029
7	140.568	157.274	0.927	38.907	67.733	0.249	0.063	1.079	0.039
8	207.026	231.039	0.93	44.319	67.907	0.249	0.063	1.079	0.05
9	291.348	324.424	0.932	49.717	68.057	0.249	0.063	1.079	0.062
10	395.557	439.61	0.935	55.103	68.189	0.249	0.063	1.079	0.076
11	521.659	578.757	0.937	60.478	68.306	0.249	0.063	1.079	0.091
12	671.645	744.004	0.939	65.844	68.413	0.249	0.063	1.079	0.108
13	847.492	937.475	0.94	71.201	68.509	0.249	0.063	1.079	0.126
14	1051.165	1161.276	0.942	76.551	68.597	0.249	0.063	1.079	0.145
15	1284.617	1417.501	0.943	81.893	68.679	0.249	0.063	1.079	0.165
16	1549.792	1708.231	0.945	87.229	68.754	0.249	0.063	1.079	0.187
17	1848.623	2035.534	0.946	92.559	68.824	0.249	0.063	1.079	0.21
18	2183.035	2401.467	0.947	97.883	68.89	0.249	0.063	1.079	0.234
19	2554.944	2808.079	0.948	103.201	68.951	0.249	0.063	1.079	0.26
20	2966.261	3257.408	0.949	108.515	69.009	0.249	0.063	1.079	0.287

Table 6: - Calculations of a CCD AIP System

Sizing Model for AIP Systems-Closed Cycle Diesel -Assumes 360 kW Power Required					
Time Deployed (Days)	Hours	Oxygen Usage Rate 0.84 Kg/Kwh	Fuel Usage rate 0.30 Kg/kwh	Plant Weight 20 Kg/Kw	Total Weight
7	168	50.8032	18.144	10.8	79.7472
8	192	58.0608	20.736	10.8	89.5968
9	216	65.3184	23.328	10.8	99.4464
10	240	72.576	25.92	10.8	109.296
11	264	79.8336	28.512	10.8	119.1456
12	288	87.0912	31.104	10.8	128.9952
13	312	94.3488	33.696	10.8	138.8448
14	336	101.6064	36.288	10.8	148.6944
15	360	108.864	38.88	10.8	158.544
16	384	116.1216	41.472	10.8	168.3936
17	408	123.3792	44.064	10.8	178.2432
18	432	130.6368	46.656	10.8	188.0928
19	456	137.8944	49.248	10.8	197.9424
20	480	145.152	51.84	10.8	207.792
21	504	152.4096	54.432	10.8	217.6416

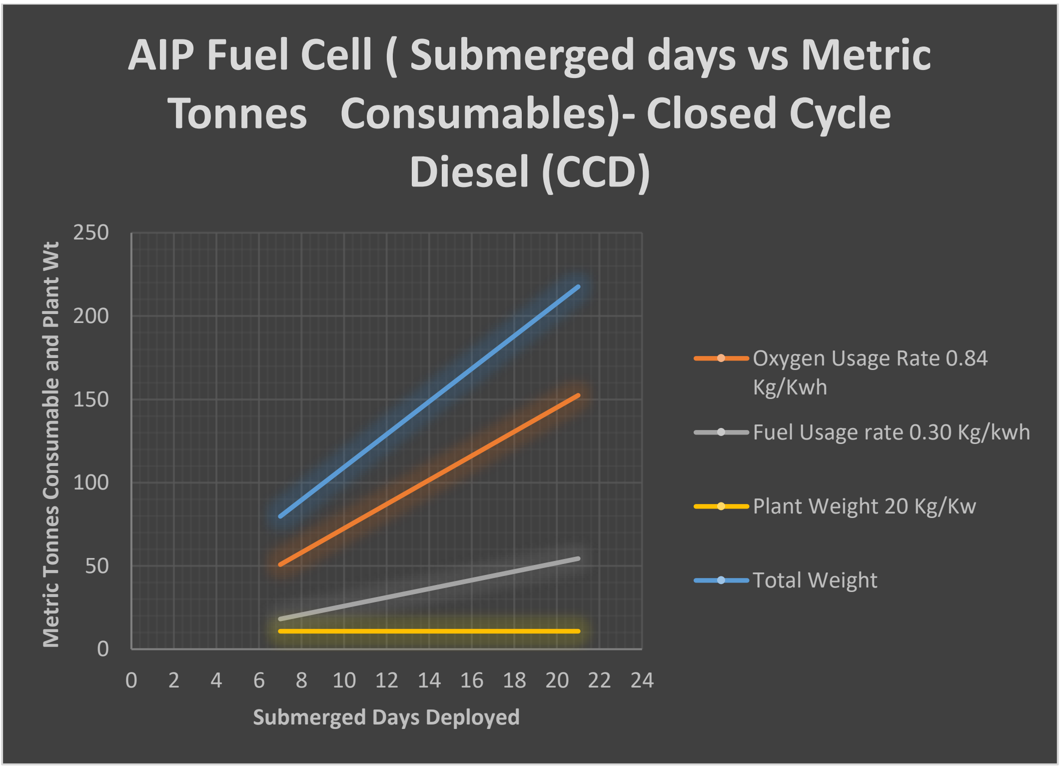


Fig 6: Graphical representation of fuel consumption of AIP-CCD system

Table 7: - Calculations of a Stirling- AIP System

sizing Model for AIP Systems-Stirling Cycle -Assumes 360 kW Power Required					
Time Deployed (Days)	Hours	Oxygen Usage Rate 1.3Kg/Kwh	Fuel Usage rate 0.33Kg/Kwh	Plant Weight 30 Kg/Kw	Total Weight
7	168	78.624	19.9584	10.8	109.3824
8	192	89.856	22.8096	10.8	123.4656
9	216	101.088	25.6608	10.8	137.5488
10	240	112.32	28.512	10.8	151.632
11	264	123.552	31.3632	10.8	165.7152
12	288	134.784	34.2144	10.8	179.7984
13	312	146.016	37.0656	10.8	193.8816
14	336	157.248	39.9168	10.8	207.9648
15	360	168.48	42.768	10.8	222.048
16	384	179.712	45.6192	10.8	236.1312
17	408	190.944	48.4704	10.8	250.2144
18	432	202.176	51.3216	10.8	264.2976
19	456	213.408	54.1728	10.8	278.3808
20	480	224.64	57.024	10.8	292.464
21	504	235.872	59.8752	10.8	306.5472

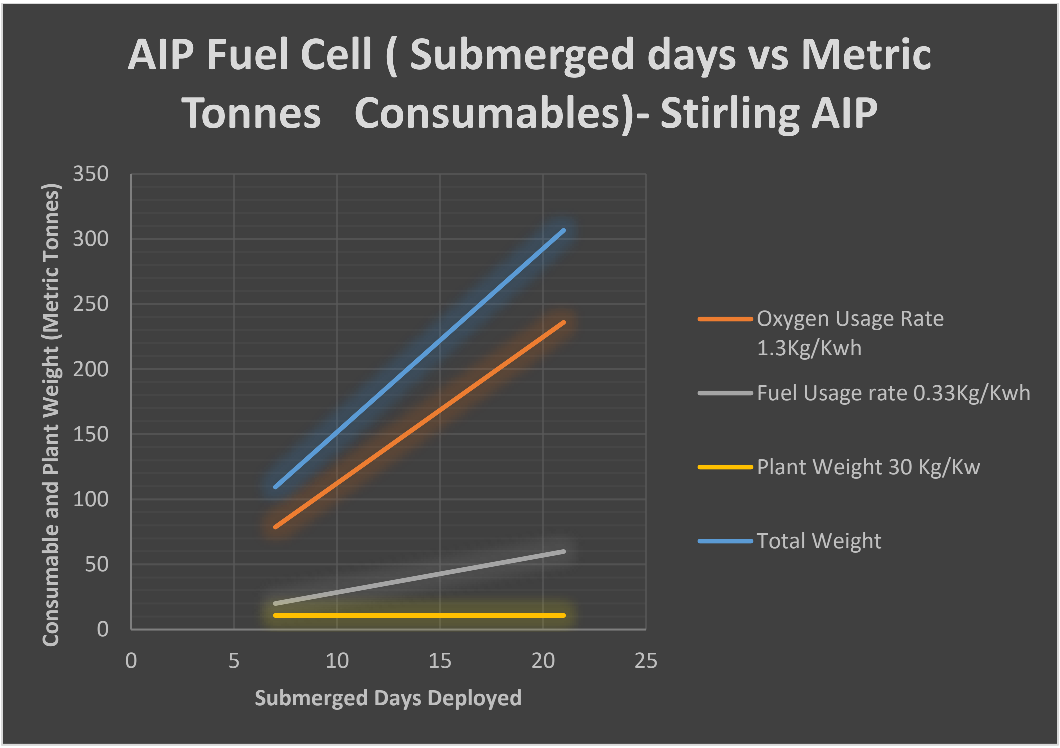


Fig 7: Graphical representation of fuel consumption of AIP-Stirling system

Table 8: - Calculations of a MESMA- AIP System

Sizing Model for AIP Systems-Stirling Cycle -Assumes 360 kW Power Required					
Time Deployed (Days)	Hours	Oxygen Usage Rate 1.9Kg/Kwh	Fuel Usage rate 0.55Kg/Kwh	Plant Weight 42 Kg/Kw	Total Weight
7	168	114.912	33.264	15.12	163.296
8	192	131.328	38.016	15.12	184.464
9	216	147.744	42.768	15.12	205.632
10	240	164.16	47.52	15.12	226.8
11	264	180.576	52.272	15.12	247.968
12	288	196.992	57.024	15.12	269.136
13	312	213.408	61.776	15.12	290.304
14	336	229.824	66.528	15.12	311.472
15	360	246.24	71.28	15.12	332.64
16	384	262.656	76.032	15.12	353.808
17	408	279.072	80.784	15.12	374.976
18	432	295.488	85.536	15.12	396.144
19	456	311.904	90.288	15.12	417.312
20	480	328.32	95.04	15.12	438.48
21	504	344.736	99.792	15.12	459.648

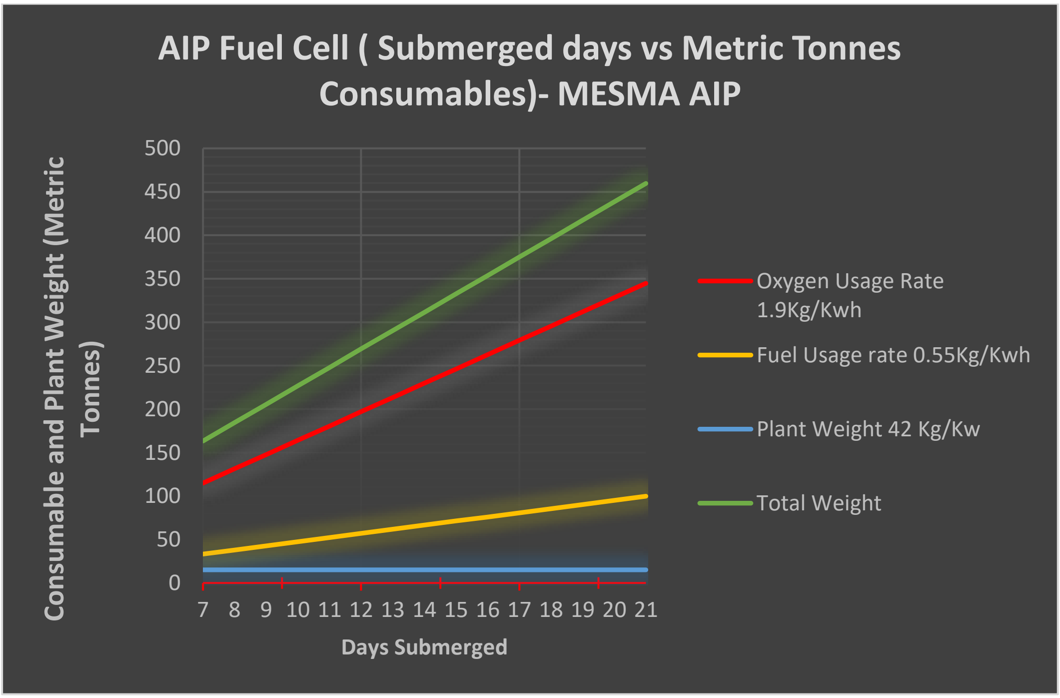


Fig 8: Graphical representation of fuel consumption of AIP-MESMA system

AIP SIZING PROGRAM OUTPUT(Plant:PEM/Battery:Lead Acid)					
INPUT DATA FOR AIP		**MARGINS**			
Total Ship Range (nm)	10000.00	Fixed Ballast (% NSC)	0.11		
Snort range @10 kts (nm)	5200.00	Variable Load(% NSC)	0.05		
Submerged @ 8 kts AIP (days)	25.00	Outboard Items (% Vph)	0.18		
Submerged creep @ 4 kts on battery (hours)	90.00	Res. Buoyancy(% Veb)	0.15		
Submerged burst @ 20 kts on battery (hours)	2.93	Freeflood Volume (% Veb)	0.06		
Submerged transit @ 13 kts on battery (hours)	14.14	**Envelope**			
Recharge time @ 4 kts (hours)	5.37	Length (m)	63.04		
SOA (m/s)	5.15	Diameter (m)	9.45		
Indiscretion Ratio	0.26	L/D	6.67		
Diving Depth (m)	274.32	Cpf	0.75		
CrewSize(m)	12.80	Cpa	0.64		
Torpedo Tubes	6.00	Cwsf	0.85		
Reloads (days)	22.00	Cwsa	0.75		
Mission Length (days)	60.00				
VOLUMES (m^3)		**WEIGHTS (ltons)**			
Weapons	213.50	Structure	795.15		
Mobility	1445.11	Mobility	1184.35		
Ship Support	412.44	Weapons	56.08		
C^3I	150.08	CI^3I	66.07		
Pressure Hull	2221.13	Ship Support	105.60		
Outboard	399.80	FixedBallast	303.39		
Everbuoyant	2620.93	Variable Load	132.14		
Main BallastTanks	379.10	Normal SurfCondition	2642.77		
Submerged	3000.03				
Freeflood	157.26				
Envelope	3171.33				
MOBILITY					
Battery Type	Lead Acid				
Number of Batteries	6.62				
Battery:Weight(lton	505.89				
Volume(m^3)	150.00				
Capacity(kW-hr @ 2hr rate)	10594.48				
Propulsive Coeff	0.86				
InstalledSHP	3998.29				
Hotel Load (kW)	142.14				
Bunker Fuel(ltons)	4770.99				
AIP					
AIP Plant Size (kW)	359.88				
Type	PEM	Weight(ltons)	6.38	Volume(m^3)	3.50
Reformer	YES	Weight(ltons)	6.38	Volume(m^3)	4.32
Oxidant	LOX	Weight(ltons)	158.58	Volume(m^3)	293.49
Breath.LOX	NO	Weight(ltons)	4.06	Volume(m^3)	7.44
Fuel	METHANOL	Weight(ltons)	72.27	Volume(m^3)	91.72
Other	COMP WATER	Weight(ltons)	34.65	Volume(m^3)	247.51
Cosworth	YES	Weight(ltons)	0.59	Volume(m^3)	23.99
Totals		Weight(ltons)	282.90	Volume(m^3)	671.96

Fig 9: Sample output of AIP Model with Lead acid battery

AIP SIZING PROGRAM OUTPUT(Plant:PEM/Battery:Lais)

INPUT DATA FOR AIP		MARGINS	
Total Ship Range (nm)	10000.00	Fixed Ballast (% NSC)	0.12
Snort range @10 kts (nm)	5200.00	Variable Load(% NSC)	0.05
Submerged @ 8 kts AIP (days)	25.00	Outboard Items (% Vph)	0.18
Submerged creep @ 4 kts on battery (hours)	90.00	Res. Buoyancy(% Veb)	0.15
Submerged burst @ 20 kts on battery (hours)	2.05	Freeflood Volume (% Veb)	0.06
Submerged transit @ 13 kts on battery (hours)	15.04	**Envelope**	
Recharge time @ 4 kts (hours)	4.83	Length (m)	58.71
SOA (m/s)	5.30	Diameter (m)	9.45
Indiscretion Ratio	0.23	L/D	6.21
Diving Depth (m)	274.32	Cpf	0.75
CrewSize(m)	12.80	Cpa	0.64
Torpedo Tubes	6.00	Cwsf	0.85
Reloads (days)	22.00	Cwsa	0.75
Mission Length (days)	60.00		

VOLUMES (m^3)		WEIGHTS (ltons)	
Weapons	213.50	Structure	719.22
Mobility	1315.71	Mobility	1043.26
Ship Support	329.11	Weapons	56.08
C^3I	150.08	CI^3I	59.76
Pressure Hull	2008.39	Ship Support	97.12
Outboard	361.51	FixedBallast	295.46
Everbuoyant	2369.91	Variable Load	119.52
Main BallastTanks	355.49	Normal SurfCondition	2390.41
Submerged	2725.39		
Freeflood	142.19		
Envelope	2867.59		

MOBILITY	
Battery Type	Lais
Number of Batteries	16.98
Battery:Weight(lton	62.66
Volume(m^3)	34.74
Capacity(kW-hr @ 2hr rate)	6266.34
Propulsive Coeff	0.86
InstalledSHP	3751.44
Hotel Load (kW)	130.87
Bunker Fuel(ltons)	5114.10

AIP					
AIP Plant Size (kW)	335.09				
Type	PEM	Weight(ltons)	5.94	Volume(m^3)	3.25
Reformer	YES	Weight(ltons)	5.94	Volume(m^3)	4.02
Oxidant	LOX	Weight(ltons)	147.65	Volume(m^3)	273.27
Breath.LOX	NO	Weight(ltons)	4.06	Volume(m^3)	7.44
Fuel	METHANOL	Weight(ltons)	67.29	Volume(m^3)	85.40
Other	COMP WATER	Weight(ltons)	32.26	Volume(m^3)	230.46
Cosworth	YES	Weight(ltons)	0.55	Volume(m^3)	22.34
Totals		Weight(ltons)	263.69	Volume(m^3)	626.18

Fig 10: Sample output of AIP Model with LAIS battery

1	AIP SIZING PROGRAM OUTPUT(Plant:PEM/Battery:Ni/Cd)					
2						
3	INPUT DATA FOR AIP		MARGINS			
4	Total Ship Range (nm)	10000.00	Fixed Ballast (% NSC)	0.11		
5	Snort range @10 kts (nm)	5200.00	Variable Load(% NSC)	0.05		
6	Submerged @ 8 kts AIP (days)	25.00	Outboard Items (% Vph)	0.18		
7	Submerged creep @ 4 kts on battery (hours)	90.00	Res. Buoyancy(% Veb)	0.15		
8	Submerged burst @ 20 kts on battery (hours)	4.59	Freeflood Volume (% Veb)	0.06		
9	Submerged transit @ 13 kts on battery (hours)	15.27	Envelope			
10	Recharge time @ 4 kts (hours)	5.84	Length (m)	63.64		
11	SOA (m/s)	5.16	Diameter (m)	9.45		
12	Indiscretion Ratio	0.26	L/D	6.74		
13	Diving Depth (m)	274.32	Cpf	0.75		
14	CrewSize(m)	12.80	Cpa	0.64		
15	Torpedo Tubes	6.00	Cwsf	0.85		
16	Reloads (days)	22.00	Cwsa	0.75		
17	Mission Length (days)	60.00				
18						
19	VOLUMES (m^3)		WEIGHTS (ltons)			
20	Weapons	213.50	Structure	805.79		
21	Mobility	1491.03	Mobility	1223.67		
22	Ship Support	395.90	Weapons	56.08		
23	C^3I	150.08	CI^3I	66.95		
24	Pressure Hull	2250.51	Ship Support	106.79		
25	Outboard	405.09	FixedBallast	284.95		
26	Everbuoyant	2655.60	Variable Load	133.91		
27	Main BallastTanks	387.48	Normal SurfCondition	2678.13		
28	Submerged	3043.08				
29	Freeflood	159.34				
30	Envelope	3213.28				
31						
32	MOBILITY					
33	Battery Type	Ni/Cd				
34	Number of Batteries	13.94				
35	Battery:Weight(lton	529.62				
36	Volume(m^3)	264.42				
37	Capacity(kW-hr @ 2hr rate)	16738.70				
38	Propulsive Coeff	0.86				
39	InstalledSHP	4032.25				
40	Hotel Load (kW)	143.69				
41	Bunker Fuel(ltons)	4727.45				
42						
43	AIP					
44	AIP Plant Size (kW)	363.29				
45	Type	PEM	Weight(ltons)	6.44	Volume(m^3)	3.53
46	Reformer	YES	Weight(ltons)	6.44	Volume(m^3)	4.36
47	Oxidant	LOX	Weight(ltons)	160.08	Volume(m^3)	296.27
48	Breath.LOX	NO	Weight(ltons)	4.06	Volume(m^3)	7.44
49	Fuel	METHANOL	Weight(ltons)	72.95	Volume(m^3)	92.59
50	Other	COMP WATER	Weight(ltons)	34.97	Volume(m^3)	249.86
51	Cosworth	YES	Weight(ltons)	0.60	Volume(m^3)	24.22
52	Totals		Weight(ltons)	285.54	Volume(m^3)	678.26
53						

Fig 11: Sample output of AIP Model with NiCd battery

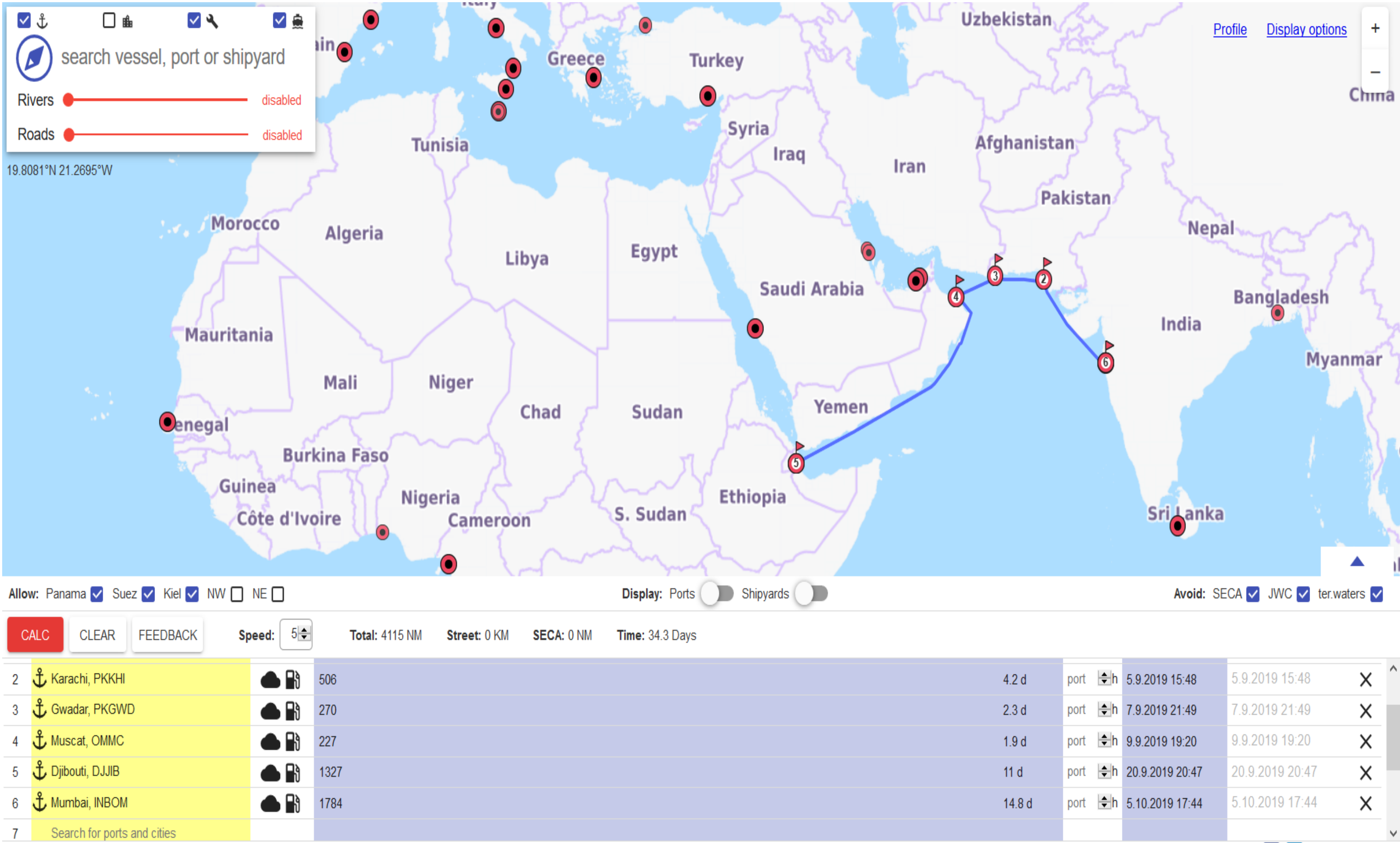


Fig 12: -Speculative route Calculations: Mumbai – Karachi- Gwadar- Muscat- Djibouti- Mumbai

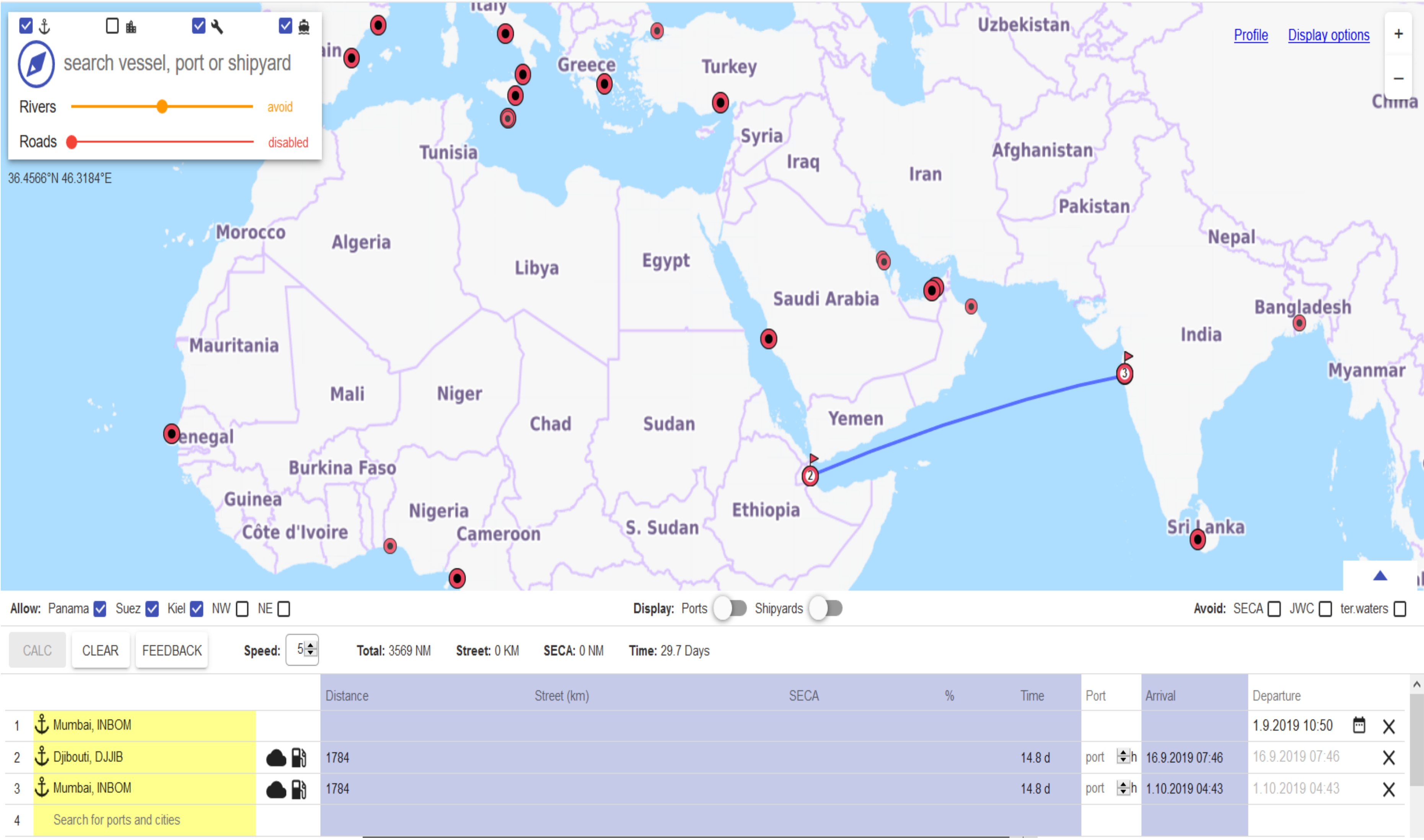


Fig 13: -Speculative route Calculations: Mumbai –Djibouti- Mumbai

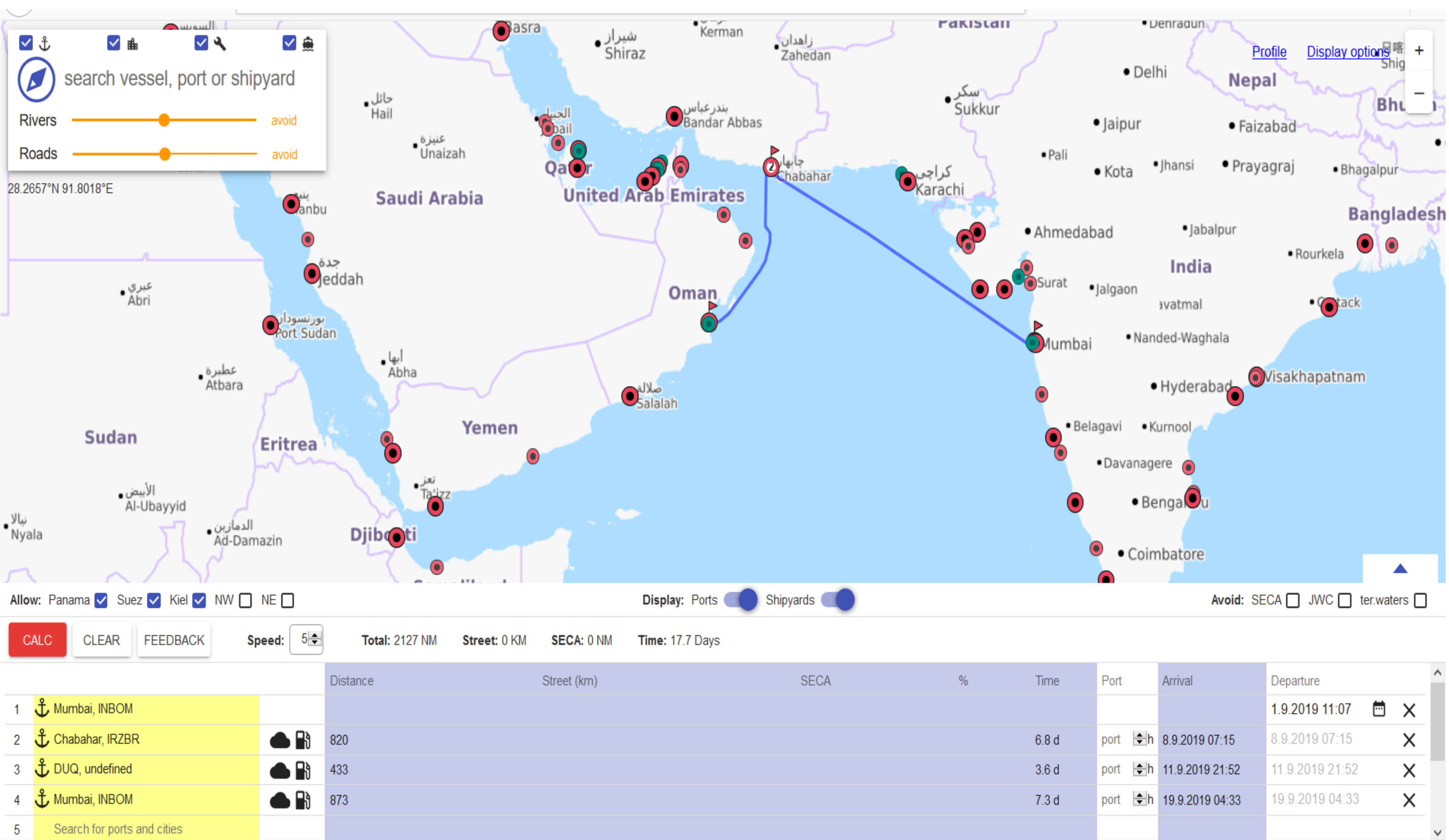


Fig 14:- Speculative route Calculations: Mumbai – Chabahar- Duqm- Mumbai

Fig 15 :- Submarine Cutsections for AIP Plug fitment at construction yard

CDR R RAAJIV

EDUCATION

(a) 2010-2013 M. Tech (Energy Management) Devi Ahiliya Vishwa Vidyalaya (DAVV), Indore.

(b) 2000-2004 B. Tech (Electrical & Electronics Engineering) Naval College of Engineering, INS Shivaji, Lonavala.

DETAILS OF PUBLICATIONS

Sr. No.	Title of Paper	Name of Journal	Status
1.	Realisation of optimal parameters of PEM fuel cell using Simple Genetic Algorithm (SGA) and Simulink Modeling	International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249-8958 (Online), Volume-8 Issue-6, August 2019, Page No.:1542-1548	Published
2.	Selection of Optimal Air Independent Propulsion (AIP) System using Forced Decision Matrix (FDM)	Defence Science Journal, 70(1), 103-109. https://doi.org/10.14429/dsj.70.13678	Published
3.	Emergence of Air Independent Propulsion (AIP) Technology – Past, Present and Future perspectives	Journal of Naval Architecture and Marine Engineering (JNAME)	Communicated and under review

4.	Determination of optimal Fuel-Cell Air Independent Propulsion (AIP) system using TOPSIS-MCDM Technique	Defence Science Journal	Communicated and under review

Conferences

Sr. No.	Name of conference	Title of Paper
1.	International Conference on Nano for Energy and Water (NEW 2017), UPES, Dehradun	Hydrogen Storage- A Game changer in Air Independent Propulsion for Submarines

Thesis

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