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THESIS

CONCEPT DEVELOPMENT AND OPERATIONAL ANALYSIS OF USING HYDROGEN AS A SINGLE NAVAL FUEL

by

Wee Sing Cheng

September 2022

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13. ABSTRACT (maximum 200 words)

This thesis focuses on using liquid hydrogen (LH_2) technologies as a single naval fuel onboard a vessel. The case study in this thesis is a 1000 twenty-foot equivalent unit (TEU) catamaran container vessel (CV) as a proxy to the United States (U.S.) Navy's Spearhead Class vessel. These two vessels are both built with catamaran hulls and have similar tonnage. The case study was assumed to have travelled a distance of 4838 nm and a travelling time of 194 hrs.

Design replacements and modifications were proposed in order to meet the case study energy requirements, following which RetScreen and Microsoft Excel were used to evaluate this system based over a 20-year project life. Overall, the proposed hydrogen fuel system as a single naval fuel is financially unfeasible as the economic profits do not look promising when compared to the estimated required investment at the start. Further investigation is recommended to determine whether the proposed hydrogen fuel system mentioned in this thesis can be combined with other renewable technologies as they become available. Actual implementation on a military vessel may not be practical now due to the high initial costs.

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CONCEPT DEVELOPMENT AND OPERATIONAL ANALYSIS OF USING HYDROGEN AS A SINGLE NAVAL FUEL

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ABSTRACT

This thesis focuses on using liquid hydrogen (LH_2) technologies as a single naval fuel onboard a vessel. The case study in this thesis is a 1000 twenty-foot equivalent unit (TEU) catamaran container vessel (CV) as a proxy to the United States (U.S.) Navy's Spearhead Class vessel. These two vessels are both built with catamaran hulls and have similar tonnage. The case study was assumed to have travelled a distance of 4838 nm and a travelling time of 194 hrs.

Design replacements and modifications were proposed in order to meet the case study energy requirements, following which RetScreen and Microsoft Excel were used to evaluate this system based over a 20-year project life. Overall, the proposed hydrogen fuel system as a single naval fuel is financially unfeasible as the economic profits do not look promising when compared to the estimated required investment at the start. Further investigation is recommended to determine whether the proposed hydrogen fuel system mentioned in this thesis can be combined with other renewable technologies as they become available. Actual implementation on a military vessel may not be practical now due to the high initial costs.

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LIST OF ACRONYMS AND ABBREVIATIONS

CV	container vessel
CO_2	carbon dioxide
GHG	greenhouse gas
hr	hours
HAWT	horizontal axis wind turbine
H_2	gaseous hydrogen
HFO	heavy fuel oil
IRR	internal rate of return
JP5	jet propulsion 5
KW	kilowatt
kn	knots
LH_2	liquid hydrogen
LMTD	log mean temperature difference
nm	nautical miles
NPV	net present value
NTU	number transfer unit
NOx	nitrogen oxides
PM	particulate matters
SOx	sulfur oxides
SFC	specific fuel consumption
TEU	twenty-foot equivalent unit
t	tons
U.S.	United States

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EXECUTIVE SUMMARY

The motivation of implementing the single naval fuel was to increase the interoperability between different platforms, simplifying logistics procurement, storage requirement and the smooth transportation of fuel. Streamlining of the JP5 fuel had its limitations due to the reasons covered in the background. Alternative fuel studies have been an ongoing for at least the past two decades, especially for the use of hydrogen fuel technology onboard a variety of land and air platforms. Hydrogen fuel technology has since been operational in ground and air platforms such as the Stalker, Blackjack unmanned aerial vehicles and reckless unmanned terrain vehicles. There are several prototypes for commercial shipping liners and sail boats available currently, but the hydrogen fuel technology is yet to be fully developed for military vessels

This thesis will focus on using liquid hydrogen (LH_2) technologies as a single naval fuel onboard a vessel. The case study in this thesis is a 1000 twenty-foot equivalent unit (TEU) catamaran container vessel (CV) as a proxy to the United States (U.S.) Navy's Spearhead Class vessel. These 2 vessels are both built with catamaran hulls, and both have similar tonnage. The case study was assumed to have travelled a distance of 4838 nm and a travelling time of 194 hrs. The estimated energy requirements for the catamaran CV are as follows:

- Fuel consumption of approximately 150 t/d
- Electrical demand of up to 2145 KW with turbines / shaft engaged.

A number of design replacements and modifications were made in order to meet the case study energy requirements:

1. Use of GE LM6000 gas turbines as main propulsion,
2. Modifications to be done on existing fossil fuel tanks to hold LH_2 fuel,
3. Replacement of current compressors to Hydro-Pac C-12-40-7000LX/SS hydrogen compressors,

4. Use of GE10-1 gas turbines as generators,
5. Replacement of current fuel transfer pumps to Becker VFD vacuum pump,
6. Modifications to be done on existing heat exchangers to allow LH_2 operation,
7. Replacement of current valves to WEKA PK-TZV LH_2 valve

RetScreen and Microsoft Excel were used to evaluate this system based over a 20-year project life. The following were calculated:

- Greenhouse gas (GHG) emissions expected to decrease by 5.37×10^5 tCO_2
- NPV of $2.21M.
- Positive IRR of 1.3%
- Initial costs of $37.85M.
- Payback period of 16.2 years; and
- Cumulative cash flow of $4.62M after a 20-year project life

Overall, the proposed hydrogen fuel system as a single naval fuel is **financially unfeasible** as the economic profits do not look promising when comparing it to the estimated amount of money required to be invested at the start. It is recommended to investigate further whether the proposed hydrogen fuel system mentioned in this thesis can combined with other renewable technologies as they become available. Actual implementation on a military vessel may not be practical now due to the high initial costs. But in terms of other environmental factors, it may be worth exploring as it will provide the following:

- An alternative energy source as the Single Naval Fuel
- Reduction in PM, NOx and SOx emissions

- The removal of equipment for fuel oil treatment
- Lower manpower, maintenance, and operating costs; and
- The reduction of risk for fire and oil spills

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Secondly, an acknowledgement must be put forward to Prof. Daniel Nussbaum who had provided technical advice on the financial calculations portion of this thesis and also provided further insights on how to improve the overall analysis portion.

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I. BACKGROUND AND MOTIVATION

This chapter will discuss on the different kinds of motivation for conducting this thesis and the background on what was done before previously.

A. BACKGROUND FOR NEED OF SINGLE NAVAL FUEL

Currently the U.S. Navy uses two types of fuel onshore and at sea. One is the F76 (Naval distillate fuel) for traditional marine propulsion engines and the other is the JP5 (Jet Propulsion 5) for aircraft propulsion (Kern et al. 2021). The concept for using a single naval fuel had been raised since the 1980s when the United States (U.S.) Army and U.S. Air Force had initiated studies for using JP4 for powering aircrafts and ground based vehicles' diesel engines (Kern et al. 2021).

These studies were then overtaken by further usability tests involving JP8 and embraced by the U.S. Army, U.S. Air Force and NATO as the single fuel to replace JP4. Despite its suitability for usage on ground and air assets, JP8 was not recommended for maritime usage and storage, primarily due to its lower flashpoint as compared to JP5. More recently, the U.S. Navy had revisited on the topic of the single fuel concept and had tried to adopt JP5 as the single fuel for maritime usage (Jimenez et al. 2020). Notwithstanding the renewed interest, higher raw costs, and production output issues for JP5 proved to be stumbling blocks to be utilized onboard non-nuclear platforms.

1. Primary Motivation – Solving Logistical Problems

The primary motivation of implementing the single naval fuel was to increase the interoperability between different platforms, simplifying logistics procurement, storage requirement and the smooth transportation of fuel. Streamlining of the JP5 fuel had its limitations due to the reasons covered in the background. Alternative fuel studies have been an ongoing for at least the past two decades, especially for the use of hydrogen fuel cells onboard a variety of land and air platforms (Kern et al. 2021).

The utilization of hydrogen as an alternative energy source has since been operational in ground and air platforms such as the Stalker, Blackjack unmanned aerial vehicles and Reckless unmanned terrain vehicles. There are several prototypes for commercial shipping liners and sail boats available currently, but the utilization of hydrogen technology is yet to be fully developed for military vessels. Thus, it is beneficial for this thesis to look at utilizing hydrogen technology to propel military platforms, her auxiliary systems and other ancillary operational equipment.

2. Secondary Motivation – Pollution from Shipping and Increased Demand for Fossil Fuels

Apart from solving logistical issues for the U.S. Navy, the need for adopting a Single Naval Fuel arises from rising cases of shipping pollution. As highlighted by Jian, Wu and Jin previously in their research paper (Jian et al. 2007) on the prospects of applying renewable energy on seaborne transportation, it is inevitable that merchant ships will cause environmental pollution through the usage and transportation of fuel. Spilling of fuel can result in huge environmental catastrophes and also provides severe disruptions to the country's tourism growth. An example of such a catastrophe is the Exxon Valdez oil spill off the coast of Alaska which happened during 1989, causing losses of up to $580M to its tourism and fishing industries.

Besides oil spills, the penalties for vessels that intentionally throw unwanted fuel oil or bilge oil overboard can be very severe. U.S. Department of Justice's 2019 reported that the Vessel Pollution Program enforced by the U.S. government had triggered more than $200M in fines and 17 years of jail time for ship officers and executives over the past 10 years. In addition to this, atmospheric emissions from the shipping industry is a key problem which needs to be solved (Cooper 2003). The main atmospheric emissions from vessels that primarily affects human health are particulate matters (PM), volatile organic compounds, nitrogen oxides (NOx) and sulfur oxides (SOx) (Corbett 2007). Due to the increase of global population and demand, it is expected that the contribution of these emissions will more than double by 2030 (Cooper 2003).

The world's energy utilization is mainly based on traditional fuels amounting to 80%, the rest are being utilized by renewable and nuclear energies. (International Energy Agency 2021). This translates to an estimated 11 billion tons of fossil fuel equivalent in

2021 and has been projected to gradually increase 10% per year in total for the world (BP 2022). Using these figures as references for the shipping industry,[1] forecasts compiled by Corbett in 2007 implies that the expansion of the world's shipping cargo fleet and increased demand for goods would be translated from the rising trend of fuel consumption for container vessels as shown in Figure 1. This directly translates in the increased demand for fuel oil in the years to come.

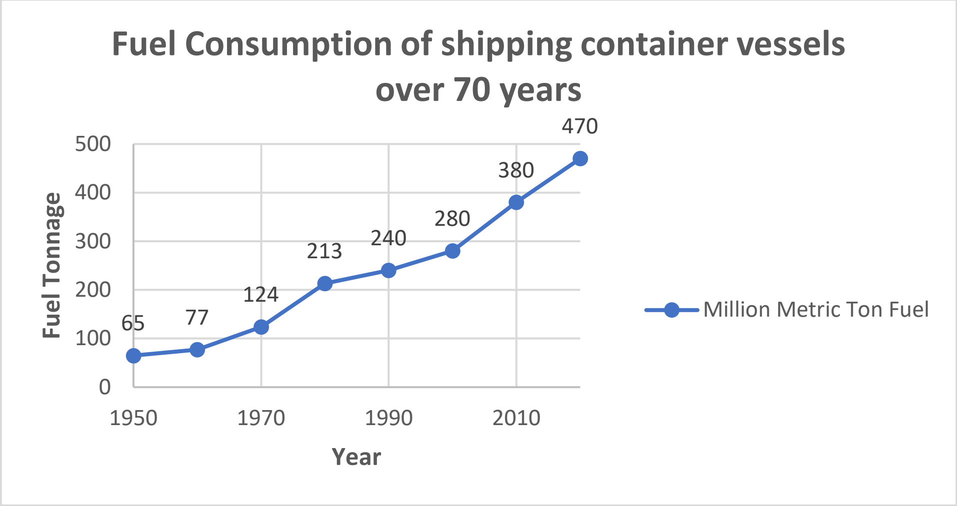

Figure 1. Fuel Consumption of Shipping Container Vessels. Source: Corbett (2007, p. 3).

B. OBJECTIVES AND RESEARCH OUTCOMES

The purpose of this thesis is to produce a developmental concept for using hydrogen as a single source of fuel for U.S. naval vessels. The questions to be answered in this thesis are as follows:

1. What are the necessary facilities required to be fitted onboard naval vessels and to support hydrogen as the single fuel concept?

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[1] For the purpose of this thesis, the shipping industry is used as an example as global fuel consumption for Navies are not available

2. What are the potential operational benefits for using hydrogen as a single fuel concept for naval vessels?
3. How is simulation software able to produce a relationship between calculated performance versus its results for Hydrogen usage onboard naval vessels?
4. Is using hydrogen as a single fuel concept recommended for naval vessels?

C. IMPACT AND EXPECTED OUTCOMES

The global maritime sector and military navies recognized that they cannot continue to develop and grow with continued dependence on fossil fuels. It will not be possible for military navies and ocean-going bulk tankers to continue to heavily burn fossil fuels. Therefore, alternative energy systems must be considered. The implementations of this thesis will result in:

- An alternative energy source as the Single Naval Fuel
- Reduction in PM, NOx and SOx emissions
- The removal of equipment for fuel oil treatment
- Lower manpower, maintenance, and operating costs; and
- The reduction of risk for fire and oil spills

II. LITERATURE REVIEW

This section will cover prior research and studies related to this thesis. It will detail readings done on operational aspects such as "The Universal Fuel at Sea" and "The Renewable Energy Initiative of the U.S. Navy." This section will further analyze the technicalities covering the hydrogen technologies and production means, followed by available alternative energy sources which is being employed on surface vessels now.

A. UNIVERSAL FUEL AT SEA

This Naval Postgraduate School thesis titled "The Universal Fuel at Sea: Replacing F76 with JP5" studied the replacement of the F76 fuel with JP5 and concluded that the single fuel concept will reap benefits in terms of flexibility during underway replenishments for the U.S Navy's logistics vessels just by using a single fuel product (Sermarini 2000). The U.S Navy had also projected that this replacement will aid them in the long run as the Military Sealift Command's long-term chartered tanker fleet had decreased from twenty-one ships to five ships. Sermarini had also pointed out that the U.S. Navy to depend on foreign tankers for overseas operations, by adding flexibility of the JP5 replacement could prove critical for operations in future.

B. THE U.S. NAVY'S POLICY FOR RENEWABLE ENERGY

In 2012, the U.S. Navy established the policy for renewable energy such that it could be energy independent in the near future. The policy focused on promoting the use of different kinds of renewable energy sources and to also decrease the reliance of traditional fuels (Department of the Navy 2012a). In an ongoing effort to ensure efficient energy consumption, the U.S. Navy will conduct audits so that it can develop better practices for its energy usage and provide regular reporting on energy consumption for its bases and shore facilities (Department of the Navy 2012b).

C. HYDROGEN CHARACTERISTICS

Properties of hydrogen has to be understood before it can be used as a means for renewable energy. The production techniques have to also be recognized such that it can be effectively utilized.

> According to the Author, “hydrogen is the lightest element in the periodic table and the density of hydrogen is measured to be at 0.0898 kg/m3 at 101.325 kPa and 273.15°K (0°C). This element was found by H. Cavendish in 1766 and was discovered to be the most plentiful. This element has no color and no odor at room temperatures but can be extremely volatile at high temperatures” (Léon 2008a).

Pure hydrogen does not exist and requires a source of high energy externally to separate it through chemical reactions. It can be produced from as water, natural gases, biomass, or even coal. An estimated 48 billion kg of hydrogen were manufactured yearly since 2006, these were used mainly for ammonia production, fuel oil refinery, and metal and food processing (Bromaghim 2010). There are numerous safety issues that needs to be need considered when managing and using hydrogen commercially as it is highly flammable. It can quickly turn into a volatile hazard if large quantities of it is very quickly decompressed in an enclosed area. Hydrogen is also much lighter than normal air and this will cause air to sink down in normal circumstances. In turn, suffocation of workers handling hydrogen is one of the main concerns due to the surrounding oxygen being displaced quickly in poorly ventilated or enclosed areas. Another form of hydrogen which is liquid hydrogen (LH_2) is an extremely cold substance and additional safety measures are required when handling hydrogen in its liquid form (Léon 2008).

D. LIQUID HYDROGEN (LH_2)

Léon’s study into hydrogen technology had provided great insights into the usage of LH_2 for practical commercial applications. Although LH_2 is an extremely cold hazard, it can also possess the highest energy masses when being kept in liquid form. However, this poses several challenges for handling LH_2, such as for storing the same amount of LH_2, more energy and volume is required. The low temperatures of $-254{\circ}C$ for LH_2 also needs a requires a good insulation system to operate efficiently. Despite these challenges,

LH_2 still is generating a lot interest for operational usage onboard vessels as it is able to work mainly on low working pressure systems due to its small physical sizing and could potentially allow vessels to have more space for other system requirements for ship builders (Léon 2008).

E. HYDROGEN FUEL CELLS

Likewise, from Léon's study of hydrogen technology, we can identify that a fuel cell is an electrochemical cell when it is stored in a portable device. The fuel cell is created similarly to a batter an also operates like it with the same fundamentals. The only difference is that a fuel cell can run very much longer when compared against a normal battery (Léon 2008). The fuel cell changes the fuel's chemical energy into electrical energy, and this is its main advantage. However, waste heat is generated due to the conversion. (Léon 2008).

F. HYDROGEN PRODUCTION

1. Natural Gas

Hydrogen is most commonly produced using the steam reforming method from natural gas. Hydrogen is produced in two stages using steam reforming. Natural gas together with methane are used in the steam reforming process. It will then react with steam the using Nickel as a reagent (Kurucz and Bencik 2014a). Nickel is commonly utilized and the changes occurs at high temperatures from 700°C to 1000°C and at low pressures from 3 to 25 bars (US Department of Energy 2014). Kurucz and Bencik's research had also mentioned that methane and natural gases costs will be relatively low till 2025, but there could be a lot of fluctuations in the future (Kurucz and Bencik 2014b).

2. Water Electrolysis

Using Kurucz and Bencik's explanation of water electrolysis, this process can separate elements such as hydrogen and oxygen from water by introducing a current to it. The electrical source is connected to two different steel plates or electrodes and is dipped into the water. The electrodes are the anode and cathode. The cathode will then be charged negatively, and the anode is charged positively. Oxygen and hydrogen gas will next be created at the anode and cathode respectively. Hydrogen production can also be done using seawater desalination using reverse osmosis systems onboard seagoing vessels (Kurucz and Bencik 2014b).

G. ALTERNATIVE ENERGY SOURCES

1. Solar Energy

Solar energy is currently the primary alternative energy source that the U.S. Navy is using (National Renewable Energy Laboratory 2019). Photovoltaic solar panels are being installed as part of the set up for capturing solar energy. They are able to be connected in either series or parallel configurations. These panels are made up of solar cells which are designed to absorb light and convert it into electricity. A 9 m^2 panel produces approximately 1 kilowatt (kw) of electrical power (Javier 2006). Figure 2 shows an example of photovoltaic solar panels installed on a passenger ferry. Some common properties of solar panels include (Fernandez Soto et al. 2010):

- Preferably to be installed in an open area where sunlight is easily available.
- Electrical energy production is not constant due to disruption of sunlight at night times and cloud cover or bad weather during the day; and
- Currently being used on passenger ships combined with other renewable energy systems.

Figure 2. Passenger Ferry Equipped with Photovoltaic Solar Panels. Source: Solar Sailor (2015).

2. Wind Energy

The most recent wind energy system started by the U.S. Navy was in operation since March 2009. It has a 1.5-megawatt (mw) wind turbine which is designed to produce about 3,000 mw per hour of electrical energy each year. Wind turbines could also be deployed onboard seagoing vessels enabling the wind energy conversion to be mobile. They have to (Fernandez Soto et al. 2010):

- Be installed on seagoing vessel's top deck
- Be combined with other renewable energy systems as part of a hybrid energy system.

One of the more developed wind energy systems are the Horizontal Axis Wind Turbines (HAWT). These turbines can produce large amounts of energy on land and it is even possible to apply them out at sea as the wind force is much greater (Soto et al. 2010). Figure 3 shows a conceptual design of a vessel with HAWTs installed at different locations on a large deck space in order to improve stability and also improve the performance of the renewable system.

Figure 3. Conceptual Design of Vessel Installed with HAWTs. Source: Gizmag (2013).

3. Bio Diesel

Biodiesel is produced by processing vegetable oils or animal fats. The properties of biodiesel are similar to conventional fossil diesel fuels but dependent on the raw material (Global Maritime Forum 2022). Biodiesel can be used just alone or mixed together with regular diesel; some of its advantages are:

- Significant reduction of pollutants in the atmosphere
- Biodegradable in water
- Can be used in any conventional diesel engine designed to combust biodiesel; and
- Can be stored in normal diesel tanks without any additional modifications.

Despite these advantages, the production of bio diesel (Global Maritime Forum 2022):

- Has high production costs. It costs twice to produce biodiesel as compared to conventional diesel and this leads to a higher selling price

- Has harmful effects on the environment requiring the destruction of forests and jungles and increased emissions of NOx

- For every ton of biodiesel produced, three hectares of cropland is required for its production.

H. SUMMARY OF FINDINGS

From the review of literatures, concepts for implementing a single naval fuel are indicating that it is promising as it could potentially streamline logistical processes and provide adequate long term operational solutions for overseas bunkering. This is also aligned to the U.S. Navy's concerted effort to implement renewable energy for their vessels and shore facilities so as to not be reliant on traditional fuels and to be self-sustainable. From the different renewable energies discovered, hydrogen shows to be the most promising as there were significant studies and trials done on hydrogen fuel cell technologies onboard surface vessels in the Netherlands, Germany, UK, and U.S. before. It was also proven that it could be used independently without being part of a hybrid energy system. Hydrogen can also be produced using water electrolysis without any harm to the environment. The water electrolysis could also be shifted out at sea coupled with a reverse osmosis plant to drive and increase hydrogen production using seawater. As there were extensive hydrogen fuel cell studies done before, this thesis would anchor its focus on analyzing on LH_2 technologies and study deeper for its implementation to be used as a single naval fuel onboard a naval vessel. Even though the LH_2 storage methods are not mature at the moment, this could be ultimately overcome by employing stringent safety standards in the future.

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III. METHODOLOGY

This proposed thesis will be scoped into two research methods. As shown in Figure 4, the first part of this thesis will be crafted towards a **Design Thesis**. A suitable commercial platform which is similar to a naval vessel from the U.S. Navy will be selected and a preliminary design of the Hydrogen energy system's layout will be drafted using computer aided designs. This design will be used as a baseline to support the vessel's propulsion and power generation. Following this, the second part of this thesis will be crafted towards an **Analysis thesis**. Modelling program RetScreen and Microsoft Excel will be used to generate the emissions and economic analysis. The overview of the research methodology is shown below:

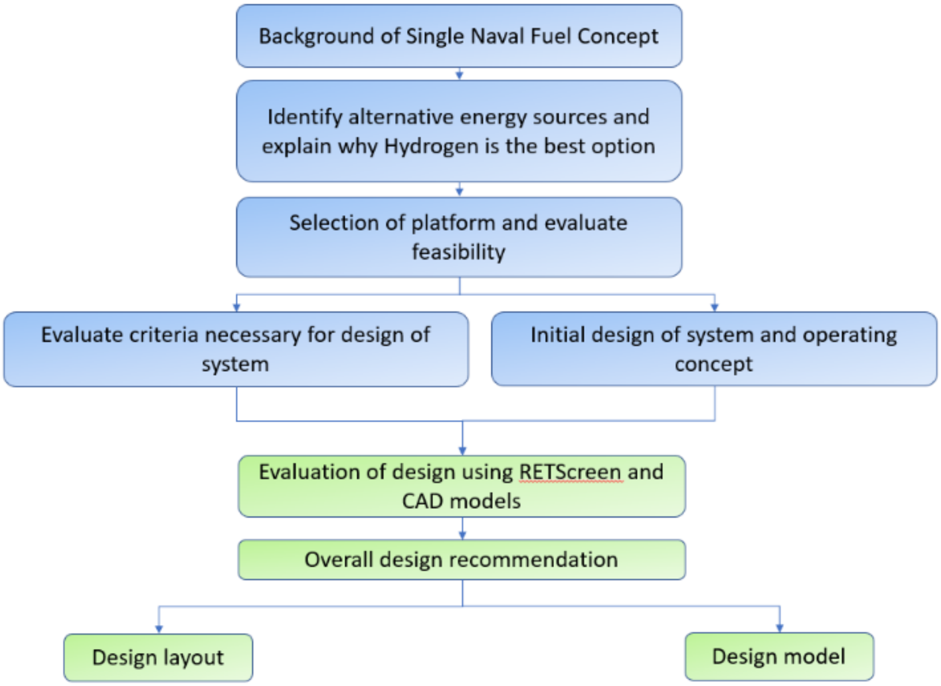

Figure 4. Methodology of Thesis

The blue boxes show the first portion of the thesis which is the design portion, and the second part are the green boxes which will be the analysis portion.

A. DESIGN PORTION

1. Case Study

The case study which will be used in this thesis is a suitable commercial platform which is similar to a U.S. Naval non-nuclear vessel. The estimated requirements for fuel, distance and electrical of the selected platform will be further discussed and elaborated in the next section. CAD modellings will also be used to develop 2-dimensional and 3-dimensional representations of the proposed system. It is an accurate and simple program, which generates high quality representations.

B. ANALYSIS PORTION

In order to evaluate the feasibility of applying alternative energy sources on a suitable commercial platform, modelling programs such as RetScreen will be utilized. RetScreen was chosen because:

- The program allows for modelling of the proposed system compared to the base case
- It has an inbuild GHG analysis; and
- The effectiveness of the energy model can be portrayed

The RetScreen model will be broken down into five sections. These are as follows:

- Load and Network
- Energy Model
- Emission Analysis

1. Load and Network

The load and network of the model was used to estimate the requirements and power loads for the base case. The key input for this section will be the energy data further elaborated in the next section. Other inputs included in this part of the model are portrayed in Table 1.

Table 1. Load and Network Parameters

Parameter	Units	Input	Source
Base Fuel Type	-	Diesel	Shipping Companies
Technology	-	Diesel Engine	Shipping Companies
Fuel Rate	$/t	$650	(BP 2022)
Electricity Rate	$/KWh	The electricity generated on board vessel will be through the generators using the same base fuel.	-

2. Energy Model

The next part of the model was the setup of the energy model, used to evaluate the proposed system. Key inputs in this section of the model include:

- Proposed case (Hydrogen powered gas turbine)
- Fuel selection method
- Gas turbine model and power capacity

However, some key assumptions were also made in this section. These included:

- The availability of the proposed hydrogen powered gas turbine will be at 95%
- Cost of hydrogen gas is estimated at $16.5/kg (from natural gases) (California Fuel Cell Partnership 2019)

3. Emissions Analysis

The main inputs for the emission analysis are depicted in Table 2.

Table 2. Emission Analysis Parameters

Parameter	Units	Input	Source
Base Case Fuel Mixture	%	Diesel – 100%	RetScreen Output
Proposed Case Fuel Mixture	%	Hydrogen – 100%	RetScreen Output
Transmission and Distribution losses	%	7%	(Federal Electricity Regulatory Commission 2022)

The proposed case was calculated to be 93.5% emission free. Realistically, this would not be the case because of the energy used in manufacturing. However, comparing these to fossil fuels, this can be allowed to be negligible.

4. Economic Analysis

The cost analysis was done using Microsoft Excel to assess the costs and credits of the project. Based on the Cost Analysis, the Financial Analysis will then be generated.

Table 3. Financial Analysis Parameters

Parameter	Units	Input	Source
Fuel Cost Escalation Rate	% / Year	10	(BP 2022)
Inflation Rate	%	3.1	(US Bureau of Economic Analysis 2022)
Project Life	Year	20	Assumption
Interest Rate	% per annum	10	(US Bureau of Economic Analysis 2022)

These inputs, coupled with the costs outlined in the cost analysis are used to evaluate some key financial indicators. Those chosen for this investigation include:

- **Net present value (NPV):** The difference between the present value of cash inflows and the present value of cash outflows over a period of time.
- **Payback period:** The time in which it takes the project to reach profit
- **Internal rate of return (IRR):** A metric used to estimate the return on an investment. The higher the IRR, the better the return of an investment.

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IV. DETAILED DESIGN PORTION

This section of the report defines the scope of thesis and identifies specific energy requirements. The results from this section will allow a better understanding of the requirements for the suitable vessel and enable a design for an alternative energy system to be developed.

A. CASE STUDY

This section will go in depth to select a suitable commercial vessel which has similar design traits close to a non-nuclear U.S. Navy vessel to implement the Hydrogen Energy System. This thesis will be focused on a catamaran container vessel (CV) as shown in Figure 6 to be used as a proxy. The catamaran CV has been selected as it is able to be modified easily and it is highly alike to the Spearhead Class Expeditionary Fast Transport with a similar hull structure as shown in Figure 5. It is also selected due to its unique hull design resulting in a decrease of propulsive power amounting to half that of a conventional mono hull design at cruise speeds (Burg and Johnson 2000). Making this choice reasonable as it would be in line with this research's top aim of reduction in atmospheric emission of PM, NOx and SOx.

Figure 5. Spearhead Class Expeditionary Fast Transport. Source: Wikipedia (n.d.).

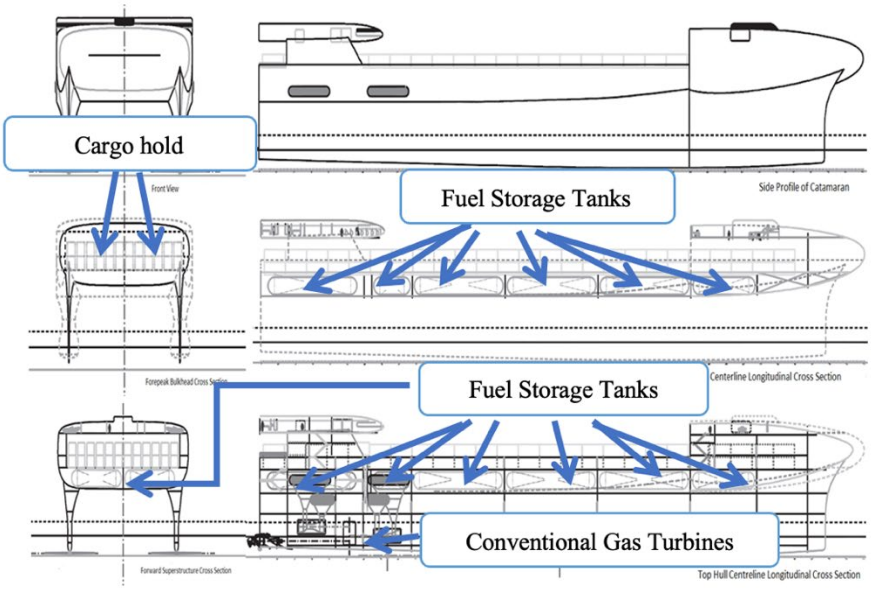

Figure 6. General Arrangement of a Catamaran Container Vessel. Source: Seacoaster (2013).

The main data for the proposed catamaran CV are as follows:

- Overall length—175.50 m
- Height—29.05 m
- Capacity—1000 TEU[2] approximate
- Main propulsion—2 x Gas turbines
- Speed—From speed range of 10–25 Knots[3] (kn)
- Fuel Capacity—2000 ton (t) approximate (12 tanks of 167 t)
- Crew—18 pax

B. ESTIMATED ENERGY REQUIREMENTS

This sub section will cover an overview of the estimated energy requirements of the selected catamaran CV. Estimations were done mainly using container vessels as a reference due to unavailability of data online.

1. Estimated Fuel Requirements

Figure 7 depicts the relation between speed and fuel consumption for six ranges of container vessels at nine different speeds.

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[2] **TEU** = Twenty-foot Equivalent Unit containers. It is a unit of measure used to calculate the sizing of container vessels and container terminals

[3] A **Knot** is a unit of measure for speed in naval terminology. If the vessel is travelling at a speed of 1 nautical mile per hour, it could be said that the vessel has a speed of 1 knot. The nautical mile is a unit of length and by international agreement, it is 1,852 meters.

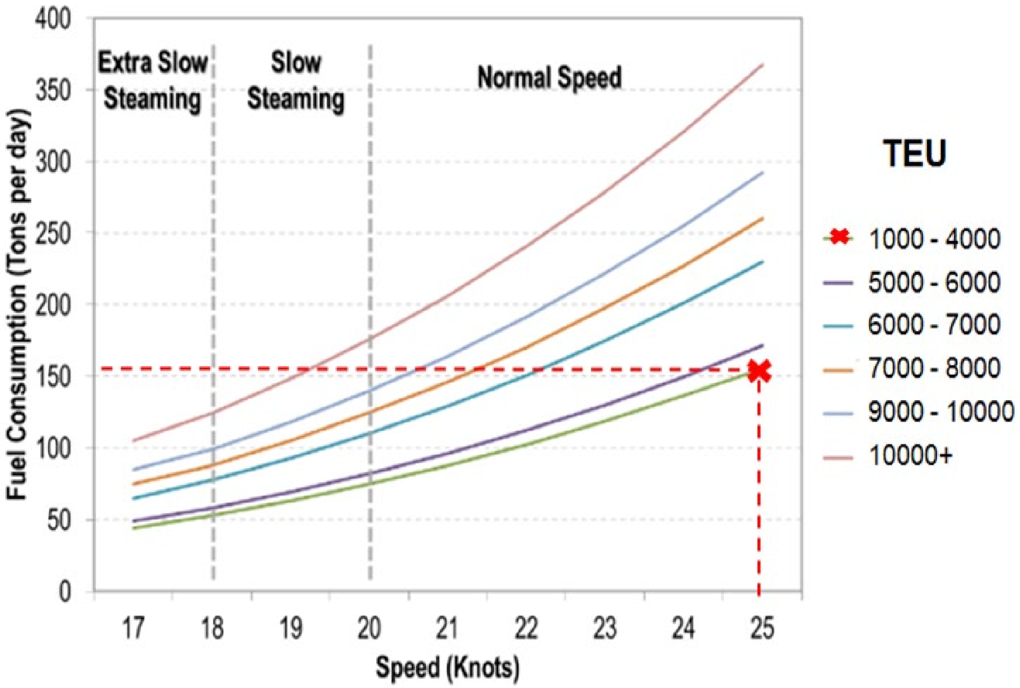

Figure 7. Estimated Fuel Requirements for Catamaran CV. Source: Notteboom and Carriou (2009, p. 4).

The fuel consumption by CVs is mainly based on the size of the vessel and versus its cruising speed. The proposed catamaran CV falls into the category of the 1,000 - 4,000 TEU range and would consume an estimated 150 t/d of fuel at 25 kn as highlighted by the red cross in Fig 7.

2. Estimated Travelling Requirements

For the purpose of this thesis, two Pacific and one Atlantic Ocean commercial crossing routes with ports have been identified which are in works to install alternative fuel plants such as dedicate biodiesel and hydrogen fuel plants (Veldhuis et al. 2007). The route distances and estimated durations at 25 kn cruising speed is highlighted in Table 4.

Table 4. Estimated Travelling Requirements for Catamaran CV. Source: Veldhuis, Richardson, and Stone (2007).

Start port	End port	Distance (nm)	Time (hr)	Fuel load (t)
Yokohama	Tacoma	4272	171	1068
Philadelphia	Cherbourg	3265	131	816
Yokohama	Long Beach	4838	194	1209

3. Estimated Electrical Requirements

The catamaran CV (1000 TEU) has an estimated electrical power demand shown in Table 5. The electrical power requirements on board a CV typically runs the entire propulsion systems, steering systems, air-conditioning, navigations, communications, deck machineries, fire-fighting, and reefers.[4]

Table 5. Estimated Electrical Requirements for Catamaran CV. Source: Nielson (2009).

	With Turbines / Shaft Engaged[5]		**Without Turbines / Shaft Engaged**	
Reefers on board CV	50%	100%	50%	100%
Normal Service (KW)	1775	**2145**	683	1300
Harbour Service (KW)	-	-	525	901

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[4] **Reefers** are containers which have refrigeration capabilities and is being used for temperature sensitive cargos

[5] Shipping and container vessels would have their turbines or propeller shafts engaged only out at sea. Disengaging of turbines or propeller shafts would occur while the vessel is approaching harbor or while anchoring out at sea

The highest demand of the catamaran CV occurs when there is 100% capacity of reefers on board with the turbines / propeller shafts engaged at the same time.

4. Summary of Energy Requirements

In summary, the estimated energy requirements for the Catamaran CV in the highest demand scenario (100% loaded, turbines / shaft engaged) is:

- Fuel consumption of approximately **150 t/d**
- Travelling distance of **4838 nm**
- Electrical demand of up to **2145 KW** with turbines / shaft engaged.

V. HYDROGEN ENERGY SYSTEM

This section will outline the operating concept and how the Hydrogen Energy System design will be proposed. Critical components of the selected catamaran CV will be highlighted and recommendations for its requirements and replacements will likewise be discussed in this section.

A. OPERATING CONCEPT

The operating concept of the Hydrogen Energy System will focus on the hydrogen fuel system and how it drives the mechanical components within the catamaran CV.

1. Hydrogen Energy Flow

For the purpose of this research, LH_2 has been chosen as the storage medium as it has a considerably high volumetric ratio of 7:1 as compared to gaseous hydrogen (Léon 2008). Marine LH_2 systems are a lot different from traditional marine diesel systems that are fitted vessels. Traditional marine diesel systems mainly uses only diesel as its fuel because of its low prices and its suitability for large diesel engines which are low speed and commonly found in CVs (Veldhuis et al. 2007).

One of the main differences between diesel and LH_2 are its storage temperature, and the internal combustion temperature. For diesel, its temperature needs to be minimally 120°C so that it can be combusted safely in the fuel injectors (Soto et al. 2010). For LH_2, its required storage temperature is extremely low at -254°C which is to keep it at its liquid state. Additional heating is also needed to evaporate the fuel before it can safely pass into the combustion chamber of the engine for the proposed catamaran CV

The proposed hydrogen fuel system needs to interact with various fuel system components. The operating concept for the hydrogen fuel system is shown in Figure 8. As shown in the diagram, the cryogenic LH_2 fuel is subjected to boil off due to temperature changes from the storage point versus the normal air temperature. The boil off gas which is created by this heat difference can be used to run the generators (Fernandez Soto et al. 2010).

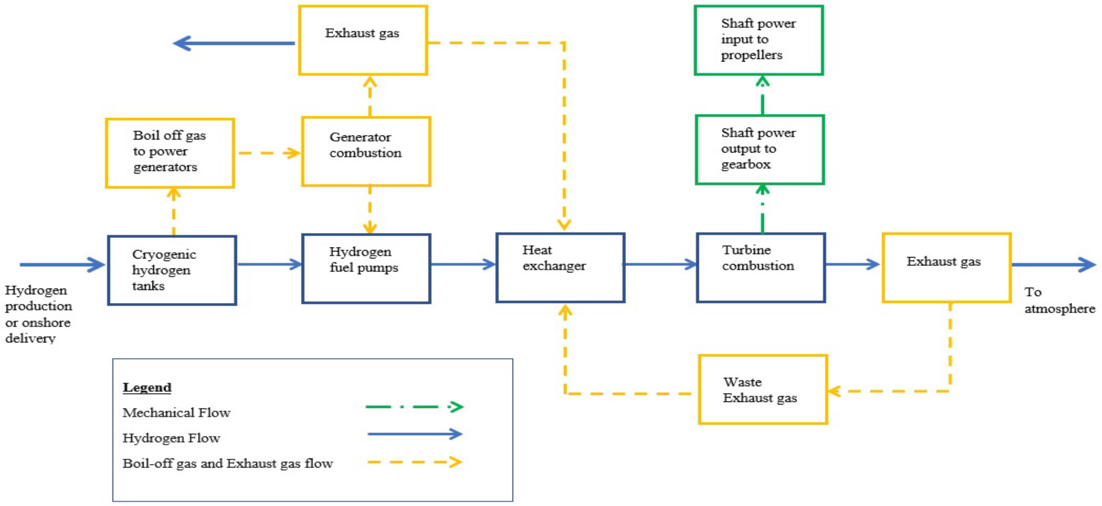

Figure 8. Energy Path of Hydrogen Energy System

B. CRYOGENIC REQUIREMENTS

1. Design Requirements

As cryogenic LH_2 has very low temperatures at -254^{o} C the mode of operations is very different from traditional diesel fuel systems. There are three main differences for its design requirements (Veldhuis et al. 2007). Firstly, the LH_2 fuel system would need to be entirely enclosed, as exposing the cryogenic LH_2 to warmer ambient conditions would cause the LH_2 to evaporate in large amounts. The enclosed LH_2 fuel system requires for it to be pressurized higher than atmospheric pressure which will prevent air from seeping into the system. If air contacts with LH_2, it will instantly freeze and the frozen LH_2 would choke up the fuel lines and cause severe damage to the system (Léon 2008).

Secondly, the fuel system would need to be able to operate with different states of the cryogenic LH_2. One of the founding fathers of cryogenic technologies Randall Barron had previously discussed that the LH_2 fluid transfer speed inside its pipes could allow a two-phase flow regime to occur (Barron 1999). This means that the LH_2 flowing in the pipes could be separated into fluid and vapour states. The mass flow rate for the LH_2 transfer piping needs to be carefully considered due to this issue.

Lastly, the LH_2 material requirements highlighted by Brewer in his hydrogen research studies are those that are needed to be capable of resisting hydrogen deterioration, maintaining ductility, crack or fracture resistance at extremely low temperatures and also must be easy to repair and maintain (Brewer 1991a). In Barron's research, he had proposed some materials which are suitable for LH_2 usage at cryogenic temperatures. These include 304 Stainless Steel, Teflon, Titanium and 2024-T4 Aluminium (Barron 1999). These materials are then being put into cryogenic conditions and its properties are observed. Only the 304 Stainless Steel had its impact strength increased and ductility reduced by half. As its mechanical properties can perform well at low temperatures, the 304 Stainless Steel has been frequently used in cryogenic applications till present.

2. Operational and Maintenance Requirements

The LH_2 fuel system is envisaged to uphold low temperatures for long periods of time. During planned maintenances, all LH_2 must be removed and the system will be warmed to atmospheric temperatures before repair and inspections can be started on the system. Such temperature changes could cause material deformations and lead to critical damage of the system (Léon 2008).

In Pohl and Malychev's research, they had established that long phases of cryogenic temperatures can lead components such as pumps and valves towards failure (Pohl and Malychev 1997). In order for these materials and machinery to operate normally during, Pohl and Malychev had proposed 10,000 working life hours to be the minimum for components that are being utilised in a cryogenic environment.

C. MAIN PROPULSION

1. Design Requirements

As the catamaran CV's current main propulsion are made up of marine gas turbines, it would be straightforward to look into methods to modify it to support hydrogen combustion. Normally gas turbines are categorised as internal combustion engines which is made of a turbine, compressor and a combustor (Çengel and Boles 2015). The use of hydrogen gas turbines for propulsion purposes dates back to 1943 with the LH_2 fuelling trials in aircraft engines at Ohio State University (Veldhuis et al. 2007).

By applying hydrogen into gas turbine research for the aviation industry, there had been significant results by Brewer, who had successfully applied hydrogen combustion in gas turbines on military low altitude aviation transports and high-speed surface ships which utilises LH_2 as its fuel source. Based on Brewer's recommendation, the catamaran CV's main propulsion would have to be modified as follows:

- Introduction of LH2 fuel pumps capable of operating with this cryogenic fluid for sufficient operating hours
- Introduction of LH2 heat exchangers allowing hydrogen fuel to evaporate before entering the combustion chamber
- Introduction of a fuel control unit capable of dealing with both gaseous and liquid stages of hydrogen within the fuel system; and
- A modified combustion chamber allowing for combustion of hydrogen (Brewer 1991b).

2. Main Engines Replacement

The current gas turbines (LM2500) on the catamaran CV will require replacement and modifications based on the above recommendations. In order to support LH_2 combustion, it is appropriate that the gas turbine is able to support large power outputs due to LH_2's variable performance (Brewer 1991a). A suitable replacement is the LM6000 gas turbines, which currently have the largest power output commercially available by GE shown in Figure 9.

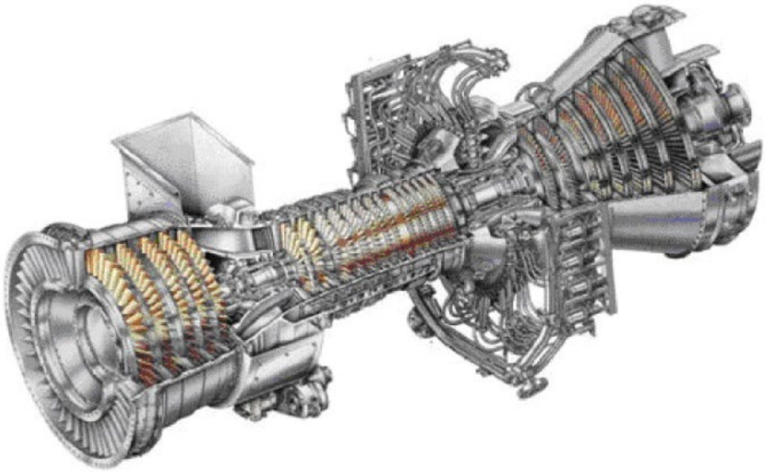

Figure 9. LM6000 Gas Turbine. Source: General Electric (2013).

This turbine is made up of low-pressure compressors with five stages and coupled with a high-pressure compressor with fourteen stages. An internal combustor comprising of thirty nozzles provides high temperature fuel injection. This turbine operates on a 3,600 rpm shaft producing power output of 49,300 KW. It is also capable to combust different fuels and gases including hydrogen (General Electric 2013a)

As highlighted by Bathie, the unique combustion characteristics of hydrogen provides an increased thermal efficiency between 2% and 4%. By establishing the Specific Fuel Consumption (SFC), the endurance of the hydrogen fuelled catamaran CV can then be found (Bathie 1996). The SFC can be derived through a series of equations:

$$\eta_{thermal} = \frac{W_{net}}{Q_{in}} \qquad [1]$$

Secondly, the heat input (Q_{in}) is obtained by the combustion of fuel. The heat input can be expressed as follows (Çengel and Boles 2015):

$$Q_{in} = Q_{fuel} \times M_{fuel} \qquad [2]$$

Thirdly, by substituting Equation 2 into Equation 1, the power output ($\dot{W}_{net}$) of a gas turbine can be expressed as (Çengel and Boles 2015):

$$\dot{W}_{net} = \eta_{thermal} \times Q_{fuel} \times M_{fuel} \qquad [3]$$

Finally, by rearranging Equation 3, an expression for the fuel mass flow ($\dot{M}_{fuel}$) or otherwise known as SFC of a gas turbine is shown (Çengel and Boles 2015):

$$\dot{M}_{fuel} = \frac{\dot{W}_{net}}{Q_{fuel} \times \eta_{thermal}} \qquad [4]$$

By applying Equation 4, the hydrogen SFC can be obtained. The fuel mass flow of the four LM6000 gas turbines is calculated to be at 0.9 kg/s and SFC obtained from these values is calculated to be at 0.067 kg of hydrogen per KW per hour. The SFC value can be then used to alter the travelling requirements with hydrogen fuel capacity on the highlighted ocean crossing routes.

D. MODIFICATION OF LH_2 TANKS

The catamaran CV's on-board storage facilities must be able to successfully contain the cryogenic temperature of approximately -254°C. For the LH_2 to maintain its cryogenic temperature, an insulation system will be needed, and the required specifications of the system will be motivated based on the time required for the LH_2 to be inside the tank

1. Energy Requirements

It was highlighted that the SFC of the four LM6000 turbines was calculated to be at 0.067kg of hydrogen per KW per hour. Based on these figures, a new table with the hydrogen fuel load can be derived from the previously mentioned ocean crossing routes.

Table 6. Estimated Travelling Requirements with Calculated Hydrogen Fuel Loads

Start port	End port	Distance (nm)	Time (hr)	LH_2 Fuel load (t)
Yokohama	Tacoma	4272	171	911
Philadelphia	Cherbourg	3265	131	696
Yokohama	Long Beach	4838	194	1031

From Table 6, it can be observed that the highest hydrogen fuel load would be at 1031 tons. This is sufficiently low enough for storage of LH_2 in the catamaran CV as its current twelve fuel tank's storage capacity is up to 2000 t. The longest travelling time would also be at 194 hours assuming if the transportation route for the catamaran CV starts at Yokohama and ends at Long Beach. This would sufficiently serve as the time required for the LH_2 to be in the tank and the amount of LH_2 combustion required for the longest journey.

2. Design Requirements

From Brewer's studies, there were two different kinds of LH_2 tanks that were mentioned. These are integral and non-integral tanks. The integral tanks has been used primarily for aircrafts and CV such that the tank shell together with the insulation portion integrates with the aircraft and vessel's main body (Brewer 1991b). This is shown in Figure 11. In addition to this, non-integral systems which have an additional spacing in between the main body and tanks were also mentioned in these studies with various insulation methods.

In traditional CV designs, the fuel tanks are designed to be integral with the vessel's structure. However, for the case of this research the non-integral tanks are preferred. These are mainly due to various reasons. Firstly, the main structure of CV would be constantly subjected to torsional forces particularly in the bow and stern[6] portion of the vessel (Veldhuis et al. 2007). Such forces may create hairline fractures in the vessel's structure with the potential of LH_2 fuel escaping if the tank was designed as an integral part of the ship. Secondly, using integral tanks would allow weight minimization in aircraft and vessel structures. However, for the case of this research, weight minimization would not play a very big role and can be ignored for the more important factor of safety. Lastly, non-integral tanks allow every single tank to be removed and replaced for maintenance or for shipping operations. Such fast tank removals avoid vessel down time and increases productivity.

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[6] The **bow** and **stern** are naval terms commonly used to describe the front and back portion of the vessel respectively.

3. Thermal Requirements

Studies on insulation requirements for cryogenic tanks have been mainly done by Brewer as well. His research describes the screening process for fifteen aviation insulation systems in areas such as system safety, system performance, production, and system operational requirements (Brewer 1991b). His research came to the integral and non-integral tanks. These tanks consist of:

- A dual layer closed cell foam with two vapor barrier systems
- A single closed cell foam layer combined with a hard vacuum layer enclosed by aluminized Mylar film and a honeycomb jacket (multi-layer) on top (Brewer 1991b).

These two tanks are shown in Figure 10 and Figure 11. Brewer had established that the foam based option has a lower fuel weight ratio of 0.42 as compared to 0.51 for the vacuum based option in his research (Brewer 1991a). Given the higher fuel weigh ratio of the vacuum-based system, it directly represents a higher rate of thermal conductivity. As such, the vacuum-based system is preferred in this research.

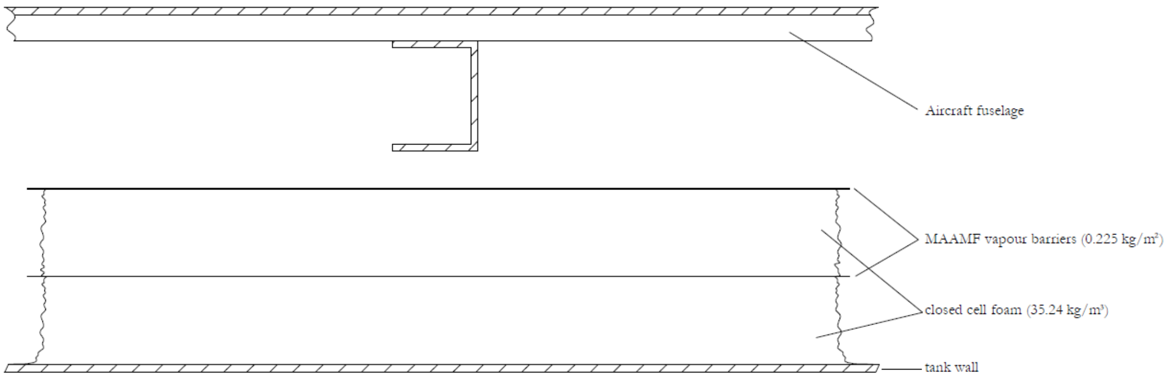


Figure 10. Non-integral Insulations. Source: Brewer (1991).

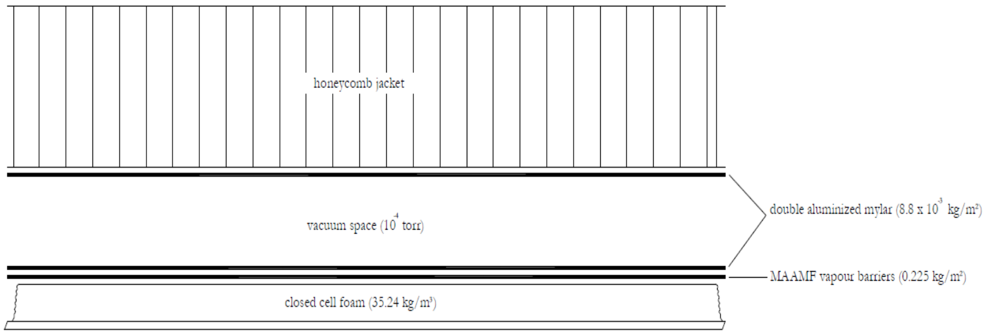


Figure 11. Non-integral Vacuum and Honeycomb Insulations. Source: Brewer (1991).

In cryogenic systems, minimizing the total amount of heat flux, evaporation rate and inactive duration are important parameters which are directly affected by heat input (Léon 2008). Due to this, increasing the insulation of the cryogenic tank can result in better system performance of storing LH_2.

The evaporation rate is directly related to the total heat flux. In the case of the catamaran CV with a 167 t LH_2 tank, with an evaporation rate of 1 bar pressure is shown in Table 7.

Table 7. Evaporation Rate for LH_2 Tank of 167 t

Heat Entry (W)	1	2	4
Evaporation Rate (%)	1.8	3.6	7.2

The inactive duration time would be the time required for a tank pressure to increase from its normal functional pressure and to reach its blow-off pressure. The pressure increase is related to the heat entry time together with the filling level of the tank. Figure 12 shows a graphical representation of this function. It can be seen that the insulation performance of the tank is the best when the filling level is at the highest

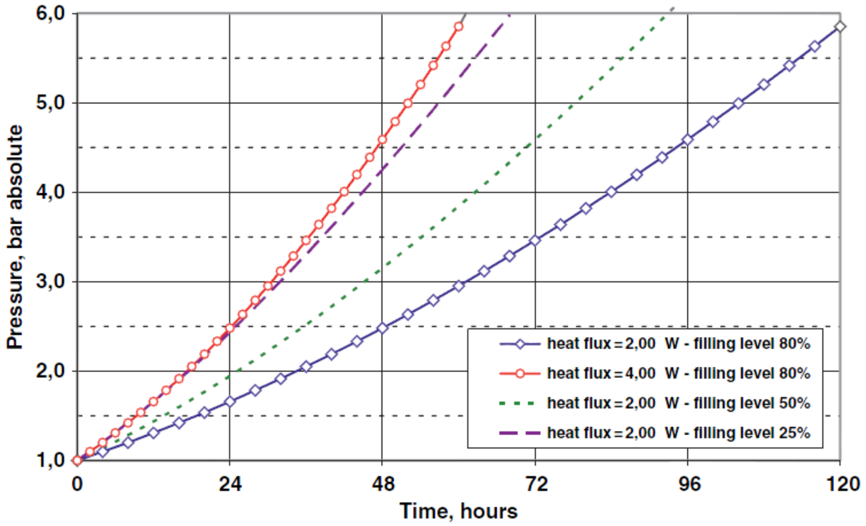


Figure 12. Pressure Rise of a Cryogenic Tank. Source: Léon (2008).

4. Pressure Requirements

When hydrogen is moved into a cryogenic tank holding LH$_2$, the tank pressure may reduce severely (Léon 2008). The tanks need to be installed with a pressure management system such that the pressure in the tank can be maintained. Figure 13 shows a proposed pressure management system for the LH$_2$ cryogenic tanks. This pressure management system consists of a pressure indicator, 2 electrical heaters and a pressure regulator

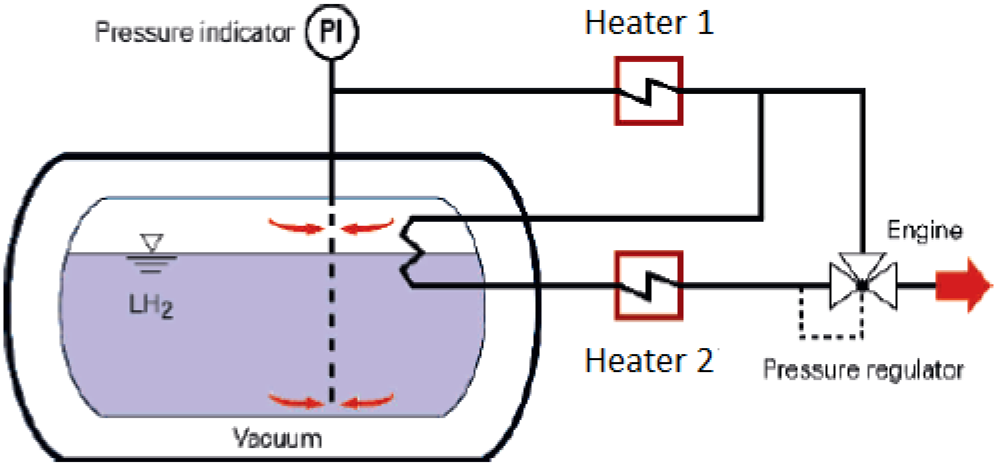


Figure 13. Pressure Management System for Cryogenic Tank

5. LH_2 Boil-Off Mechanisms

Boil-off for Cryogenic LH_2 fuel is normally due to large temperature changes between the tank and the atmospheric. In order for boil-off to occur in the LH_2 fuel tanks, there are several mechanisms which need to be highlighted:

- Shape and size effect,
- Thermal stratification,
- Insulation, radiation, conduction, and cool-down and
- Sloshing. (Sherif et al. 2005)

Sherif et al's research further explain that for the shape and size mechanism, the LH_2 tanks are required to be designed in a spherical shape which can prevent the tank from being uncovered and being exposed to the warm atmospheric temperature which can lead to lowering of boil-off.

For thermal stratification mechanism, the requirements of having different layers with different temperature ranges in the LH_2 tank. This is cause by leaving the LH_2 to be inactive for long periods of time. Warm LH_2 will move up to the surface as it is more buoyant and increase the rate of boil-off in the fuel tanks.

The next mechanism would have to depend on the type and performance of the insulation. Hot air at normal temperatures will enter the tank with transfer rates that is reliant on the performance of the insulation. Furthermore, the hot air could also enter via other sources such as piping or external connections which will cause the rate of boil-off to go higher or lower.

The last mechanism provides an alternative to produce boil-off. Whenever a vessel moves it will cause the LH_2 to knock against the fuel tank walls and the energy from the impact of the knocking can be turned into thermal energy to generate boil-off. The knocking of the LH_2 against the fuel tank walls is otherwise known as sloshing.

E. COMPRESSORS AND GENERATORS

In general, compressors on-board vessels are used to create pressurized gas levels which are required main engine and generators start up usage and to also power up other necessary auxiliary systems. For the case in the catamaran CV, the compressors will then be used to boost the hydrogen boil-off gas for positive usage in the gas turbines and generators.

1. Replacement of Compressors

There is currently no data on the current compressors being used on the catamaran CV. The assumption would be that of a mechanical piston compressor which is widely used on-board shipping vessels (Soto et al. 2010). To support the compression of hydrogen boil off gas, it is appropriate that the current compressor be replaced to one which could accommodate the properties of hydrogen. A suitable replacement would be the C-12-40-7000LX/SS by Hydro-Pac, Inc. as shown in Figure 14.

Figure 14. Hydrogen Gas Compressor. Source: Hydropac (2010).

The hydrogen gas compressor is an electrical driven compressor with two single stage units on each sides (Hydropac 2010). Figure 15 shows schematic of the hydrogen gas compressor. The pistons will begin to compress the gas at the start. Once this is completed, the multi-directional four-way valve will allow the fluid to flow in the opposition direction of the pistons. This will allow the fluid and gas to have no contact with one another.

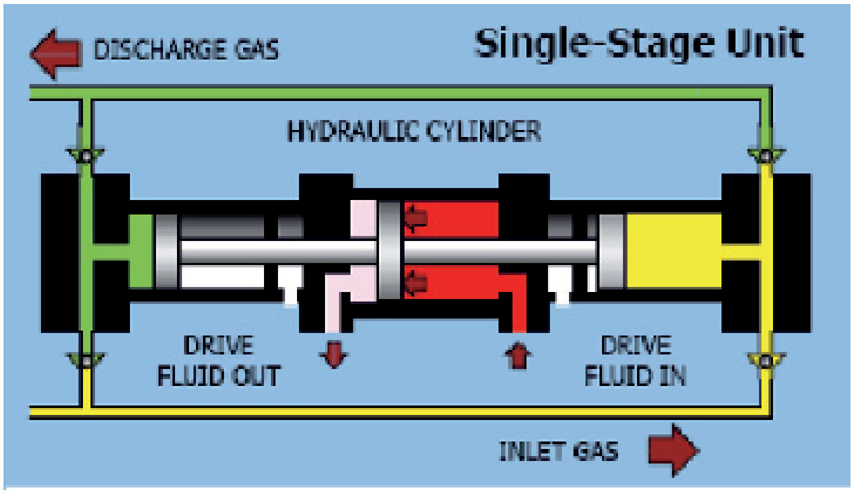


Figure 15. Schematic of Hydrogen Gas Compressor. Source: Hydropac (2010).

2. Replacement of Generators

Similar to the compressors, there is no data available for the generators being used currently on the catamaran CV. As mentioned earlier, the boil-off gas generated by the LH_2 fuel tanks will be utilised to power the generators. In order to positively use this boil-off gas, a gas turbine is required to be installed. This gas turbine will then be connected to a gearbox and an electric generator to produce electricity required for the catamaran CV(Brewer 1991a).

A suitable proposal in this case would be the GE10-1 gas turbine capable of producing an electrical output of up to 5625 KW each. There would be 2 of these gas turbines installed on the catamaran CV and this is roughly four times the maximum electrical requirement for the catamaran CV. Figure 16 shows a model of the GE10-1 gas turbine connected to an electric generator.

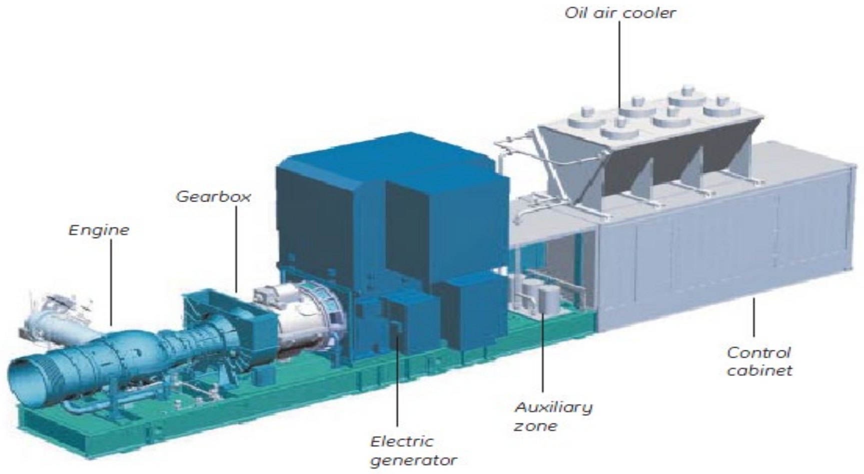


Figure 16. GE10-1 Gas Turbine and Electric Generator. Source: General Electric (2013b).

As mentioned in General Electric's website,

> [T]his particular generator is a multi-purpose gas turbine which can produce 5 MW of power It has a rotational speed of 11000 rpm and a mass flow of 47 kg/s. The GE10-1 is optimized for power generation applications and consists of 3 reaction stages. The combustion system of the GE10-1 is also

able to burn a range of liquid and gas fuels including hydrogen. (General Electric 2013b)

F. LH_2 TRANSFER PUMPS

Brewer's recommendation had stated that there is a need to introduce fuel transfer pump that are capable of handling the cryogenic LH_2 fuel. There are currently two main types of pumps being used for LH_2 purposes. They are the oil-sealed mechanical pumps and oil-free vacuum pumps.

The main consideration that affects the decision of whether to use an oil-free or an oil-sealed pump is the determination of whether the application is sensitive to oil contamination. If it is determined that the application is oil sensitive, the next consideration is whether or not an oil-sealed mechanical pump is sufficient to prevent the back streaming of oil from entering the process chamber in quantities that will cause contamination problems, if not then consideration should be given to use of oil-free pump (NASA 1999).

The major benefits for the use of oil-free vacuum pumps in the LH_2 transfer system is that these pumps eliminate the danger of oil or oil molecule contamination and can be safely operated unmanned. This results in both cost-saving and a reliability improvement in the pumping process. The proposed vacuum pump to be used on the catamaran CV is shown in Figure 17.

Figure 17. Becker VFD Vacuum Pump. Source: Becker Pumps (2013).

Berker Pumps highlighted that its

> Becker VFD vacuum pump has a 20:1 flow ratio, a remote variable speed controller, 100% oil-less operation and the pump is able to withstand cryogenic temperatures. The pump housing is made up of stainless steel and its internal components are forged from Aluminum 6061 T6. (Becker Pumps 2013)

G. LH_2 HEAT EXCHANGERS

In order for the gas turbines on the catamaran to combust the LH_2 fuel, there is need to heat up the LH_2 to ambient temperature, which converts the LH_2 to H_2. This would then be suitable for injection into the combustion chamber. In order to achieve this, a specially designed heat exchanger using Brewer's recommendation has to be installed between the LH_2 tanks and the gas turbines.

1. Heat Exchanger Design

Heat exchanger designs varies greatly throughout the maritime industry (Veldhuis et al. 2007) and to select the most ideal design, there is a need to understand the boundary conditions of the fluids and to also determine the methods of calculations to be used to estimate the heat transfer rate and the heat transfer area.

The most common heat exchanger calculation methods that are being used currently are the log mean temperature difference (LMTD) method and the number transfer units (NTU) method (Incropera and DeWitt 2007). If the inlet temperatures of the fluids that are going to be used in the heat exchanger are known, the use of the LMTD method would require an iterative procedure, which is not favourable and tedious for calculations. Hence, the NTU method will be used for the design on the catamaran CV heat exchanger.

The two fluids that will be used in the heat exchanger are seawater and LH_2. In order to totally prevent the two fluids from coming into contact with each other, a finned tube unmixed cross flow arrangement would be recommended to be utilised on the catamaran CV as shown in Figure 18.

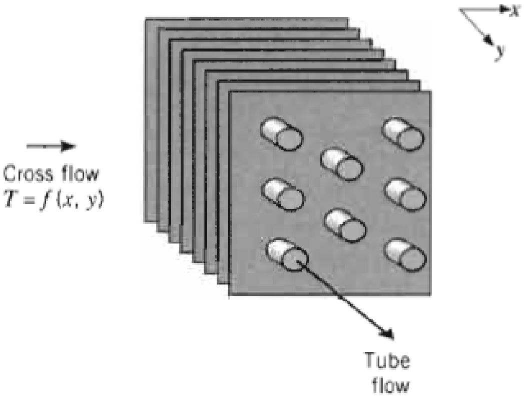


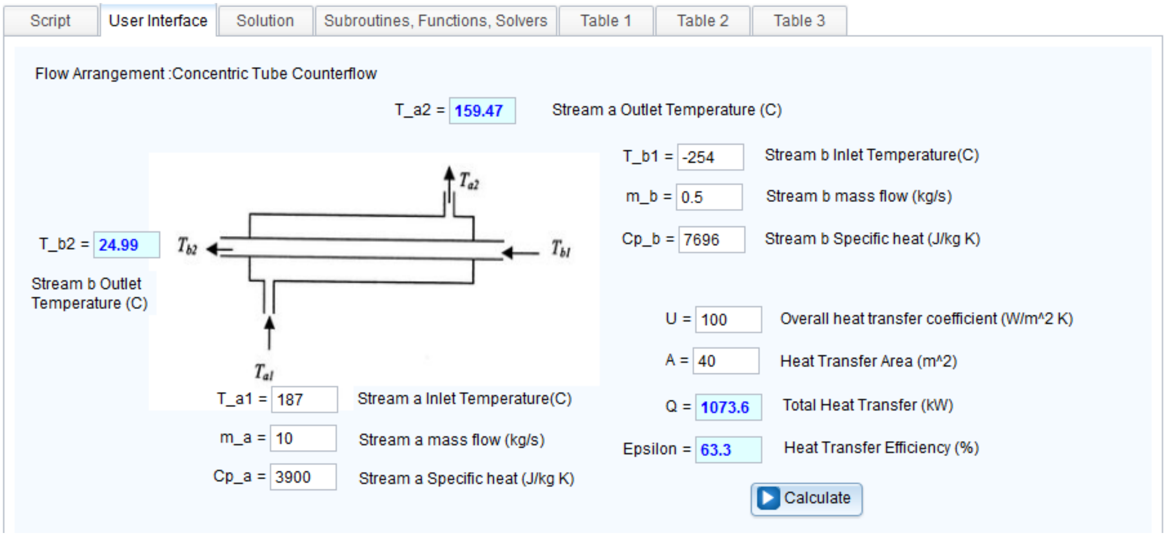
Figure 18. Fin Type Cross Flow Heat Exchanger. Source: Incropera and DeWitt (2007).

2. Heat Exchanger Calculations

The catamaran CV LH_2 heat exchanger calculation will be modelled in the following way:

- LH_2 enters the finned tube cross flow heat exchanger at -254 °C and leave at ambient temperature of 25 °C causing it to vaporise;
- Seawater is required to be heated up till a temperature of 187 °C in order to cause the vaporisation of LH_2; and
- The overall heat transfer coefficient and heat transfer area are assumed to be 100 $W/m^2.K$ and 40 m^2 respectively. The mass flow for seawater and LH_2 is also assumed to be 10 kg/s and 0.5 kg/s

A schematic of the system is as shown in Figure 19 which uses a heat exchanger calculator applying the NTU method towards deriving the required temperatures for the heated seawater inlet and outlet. This level of analysis may not be adequate for the full design of the LH_2 heat exchanger as much more testing and other calculations may be needed, the assumptions of the mass flow rates likewise may not be accurate. But given the current resources, this research will only focus on the inlet and outlet temperatures for the seawater and LH_2.



Flow Arrangement :Concentric Tube Counterflow

T_a2 = 159.47 Stream a Outlet Temperature (C)

T_b1 = -254 Stream b Inlet Temperature(C)

m_b = 0.5 Stream b mass flow (kg/s)

Cp_b = 7696 Stream b Specific heat (J/kg K)

T_b2 = 24.99 Stream b Outlet Temperature (C)

U = 100 Overall heat transfer coefficient (W/m^2 K)

A = 40 Heat Transfer Area (m^2)

T_a1 = 187 Stream a Inlet Temperature(C)

Q = 1073.6 Total Heat Transfer (kW)

m_a = 10 Stream a mass flow (kg/s)

Epsilon = 63.3 Heat Transfer Efficiency (%)

Cp_a = 3900 Stream a Specific heat (J/kg K)

Figure 19. Schematic of LH_2 Heat Exchanger. Source: Mathtab (2015).

H. LH_2 VALVES

The overall LH_2 fuel system requires the valves to operate and maintain the functions of the gas turbines and fuel tanks. Given the cryogenic properties of LH_2, it is necessary for the valves to be able to withstand the freezing temperatures and to be able to operate effectively at the same time. One such valve that would be able to do so is the WEKA PK-TZV LH_2 pneumatic valve shown in Figure 20.

> Arca's website had mentioned that their valves are able to operate in cryogenic environments and "To avoid freezing at the warm end of the valve, Arca Valves had integrated a spindle of that is able to operate in low temperatures and is made in composite material. The valve design has an overall length of 300 mm and the valve has to handle a temperature change of over 200 degrees over a maximum cryogenic length of 130 mm" (Arca Valves 2012a).

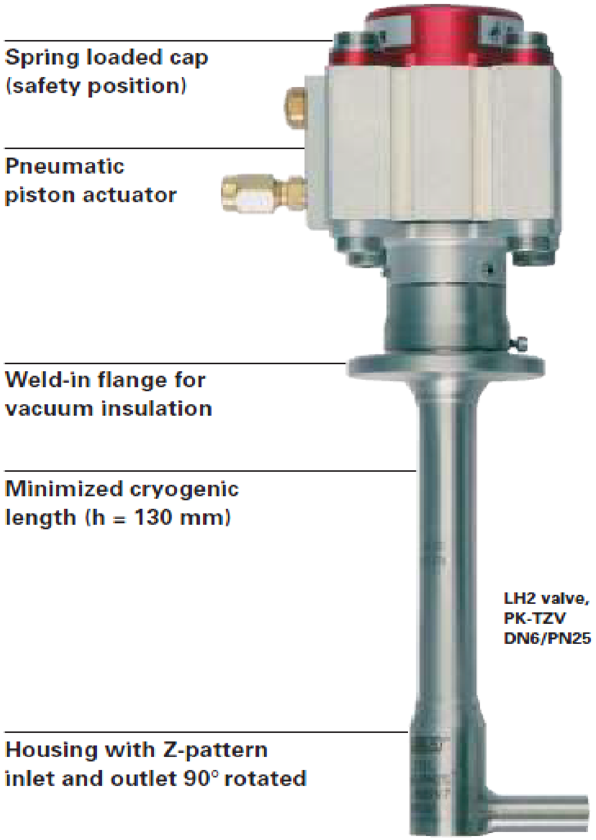


Figure 20. WEKA PK-TZV LH_2 Valve. Source: Arca Valves (2012).

I. SUMMARY OF PROPOSED DESIGN

The proposed Catamaran CV with the hydrogen energy system will comprise of the following requirements, replacements and modifications shown in Table 8:

Table 8. Summary of Proposed Catamaran CV Design

System	Critical Component	Replacements	Modifications	Remarks
Hydrogen	Main propulsion	GE LM6000 gas turbine	N/A	In accordance with Brewer’s (1991) LH_2 requirements for supporting systems
	LH_2 fuel tanks	N/A	Modify existing fuel tanks to hold LH_2	Performance, design, thermal, pressure and boil-off requirements
	Compressor	Hydro-Pac C-12-40-7000LX/SS hydrogen compressor	N/A	Able to compress hydrogen gas and non-contamination features.
	Generator	GE 10–1 gas turbine	N/A	In accordance with Brewer’s (1991) LH_2 requirements and able to produce 5625 KW of electricity.
	LH_2 transfer pump	Becker VFD vacuum pump	N/A	Non-contamination features and able to withstand cryogenic temperatures.
	LH_2 heat exchanger	N/A	Fin type cross flow heat exchangers. Retrofitting to be done to allow LH_2 operations	Installing electrical heaters to bring seawater temperature up to 187 °C. Materials in the heat exchanger to be able to withstand cryogenic temperatures.
	LH_2 valves	WEKA PK-TZV valves	N/A	Able to operate in cryogenic temperatures.

J. OVERALL DESIGN LAYOUT

An overall schematic of the hydrogen fuel system is able to be produced as shown further in Figure 26. The lines highlighted in magenta represent the gaseous line for boil-off effects of the LH_2 and also after passing through the heat exchanger. The lines in black represent the liquid line. An addition to this, a model of the catamaran CV was drafted using AutoCAD showing the external layout of the vessel as also shown in Figure 21 and Figure 22.

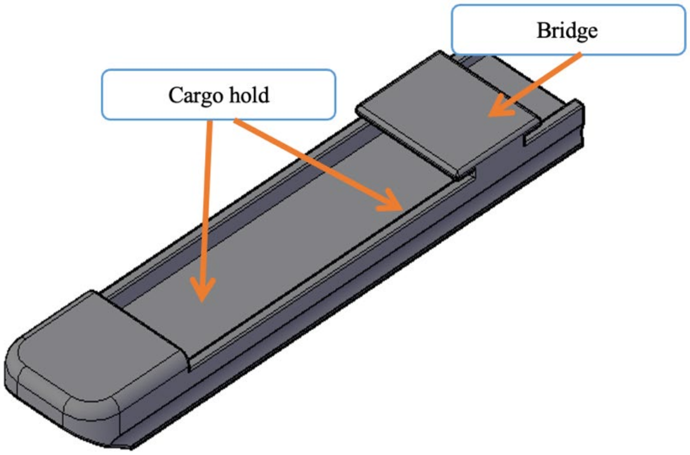


Figure 21. Top View of Catamaran CV Model

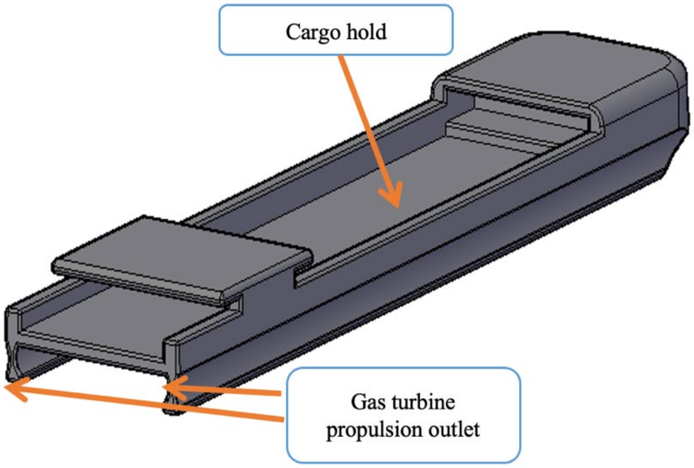


Figure 22. Back View of Catamaran CV Model

The layout for the hydrogen fuel system to be fitted into the catamaran CV can be produced as shown in Figures 23, 24 and 25. The dimensions of this layout had been estimated and drafted in AutoCAD using blocks to represent the critical components. The LH_2 valves were left out of the diagram so as to prevent cluttering of the layout.

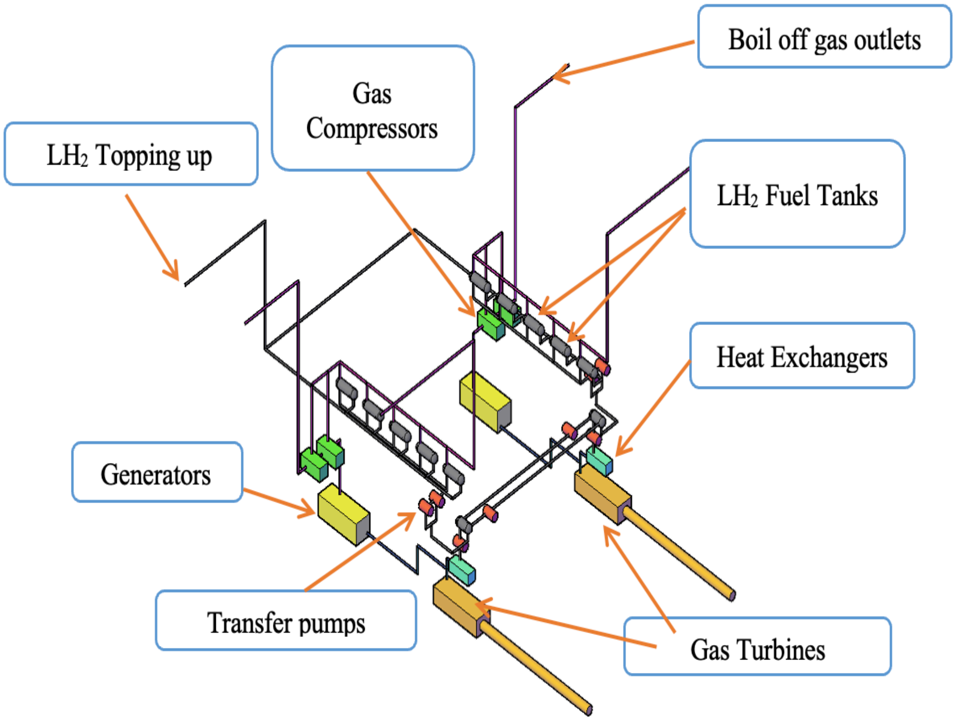


Figure 23. 3D View of Hydrogen Fuel System Layout

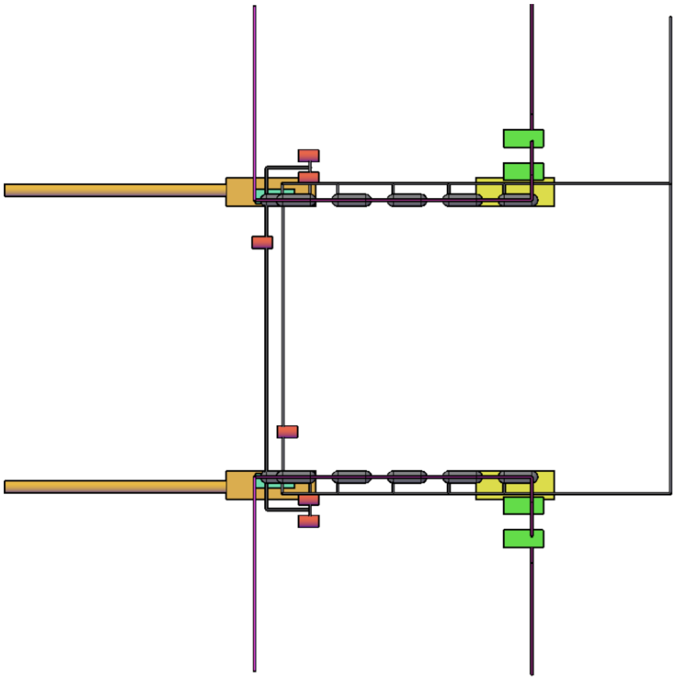


Figure 24. Top View of Hydrogen Fuel System Layout

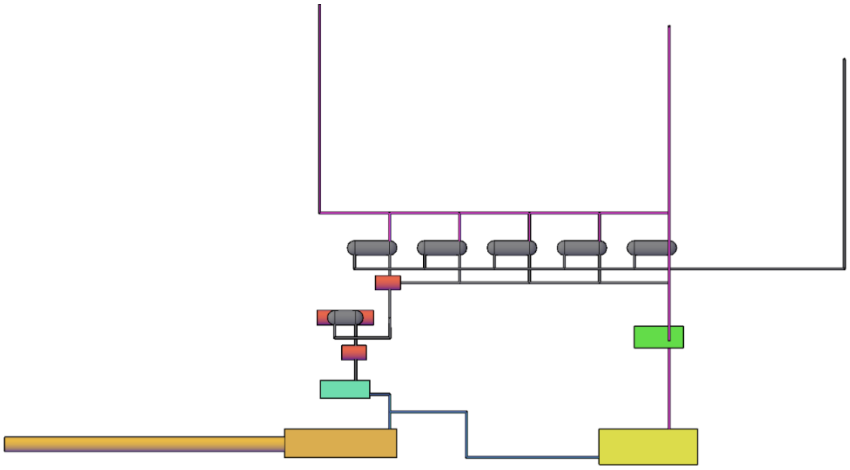


Figure 25. Side View of Hydrogen Fuel System Layout

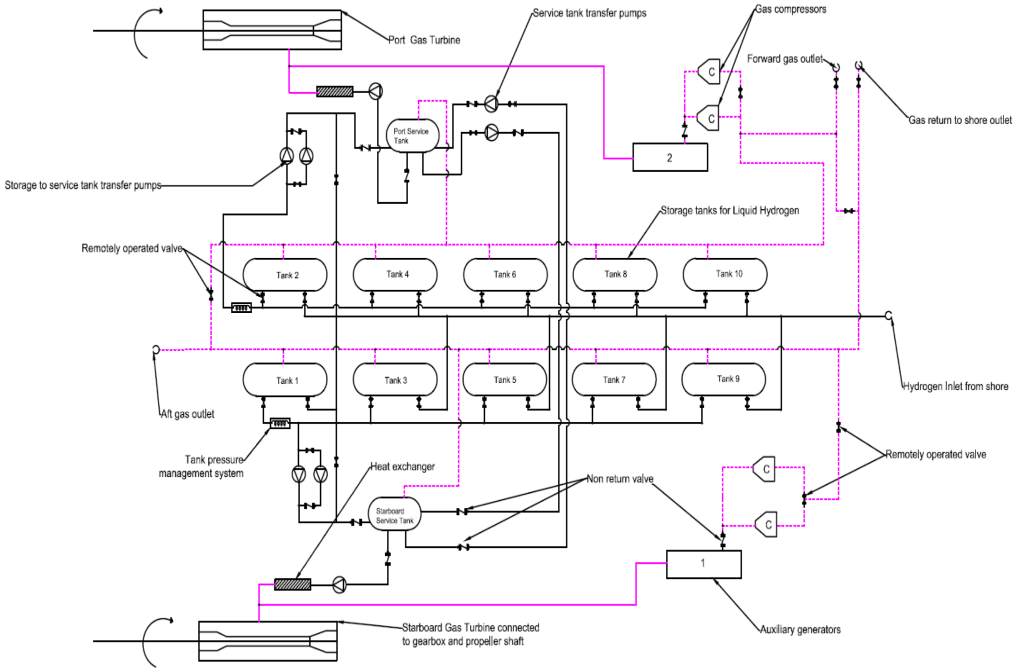


Figure 26. Schematic of Hydrogen Energy System

VI. EVALUATION OF DESIGN

This section will cover the design analysis, which will cover more details on the derived RetScreen data for evaluation of the hydrogen energy system design. These data will be separated into different parts that will dwell into the emissions analysis, economic analysis, sensitivity analysis, reliability, and efficiency.

A. DESIGN ANALYSIS

The current energy requirements of the catamaran CV are estimated to be (at the highest demand scenario):

- Fuel consumption of approximately 150 t/d
- Travelling distance of 4838 nm and travelling time of 193.5 hours
- Electrical demand of up to 2145 KW with turbines / shaft engaged.

With the proposed design, the catamaran CV with the hydrogen energy system is able to meet the current energy requirements through the following:

- With the calculated SFC of hydrogen fuel load, the hydrogen fuel consumed for the highest demand ocean crossing route will then be at 1031 t
- The LH_2 fuel tanks are also able to hold up to 2000 t of fuel. This is roughly about twice the highest demand scenario. Hence, the catamaran CV will be able to meet requirements (a) and (b); and
- In order to meet requirement (c), the catamaran CV would require a generator capable of working with hydrogen gas and able to provide an electrical demand of up to 2145 KW. The proposed gas turbine GE10-1 is able to provide twice the current electrical demand at around 5625 KW.

The energy requirements used in this thesis are the basic conditions for the catamaran CV to be able to travel on the specified ocean crossing routes. In actual designs for shipping vessels, many more energy requirements and design criteria would be used to investigate the effectiveness of a system (e.g., weight, bouncy, hull shape). For the purpose of this thesis, the energy requirements used would be significant enough to gain an understanding of how the hydrogen energy system would be applied to be able to support and supplement the propulsion of the catamaran CV.

B. EMISSIONS ANALYSIS

Through the aid of RetScreen modelling, the greenhouse gas emission reduction is calculated by comparing the expected emissions from the proposed design to those of the current base case. The current main propulsion gas turbines installed on the catamaran CV are the GE LM2500 which is running fully on diesel. Hence, the base case will be comprised of a 100% diesel combustion gas turbine.

Table 9. Proposed System Emission Reduction

Source	**GHG emission factor (tCO_2/MWh)**	**GHG emission (tCO_2)**
Base Case (Diesel)	0.888	5.7×10^5
Proposed Case (Hydrogen)	0.007	0.4×10^5
Total Reduction (%)		**93.5**

To further understand the equivalence of this reduction, Table 10 has been developed and describes practical applications which are equivalent to the reduction in GHG emissions over the period of the 20-year project life. It provides a useable reference for the reduction and assists in assessing the advantages of the proposed design.

Table 10. Equivalent GHG Reduction

Net GHG Reduction (tCO_2)	Equivalent Reduction	
5.3×10^5	98,479	Cars and light trucks not used
	231,033,005	Litres of gasoline not consumed
	1,250,456	Barrels of crude oil not consumed
	185,412	Tonnes of waste recycled

Based on the equivalent reductions obtained from RetScreen, it is clear that with respect to GHG emission reduction of the proposed design is definitely worthwhile pursuing.

C. ECONOMIC ANALYSIS

A crucial part of this thesis is the economic analysis. There would be two main portions to this analysis. Firstly, is the costing of the project which leads to the financial analysis. Secondly, outcomes will be presented from the analysis that will lead to conclusions regarding the financial feasibility of this research

1. Estimated Project Costing

Within this feasibility study, the total costing of the thesis has been taken into consideration. If this project will take a period of 1 year (365 days) and is undertaken by a team of 16 pax. It was also assumed that the average number of hours worked per week is 8 hours per day or 40 hours per week without accounting for weekends This was then further broken down into two sections. These include:

- Initial Costs: outlines the labour costs associated with the project management, engineering design, procurement of new engines, delivery, installation of engines and lastly the testing and evaluation,

- Annual Costs: Assesses the costs associated with the organisation, management of the project and recurrent maintenance costs

a. *Initial Costs*

When assessing the initial costs of the thesis, the figures presented are estimated based on industry experience and standards. Table 11 describes the breakdown of costs within this section of the analysis. The number of days required to complete the task as well as the ratio of each phase cost with respect to the total initial cost of the thesis have been included.

Table 11. Initial Cost Breakdown

Project Phase	**Total Labor Cost ($M)**[7]	**Total Material Cost ($M)**[8]		**Total Cost ($M)**
Project Management	0.120	0		0.120
Systems Engineering	0.275	0		0.275
Mechanical and Electrical Engineering	1.650	Main Engines	20	28.422
		Hydrogen Compressors	0.24	
		Generators	8	
		Vacuum Pumps	0.09	
		Heat Exchangers	0.016	
		Valves	0.078	
Software Engineering	0.390	0		0.390

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[7] The labor costs were referenced from (US Bureau of Labor Statistics 2022). Each occupation's mean hourly wage was used to do the calculation

[8] Material costs were referenced from the following: (Teal Engineering Group 2019), (Richardson et al. 2015), (A&J Vacuum Services 2022), (Vacuum Process Engineering 2020), (Valveman 2022)

Project Phase	Total Labor Cost ($M)[7]	Total Material Cost ($M)[8]	Total Cost ($M)
Test and Evaluation	0.117	0	0.117
Total			**<u>29.324</u>**

b. Annual Costs and Cost Savings

The estimated annual costs of the hydrogen fuel system are displayed in Table 12. These are broken down based on the author's experience on previous contract management. These approximations are over-estimated as to provide a worst-case scenario.

Table 12. Annual Costs

Annual costs ($M)	
Preventive Maintenance	2.8422
Corrective Maintenance	1.4211
Spares	2.8422
Operational Costs[9]	1.4211
Sub Total	8.5266
Total Cost for 1st year	29.324 + 8.5266 = **37.85**

The total annual costs for the 1st year will amount to $37.85M. This set of annual costs will also be incurred every year. Currently the catamaran CV requires about 1209 t of diesel per trip and assuming that it makes 30 trips a year at $650 per t (BP 2022), it will then accumulate an approximate total diesel fuel cost of $23.5M a year. Comparing this to

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[9] Operational costs include the costs of hydrogen fuel, delivery and preparation of the engineering equipment, training, and commissioning of engineering equipment.

the estimated total costs in Table 12, there will be no savings for the first year. The initial investment costs to modify the catamaran CV is calculated to be even higher as compared to the normal operation of an unmodified catamaran CV

2. Financial Analysis

In order to provide an accurate conclusion on the financial feasibility of the preliminary design, some key financial indicators were used:

- NPV
- Payback period
- IRR (Internal Rate of Return)

IRR and NPV were used so that the capital gain for the preliminary design as a whole could be assessed. The payback period is also used so as to gauge the time when profit is made, and these profits could be allocated to other initiatives. The results from the financial analysis evaluated by RetScreen are displayed in Table 13.

Table 13. Key Financial Results

Key Financial Results	
Debt	$37.85M
IRR	1.3%
Equity Payback Period	16.2 years
NPV	$2.21M
Cumulative Cash Flow	$4.62M

From Table 13, the preliminary design is shown to be **financially unfeasible**. Although the payback period has been calculated to be at 16.2 years which is lower than the 20-year project life, but this only culminates in an expected gain of $4.6M. Having a positive net present value of $2.2M and a positive rate of return for both equity and assets leads to the hydrogen fuel system to be unpromising at the present moment with only a 10%

profit gain after 20 years. These figures seem discouraging given the large amount of funds that is required to be invested at the start of the project.

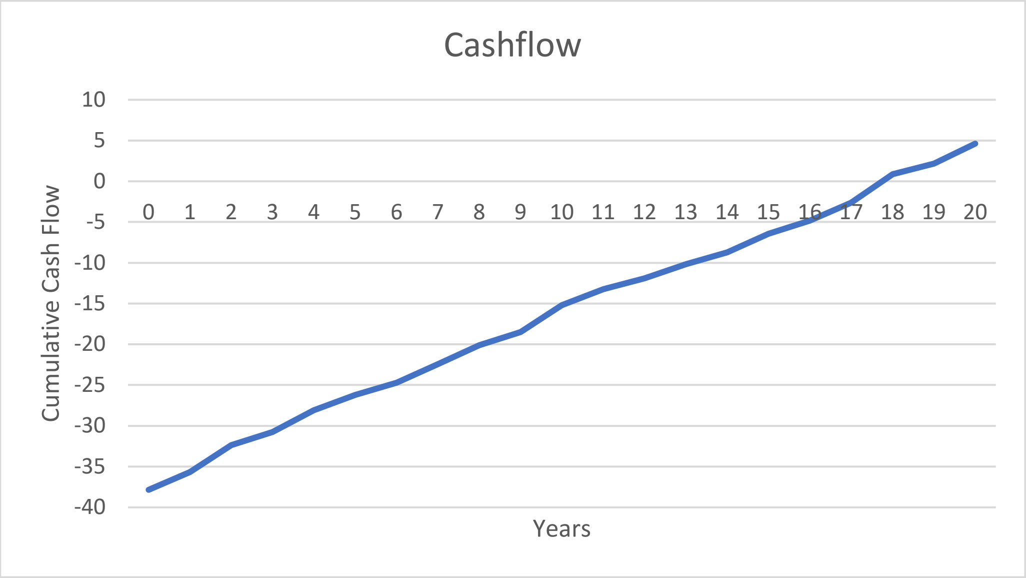

Figure 27. Cumulative Cash Flow Graph

D. SENSITIVITY ANALYSIS

To assess the output data from the excel model, a sensitivity analysis has been conducted. Two combinations of financial parameters have been analyzed with a sensitivity range of ±50%. Table 14 shows that the main effect on the NPV for this case would be the hydrogen fuel cost reduces when the sensitivity range increases. This would be unlikely as present data shows an average increase of 1%–5% per year (depending on the type of technology used to produce hydrogen) for hydrogen fuel prices (Yumutarci and Toprak 2011). However, it can also be seen that reducing the interest rate will improve the financial feasibility of the hydrogen fuel system

Table 14. Sensitivity Analysis (Hydrogen Fuel Cost and Interest Rate)

		Hydrogen Fuel Cost ($/per kg)[10]				
Interest Rate	**$4.62M**	**8.25**	**12.375**	**16.5**	**20.625**	**24.75**
	1.5%	-$0.86M	-$0.64M	$8.36M	$10.61M	$12.94M
	2.25%	-$1.82M	-$0.98M	$6.19M	$8.9M	$10.75M
	3%	-$2.69M	-$1.37M	$4.62M	$6.77M	$8.42M
	3.75%	-$3.93M	-$4.71M	$2.31M	$4.85M	$6.27M
	4.5%	-$5.11M	-$6.36M	$1.64M	$3.57M	$5.92M

The next sensitivity analysis between project life and hydrogen fuel cost is shown in Table 15. It is observed that the NPV will only reduce in the event of the hydrogen fuel cost reducing. The probability of this scenario has already been discussed in Table 14. The effects on the NPV caused by changing the project life are also displayed. If the project life is reduced, the NPV can be observed to be increased for cases where the hydrogen fuel cost is higher, but NPV can be observed to be going lower for its original price. If the project life is increased, it is observed that the NPV is increased more Therefore, lengthening the project life could have its benefits.

Table 15. Sensitivity Analysis (Hydrogen Fuel Cost and Project Life)

		Hydrogen Fuel Cost ($/per kg)				
Project life	**$4.62M**	**13.365**	**14.85**	**16.5**	**18.15**	**19.965**
	10 years	-$6.06M	-$4.89M	-0.81	8.12	11.92
	15 years	-$5.41M	-$3.18M	1.48	7.52	10.57
	20 years	-$4.79M	-$2.64M	4.62	6.94	9.29
	25 years	-$3.99M	-$1.14M	6.31	8.11	10.98
	30 years	-$3.74M	-$1.96M	8.17	7.63	9.07

Overall, the only parameter which will cause the NPV to drop below the threshold is a reduction in the proposed case fuel cost. This is very unlikely to happen as current trends project a 1%–5% rise per year in hydrogen fuel prices (Yumutarci and Toprak 2011).

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[10] Hydrogen Fuel Cost is reference from California Fuel Cell Partnership (2019)

E. RELIABILITY ANALYSIS

The reliability of the hydrogen fuel system would largely be dependent on the gas turbines ability to perform while out at sea and at this stage it would not be possible to derive any figures until there has been a similar prototype of hydrogen fuel system that has undergone sea trials. In addition, this thesis is a preliminary design which is focused on utilizing LH_2 as its main fuel source, it may not be commercially available at this point of time.

F. EFFICIENCY ANALYSIS

There are two types of efficiencies to consider when analyzing the proposed design. First is the electrical efficiency of the generators. This is based on the GE10-1 gas turbine's electrical efficiency. The electrical efficiency is at 31.4%. This is considered high for a small scale generator where comparing this to the base case; fossil fuel power stations have higher efficiency of about 36–40% (Incropera and DeWitt 2007). The next efficiency to consider the mechanical shaft output efficiency of the main propulsion. This would be based on the LM6000 gas turbines shaft output efficiency. The mechanical efficiency is at 43%. This is considered high for a gas turbine as the standard norm for useful energy used in fossil fuel transportation is around 25–30% (Incropera and DeWitt 2007).

G. SUMMARY OF ANALYSIS

With the aid of the RetScreen program and Excel, the preliminary design of the Hydrogen Fuel System was analyzed with the main results being validated by a sensitivity analysis. The final results are:

- GHG emissions expected to decrease by 5.37×10^5 tCO_2
- NPV of \$2.21M
- Positive IRR of 1.3%
- Initial costs of estimated \$37.85M
- Payback period of 16.2 years
- Cumulative cash flow of \$4.62M after a 20-year project life

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VII. CONCLUSION AND RECOMMENDATION

The Hydrogen Fuel System primarily utilizing LH_2 looks to be a feasible alternative energy source for military and shipping vessels in terms of reducing emissions. But financially, the economic profits do not look promising when comparing it to the estimated amount of money required to be invested at the start. In the case of this thesis, the catamaran CV was used as a proxy to be designed as close as possible to a military vessel namely the U.S. Navy's Spearhead Class ships. The design specifications were gathered to allow the catamaran CV to have sufficient energy requirements to travel through a specific ocean crossing route.

During the course of conducting this research and from the results obtained, there were several areas discovered which requires further attention. The LH_2 heat exchanger calculations were done entirely based on achieving the inlet and outlet temperatures for the LH_2 and seawater (heating medium) with assumptions made on their mass flow rates. There are several more areas of design calculation that requires be accomplished in order to actualize a fully functioning LH_2 heat exchanger. Given the limited resources and scope of this thesis, this is one design area which could be further looked into.

Secondly, the material costs within the initial costs were estimated based on external websites and past purchasing costs different corporations. In order to conduct a more accurate financial analysis, a separate study needs to be conducted so as to verify the actual current costs of these systems.

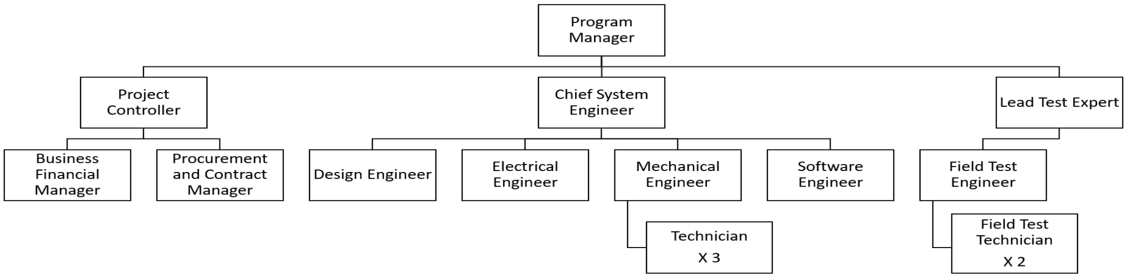
Lastly, a more accurate and technical modelling of the system would be required. Prototyping and pilot-scale testing can be undertaken by interested parties. A prototype system would be ideal, as this may reveal any effects that were not expected in this research. Furthermore, a prototype would allow for the proposed modifications to be integrated and practically evaluate the effects caused by any changes. Finite element analysis of the design is also highly recommended. This would further analyse if the design specifications of the vessel could actually hold the critical components and whether they could be safely operated out in the sea.

Hydrogen fuel propulsion technology is advancing rapidly. Therefore, it is recommended to investigate further whether the proposed hydrogen fuel system mentioned in this thesis can combined with other renewable technologies as they become available. Actual implementation on a military vessel may not be practical due to the high initial costs. But in terms of other environment factors, it may be worth exploring as it will provide the following:

- An alternative energy source as the Single Naval Fuel
- Reduction in PM, NOx and SOx emissions
- Constant efficiency for a specific range of power requirements (5000–10000 KW)
- The removal of equipment for fuel oil treatment
- Lower manpower, maintenance, and operating costs; and
- The removal of risk for fire and oil spill

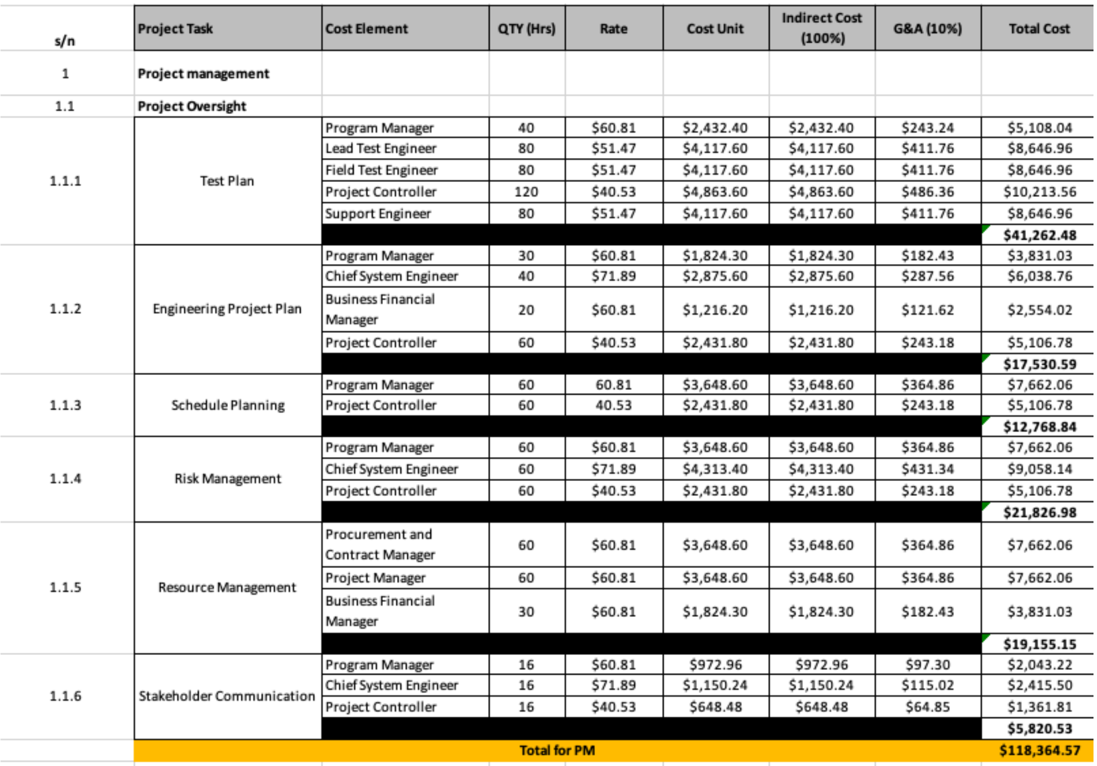
APPENDIX. INITIAL COSTS DATA

A. PROPOSED PROJECT TEAM STRUCTURE



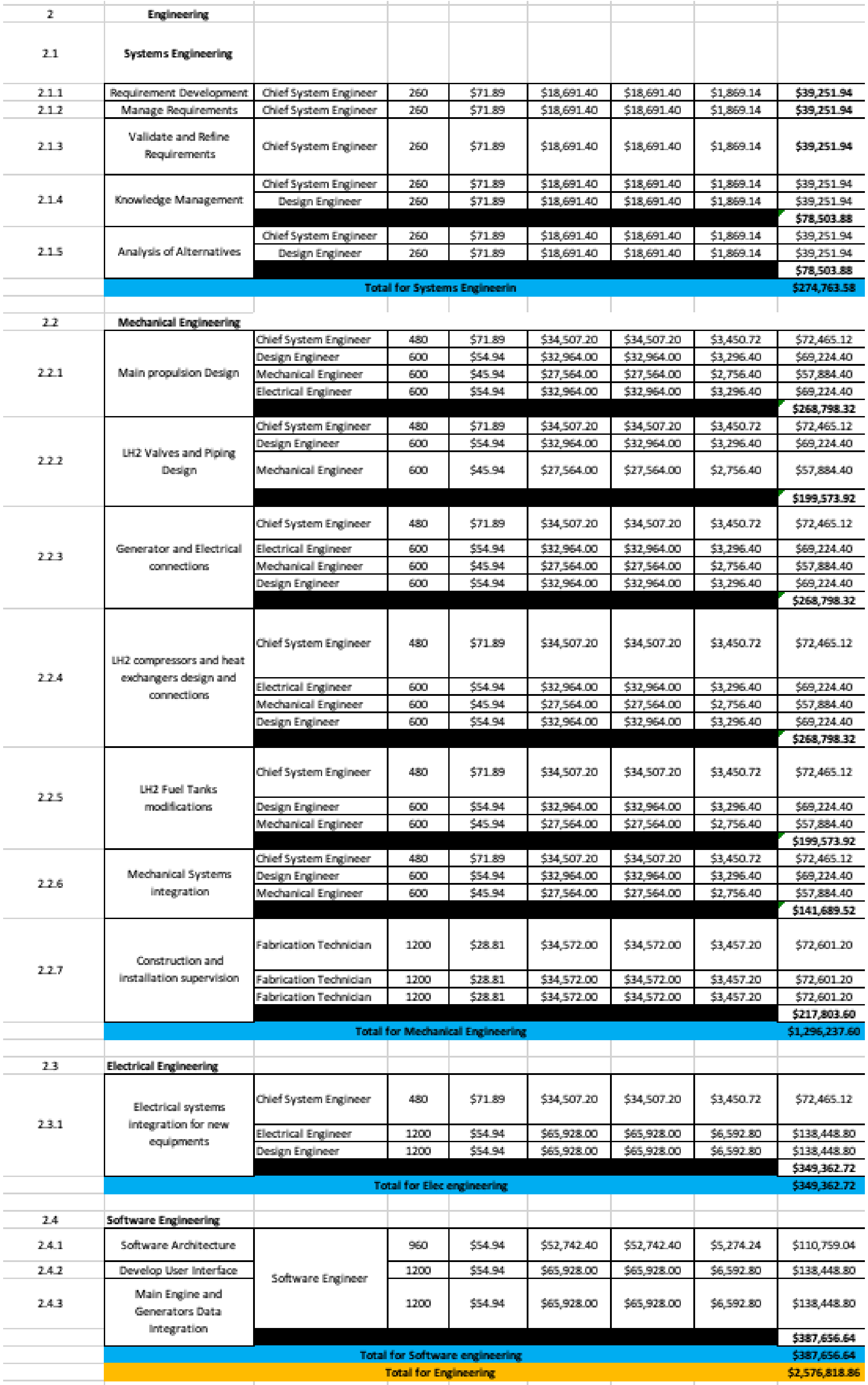
B. PROPOSED WORK BREAK DOWN STRUCTURE WITH LABOR COSTS

1. Project Management



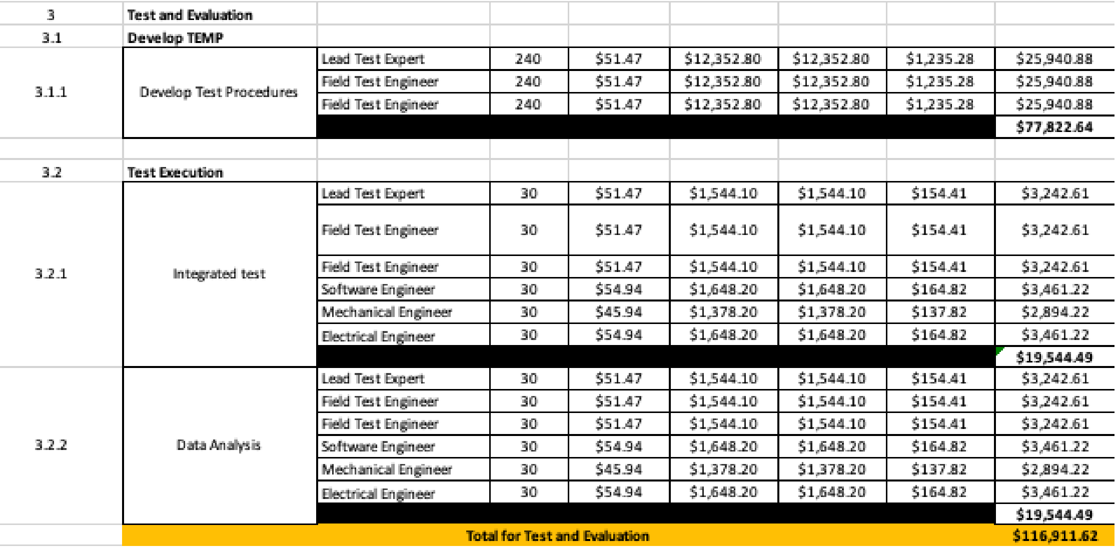
s/n	Project Task	Cost Element	QTY (Hrs)	Rate	Cost Unit	Indirect Cost (100%)	G&A (10%)	Total Cost
1	**Project management**							
1.1	**Project Oversight**							
1.1.1	Test Plan	Program Manager	40	$60.81	$2,432.40	$2,432.40	$243.24	$5,108.04
		Lead Test Engineer	80	$51.47	$4,117.60	$4,117.60	$411.76	$8,646.96
		Field Test Engineer	80	$51.47	$4,117.60	$4,117.60	$411.76	$8,646.96
		Project Controller	120	$40.53	$4,863.60	$4,863.60	$486.36	$10,213.56
		Support Engineer	80	$51.47	$4,117.60	$4,117.60	$411.76	$8,646.96
								$41,262.48
1.1.2	Engineering Project Plan	Program Manager	30	$60.81	$1,824.30	$1,824.30	$182.43	$3,831.03
		Chief System Engineer	40	$71.89	$2,875.60	$2,875.60	$287.56	$6,038.76
		Business Financial Manager	20	$60.81	$1,216.20	$1,216.20	$121.62	$2,554.02
		Project Controller	60	$40.53	$2,431.80	$2,431.80	$243.18	$5,106.78
								$17,530.59
1.1.3	Schedule Planning	Program Manager	60	60.81	$3,648.60	$3,648.60	$364.86	$7,662.06
		Project Controller	60	40.53	$2,431.80	$2,431.80	$243.18	$5,106.78
								$12,768.84
1.1.4	Risk Management	Program Manager	60	$60.81	$3,648.60	$3,648.60	$364.86	$7,662.06
		Chief System Engineer	60	$71.89	$4,313.40	$4,313.40	$431.34	$9,058.14
		Project Controller	60	$40.53	$2,431.80	$2,431.80	$243.18	$5,106.78
								$21,826.98
1.1.5	Resource Management	Procurement and Contract Manager	60	$60.81	$3,648.60	$3,648.60	$364.86	$7,662.06
		Project Manager	60	$60.81	$3,648.60	$3,648.60	$364.86	$7,662.06
		Business Financial Manager	30	$60.81	$1,824.30	$1,824.30	$182.43	$3,831.03
								$19,155.15
1.1.6	Stakeholder Communication	Program Manager	16	$60.81	$972.96	$972.96	$97.30	$2,043.22
		Chief System Engineer	16	$71.89	$1,150.24	$1,150.24	$115.02	$2,415.50
		Project Controller	16	$40.53	$648.48	$648.48	$64.85	$1,361.81
								$5,820.53
	Total for PM							**$118,364.57**

2. Engineering



2	**Engineering**							
2.1	**Systems Engineering**							
2.1.1	Requirement Development	Chief System Engineer	260	$71.89	$18,691.40	$18,691.40	$1,869.14	**$39,251.94**
2.1.2	Manage Requirements	Chief System Engineer	260	$71.89	$18,691.40	$18,691.40	$1,869.14	**$39,251.94**
2.1.3	Validate and Refine Requirements	Chief System Engineer	260	$71.89	$18,691.40	$18,691.40	$1,869.14	**$39,251.94**
2.1.4	Knowledge Management	Chief System Engineer	260	$71.89	$18,691.40	$18,691.40	$1,869.14	$39,251.94
		Design Engineer	260	$71.89	$18,691.40	$18,691.40	$1,869.14	$39,251.94
								$78,503.88
2.1.5	Analysis of Alternatives	Chief System Engineer	260	$71.89	$18,691.40	$18,691.40	$1,869.14	$39,251.94
		Design Engineer	260	$71.89	$18,691.40	$18,691.40	$1,869.14	$39,251.94
								$78,503.88
	Total for Systems Engineerin							**$274,763.58**
2.2	**Mechanical Engineering**							
2.2.1	Main propulsion Design	Chief System Engineer	480	$71.89	$34,507.20	$34,507.20	$3,450.72	$72,465.12
		Design Engineer	600	$54.94	$32,964.00	$32,964.00	$3,296.40	$69,224.40
		Mechanical Engineer	600	$45.94	$27,564.00	$27,564.00	$2,756.40	$57,884.40
		Electrical Engineer	600	$54.94	$32,964.00	$32,964.00	$3,296.40	$69,224.40
								$268,798.32
2.2.2	LH2 Valves and Piping Design	Chief System Engineer	480	$71.89	$34,507.20	$34,507.20	$3,450.72	$72,465.12
		Design Engineer	600	$54.94	$32,964.00	$32,964.00	$3,296.40	$69,224.40
		Mechanical Engineer	600	$45.94	$27,564.00	$27,564.00	$2,756.40	$57,884.40
								$199,573.92
2.2.3	Generator and Electrical connections	Chief System Engineer	480	$71.89	$34,507.20	$34,507.20	$3,450.72	$72,465.12
		Electrical Engineer	600	$54.94	$32,964.00	$32,964.00	$3,296.40	$69,224.40
		Mechanical Engineer	600	$45.94	$27,564.00	$27,564.00	$2,756.40	$57,884.40
		Design Engineer	600	$54.94	$32,964.00	$32,964.00	$3,296.40	$69,224.40
								$268,798.32
2.2.4	LH2 compressors and heat exchangers design and connections	Chief System Engineer	480	$71.89	$34,507.20	$34,507.20	$3,450.72	$72,465.12
		Electrical Engineer	600	$54.94	$32,964.00	$32,964.00	$3,296.40	$69,224.40
		Mechanical Engineer	600	$45.94	$27,564.00	$27,564.00	$2,756.40	$57,884.40
		Design Engineer	600	$54.94	$32,964.00	$32,964.00	$3,296.40	$69,224.40
								$268,798.32
2.2.5	LH2 Fuel Tanks modifications	Chief System Engineer	480	$71.89	$34,507.20	$34,507.20	$3,450.72	$72,465.12
		Design Engineer	600	$54.94	$32,964.00	$32,964.00	$3,296.40	$69,224.40
		Mechanical Engineer	600	$45.94	$27,564.00	$27,564.00	$2,756.40	$57,884.40
								$199,573.92
2.2.6	Mechanical Systems integration	Chief System Engineer	480	$71.89	$34,507.20	$34,507.20	$3,450.72	$72,465.12
		Design Engineer	600	$54.94	$32,964.00	$32,964.00	$3,296.40	$69,224.40
		Mechanical Engineer	600	$45.94	$27,564.00	$27,564.00	$2,756.40	$57,884.40
								$141,689.52
2.2.7	Construction and installation supervision	Fabrication Technician	1200	$28.81	$34,572.00	$34,572.00	$3,457.20	$72,601.20
		Fabrication Technician	1200	$28.81	$34,572.00	$34,572.00	$3,457.20	$72,601.20
		Fabrication Technician	1200	$28.81	$34,572.00	$34,572.00	$3,457.20	$72,601.20
								$217,803.60
	Total for Mechanical Engineering							**$1,296,237.60**
2.3	**Electrical Engineering**							
2.3.1	Electrical systems integration for new equipments	Chief System Engineer	480	$71.89	$34,507.20	$34,507.20	$3,450.72	$72,465.12
		Electrical Engineer	1200	$54.94	$65,928.00	$65,928.00	$6,592.80	$138,448.80
		Design Engineer	1200	$54.94	$65,928.00	$65,928.00	$6,592.80	$138,448.80
								$349,362.72
	Total for Elec engineering							**$349,362.72**
2.4	**Software Engineering**							
2.4.1	Software Architecture	Software Engineer	960	$54.94	$52,742.40	$52,742.40	$5,274.24	$110,759.04
2.4.2	Develop User Interface		1200	$54.94	$65,928.00	$65,928.00	$6,592.80	$138,448.80
2.4.3	Main Engine and Generators Data Integration		1200	$54.94	$65,928.00	$65,928.00	$6,592.80	$138,448.80
								$387,656.64
	Total for Software engineering							**$387,656.64**
	Total for Engineering							**$2,576,818.86**

3. Test and Evaluation



3	**Test and Evaluation**							
3.1	**Develop TEMP**							
3.1.1	Develop Test Procedures	Lead Test Expert	240	$51.47	$12,352.80	$12,352.80	$1,235.28	$25,940.88
		Field Test Engineer	240	$51.47	$12,352.80	$12,352.80	$1,235.28	$25,940.88
		Field Test Engineer	240	$51.47	$12,352.80	$12,352.80	$1,235.28	$25,940.88
								$77,822.64
3.2	**Test Execution**							
3.2.1	Integrated test	Lead Test Expert	30	$51.47	$1,544.10	$1,544.10	$154.41	$3,242.61
		Field Test Engineer	30	$51.47	$1,544.10	$1,544.10	$154.41	$3,242.61
		Field Test Engineer	30	$51.47	$1,544.10	$1,544.10	$154.41	$3,242.61
		Software Engineer	30	$54.94	$1,648.20	$1,648.20	$164.82	$3,461.22
		Mechanical Engineer	30	$45.94	$1,378.20	$1,378.20	$137.82	$2,894.22
		Electrical Engineer	30	$54.94	$1,648.20	$1,648.20	$164.82	$3,461.22
								$19,544.49
3.2.2	Data Analysis	Lead Test Expert	30	$51.47	$1,544.10	$1,544.10	$154.41	$3,242.61
		Field Test Engineer	30	$51.47	$1,544.10	$1,544.10	$154.41	$3,242.61
		Field Test Engineer	30	$51.47	$1,544.10	$1,544.10	$154.41	$3,242.61
		Software Engineer	30	$54.94	$1,648.20	$1,648.20	$164.82	$3,461.22
		Mechanical Engineer	30	$45.94	$1,378.20	$1,378.20	$137.82	$2,894.22
		Electrical Engineer	30	$54.94	$1,648.20	$1,648.20	$164.82	$3,461.22
								$19,544.49
	Total for Test and Evaluation							**$116,911.62**

C. ESTIMATED MATERIAL COSTS

Material costs			
Item	Price ($M)	Qty	Total ($M)
GE LM6000	10	2	20
Hydrogen Compressors	0.12	2	0.24
GE 10–1 gas turb	4	2	8
Vacuum pumps	0.011	8	0.09
Heat exchangers	0.008	2	0.016
Valves	0.003	26	0.078
			28.422

D. BLS LABOR RATES

Occupation	Occupational Code	Mean Hourly Wage
Program Manager	11-0000	$60.81
Project Controller (Specialist)	13-1198	$40.53
Financial Manager	11-0000	$60.81
Procurement and Contract Manager	11-0000	$60.81
Chief System Engineer	11–9041	$71.89
Mechanical Engineer	17-2141	$45.94
Electrical Engineer	17-2071	$50.96
Design Engineer	15-1256	$54.94
Software Engineer	15-1256	$54.94
Fabrication Technician	17-3026	$28.81
Lead Test Expert	17-2199	$51.47
Field Test Engineer	17-2199	$51.47
Support Engineer	17-2199	$51.47
Field Test Technician	17-3020	$30.64

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