

**OPTIMIZATION OF AN ON-BOARD FUEL CELL SYSTEM
FOR SUBMARINE OPERATION**

by

Dongmin Shin

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

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ABSTRACT

The goal of this research is to model, simulate, and optimize an AIP (air independent propulsion) system for submarines. The basic submarine power plant platform chosen for the simulations is the diesel generator with fuel cells.

The submarine simulator was formulated in Matlab/Simulink with a dedicated model for every onboard subsystem such as the diesel generator, the battery, the fuel cell, as well as propulsion and hotel loads. The simulator was validated with performance data obtained from a standard conventional submarine. Considering the physical volume of the equipment and required fuels, four power plant configurations are suggested. The baseline configurations consist of three 1500kW diesel generator systems and no fuel cells (3/0). The other three configurations were defined by sequentially replacing each diesel generator with a 240kW fuel cell, viz. two diesels with one a 240kW-FC (2/1), one diesel with a 480kW-FC (1/2), and a 720kW-FC only (0/3).

Analyzing various submarine operations (anti-surface ship/submarine warfare, land attack operation, intelligence gathering mission, and network-centric warfare), we formulated four representative duty cycles which are expressed as velocity vs. time profiles. The power plant configurations were implemented into our simulator, and we obtained results for diesel/hydrogen consumption, and battery state-of-charge vs. time. The optimal configuration was obtained as one diesel with a 480kW-FC (1/2).

Finally, we suggested other practical applications of our simulator and presented some examples. We then forecast potential deployments of fuel cell systems in the naval security environment.

Chapter 1

INTRODUCTION

1.1 Introduction to Air Independent Propulsion (AIP) System

The submarine is a vital part of the defense strategy for most naval powers around the world. Its strategic value has been proved repeatedly since the time of World War I. German U-boats brought the United Kingdom close to surrender in World War II, and Argentinian submarines thwarted the United Kingdom's naval forces for a long time during the Falklands War. Today, the submarine represents a critical naval platform for asymmetric warfare and constitutes one of the most lethal weapon systems at sea. Nevertheless, the conventional submarine also has a critical weak point.

There was high loss rate of U-boats in the battle of the Atlantic, when confronted by Allied maritime patrol aircraft. Diesel-electric U-boats needed to surface to recharge their battery systems, which made them susceptible to detection by the rudimentary radar equipment carried by Allied forces. To enable longer periods of submerged U-boat operation, a snorkeling system was developed whereby the submarine erected a "snorkel mast" to inhale external air while still submerged to feed the on-board diesel engines to recharge the battery. The invention and development of the snorkel mast was a breakthrough during its time; today the snorkel mast has undergone significant improvements such as cladding with radar-absorbent materials and streamlining to minimize its bow wave and signature as shown in Figure 1.1 [1].

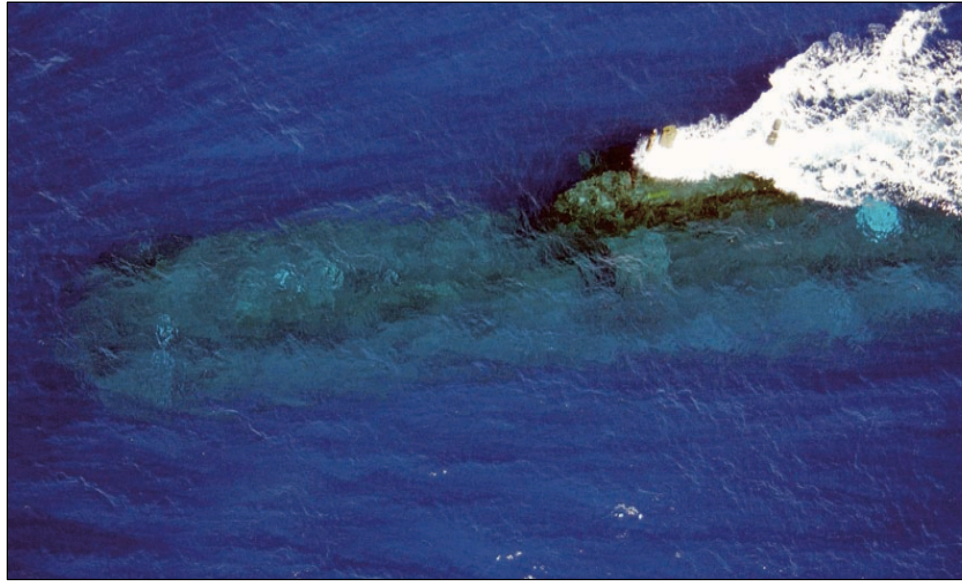


Figure 1.1: Submarine deploying its snorkel while running submerged [1]

As radar technologies have evolved, aircraft are able to detect even snorkeling submarines more easily. For example, the high resolution Synthetic Aperture Radar (SAR) employed by the P-3C (a representative Maritime Patrol Aircraft) can detect a snorkeling submarine from a long distance away [2].

The obvious solution to prevent detection is to minimize snorkeling by spending as much time fully submerged as possible. Nuclear submarines are, of course, able to spend very long periods fully submerged. However, non-nuclear submarines, which are the subject of this thesis, employ air-breathing Diesel engines for surface propulsion. When operating below the surface, such submarines require an auxiliary power source for air independent propulsion(AIP). AIP has been under development for more than half a century. Although different countries adopted different AIP technologies under their own specific situations, most of them were successful in increasing the submarine's submerged endurance.

1.2 Comparison of AIP system for submarines

One of the most important requirements for an AIP system is not to rely on atmospheric intake air from the surface in order to increase the submerged time. Various AIP technologies have been developed by different countries as described below.

1.2.1 The Closed Cycle Diesel system

The closed-cycle diesel system is an adaptation of the diesel generators that are already used on diesel-electric submarines for surface propulsion. During submerged operation, the diesel engine must be supplied with a stored oxidant, typically liquid oxygen. In order to avoid excessively high combustion temperatures, the oxidant is diluted with exhaust gas. Therefore, the engine's exhaust gas must be captured, and some of the carbon dioxide is absorbed using a high-pressure seawater management system. This CO₂-depleted exhaust gas is then mixed with stored oxygen and argon before entering the diesel engine. This system is very vulnerable to fires while providing very limited endurance gain; as a result, submarines employing such systems were scrapped in the 1970s [1]. Although the technology developed by the German company Nordsweerde mitigated some of these problems, there is no modern submarine adopting this system. The closed-cycle diesel system can be installed as a retrofit package on existing conventional submarines. Despite the additional complication of regular replenishment of cryogenic oxygen and inert gas, the closed-cycle diesel system offers logistical advantages in retaining the standard diesel engine and using regular diesel fuel [3]. If necessary, it may be appropriate to adapt it into existing conventional submarines.

1.2.2 Stirling engine system

A Stirling engine is a closed cycle engine with a working fluid which is permanently contained in the system as shown in Figure 1.2 [4]. A source of energy is used to heat this working fluid, which in turn moves the pistons and runs the engine. The engine is coupled to a generator, which generates electricity and charges the battery. The source of energy used here is typically Liquid oxygen (LOX) as oxidizer and diesel fuel, which is burnt in order to generate heat for the working fluid. The exhaust is then scrubbed and released into the seawater.

Furthermore, the Stirling engine system is the easy availability of diesel fuel and low refueling costs. Although the system is relatively noisy due to the presence of a large number of moving parts, the noise can be tolerated to some extent because most surface ships use active sonar to detect submarines.

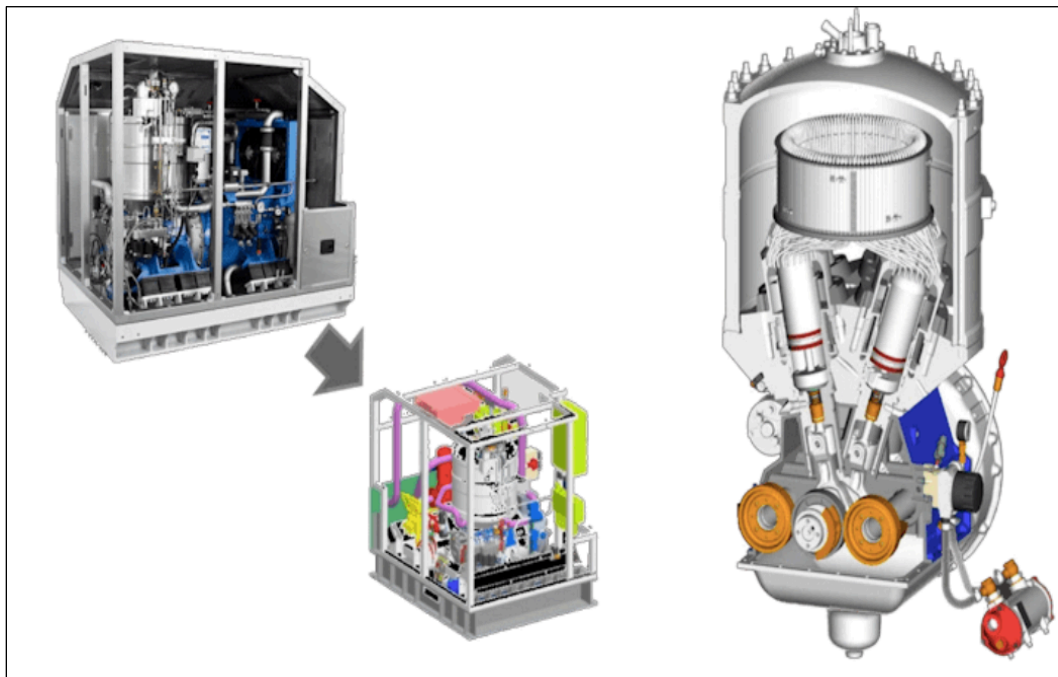


Figure 1.2: Stirling engine system [4]

1.2.3 Nuclear propulsion

Nuclear submarines employ a nuclear fission reactor to generate heat and make high-pressure steam which drives a turbine to propel the submarine. Figure 1.3 shows the working principle of the pressurized-water naval nuclear propulsion system [5]. In fact, the nuclear propulsion system is the ultimate AIP system because it offers virtually unlimited submerged time. Moreover, it enables a submerged submarine to be driven at high speeds without concern of fuel consumption, operate fully capable sensors and weapons systems during extended deployments, and to support a safe and comfortable living environment for the crew [6]. However, the need to constantly pump coolant through the reactor causes some degree of noise although current technologies can decrease the noise to some extent. Nevertheless, nuclear propulsion systems are politically sensitive. For instance, the Republic of Korea (ROK) has limitation to adopt the highly enriched Uranium required for the nuclear propulsion system because of the ROK-U.S. Atomic Energy Agreement.

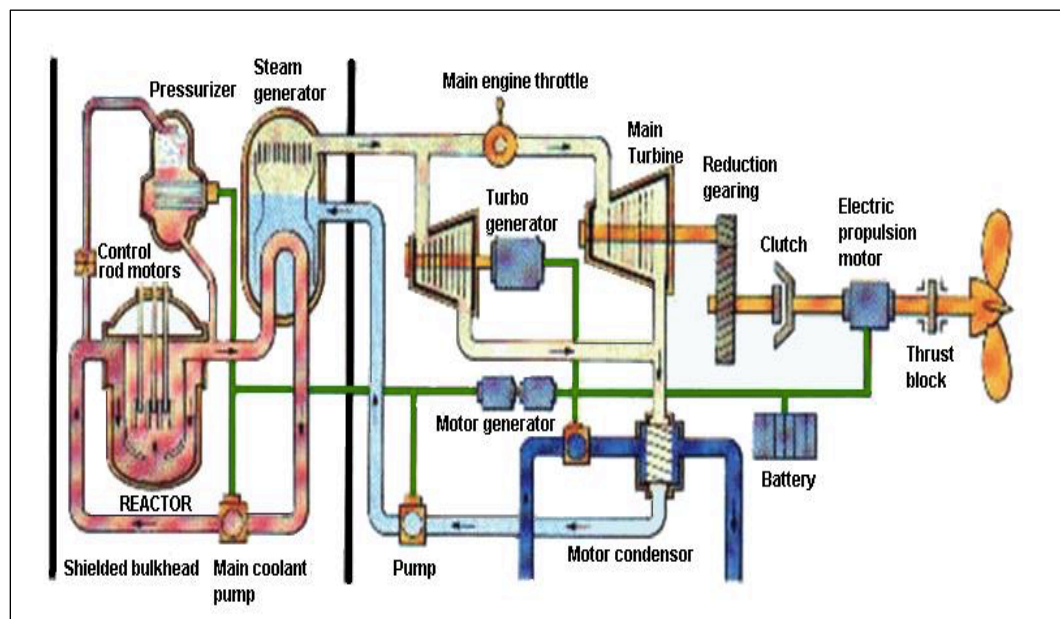


Figure 1.3: Pressurized-water naval nuclear propulsion system [6]

1.2.4 Fuel cell system

Fuel cells systems typically employ a hydrogen-oxygen fuel cell to generate electrical current. These systems have been employed successfully for decades in space vehicles as an energy source for various equipment. The preferred system for a submarine is the polymer electrolyte membrane (PEM) fuel cell system (Figure 1.4) [4]. Among the various fuel cell systems, PEM fuel cells operate at a low temperature of around 80°C and offer high-power density. Although the on-board hydrogen storage tank occupies a large volume, the lack of moving parts makes the system outstanding in terms of noise abatement among all types of current AIP systems. Such a system would be highly desirable for a submarine engaged in intelligence operations or network-centric warfare.

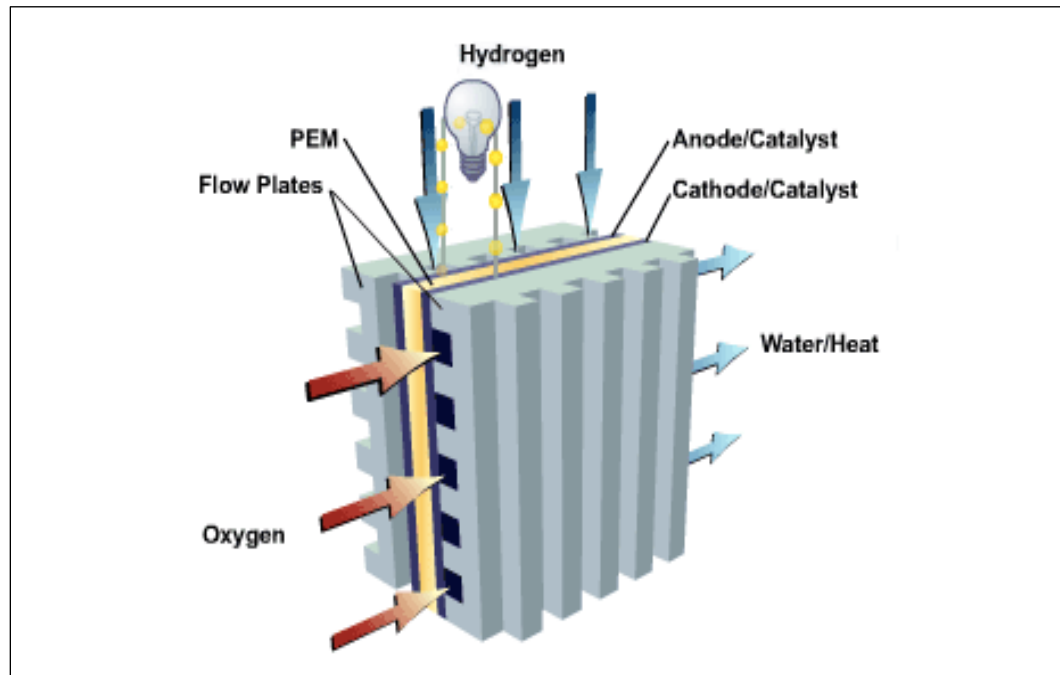


Figure 1.4: Polymer electrolyte membrane fuel cell power system [4]

1.3 Current state of AIP submarines

The end of the Cold War has resulted in reduced East-West polarization, and interstate wars are becoming increasingly unlikely due to economic and political integration, international treaties and disarmament. However, in the post-September 11 world, the threat now comes from low-intensity conflicts which are spawned by and in turn create terrorism, displacement of populations due to lack of economic opportunity, famine, and disease, and the smuggling of drugs and persons on a national and international scale [7]. Small and quiet conventional submarines are considered to be more important than before under this new global security environment. Although their submerged endurance cannot be compared with nuclear-powered submarines as yet, the AIP technology is evolving rapidly and becoming more reliable and powerful. Moreover, the life-cycle cost of the AIP submarine is about three to four times lower, and it is more politically acceptable as well.

The market for conventional submarines with AIP systems is expected to grow all over the world. Figure 1.5 shows that the Asia-Pacific (APAC) region and Europe seem to be the two most significant markets according to current forecasts by Region Global [8]. All major navies in these regions are implementing submarine programs: APAC—China (Yuan class-3,500ton), India (Scorpène class-2,000ton and Project 75I-1,800ton), Japan (Soryu class-3,000ton) and Republic of Korea (Son Won-il U214 class-1,700ton and the anticipated DSX 3000 project-3,000ton); Europe—Germany/Italy U212-1,800ton), Greece/Turkey (U214-1,700 ton), Spain (S-80-2,200ton), Sweden (A-26 project-1,900ton) and Norway (Ula class-1,100ton). Among the above AIP submarines, most have adopted the fuel cell propulsion system because of its outstanding quietness.

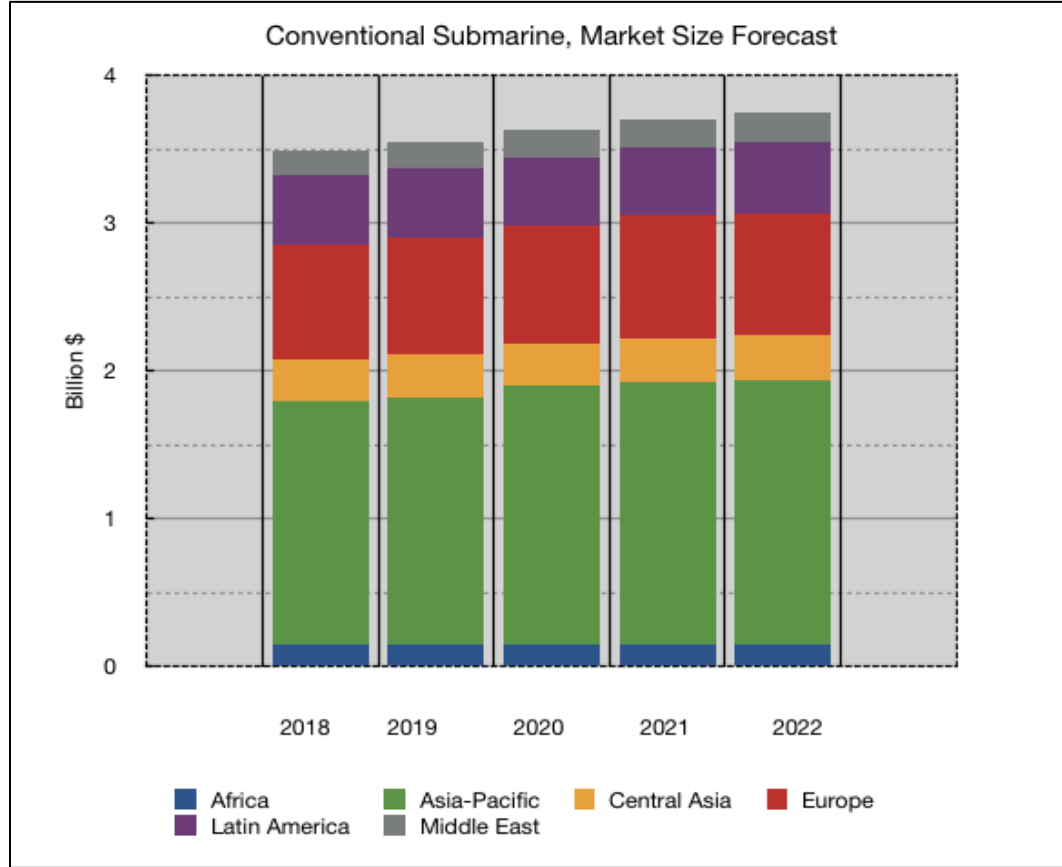


Figure 1.5: Conventional submarine market size forecast [8]

1.4 Related technology for fuel cell propulsion system

1.4.1 Hydrogen storage technology

Polymer electrolyte membrane fuel cells require hydrogen and oxygen to produce electricity. Hydrogen can be stored in many ways as summarized in Figure 1.6 [9]. For a submarine, the volume occupied by the fuel is much more important than the fuel weight which can be compensated for with ballast. Also, the storage method needs to be safe, reliable and easy to maintain. Compressed hydrogen stored in

composites tanks has a relatively low volumetric efficiency ($\text{kg H}_2/\text{m}^3$). Liquid hydrogen has a slightly higher specific volume but must be maintained at cryogenic temperatures to remain a liquid. It is also possible to generate hydrogen on-board by reforming stored methanol by partial oxidation, but the reformer operates at high temperature and produces carbon monoxide which would be very dangerous to submarine crews [10]. Other hydrogen storage options such as physisorption in carbon nanofibers and so on are currently in development and may provide a good option in the future. However, at present the most suitable storage medium for submarine applications is metal hydrides which can store hydrogen with good volumetric efficiency of up to $100\text{kg}/\text{m}^3$ [9]. The process of charging hydrogen into the hydride bed is exothermic, and therefore the hydride bed must be cooled during the hydriding process. During discharge, hydrogen is liberated via an endothermic process which can be driven using waste heat from the fuel cell. Another benefit is that it can be stored outside of the pressure hull as on the board likes U-212 [11].

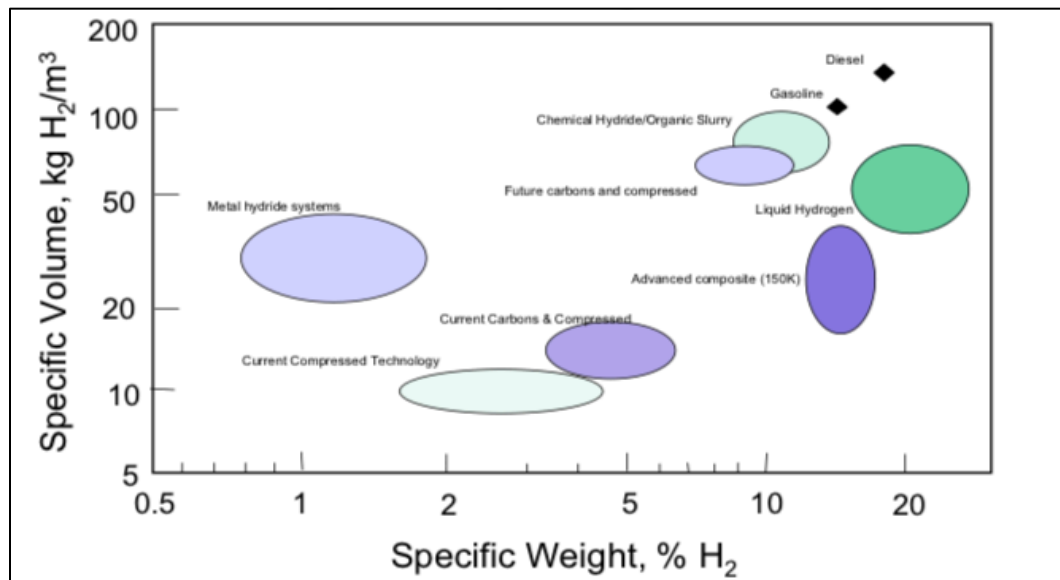


Figure 1.6: Hydrogen storage techniques [9]

1.4.2 Oxygen storage technology

Oxygen can also be stored in various ways as summarized in Figure 1.7 [9]. Liquid oxygen (LOX) is superior to the other storage techniques with a volumetric efficiency of 840 kg/m^3 . Although LOX presents some difficulties such as the need to maintain a low temperature (-118°C) and high pressures (50 bar), submarines such as the U-212 and U-214 have already deployed this technology [12]

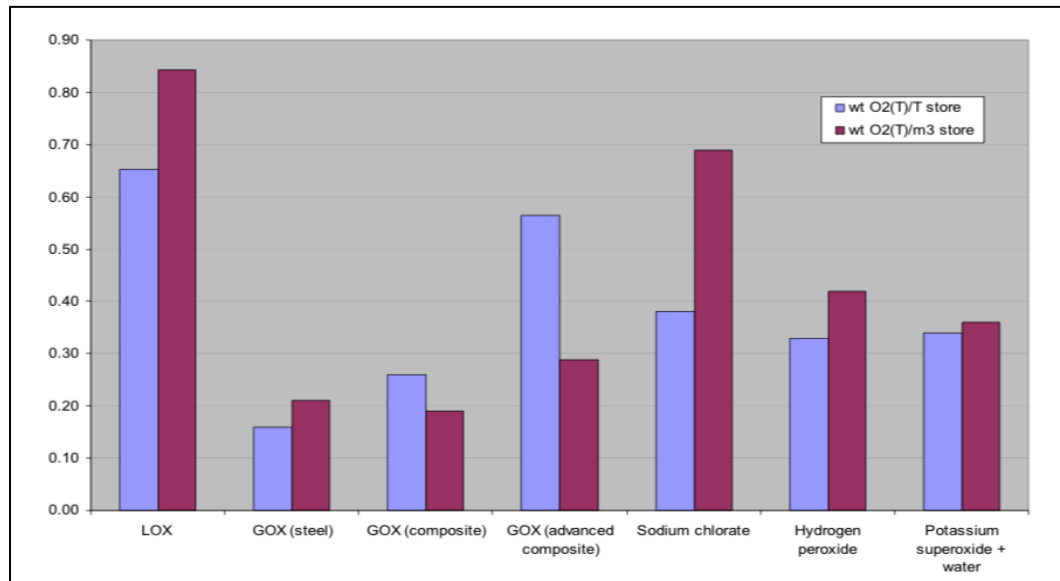


Figure 1.7: Comparison of oxygen storage techniques [9]

1.4.3 Battery technologies

Lead acid batteries have been used on submarines since World War I [3]. The benefits of lead acid batteries are the high discharge currents, deep cycle capability, and high charge acceptance rates which means that the submarine can minimize surface operation time whilst charging its batteries, and thereby reduce its vulnerability. Furthermore, this technology is now fully matured and has proved its reliability in submarine operations over many decades.

Despite the fact that lead acid batteries are currently the state-of-the-art in submarines, lithium-ion batteries battery technology will likely replace them in the near future. Figure 1.8 shows a comparison between the two types of batteries [13]. The Li-ion battery exhibits much better metrics than lead-acid in almost all aspects except cost. For example, the first Li-ion-powered Soryu-class submarine, which will be commissioned in March 2020 in Japan, will cost \$566 million as opposed to \$454 million for its predecessor in the same class. Much of this \$112 million difference is due to the batteries and battery management system [14]. Nevertheless, cost is less of a factor in matters relating to security and defense. In fact, Japan Maritime Self-Defence Force (JMSDF) continues to ask for a Li-ion powered Soryu-class boat in its budget request [14]. Similarly, the Republic of Korea Navy also plans to build three Li-ion battery-powered submarines by 2027 [15]. Therefore, we will adopt the Li-ion battery in the current submarine simulations.

	Flooded lead acid	VRLA lead acid	Lithium-ion (LiNCM)
Energy Density (Wh/L)	80	100	250
Specific Energy (Wh/kg)	30	40	150
Regular Maintenance	Yes	No	No
Initial Cost (\$/kWh) - prices are only a market average and estimate	65	120	600
Cycle Life	1,200 @ 50%	1,000 @ 50% DoD	1,900 @ 80% DoD
Typical state of charge window	50%	50%	80%
Temperature sensitivity	Degrades significantly above 25°C	Degrades significantly above 25°C	Degrades significantly above 45°C
Efficiency	100% @20-hr rate 80% @4-hr rate 60% @1-hr rate	100% @20-hr rate 80% @4-hr rate 60% @1-hr rate	100% @20-hr rate 99% @4-hr rate 92% @1-hr rate
Voltage increments	2 V	2 V	3.7 V

Figure 1.8: Comparison summary between lead acid and Li-ion batteries [13]

MATLAB/SIMULINK MODEL FOR SUBMARINE AIP

2.1 Introduction

Simulation is a very powerful and useful tool to design, evaluate and optimize the performance of the submarine fuel cell AIP system. An accurate and reliable numerical model is extremely cost-effective as it allows us to optimize designs in software without having to build a real system. The simulator used in this thesis to perform AIP performance studies is based on the Matlab/Simulink environment. Matlab is one of the most powerful programs for this type of investigation. Simulink is a graphics-based system within Matlab and can be used to develop the full AIP model.

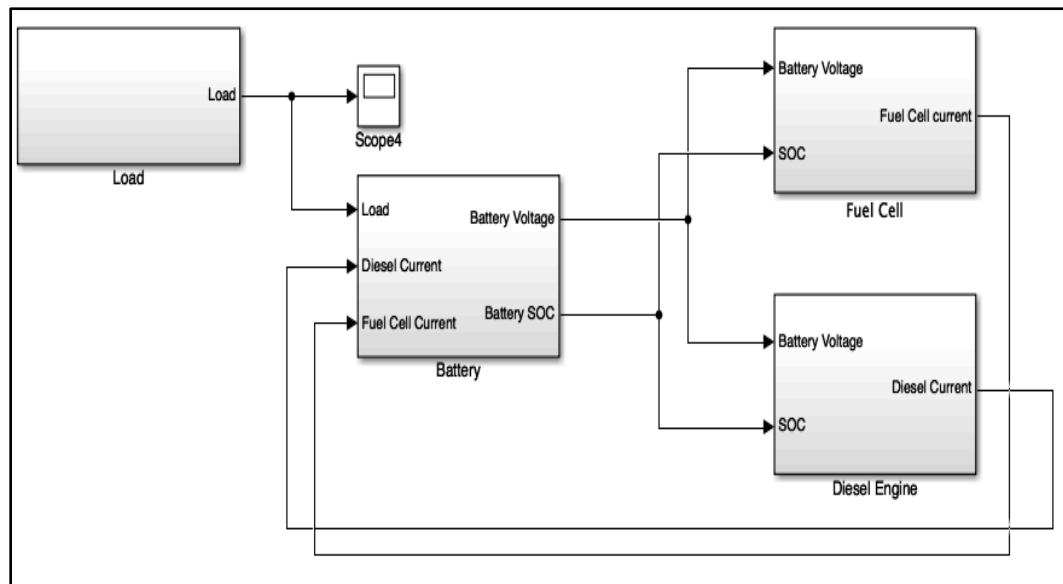


Figure 2.1: The Simulink model for the submarine AIP system

Figure 2.1 shows our Simulink model for the fuel cell AIP system for the submarine. The four main components of the model are the submarine load, the battery, the fuel cell and the diesel engine. The model is designed to simulate and optimize the performance of a fuel cell submarine AIP system under various operating conditions. The following sub-sections present a detailed description of how each subsystem within the overall AIP is constructed, followed by the validation of the model against actual submarine performance data.

2.2 Submarine load

The submarine load is divided into the main propulsion load and the hotel load as shown in Figure 2.2. The main propulsion load is the power required to propel the submarine which is accomplished with a large DC propeller. The hotel load is the power required to sustain the submarine's auxiliary systems such as weapons systems, combat systems, navigation systems, communications systems, and human-support systems including air quality, lighting, and other essential on-board equipment.

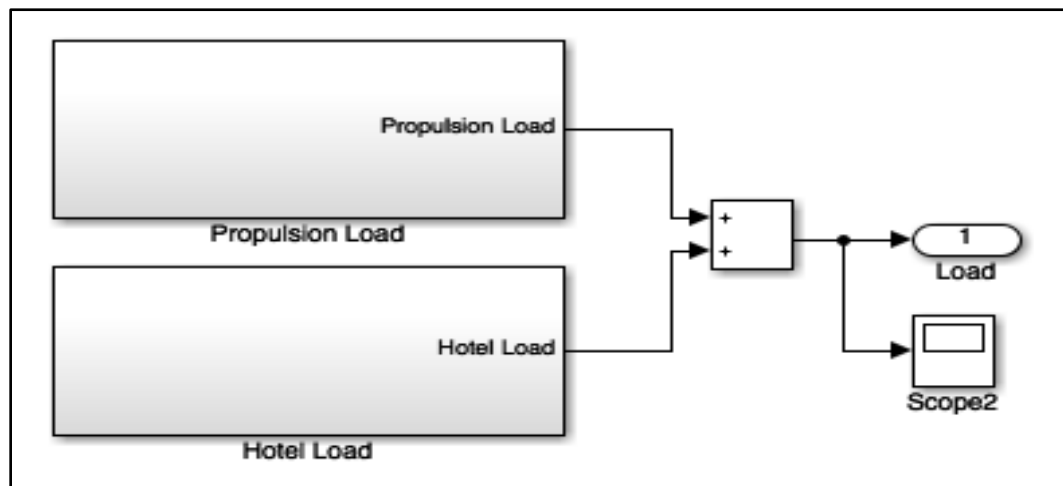


Figure 2.2: The Simulink model for the submarine load

The propulsion load in kW is a function of the submarine's displacement (D) in tons and speed (V) through the water in knots. The drag force on a body moving through a fluid is usually given by $R = C_D \rho_f A V^2$ where C_D is the drag coefficient related to the shape of body, ρ_f is the density of the fluid, and A is the representative (frontal) area of the body. For submarines, however, the representative area is usually expressed as the volume, or equivalently, displacement raised to the 2/3 power. Hence, the drag force acting on the submarine can be expressed as $R = K D^{2/3} V^2$ where K is a coefficient related to the shape and configuration of the hull [16]. Usually, the value of K is obtained from model tests. Finally, the propulsion power is given by $P_{prop} = RV = K D^{2/3} V^3$. It should be noted that this expression for propulsion power is strictly valid when the submarine is fully submerged, although there is not a substantial difference when the submarine is operating along the surface [16]. Considering all of these effects, the adjusted propulsion power for a xxx-class¹ submarine is given as [17]:

$$P_{prop} = 0.0035 D^{0.73} V^{2.95}$$

It is seen that the empirically obtained values for the exponents on D and V are close, although not identical, to their theoretical values.

The hotel load is somewhat more difficult to model as it largely depends on the given operating conditions and the inventory of equipment running on board, but it can be reasonably accurately estimated in kW as $P_{hotel} = D/22 + 25$. This equation was obtained from a statistical analysis of hotel loads of various submarines [18]. However, in our model, we will account for one additional hotel load component

¹ The actual submarine class is withheld for security reasons.

consisting of a static CO₂ scrubber, which requires a fixed power of 54kW [19].

Therefore, the final hotel load can be expressed as

$$P_{hotel} = D/22 + 25 + 54$$

Using the above equations, the combined propulsion load plus hotel load for a 3,000ton submarine is presented in Figure 2.3. It is seen that the overall load increases dramatically as the submarine's speed increases beyond 8 knots due to the approximately cubic dependence of propulsion power on velocity.

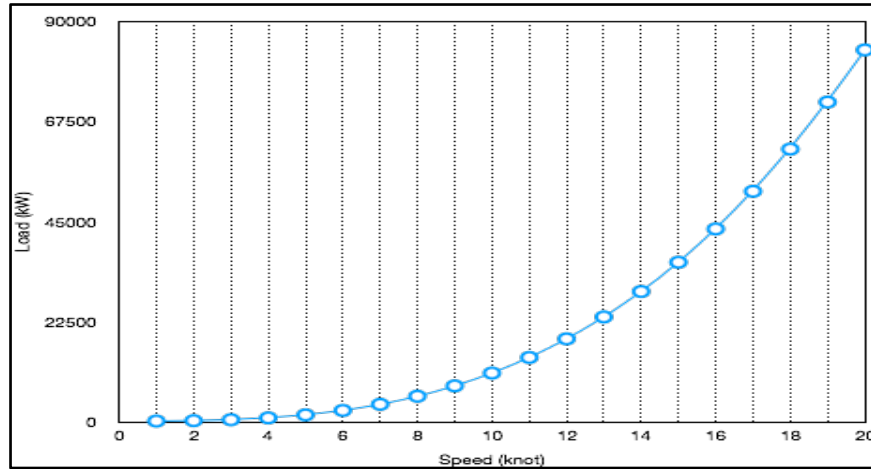


Figure 2.3: Variation of overall load for a 3000 ton submarine with speed

2.3 Diesel generator

Conventional submarines have employed a Diesel generator to recharge their on-board batteries. Currently, even fuel cell AIP submarines such as U-212 and U-214 employ Diesel generators to recharge batteries. Diesel fuel possesses very high energy density which is a critical factor for submarine operation, hence the diesel generator would be still required in future cell AIP submarines. The MTU 12V-4000 Diesel generator (Figure 2.4), considered the next generation of submarine engines, was

developed to meet the operational requirements of advanced AIP submarines [20]. The rated power of the MTU 12V-4000 is 1,500kW and fuel usage rate at 100% of power rating is 420 L/hr [21].

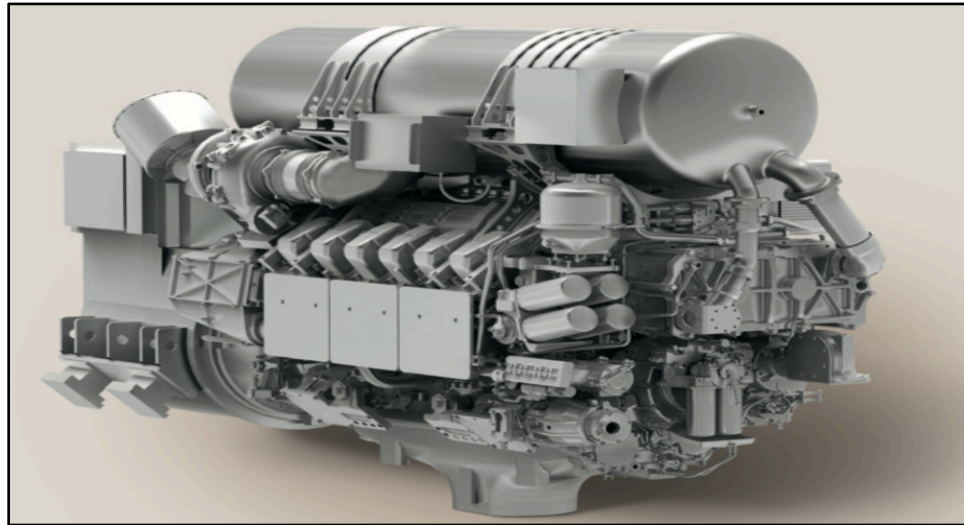


Figure 2.4: MTU 12V 4000 submarine charging unit [21]

The Simulink model for our submarine's Diesel generator system is based on the MTU 12V-4000 and depicted in Figure 2.5. Considering our submarine's displacement (3,000ton), we have employed three Diesel generators and a fuel tank size of 150,000 L. As shown in Figure 2.5, the role of the Diesel generators is to ensure that the battery state-of-charge (SOC) is maintained at the appropriate level. In practice, submarine crews must ensure that the battery SOC does not fall below some pre-determined minimum level; this minimum SOC level depends on the discretion of the submarine captain. Here, we assume that minimum SOC level is 30%. A relay switch is employed in the Simulink model to prevent the battery SOC from falling below the minimum level. The power produced from these Diesel generators is supplied to the battery during charging; the charging current is obtained by dividing the power by the battery voltage. The amount of Diesel fuel consumed is obtained by

integrating the power over time and multiplying by the fuel consumption rate ($= 7.778 \times 10^{-8} \text{ L/J}$). The fuel consumption rate is the reciprocal of the calorific value of Diesel fuel times the efficiency of the Diesel engine/generator.

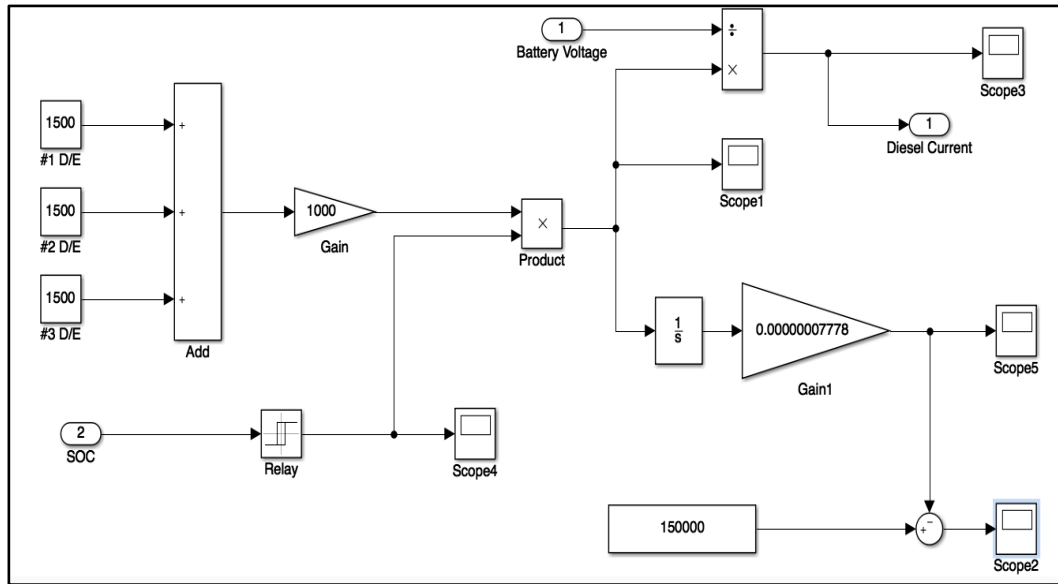


Figure 2.5: The Simulink model for the diesel generator system

2.4 Battery

As the Li-ion battery exhibits much better metrics than lead-acid in almost all aspects, we will employ Li-ion batteries in our simulation program. The XALT Energy is a leading manufacturer of automotive Li-ion batteries. For example, the University of Delaware operates a 40-ft fuel cell/battery hybrid bus (Figure 2.6) with 24kWh of XALT Energy Li-ion batteries. The Li-ion battery pack employed in our simulations will be based on the required battery performance for the Type 209 submarine which actually employs lead-acid batteries. Sunlight Company has published the performance data for the lead-acid battery a conventional submarine

[18]. Considering the Li-ion battery’s volumetric energy density, DC resistance, and rated discharge capacity, we have defined an equivalent Li-ion battery specification for our simulations as shown in Table 2.1 [17].



Figure 2.6: University of Delaware’s 40-ft Fuel cell bus

Table 2.1: Input data for the submarine’s Li-ion battery

Battery Type	Li-ion
Nominal Voltage	250V
Rated Capacity	158,160A
Internal Resistance	0.021 Ω

The overall Simulink model for the chosen battery system is shown in Figure 2.7. There are three input signals to the battery. The first one is the submarine’s overall load which determines the battery’s discharge current. To transform the power into current, the power has to be divided by battery voltage. The other two signals are

the charging current from the fuel-cell and from the diesel generator. The battery system outputs two signals which are its overall voltage and SOC.

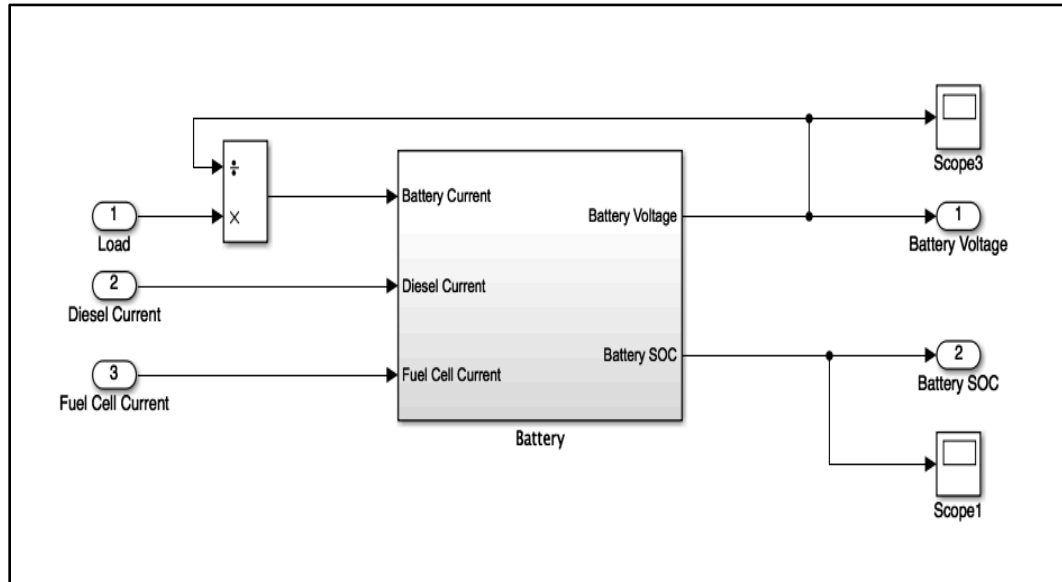


Figure 2.7: The Simulink model for the Li-ion battery system

2.5 Fuel cell

The 120kW fuel cell stack for submarines from Siemens is shown in Figure 2.8 [22]. The U212 submarines employ this fuel cell stack and related the balance of plant (BOP). Although the space occupied by the fuel cell stack itself is small compared to a single diesel generator, the overall fuel cell system occupies a larger space owing to safety system requirements. For example, nitrogen gas is used in the submarine to inert possible mixtures of oxygen and hydrogen and vent the gases before and after operation. The volume of nitrogen tank is considerable. As a result, four fuel cell stacks and their BOP would occupy a space equivalent to a single diesel generator [18]. In our simulation, we examine three configurations consisting of 3/0, 2/1, 1/2,

and 0/3 diesels/fuel cells. Of course, for each diesel generator replaced with a fuel cell system, 1/3 of the original diesel fuel volume would be replaced with an equivalent volume of hydrogen and oxygen. It should be noted here that we are replacing a 1500kW diesel generator with a twin fuel cell stack that only produces a combined 240kW. This discrepancy in power is acceptable because the fuel cell can be operated continuously even while submerged due to the stored oxygen, whereas the diesel generator can only be operated while snorkeling.

As discussed in Section 1.4, we will choose liquid oxygen and metal hydride as the storage mediums. The specific volumes of liquid oxygen and metal hydride are 840kg/m^3 and 100kg/m^3 [9]. A summary of the power system design configurations is shown in Table 2.2. The masses of stored hydrogen and oxygen in Table 2.2 are obtained by employing two constraints: (1) the sum of the volumes of stored hydrogen and oxygen must equal the volume of diesel displaced, and (2) the mass of stored oxygen is equal to 8 times the mass of sorted hydrogen (as dictated by stoichiometry).

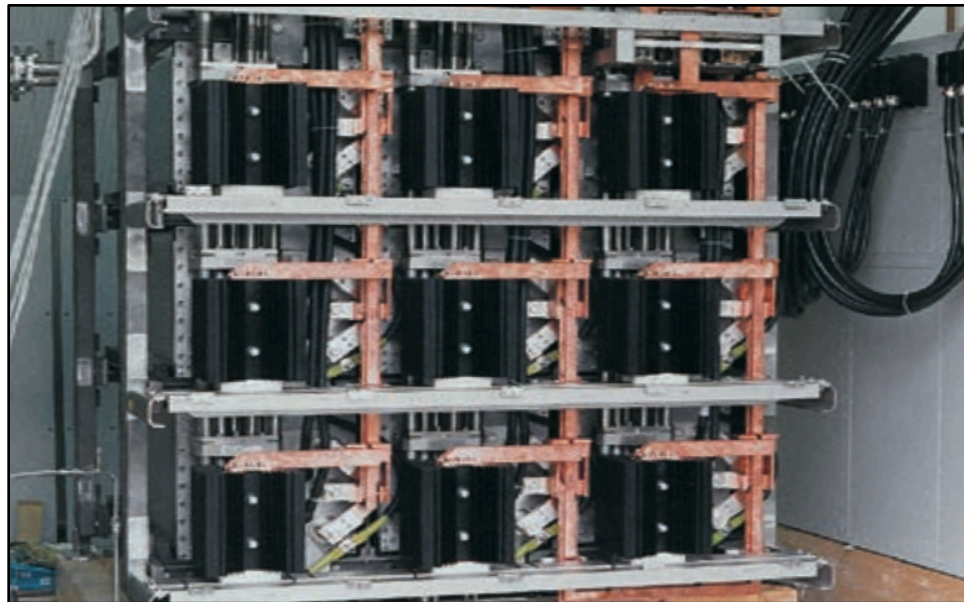


Figure 2.8: PEM Fuel cell modules assembled in a test rack [22]

Table 2.2: Power system design parameters

Configuration	Diesel Generators	240kW Fuel Cell system	Diesel (L)	Hydrogen Storage(kg)	Oxygen Storage(kg)
Only Diesel Gen (3/0)	3	0	150,000	0	0
2 Diesel Gen/1 FC (2/1)	2	1	100,000	2,561	20,487
1 Diesel Gen/2 FC (1/2)	1	2	50,000	5,122	40,974
Only FC (0/3)	0	3	0	7,683	61,461

The Simulink model for our 240kW fuel cell system is shown in Figure 2.9. Considering PEM fuel cell's efficiency, we input the hydrogen and oxygen flow rates as $1.05\text{E-}8 P_e/V_c$ kg/sec and $8.29\text{E-}8 P_e/V_c$ kg/sec, respectively where P_e is the electrical power produced by the fuel cell system, and V_c is the average cell voltage. The role of the fuel cell system is to supply current to the batteries. Therefore, the generated power from fuel cell has to be divided by the battery voltage to get the appropriate battery input current. In most cases, the fuel cell power is relatively small compared to the battery capacity and the submarine's total load, so the submarine crews usually keep the fuel cells operating continuously [25]. However, since we are employing up to 720 kW fuel cell system in our simulations, we must take care to prevent battery overcharge. Hence, we will program the fuel cell system to begin operation when the battery SOC drops to 60% and stop when the SOC climbs to 80%.

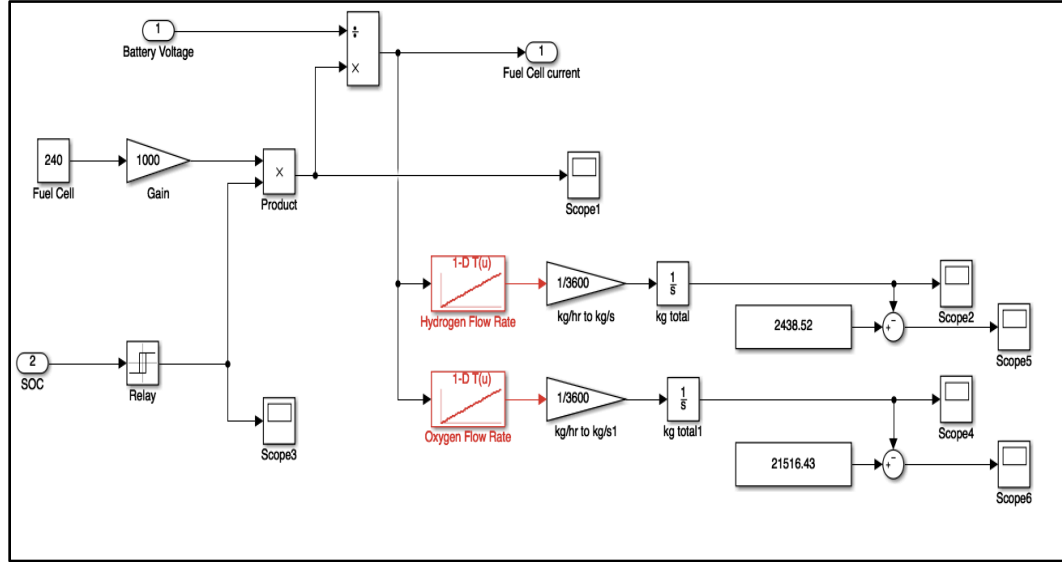


Figure 2.9: The Simulink model for the fuel cell system

2.6 Model verification

As we discussed in Section 2.1, the simulator is a useful tool for various design and optimization studies. However, it is essential to assure the accuracy of the simulator. Only when the simulator generates valid results can one develop confidence in its predictions. Therefore, model verification must be accomplished before employing the Simulink model to conduct design studies of the submarine AIP system.

The Simulink model for the submarine AIP system was validated by comparing battery discharge current between the model and operational data from the actual xxx-class submarine. According to the general specification of the submarine, we adjusted the displacement value from 3,000s ton to 1,200 tons and removed the static CO₂ scrubbers power (=54 kW) from our Simulink model. The Simulink model for the xxx-class submarine is shown in Figure 2.10.

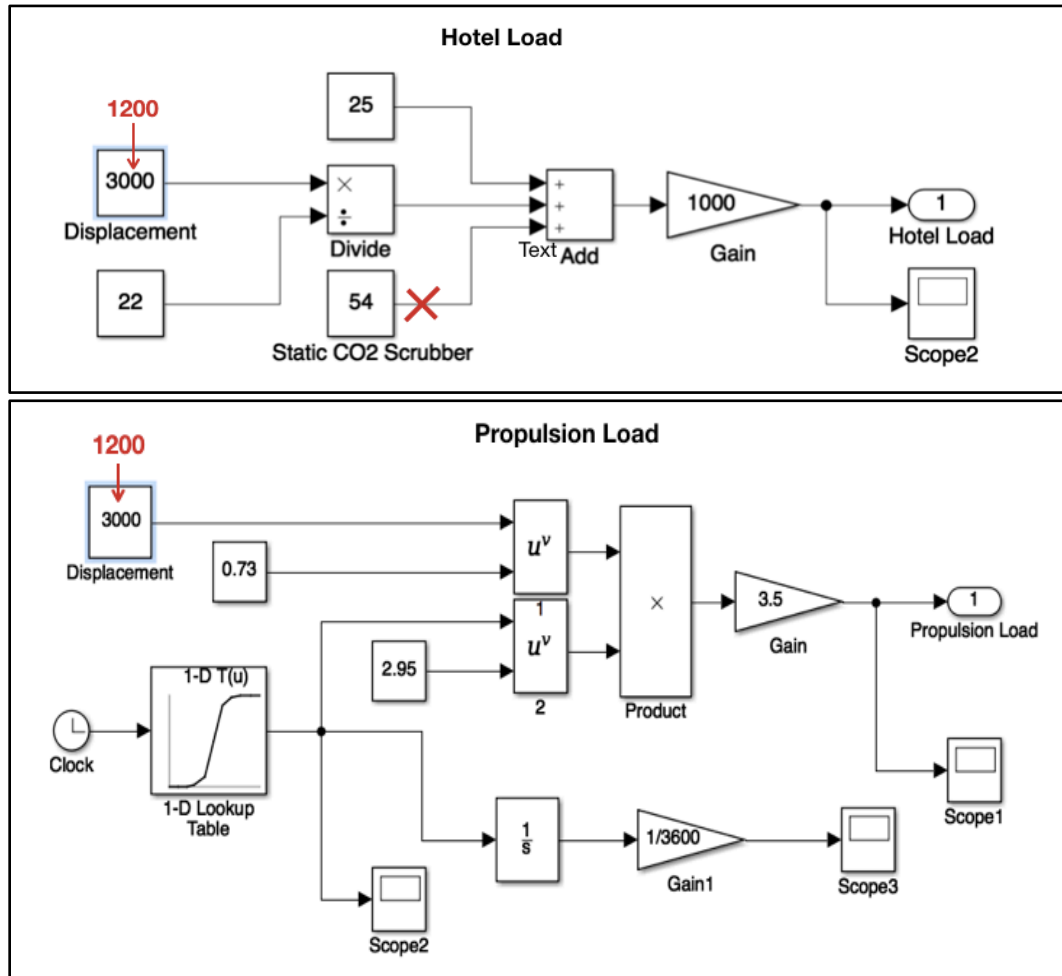


Figure 2.10: Adjusting value for model verification

The validity of the model can be assessed by comparing the predicted discharge current with operational data. If the values are similar, then the simulator can be assumed to be reliable [17]. The other data, for example, the amount of consumed Diesel, Hydrogen, and Oxygen consumed are entirely determined by the discharge currents. The comparison of real and simulated discharge current is shown in Figure 2.11. The values are very similar in most of the speed range, but we can see some relatively big differences in the burst speed region.

Although the actual submarine is usually operated at low speeds to minimize its acoustic signature, it is also important to pay attention to the burst speed which is employed in critical situations such as enemy evasion or to outmaneuver a torpedo. Nevertheless, we can say that the error even in the burst speed region is acceptable. It should be noted that the relative error, which is about 9%, is much less than the safety factor of the battery. Battery companies usually guarantee greater than 90% performance for five years for a C-rate corresponding to 20 hours, i.e. a current discharge rate which would completely drain the battery in 20 hours. Burst speeds employ very much higher currents, wherein the battery would be drained in just 2 hours. However, no battery company is able to guarantee performance for a current discharge corresponding to 2 hours. In addition, the batter managements system must engage a complicated and vulnerable auxiliary support battery-air system under burst speed, and therefore the error in battery performance is expected to increase. Therefore, we can conclude that the error of only 9% incurred by our model under burst speed is acceptable.

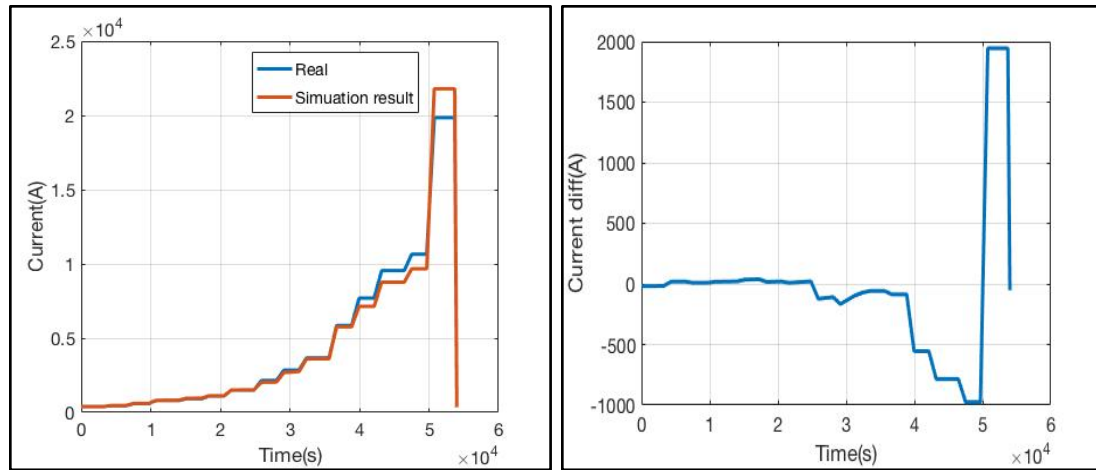


Figure 2.11: Comparison of real and simulated discharge current

Chapter 3

PERFORMANCE COMPARISON

3.1 Various practical military operation scenarios considered

Submarines are uniquely suited for a wide range of operational contingencies, including sea denial, interdiction, mine-laying, blockading and intelligence-gathering missions. The implementation of sophisticated AIP systems will likely expand the scope of diverse submarine operations than ever before. However, it is unreasonable to design submarines to execute every possible military mission. In fact, the US Navy employs two types of submarine in its fleet to accomplish its maritime strategy efficiently. The first type is the attack submarine (SSN) which specializes in combat with other vessels and in attacking land-based tactical targets; the other is the ballistic missile submarine (SSBN) which is for nuclear deterrence [23]. Considering the regional maritime environment of Northeast Asia, we assumed two maritime security regimes for our AIP submarines and selected a suitable subset of military operations to accomplish each strategy.

3.1.1 Military operations to deter the high intensity conflict

Traditionally, one of the most crucial roles for the armed forces is to provide the robust deterrence to high intensity confliction between nations. Most nations today support established institutions and processes dedicated to preventing conflict, respecting sovereignty, and furthering human rights. Some countries, however, are attempting to revise key aspects of the international order and are acting in a manner that threatens the national security interests of other nations [24]. Although none of

these nations are believed to be seeking direct military conflict, we must never underestimate the possibility of a general war.

To begin with, we consider the role of submarines during a battle between two different fleets. Submarines would be expected to engage in warfare with high-value targets such as aircraft carriers and modernized missile cruise ships. In particular, submarine torpedoes are very effective in sinking any surface ship as shown in Figure 3.1 [25]. While high speeds are critical to avoid counterattacks by the target, improving stealth by reducing the submarine's acoustic signature is also very important.



Figure 3.1: Ex USS kilaua sinks following torpedo attack from HMAS Farncomb [25]

Furthermore, it is likely that the battle environment will transition to the coastal area of the defeated fleet after a decisive battle. Now the submarines would concentrate on land-attack to support amphibious forces under the command-of-sea status. A greater operational range guarantees effective naval fire support to

amphibious forces. On the other hand, submarines on defense side still are forced to have anti-surface ship/submarine warfare (ASW).

We will consider ASW and land-attack operation (LAO) under general war as relevant to this thesis. Although other military operations such as deploying naval mines, etc. could be considered, these do not place significant demands on submarine propulsion.

3.1.2 Military operations against the low intensity conflict

As we discussed in Section 1.3 aspects, most of the recent security threats arise from low-intensity conflicts such as terrorism, smuggling of drugs, human trafficking, etc. Unlike a military clash between nations, such low-intensity security threats do not demand large and powerful armed forces. Elaborate military operations must be executed precisely under complicated international laws and relationships between nations. This kind of operation puts new demands on the armed forces.

Above all, plentiful and correct information is essential. Military operations are sensitive to domestic and international politics. Only robust evidence can guarantee full and proper justification for the operations. As the world becomes increasingly urban with population centers concentrated in coastal areas, it is apparent that submarines with modern surveillance hardware could be the best medium to obtain information. Submarine operation with extended submerged periods would be essential to undertake such intelligence gathering missions (IGM).



Figure 3.2: Narcotics from the fifth and largest HMAS Newcastle seizure [27]

Moreover, interoperability is mandatory to facilitate operations; it is very difficult to confront terrorism or pirates without the related state's cooperation. For example, the Combined Maritime Forces (CMF) is a multinational naval partnership, which exists to promote security, stability and prosperity across Northeastern Africa and Southern Middle East maritime area [26]. When the author worked in Combined Maritime Forces (CMF) in 2015, a suspicious fishing boat was identified by a Spanish battleship off the coast of northwest Africa. The Spanish warship was heading toward her base on her regular plan, so she was unable to give chase to the suspicious boat. A Japan Maritime Self-Defense Force (JMSDF) P3-C aircraft tracked the boat and recognized it as a narcotic smuggling boat. According to Japanese policy, the JMSDF can only intervene pirate activities and so could not intervene. Finally, a New Zealand battleship apprehended the suspicious fishing boat and seized drugs as shown in Figure 3.2 [27]. Based on this example, we can conclude that if submarines could

perform network-centric warfare (NCW) for extended durations with required movements in the area, anti-terrorism/pirate operations would be far more effective.

In fact, about ten missions including special operations, control of autonomous underwater vehicle (AUV), etc. can be categorized for modern submarines. However, special operations require less submerged time and less mobility and do not place significant demands on propulsion power. Therefore, intelligence operations and network-centric warfare will be sufficient to assess the required propulsion capability in this thesis.

3.2 The need for specific operation scenarios

As we discussed in Section 3.1, the above four military operations (anti-surface/submarine warfare, land-attack under general war, intelligence operation, and network-centric warfare) are sufficient to fully define the propulsion demands of AIP submarines. However, the full range of military operations is too general for specific performance comparisons and optimization of the fuel cell system. Therefore, some precise scenarios need to be prescribed to specify different operations and thus obtain meaningful quantitative data. Considering the regional maritime environment of Northeast Asia, we have proposed some reasonable scenarios to express the required capabilities in each operation.

3.2.1 Anti-surface ship/submarine warfare (ASW)

The first military operation selected here is the ASW under a high intensity conflict. We will assume that a decisive battle between two fleets is occurring on the open sea at a location that is 140 nautical miles away from our submarine base. During this scenario, our submarine undertakes ASW a total of four times. The total operation, as shown in Figure 3.3, is divided into the following segments:

- 1) Traveling to the operation area: our submarine departs from our base towards the operation area and travels at 7 kts for 20 hours while keeping up with other fleet assets. Unlimited snorkeling is possible during this leg of the operation.
- 2) ASW: our submarine commences a search for the designated high-value (HV) targets by slowing down to 2 kts for 30 minutes. After identifying a target, our submarine speeds up to 9 kts while giving chase and confirms its identify with a non-acoustic sensor before firing its torpedo. This portion of the mission lasts 1.5 hours. After checking the damage to the target, our submarine rapidly accelerates to burst speed (20 kts) for 30 mins in order to avoid counterattack by the enemy. The ASW is executed in repetitive fashion three times. Snorkeling is not allowed during this second leg of the operation.
- 3) Return to Base (RTB): our submarine now heads back to the base for replenishment. As the decisive war between two fleets has concluded, she is able to return to the base at an economical speed (4 kts) for 35 hours with unlimited snorkeling.

The speed vs. time graph for the entire ASW operation lasting about 63h is shown in Figure 3.3. The red box signifies that snorkeling is not possible.

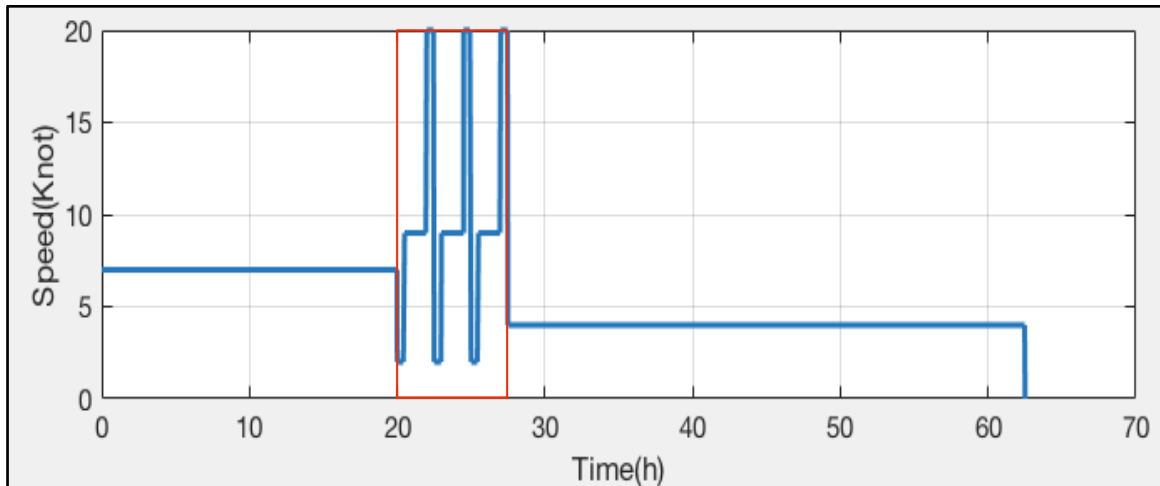


Figure 3.3: Speed vs. time for ASW

3.2.2 Land-attack operation (LAO)

The second military operation is the land-attack operation at the enemy's coastal area. The operation area is located 300 nautical miles away from the submarine base under the command-of-sea status. The land-attack operation is executed a total of four times as shown in Figure 3.4. under this scenario. The following steps comprise this operation:

- 1) Traveling to the operation area: our submarine departs to the operation area from the base keeping pace with the amphibious fleet which is traveling at 7 kts for 40h. Unlimited snorkeling is possible during this portion of the operation.
- 2) LAO: since the location of HV and targets have already been identified by information warfare, our submarine just approaches the designated spot to

launch its missile. The missile launch can only be accomplished at slow speeds; hence she slows down to 2 kts. After confirming damage to the targets from other information-gathering assets, she speeds up to 9 kts and launches a second missile. The land-attack operation is executed a total of four times and lasts 15h. Snorkeling is not allowed during this second leg of the operation.

3) RTB: Under the command-of-sea status, our submarine returns to the base at an economical speed (4 kts) over 70h with unlimited snorkeling.

The speed vs. time graph for the land attack operation is shown in Figure 3.4. The red box signifies that snorkeling is not possible.

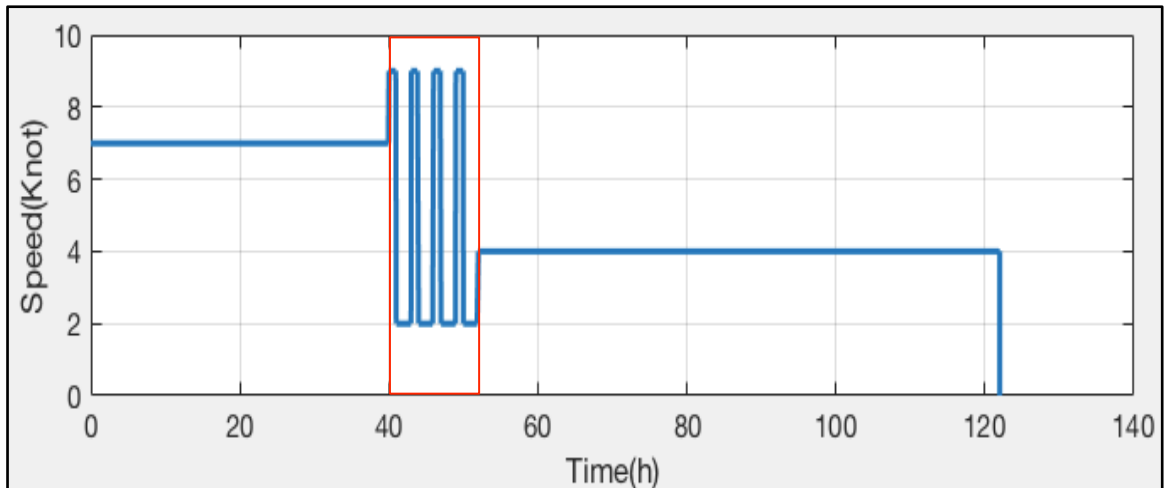


Figure 3.4: Speed vs. time for LAO

3.2.3 Intelligence gathering mission (IGM)

The third military operation is IGM at the enemy's costal area. We will assume that (1) the operation area is 300 nautical miles away from the submarine base, and (2) the entire operation is limited to one month.

- 1) Traveling to the operation area: our submarine departs to the operation area at an economical speed (4kts) over 75h with unlimited snorkeling.
- 2) IGM: our submarine concentrates on collecting electronic and acoustic signals during the night, while undertaking reconnaissance missions during the day. This leg lasts for two weeks at speeds between 2 and 3 kts. Snorkeling is not allowed during this period.
- 3) RTB: our submarine returns to the base at 4 kts over 75h with unlimited snorkeling.

The speed vs. time graph for the IGM is in Figure 3.5. The red box signifies that snorkeling is not possible.

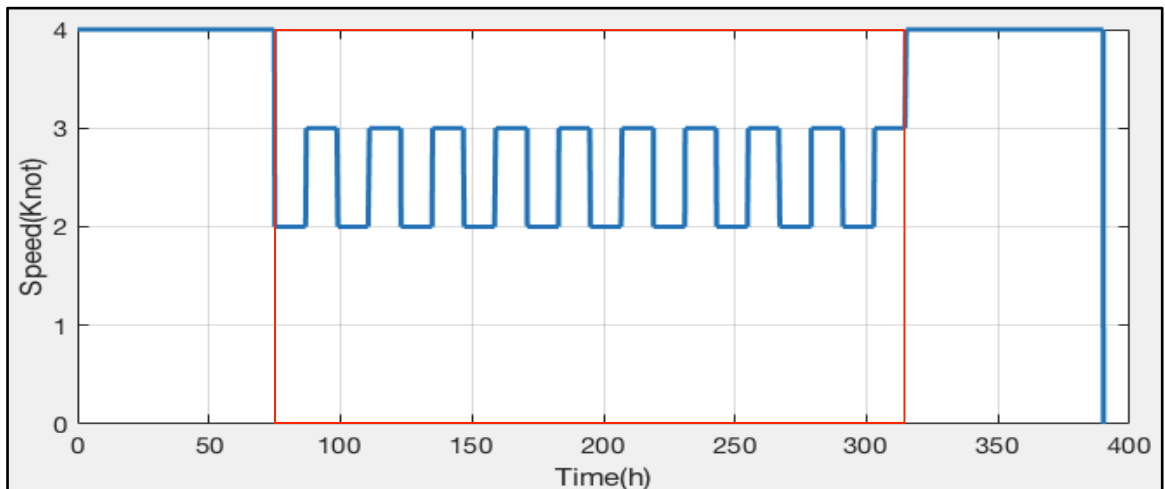


Figure 3.5: Speed vs. time for IGM

3.2.4 Network-centric warfare (NCW)

The last military operation is the NCW. Here, our submarine is traveling to location 1,000 nautical miles away to participate in military exercises. During the journey she receives an order to track a suspicious ship. This portion of the operation is repeated for a second time during the trip.

- 1) Traveling to the operation area: our submarine sets off to join the military exercise at an economical speed (4 kts) with unlimited snorkeling. She receives her first order to track the suspicious ship 48h into the trip.
- 2) NCW: she changes her heading and speed to intercept the suspicious ship. Considering the closest point of approach (CPA), she approaches and chases the target under submerged condition for 48h. After turning over the collected information, she changes heading back to her original sea lane at a higher-than-economical speed (5kts) to catch up to the original exercise schedule. She then receives a second order to undertake a similar tracking operation. Snorkeling is not allowed during this period.
- 3) Arriving at the destination: She travels at a higher-than-economical speed (6 kts) with unlimited snorkeling to join the military exercise at the scheduled time.

The speed vs. time graph for this NCW is shown in Figure 3.6. The red box indicates that snorkeling is not possible.

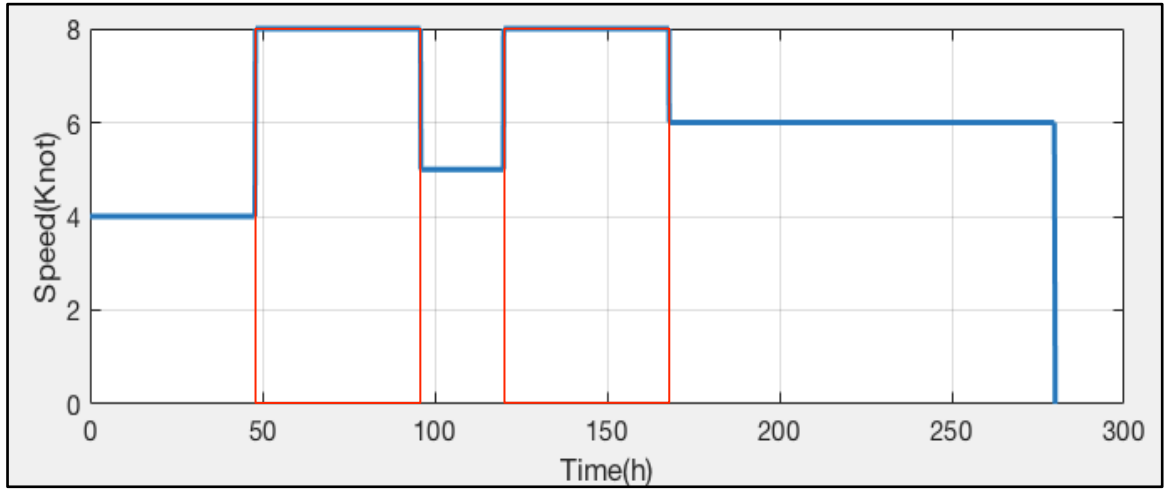


Figure 3.6: Speed vs. time for NCW

3.3 Capability comparison

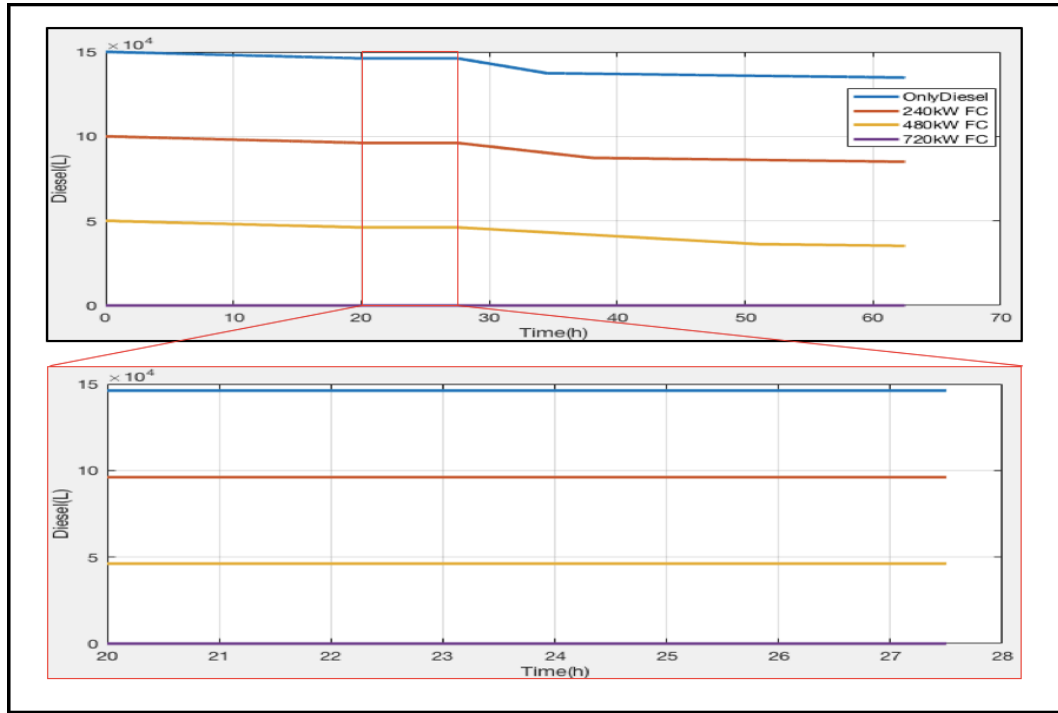
The four submarine operations described in Section 3.2 are simulated using our Matlab model to optimize the fuel cell size according to the four diesel generator/fuel cell configurations listed in Table 2.2, viz. 3/0, 2/1, 1/2, and 0/3. For quick reference, the diesel generator is rated at 1,500 kW and the fuel cell is rated at 240 kW. The first configuration (3/0) consists of three diesel electric generators and no fuel cells. This configuration will serve as a suitable baseline reference to compare the capabilities of the other three configurations and will be helpful to define the optimal size of the fuel cell stack for each military operation.

In Section 3.2, we presented velocity vs. time duty cycles to represent the four submarine military operations. We will use these duty cycles within our simulation program to obtain our submarine's performance and mission capability for each power-plant configuration. We will investigate which of the four power plant configurations are able to sustain the entirety of the operation (including both surface and submerged legs). In particular, we will focus on submerged capability during which snorkeling is prohibited as marked by the red boxes in Figures 3.3-3.6.

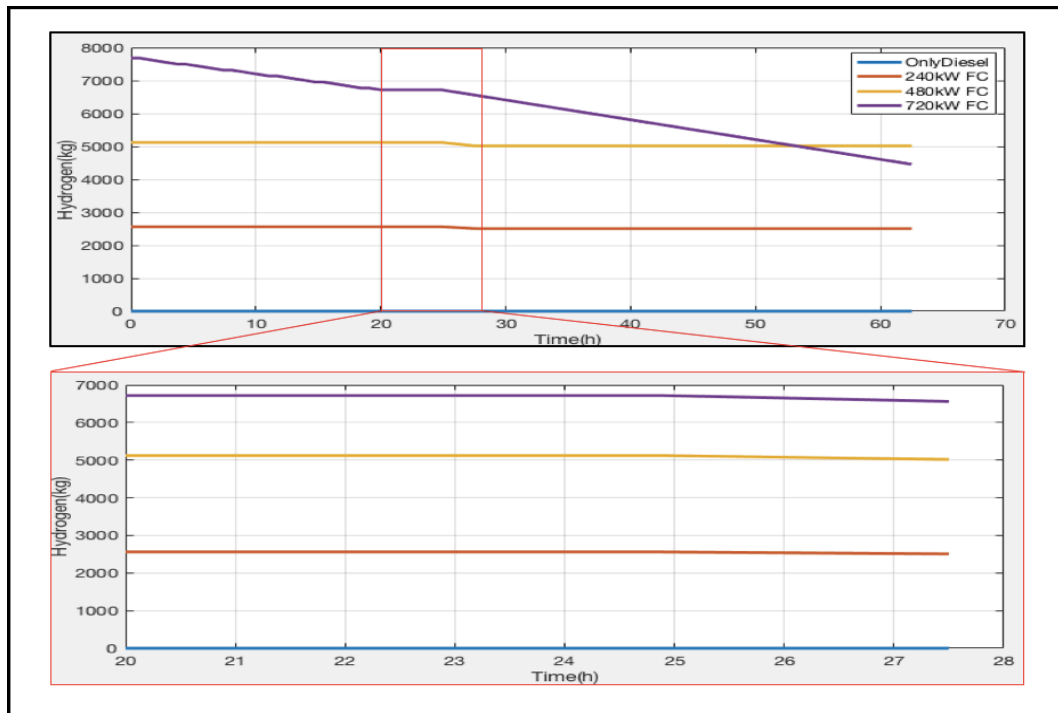
3.3.1 Anti-surface ship/submarine warfare (ASW) capability

The consumption rates of diesel and hydrogen, as well as battery SOC, are plotted against operating time in Figure 3.7. As explained in Section 3.2.1, the entire ASW lasts 63h and incorporates 7.5h of submerged operation commencing at 20h. Since the diesel generator cannot operate while submerged due to a lack of access to atmospheric air for combustion, the intent is to ensure that hydrogen and oxygen supply is preserved as far as possible exclusively for submerged operation. Similarly, the energy management system aims to ensure battery SOC of 100% during surface operation in the event that a sudden submerging is required. Accordingly, our submarine consumes only diesel for the first 20h of ASW, except in the 720kW-FC (0/3) case where hydrogen must be consumed as no diesel generator is present.

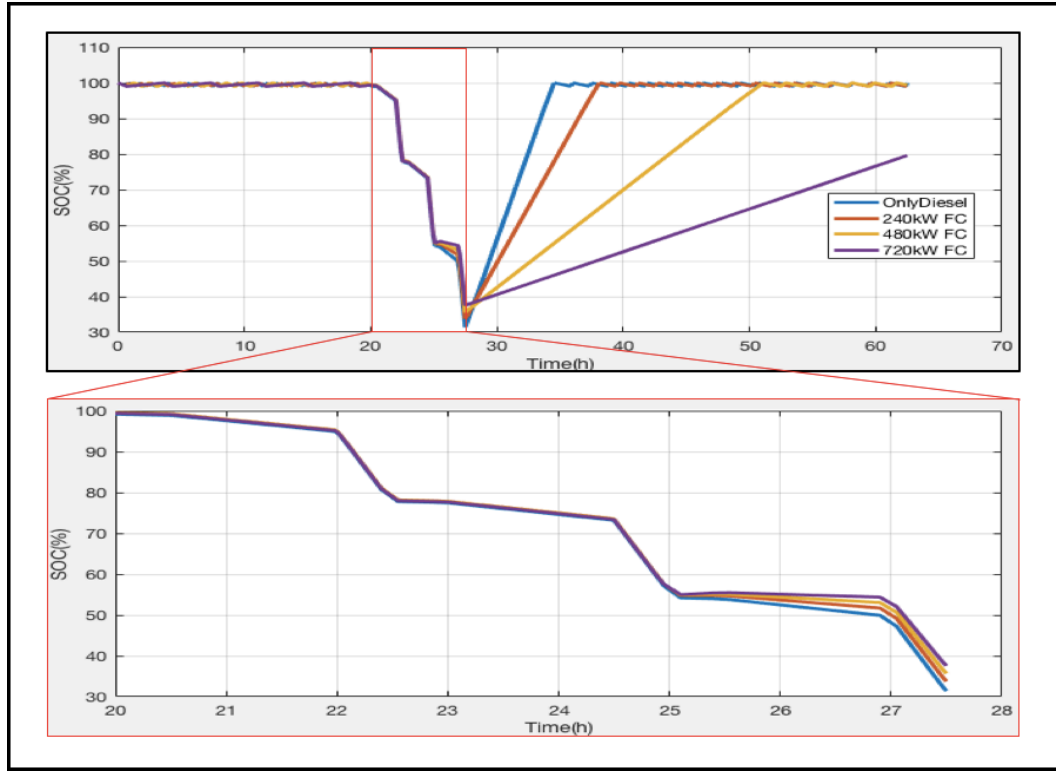
Figure 3.7 shows that upon submerging, we stop operating the diesel generator and diesel consumption is halted. The submarine now operates purely on battery power when the submerged leg commences. When the battery SOC drops to 60% at 25h, the fuel cell is switched on and hydrogen begins to get consumed as shown in Figure 3.7(b). We see that even the most powerful fuel cell configuration (0/3) is unable to sustain the battery SOC which continues to drop steadily till the end of the submerged leg. The battery SOC drops the most for the diesel-only case (3/0) as battery replenishment is not possible for this case while submerged; however, even in this case, the battery SOC drops to only 31% at the end of the submerged leg. Since the diesel generator only needs to be switched on when the battery SOC drops to 30%, the battery has enough charge to sustain the entire submerged leg. After resurfacing at 27.5h, we can restart the diesel generator and recharge the battery system. The rate of battery replenishment is highest for the diesel-only (3/0) case, and drops as the number of diesel generators is reduced. However, even the 720kW-FC (0/3) configuration is able to recharge the battery SOC steadily while consuming less than half of its total onboard hydrogen by the end of the mission. Therefore, we can conclude that all configurations (3/0, 2/1, 1/2, and 0/3) can successfully undertake ASW.



(a) Full operation (top); submerged operation(bottom)



(b) Full operation (top); submerged operation(bottom)



(c) Full operation (top); submerged operation(bottom)

Figure 3.7: (a) Diesel/ (b) Hydrogen consumption; and (c) battery SOC during ASW

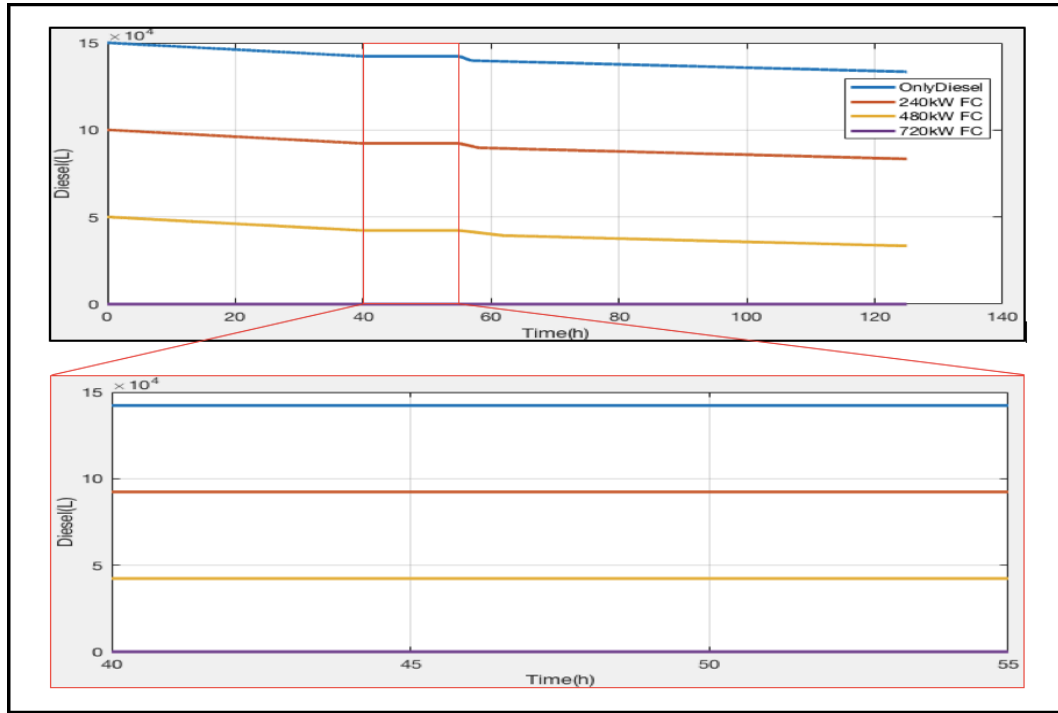
3.3.2 Land-attack operation (LAO) capability

The consumption rates of diesel and hydrogen, as well as battery SOC, are plotted against operating time in Figure 3.8. As explained in Section 3.2.2, the entire LAO lasts 122h and incorporates 15h of submerged operation commencing at 40h. Here too, the intent is to ensure that hydrogen and oxygen supply is preserved as far as possible exclusively for submerged operation. Accordingly, our submarine consumes only diesel for the first 40h of LAO, except in the 720kW-FC (0/3) case where hydrogen must be consumed as no diesel generator is present. Figure 3.8 shows that

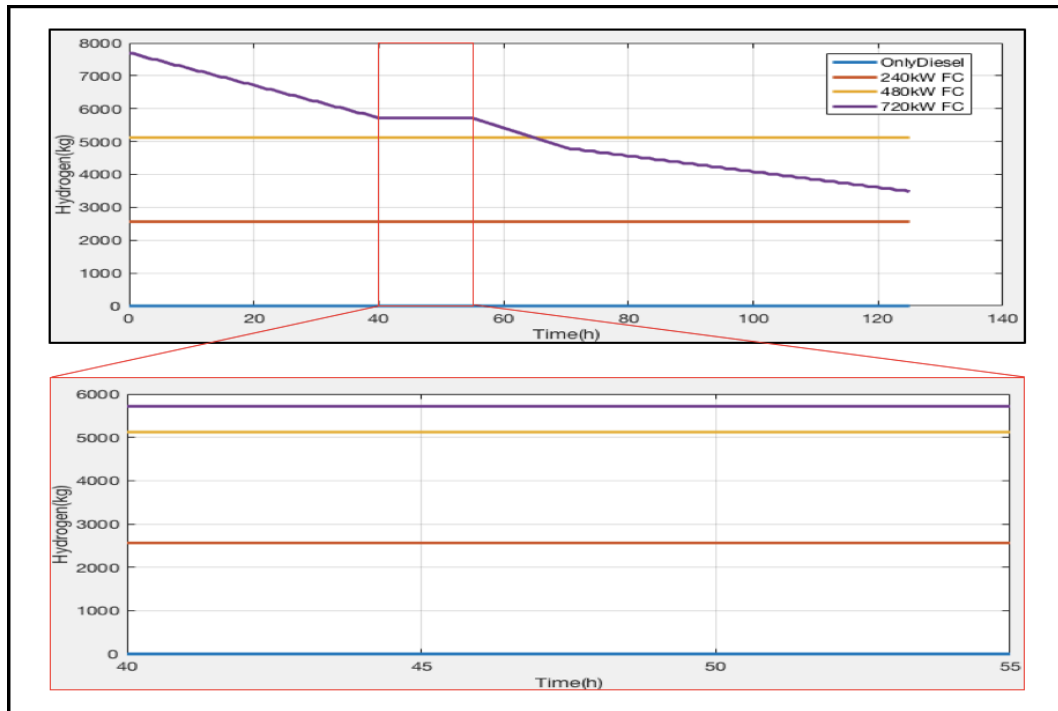
upon submerging, the submarine operates purely on battery power. The submerged leg places a modest demand on the battery such that the SOC remains above 80% by the end of the submerged leg (see Figure 3.8.c). Thus, the battery has enough charge to sustain the entire submerged leg and the fuel cell does not need to be switched on as shown in Figure 3.8b

The small fluctuations in battery SOC during surface operation in Figure 3.8c require some explanation. Although, our intent is to ensure battery SOC = 100% during surface operation, our simulation cannot guarantee exactly 100% as the diesel generator (or fuel cell in the 0/3 case) would need to switch on and off with infinite frequency. Therefore, we set the diesel generator or fuel cell to switch on only when the SOC drops to 99%. A threshold of 99% ensures a reasonably high battery SOC without placing a high computational burden on the simulator. This value of threshold results in the wavy pattern and slightly different starting SOC values seen in Figure 3.8c at the start of submerged operation.

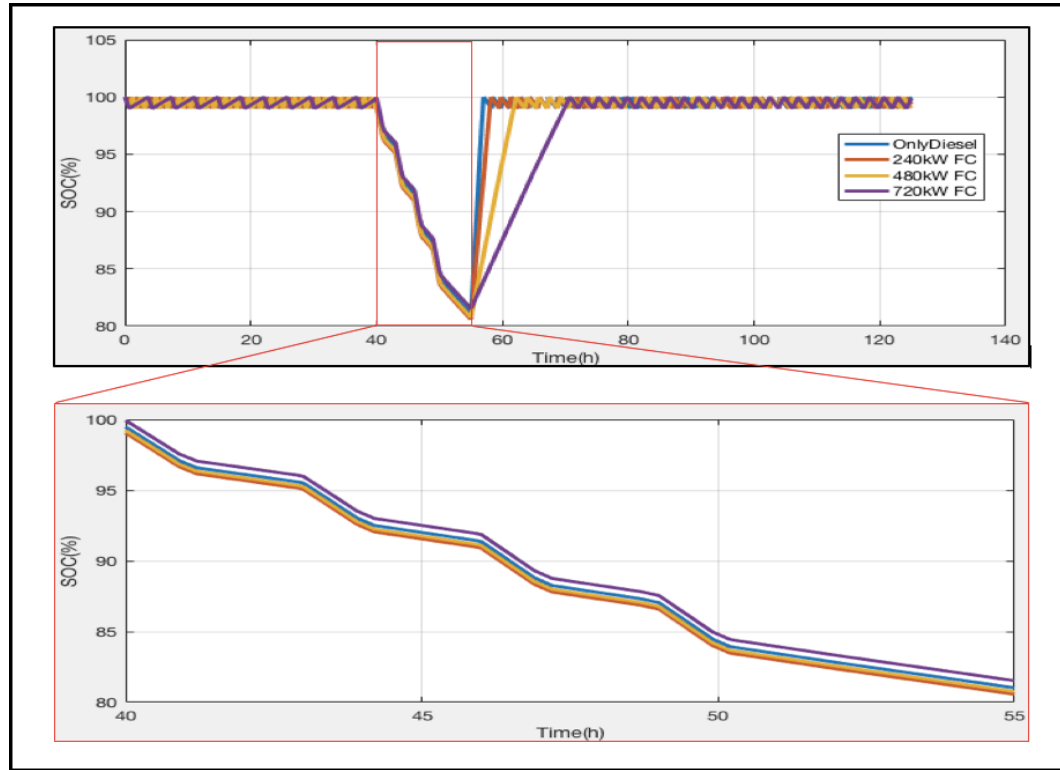
After resurfacing at 55h, we can restart the diesel generator and recharge the battery system. Again, the rate of battery replenishment is highest for the diesel-only (3/0) case, and drops as the number of diesel generators is reduced. These results indicate that all configurations (3/0, 2/1, 1/2, and 0/3) can successfully undertake LAO.



(a) Full operation (top); submerged operation(bottom)



(b) Full operation (top); submerged operation(bottom)



(c) Full operation (top); submerged operation(bottom)

Figure 3.8: (a) Diesel/ (b) Hydrogen consumption; and (c) battery SOC during LAO

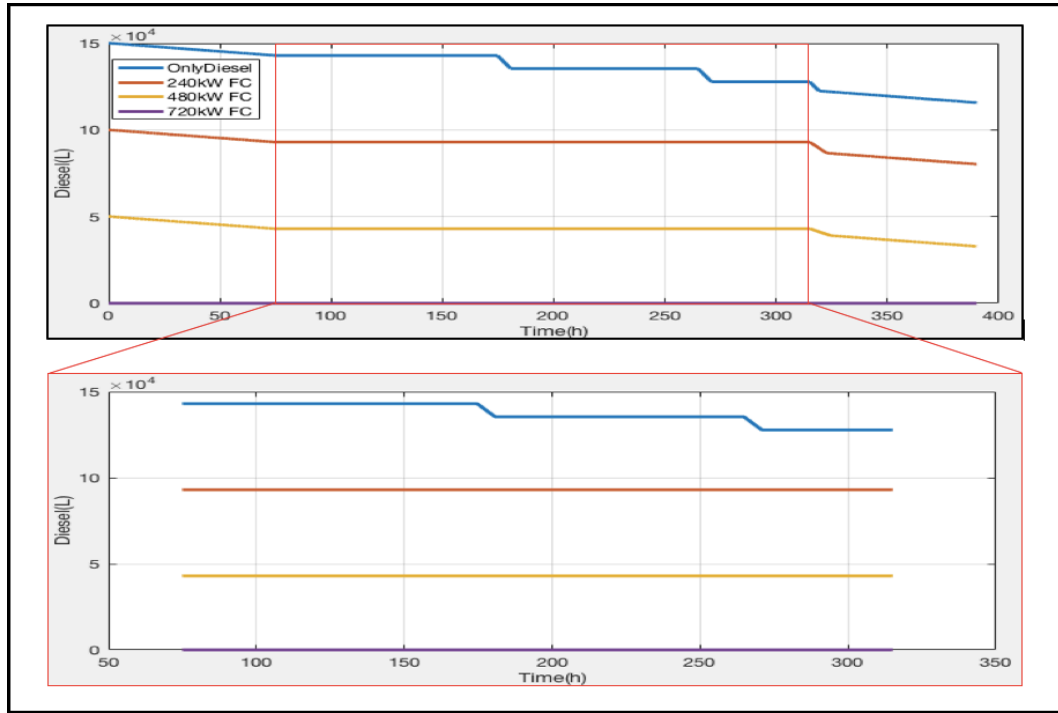
3.3.3 Intelligence gathering mission (IGM) capability

The consumption rates of diesel and hydrogen, as well as battery SOC, are plotted against operating time in Figure 3.9. As explained in Section 3.2.3, the entire IGM lasts 390h and incorporates 240h of submerged operation commencing at 75h. Accordingly, our submarine consumes only diesel for the first 75h of ASW, except in the 720kW-FC (0/3) case where hydrogen must be consumed as no diesel generator is present.

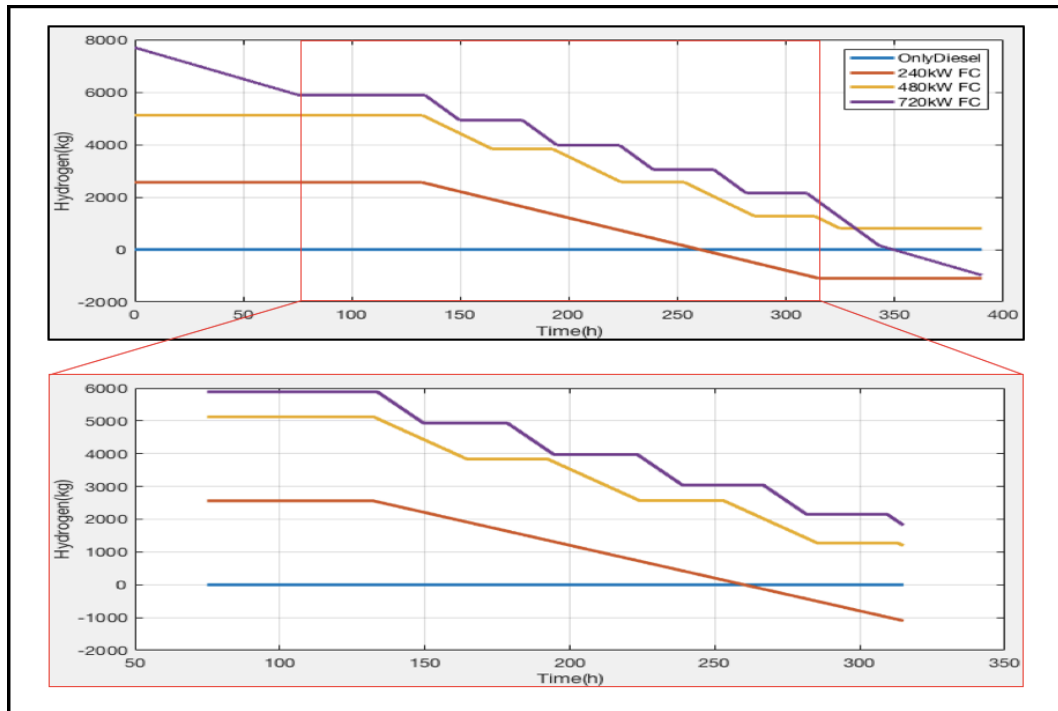
Figure 3.9 shows that upon submerging, the submarine operates purely on battery power. When the battery SOC drops to 60% at 130h, the fuel cell is switched on, and hydrogen begins to get consumed as shown in Figure 3.9b. When the battery SOC for the diesel-only case (3/0) drops to 30% as shown in Figure 3.9c, it would cause the diesel generators to switch on with the corresponding consumption of diesel. However, diesel consumption is not possible when submerged, therefore the 3/0 case would not be able to accomplish the IGM mission.

Both the 480kW (1/2) and 720kW (0/3) systems are able to comfortably replenish the battery SOC while submerged as shown in Figure 3.9c. The fuel cells switch on at SOC = 60% and charge the battery to 80% SOC before switching off. On the other hand, the 240kW fuel cell configuration (2/1) experiences a continuous drop on battery SOC to 51% by the end of the submerged leg. However, it is seen that the amount of stored hydrogen drops below 0 during the submerged leg for the 240kW fuel cell configuration as shown in Figure 3.9b. For the 720kW case, although about 1800 kg of hydrogen are still remaining at the end of submerged leg, these are fully consumed well before the end of the third leg. Therefore, both the 240kW and 720kW configurations are unable to accomplish the IGM mission.

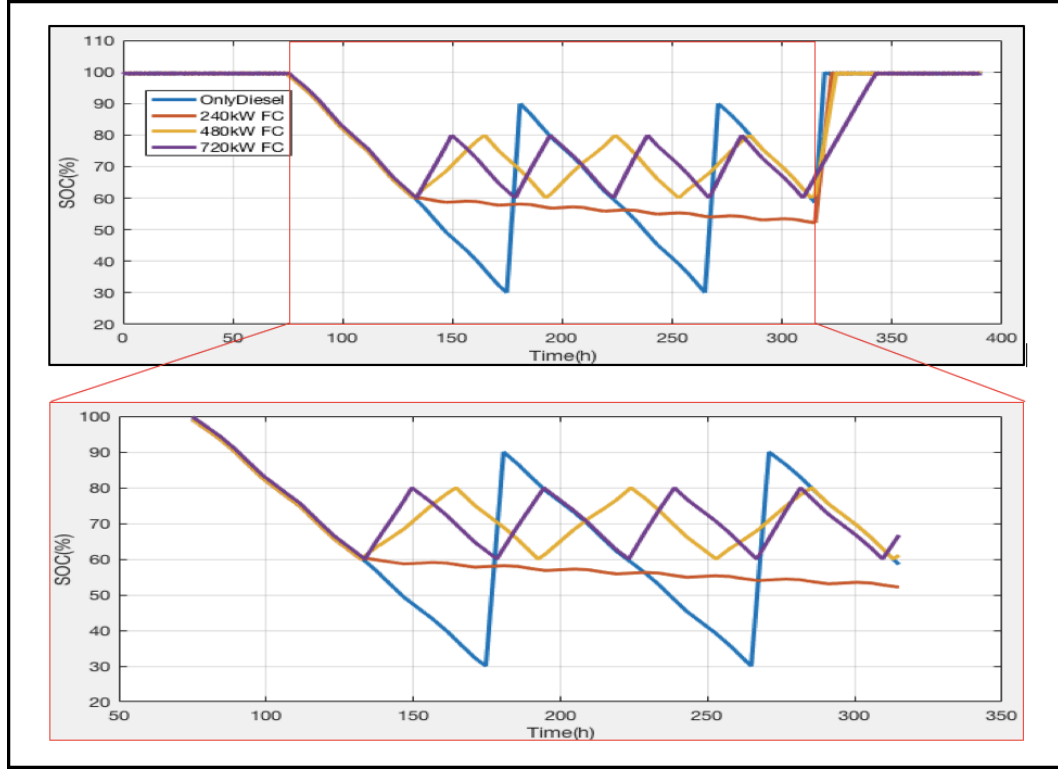
Therefore, we can conclude that only the 480kW fuel cell configuration (1/2) can successfully undertake IGM.



(a) Full operation (top); submerged operation(bottom)



(b) Full operation (top); submerged operation(bottom)



(c) Full operation (top); submerged operation(bottom)

Figure 3.9: (a) Diesel/ (b) Hydrogen consumption; and (c) battery SOC during IGM

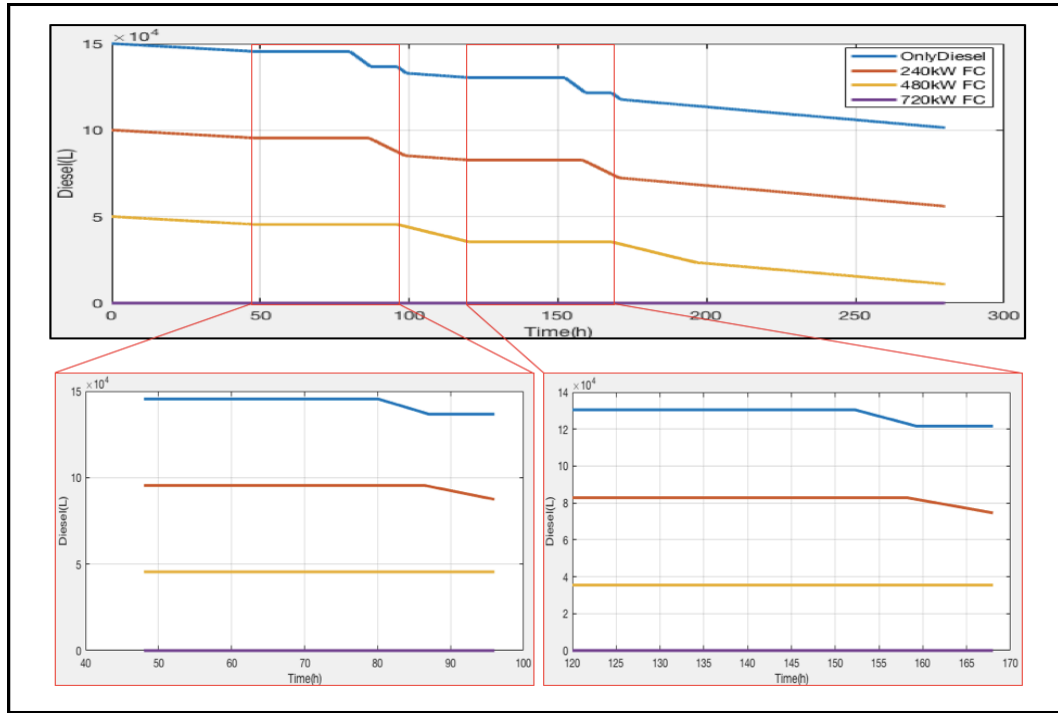
3.3.4 Network-centric warfare (NCW) capability

The consumption rates of diesel and hydrogen, as well as battery SOC, are plotted against operating time in Figure 3.10. As explained in Section 3.2.4, the entire NCW lasts 280h and incorporates two 48h segments of submerged operations with the first one commencing at 48h, and the second at 120h. Accordingly, our submarine consumes only diesel for the first 48h of NCW, except in the 720kW-FC (0/3) case where hydrogen must be consumed.

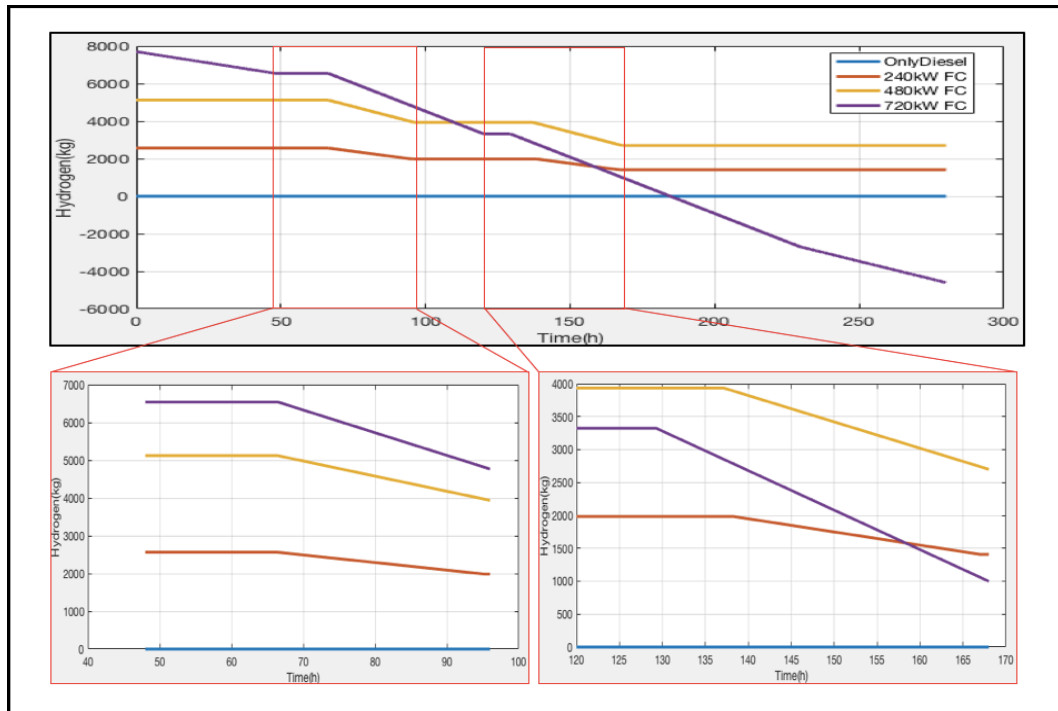
Upon submerging, when the battery SOC drops to 60% at 67h, the fuel cell is switched on and hydrogen begins to get consumed as shown in Figure 3.10b. The diesel-only case (0/3) is the first to drop its battery SOC to 30% while submerged. Of the three fuel cell configurations, the 240kW fuel cell configuration (2/1) is also unable to sustain the battery SOC above 30% before the end of the first submerged leg. The battery SOC drops to below 30% at 80h and 86h for the diesel-only case and 240kW case, respectively. On the other hand, the remaining two fuel cell case (480kW and 720kW) are able to sustain battery SOC > 30% during the first submerged leg.

After resurfacing at 96h, we can restart the diesel generator and recharge the battery system. The single diesel generator allows the 480kW-FC (1/2) configuration to recharge to almost 100% SOC before the second submerged leg commences at 120h. However, the 720kW-FC (0/3) configuration is only able to recharge up to 82% SOC. For the second submerged leg, the results are similar. Even though the 720kW-FC configuration starts its second submerged leg with only 82% SOC, it remains above 30% throughout. Nevertheless, the amount of hydrogen for the 720kW-FC (0/3) configuration drops below to 0 during the return leg as shown in Figure 3.10b.

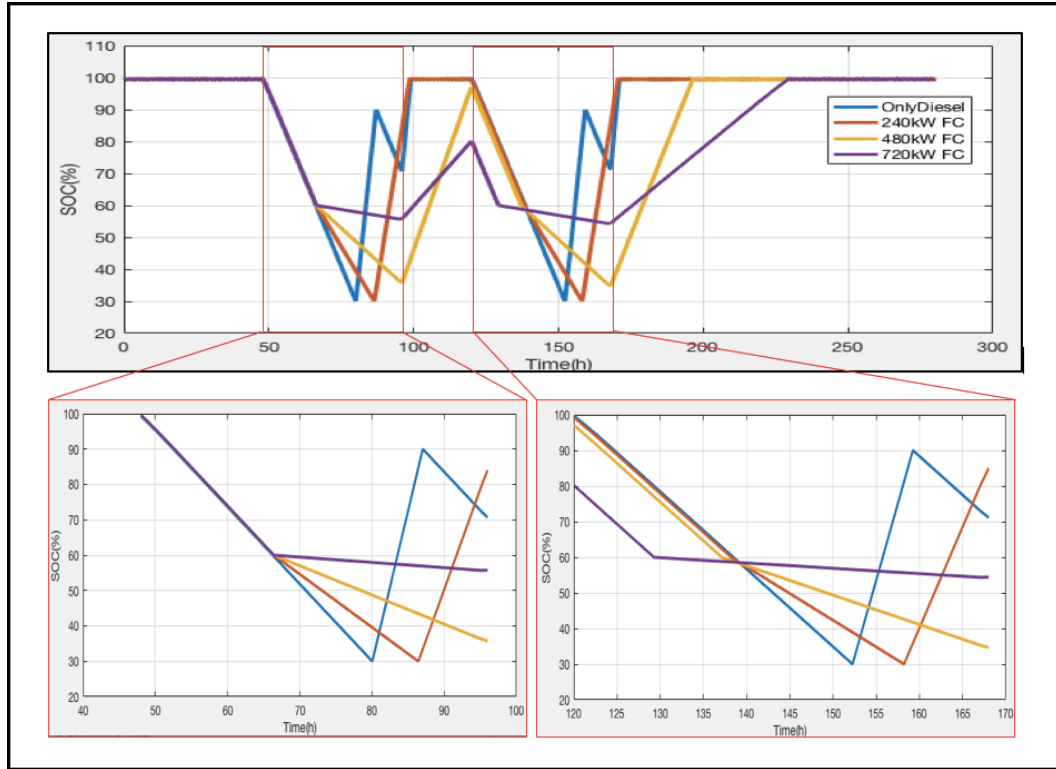
Therefore, we can conclude that only 480kW fuel cell configuration (1/2) can successfully undertake NCW.



(a) Full operation (top); submerged operation(bottom)



(b) Full operation (top); submerged operation(bottom)



(c) Full operation (top); submerged operation(bottom)

Figure 3.10: (a) Diesel/ (b) Hydrogen consumption; and (c) battery SOC during NCW

3.4 Overall optimal sizing of fuel cell/battery system

The results show that traditional military operations such as ASW and LAO can be accomplished by a conventional diesel-only configuration without the addition of a fuel cell system. In fact, all four configurations studied here can handle ASW and LAO. Although both our ASW and LAO scenarios include challenging submerged operations, current Li-ion battery systems are sufficiently capable to undertake them. On the other hand, modern military operations like IGO and NCW require extended

submerged time and operational range. Table 3.2 indicates that only the 1/2 configuration is capable of successfully handling IGO and NCW. Therefore, we can conclude that the overall optimal sizing of fuel cell/battery system for the next generation submarine is the 1500kW-diesel/480kW-FC (1/2) configuration.

Table 3.1: Overall result of submarine propulsion capability comparison

No	Configuration	Performance of military operation			
		ASW	LAO	IGO	NCW
1	Only DG (3/0)	⊙	⊙	×	×
2	2 DG/1 FC (2/1)	⊙	⊙	×	×
3	1 DG/2 FC (1/2)	⊙	⊙	⊙	⊙
4	Only FC (0/3)	⊙	⊙	×	×

Chapter 4

APPLICATION

In Chapter 3 we defined various military operations for our submarine. Considering the submarine's specifications and the relevant security environment, we obtained results for our submarine's performance from our Matlab/Simulink simulator for four different diesel/fuel cell power plant configurations. It was found that the 1500kW-diesel/480kW-FC (1/2) configuration was able to successfully undertake all of the prescribed military operations. Therefore, our submarine simulator has proved its worth in terms of identifying the optimal power plant for the specified scenarios. In this chapter, we will explore how we can use the submarine simulator in two other useful applications.

4.1 Design of submarine Required Operational Capability (ROC)

Military strategies and tactics are constrained by the available military assets in the modern security environment. Therefore, well-developed military weapon systems must be designed to cope with diverse security threats. Developing or acquiring the appropriate weapon system begins with defining the Required Operational capability (ROC).

ROC for submarines is usually expressed in terms of maneuvering range without refueling, submerged time without snorkeling, and sustaining a certain speed. Military HQs are responsible for prescribing the ROC while considering the development of technology, military budget, etc. Our submarine simulator can be very useful in this exercise, as it can translate the ROC into an actual system specification, for example battery capacity, diesel generator power, etc.

Let us consider the following example where we define the ROC with the help of our simulator. Upcoming weapons smuggling is predicted by a belligerent non-state actor in some country. As these activities are a new type of threat, the military HQs should develop a new strategy to cope with it. Various kinds of operations can be considered such as reconnaissance aircraft sorties, dispatching an additional battalion of the army, and deploying a submarine. As the military HQs would prefer covert operations, submarine operations would be the first choice. Nevertheless, the other options could also be chosen if the military HQs cannot fulfill its ROC with up-to-date technology. If the submerged time capability needed for this operation is uncertain even with an up-to-date fuel cell and/or battery system, the submarine option would be withdrawn. The military HQs can employ the simulator with modern technology to express submerged time capability with confidence. Furthermore, the overall ROC of submarine propulsion system can be designed to fit its strategic needs.

4.2 Managing submarine forces

According to the ROC defined in Section 4.1, submarines would need to be acquired and operated to cope with expected security threats. Urgent and temporary threats, on the other hand, should be dealt with currently available forces. The Command Center (CC) designates the most appropriate unit to undertake a needed mission. The CC also communicates with the designated unit simultaneously and supports the unit to accomplish the mission successfully. In the submarine case, continuous communication is not possible. The CC only can issue an order to a designated submarine unit. So, figuring out the characteristics of the operation and capability of the unit are very important to choose an appropriate unit. For those two

purposes, our submarine simulator can be provided valuable insight to determine its operational capability.

Let us consider the following example where we manage submarine forces with the help of our simulator. CC has to issue an order to covertly monitor a certain suspicious activity near the coastline. The order requires 30% of typical IGM and 40% of typical NCW, and the CC assumes that three submarines may be deployed for this purpose. In fact, the CC always maintains all submarine's draft locations and Daily Operation Reports (DOR), which logs the amount of fuel, food, ammunition and other onboard logistic information. If the three different types of submarines have different DOR and stats different starting locations, the CC will find it difficult to designate the most suitable submarine unit. In this scenario, our simulator can assist the CC in choosing the most appropriate submarine given their propulsion performance comparisons.

Chapter 5

CONCLUSIONS AND FUTURE DEVELOPMENT

The goal of this thesis has been designing the optimum AIP submarine propulsion system by our simulator. Although we concluded that a 480kW-FC/1500kW AIP system was optimum for the next generation submarine, the author wishes to emphasize the designing procedure itself. Our simulator based on the Matlab/Simulink software environment has been validated using field data from an operating submarine. Therefore, we could input any imaginable propulsion system and operation legs to test the capabilities of new and evolving technologies or improvements to current technologies. The viability of the new systems can be effectively and rapidly assessed by simply adjusting the input values for the various propulsion systems.

As the automotive industry invest heavily in research and development of fuel cell technologies for zero emission vehicles [28], those same technology advancements can be profitably transferred to the submarine field. For example, fuel cell stack power density, hydrogen and oxygen volumetric and gravimetric storage per efficiencies, and battery capacity can be expected to increase dramatically. We might even be able to eliminate the diesel generator system altogether and find the optimum combination between battery and fuel cell stacks.

Additionally, we could consider modifying our simulator for application in surface ships which has a hybrid (fuel cell and battery) propulsion system. Although military surface ships are relatively immune from the Paris climate agreement [29], military HQs should prepare for energy scarcity as fossil fuels are depleted or their supply is threatened. Hydrogen, of course, can generated from non-fossil sources.

Furthermore, lowering the level of radiated noise and heat signature is very important for surface ships to protect against torpedoes and missiles. In this case, a simulator for surface ships would be useful to design the hybrid (fuel cell and battery) system.

REFERENCES

- [1] Carlo Kopp, "Air Independent Propulsion-now a necessity", Defence focus, December 2010
Web: <https://www.ausairpower.net/SP/DT-AIP-SSK-Dec-2010.pdf>
- [2] Robert Sherman, "Air Anti-submarine warfare", US Navy Patrol Squadrons a great source for VP information, March 14, 1999
Web: <https://fas.org/man/dod-101/sys/ac/asw.htm>
- [3] Edward C. Whitman, "AIP Technology Creates a New Undersea Threat", Fall 2001
Web: http://www.public.navy.mil/subfor/underseawarfaremagazine/Issues/Archives/issue_13/propulsion.htm
- [4] N.R.P, "Explained : How Air Independent Propulsion (AIP) Works", Defencyclopedia (The Ultimate Defence Encyclopedia), July 6, 2016
Web: <https://defencyclopedia.com/2016/07/06/explained-how-air-independent-propulsion-aip-works/>
- [5] "Nuclear propulsion-illustration"
Web: <http://www.public.navy.mil/subfor/underseawarfaremagazine/Issues/Archives/>
- [6] "The United States Naval Nuclear propulsion program", Department of the Navy / Energy in the US, March 2013.
Web: https://nnsa.energy.gov/sites/default/files/nnsa/04-14-inlinefiles/2014-04-09%202013_Naval_Nuclear_Propulsion_Program.pdf
- [7] "Smart Non-Nuclear Submarines in Changing Times – A HDW Industrial View", North Atlantic Treaty Organization (NATO), October 2002.
Web: <http://docplayer.net/54860097-Smart-non-nuclear-submarines-in-changing-times-a-hdw-group-industrial-view.html>
- [8] Dominik Kimla, "Conventional (AIP) Submarine – a Weapon of Choice for the 21st Century", Frost & Sullivan, February 2013.
Web: <http://www.iqpc.com/media/7250/3472.pdf>
- [9] J.B. Lakeman, D.J. Browning, "The role of fuel cells in the supply of silent power for operations in littoral waters", QuinetiQ Centre for marine Technology Halsar, April 2004.
Web: <https://pdfs.semanticscholar.org/06eb/75750d1dcfb762c0e3500f4658a65e050055.pdf>

[10] G. Sattler, "PEFCs for naval ships and submarines: many tasks one solution", in *Journal of Power Sources*, Vol. 71, pp. 144-149, March 1998.

Web: <https://www.sciencedirect.com/science/article/pii/S0378775397027171>

[11] G. Sattler, "Fuel Cells Going on Board", *Journal of Power Sources*, Vol. 86, pp. 61-67, March 2000.

Web: <https://www.sciencedirect.com/science/article/pii/S0378775399004140>

[12] Psallidas, Konstantinos, "Design of a conventional submarines with advanced air independent propulsion systems and determination of corresponding theatre-level impacts", Calhoun, 2010

Web: https://calhoun.nps.edu/bitstream/handle/10945/43450/Whitcomb_Design_of_2010.pdf?sequence=1&isAllowed=y

[13] "Lead acid vs lithium-ion battery comparison", Michael mobbs

Web: https://static1.squarespace.com/static/55d039b5e4b061baebe46d36/t/56284a92e4b0629aedbb0874/1445481106401/Fact+sheet_Lead+acid+vs+lithium+ion.pdf

[14] Gordon Arthur, "Japan leads way with Li-ion submarines", *DN-Defence Note*, February 16, 2017

Web: <https://www.shephardmedia.com/news/defence-notes/japan-leads-way-li-ion-submarines/>

[15] Jun Ji-hye, "Korea to develop battery-powered submarine by 2027", *Korea Times*, March 25, 2017

Web: http://www.koreatimes.co.kr/www/nation/2017/03/205_226295.html

[16] Roy Burcher, Louis Rydill, "Concepts in Submarine Design", Cambridge University Press, 1994

Web: <http://dl.kashti.ir/ENBOOKS/Concepts%20in%20Submarine%20design.pdf>

[17] Discharging and Recharging Current Table for xxx class submarines.

[18] L. Piper, "Design of a fuel cell based submarine power system", *IEEE ICSET*, 2010

Web: <http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=5684460&tag=1>

[19] R. Carey, A. Gomezplata, A. Sarich "An overview into submarine CO₂ Scrubber development", *Ocean Engng*, vol 10, No. 4, pp. 227-233, 1983.

Web: <https://ac.els-cdn.com/0029801883900100/1-s2.0-0029801883900100-main.pdf>

[20] MTU Friedrichshafen GmbH, "Battery Charging Technologies for Advanced Submarine Requirements", 88045 Friedrichshafen www.mtu-online.com, September 2011

Web: https://mtu-online-shop.com/print/3100721_MTU_General_WhitePaper_SubmarineChargingUnit_2011.pdf

[21] "MTU 12V4000 DS1500 for Prime Rating Technical Data", MTU Onsite Energy

Web: <http://www.mtuonsiteenergy.com>

[22] "SINAVY PEM Fuel Cell for submarines", Siemens AG 2013

Web: <https://www.industry.siemens.com/verticals/global/de/marine/marineschiffe/energieverteilung/Documents/sinavy-pem-fuel-cell-en.pdf>

[23] Wikipedia, "Ballistic missile submarine", Edited on 3 Jan 2018

Web: https://en.wikipedia.org/wiki/Ballistic_missile_submarine

[24] "The National Military Strategy of the United States of America 2015", The US Joint chief of staff, June 2015

Web: http://www.jcs.mil/Portals/36/Documents/Publications/2015_National_Military_Strategy.pdf

[25] Tamir Eshel, "Ex USNS Ship Concord and Kilaua sunk by Australian, Canadian submarine", Defense update, July 25, 2012

Web: http://defense-update.com/20120725_farncomb_collins_sub_sinks_target_ship_kilauea.html

[26] "About Combined Maritime forces", 2018 Combined Maritime Forces (CMF)

Web: <https://combinedmaritimeforces.com/about/>

[27] "More success against drug smuggling for CTF-150 units", CMF, June 25, 2015

Web: <https://combinedmaritimeforces.com/2015/06/25/more-success-against-drug-smuggling-for-ctf-150-units/>

[28] "The zeroemission vehicle program", Natural Resource Defense Council, May, 2010

Web: https://www.nrdc.org/sites/default/files/ene_10070701a.pdf

[29] "Adoption of the Paris agreement", United Nations FCCC, December 12, 2015

Web: <https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf>