The Feasibility of Ammonia Use Aboard a Warship in the US Navy

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non sibi sed patrie,
Ad maiorem Dei gloriam

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Abstract

The United States (US) Department of Defense (DoD) is the largest institutional user of energy in the world [1]. Within the DoD the Department of the Navy consumes the most fuel. This is an expensive endeavor that costs the taxpayer over 9 billion dollars a year [2]. Fossil fuels also carry externalities, from environmental, to social, and even strategic availability. Alternative fuels such as ammonia can in theory offer a path not only to decarbonize but also to have a more secure and potentially cheaper fuel for the future. Ammonia is already a leading alternative fuel in the shipping industry [3]. This report explores the potential for ammonia to serve as fuel for a warship.

The novelty of this work is multi faceted, and can be understood through the points below:

1. A geospatial analysis of ammonia production and transport infrastructure in comparison to US naval bases.
2. An application of an advanced fuel tank model for cryogenic fluids on board a warship.
3. An analysis of public sentiment on naval fuel use.
4. A defense specific techno-economic analysis for an ammonia fueled warship.

The report also consolidates information on technology maturity, safety, environmental, and education concerns into one place in order to provide the most comprehensive analysis of ammonia as a defense fuel.

The report concludes that limitations to ammonia adoption include: fuel location, range limitations, sunk capital costs, powertrain maturity, damage control challenges, and fuel cost uncertainty. Potential drivers of change include: diplomatic pressure from allied nations, political pressure from citizens to decarbonize the fleet, and a constant or increasing oil price. At this time, the use of ammonia onboard a warship is technically possible but strategically unlikely due to the absence of pressure to change.

Keywords— ammonia - warship - feasibility

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List of Abbreviations

US	United States
DoD	Department of Defense
ICE	Internal Combustion Engine
GT	Gas Turbine
LNG	Liquified Natural Gas
°C	Degrees Celsius
MJ	Megajoule
GJ	Gigajoule
m	meter
kg	kilogram
atm	atmosphere
LCA	Life Cycle Analysis
ppm	Parts Per Million
IMO	International Maritime Organization
HFO	Heavy Fuel Oil
MFO	Marine Fuel Oil
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
DDG	Destroyer
FFG	Frigate
gpm	Galllons Per Minute
UK	United Kingdom
BOG	Boil of Gas
W	Watts
K	Kelvin
AM	Additive Manufacturing
EPA	Environmental Protection Agency
USD	United States Dollar (2023)

1 | Introduction

> Fuel stands first in importance of the resources necessary to a Fleet. Without ammunition, a ship may run away, hoping to fight another day, but without fuel she can neither run, nor reach her station, nor remain on it, if remote, nor fight.
> The distribution and storage of fuel is therefore eminently a strategic question... the positions for storing, and... the quantity to be stored at each position, are amenable strategic consideration
>
> *The Influence of Sea Power Upon History*
> *Alfred Thayer Mahan* [4]

1.1 Motivation

The US Department of Defense is the largest institutional polluter in the world [1].[1] This high level of pollution and corresponding energy use increases global security risks, raises concerns about fuel availability in remote locations, and is a potential choke point due to the financial pressure of a global fuel market. The global footprint of the US Navy requires a greater use of fuels that are clean, affordable, and in friendly waters. This report will address the question of whether ammonia can play this role on board a warship. Motivation is multifaceted. In one sense, the pollution from the fleet leads to greater conflict, conflict it aims to prevent. The other motivation is strategic. One that relies on fuels that are socially acceptable, easy to access, and affordable. The following points develop these four distinct but intersecting points.

If the navy is intended to prevent conflict through deterrence, the pollution it creates cannot lead to more war. Future fuels must be sustainable and carbon-free because planetary warming is linked to increased conflict. The widespread effects of global warming have led to higher rates of natural disasters and rising sea levels, which affect the 40% of the world's population that lives within 100 km of the coast [5]. Rising sea levels, increased saline content in tidal areas, the resulting lower crop yields and impotable water can raise security concerns in strategically sensitive areas [6, 7]. Wars are fought for security [8]. Impotable water, failed crops, and unlivable homes cause insecurity. The logic is not hard to follow; a warmer planet will have more conflict; this is backed by the DoD's own analysis [9]. The increase in carbon dioxide in the atmosphere since the beginning of industrialization is responsible for much of this warming [10]. Reducing the amount of carbon dioxide emitted is critical to slowing the warming of the planet and also reducing future conflicts. As protectors of nations, the military must be aware of future conflicts that their polluting actions cause.

The carbon impact of oceangoing vessels represents a large part of global emissions. CO_2 emissions from international shipping represented 2.1% of the total global emissions in 2019, and the volume of global shipping continues to increase by 3% annually [11]. This does not include the emissions of the US Navy, which is hoping to grow its fleet from 241 to 355 vessels (an increase close to 50%) [12]. On average, a destroyer emits the same amount of carbon as more than 6800 passenger vehicles, or approximately 31,500 metric tons of CO_2 per year.[2] With 74 destroyers in the fleet, the annual emissions of destroyers alone are equivalent to all carbon emissions in Niger [14], a nation of more than 20 million people. The current fuel supply is not clean, and ammonia deserves further investigation.

The fiscal cost of fossil-based fuels is an additional concern. The Navy spends more than 9 billion dollars on fuel per year [2] more than Chile and Argentina spend on all of defense combined [15, 16]. These costs pose a burden on the tax payer. Future oil prices are unknown, but historically prices for

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[1] In the 43 years from 1975-2018 the DoD produced, on average, more than 85 million metric tons of CO_2 a year. More than industrialized nations such as Portugal, Austria, and Sweden.

[2] Calculated using annual usage from Anderson [13] and a value of 2.6 kg CO_2 per liter of diesel

fossil fuels have increased and have been vulnerable to price shocks [17]. Price shocks can threaten the power of the military, whose budget is set annually by Congress. Renewable fuels such as ammonia may not be as dependent on exogenous factors, allowing the Navy to predict its operations more easily and save the taxpayer money.

Finally, fossil fuels are only available in certain areas. They require the establishment of forward operating bases, a long-time tenet of naval strategy. Credit is given to Nelson, the practitioner, and Mahan, the scholar, for establishing this tradition [4, 18]. The availability of a fossil fuel is limited to the ability to remove it from the ground or store it. Ammonia can be produced anywhere with electricity and the required plant. This means that all that is required is real estate and electricity. There is no geological requirement, as is the case with oil. This is a potential benefit for ammonia. Adopting alternative fuels that can be produced anywhere regardless of geological constraints would be valuable from an energy security perspective.

The motivation is therefore three fold, largely following the outlines of the energy trilemma (a defense fuel should be: clean, cost-effective, and available). It must be clean to prevent future conlfict, it must be cost effective to allow operational consistency, and it must be secure to allow for operational flexibility.[3] To date, ammonia has not been analyzed from a defense perspective. This report seeks to serve as a first step to seriously consider the use of ammonia fuel for use on a warship.

1.2 Aims and Objectives

Ammonia was selected to be investigated in this thesis because it is widely produced, easy to store, carbon-free, and energy-dense. Furthermore, there is already interest among the commercial shipping sector to switch to ammonia fuels to reduce carbon and sulfur emissions from current fuels and thus the navy could follow this example [11, 19, 20].

To analyze feasibility, the following questions relevant to ammonia are systematically addressed:

- Is ammonia accessible for warships?
- Can ammonia be transferred between ships?
- What happens to ammonia in the fuel tank?
- Are ammonia powertrains available?
- Is it possible for sailors to learn to use ammonia safely?
- How safe is ammonia under standard operating procedures?
- How safe is ammonia in the event of a casualty?
- Is the release of ammonia into the environment a greater challenge than an oil spill?
- Does the US Navy follow environmental standards?
- Does the citizenry of the US have the power to influence naval policy?
- Is ammonia cost competitive?

Justification for these questions is provided in Chapter 3.

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[3] Often times only the latter two are acknowledged by the defense community. Due to this dominant trend in the community, a trend that places operational readiness above climate (an assertion further supported in Section 6.2) economics and availability are the main focus of this report.

1.3 Dissertation Outline

The remainder of this report is organized as follows:

Chapter 2 — Highlights the benefits and challenges of ammonia use, and provides a critical review of relevant literature for the other topics covered in the report.

Chapter 3 — Outlines the methodology used in this feasibility study with a discussion of the approach used in each chapter.

Chapter 4 — Analyzes the geographic availability of fuel, the potential to transfer fuel between ships and presents a fuel tank model.

Chapter 5 — Presents the technology readiness of ammonia powertrains and evaluates the Navy's ability to adapt to new technologies.

Chapter 6 — Discusses the safety, environmental, and social feasibility of ammonia adoption.

Chapter 7 — Presents the results of a techno-economic analysis.

Chapter 8 — Summarizes all of the conclusions in this report, and recommends areas for future work.

2 | Background and Literature Review

This chapter provides general background information on ammonia, as well as important context for some of the other discussions that occur in the report. This chapter also defends the use of an alternative fuel (Section 2.1.4).

2.1 Benefits of Ammonia Use

The following information is structured into four main points. In Subsection 2.1.1 the wide availability of ammonia is discussed, followed by Subsection 2.1.2 discussing its easy storage. Subsection 2.1.3 shows the carbon neutrality of ammonia, and the section is concluded with a comparison of the high volumetric energy density in Subsection 2.1.4.

2.1.1 An Already Existing System

One benefit of ammonia is that it is already a widely produced chemical of >160 million tons per year. Ammonia is already a part of our society, used mainly for fertilizers, but also for pharmaceuticals and a few other fields [21]. Annually, 20 million tons are traded internationally [22]. The production method, known as the Haber Bosch process, involves using hydrogen–commonly sourced from methane–and nitrogen from the air. The two gases are heated among pressure and catalyst [23].

When ammonia is compared to other alternative fuels, such as methanol, it stands out as the most widely produced fuel with potential to grow. Two times more ammonia is produced than methanol by weight annually [24]. Other biofuels, such as ethanol and biodiesel, are land-constrained and estimates produced by energy agencies tend to overestimate potential [25]. When ammonia is compared to hydrogen, the mass of hydrogen produced is less than half that of ammonia, and half of all hydrogen produced is used in the production of ammonia [26].

Beyond production, ammonia transport is well developed and less damaging than other alternative fuels. Ammonia is transported mainly by rail, but also by some pipelines [23]. The pipelines currently in existence were cheaper than hydrogen pipelines and some fossil fuel pipelines [27]. The US currently has 3000 miles of ammonia pipelines and, despite widespread use by the general population (800 outlets in Iowa for farmer use), there have been few accidents [27].[1]

In contrast, biofuel exclusive pipelines are non existent, and pose problems to implementation. Both methanol and ethanol are hygroscopic, unlike fossil fuels, and become corrosive when exposed to water. Biofuels would endanger existing pipelines and cause rapid corrosion. This problem is currently avoided because biofuels (such as ethanol) are currently mixed in low percentages in existing petroleum products [29]. However, if biofuels are put in wider use, new pipelines and transport mechanisms would need to be developed to carry biofuels. Ammonia does not become more corrosive when exposed to water, making transport easier, explaining the current existence of infrastructure.

2.1.2 Storage

Once transported, ammonia has benefits for storage. Chemical storage (fuel) is often viewed as the most practical long-term storage option. Batteries, capacitors, pumped hydro, and flywheels are all options for shorter-term storage, but the energy stored in chemical form allows it to be used in transport applications. The benefit of ammonia over other fuels comes from the technical simplicity of its storage. Ammonia can be stored as a liquid at 10 atm or -33°C, similar to the conditions for propane storage. Fuels such as hydrogen or liquefied natural gas (LNG) require lower temperatures and higher pressures,

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[1] 8 accidents in the US since 1969 with 0 fatalities [28].

as shown in Table 2.1 (adapted from de Vries [30]). These requirements not only mean more equipment to balance the pressure and temperature of the tanks, but also higher energy costs. One analysis found that hydrogen storage was 30 times more expensive than ammonia storage [31].

Although methanol and other biofuels can be stored at standard temperature and pressure, water contamination is a serious concern. Standard storage tanks could not be used for biofuel storage, and fuel handling lines would also degrade in direct swap scenarios [29]. In a maritime environment where salt and water cannot be avoided, methanol poses serious corrosion concerns that ammonia avoids.

In fact, water acts as a corrosion inhibitor in the ammonia storage industry [32]. Literature dating back to the 1950s has explored the mechanisms of corrosion failure and the appropriate steps to counteract ammonia corrosion [33]. Most solutions rely on low-strength steels, while stainless steel and other more expensive corrosion resistant materials are only required in certain parts such as pumps [32]. Aluminum also shows little corrosion in the presence of ammonia [34]. The ammonia bearing pipes fail more easily due to external corrosion and the environment than due to the ammonia that runs through them [28]. Corrosion can be completely prevented by excluding oxygen from the storage or transport system. However, this can be difficult, and while the presence of oxygen can increase the speeds of corrosion failure, it should be noted that the stress crack corrosion method of failure is very slow. Typical tanks have a lifetime of more than 40 years with low predicted failure rates even with oxygen contamination [35].[2]

Table 2.1: Fuel Properties

	Diesel	**LNG**	**Methanol**	**Hydrogen**	**Ammonia**
Chemical Forumla	Hydrocarbon Mix ($C_{12}H_{23}$)	Hydrocarbon Mix (CH_4)	CH_3OH	H_2	NH_3
Storage Temperature at 1 atm (°C)	20	-162	20	-253	-33
Lower Heating Value (MJ/kg)	42.7	50	19.9	120	18.6
Volumetric Energy Density (GJ/m^3)	36.6	23.4	15.8	8.5	12.7
Combustion Products	CO_2, H_2O	CO_2, H_2O	CO_2, H_2O	H_2O	NOx, H_2O

Even conventional fossil fuels face storage challenges that ammonia would not face. A typical naval vessel holds $\sim$1.56 million liters of fuel. However, not all of this fuel can be used without causing damage to the engineering plant. At fuel levels below 10% the water used as a ballast in fuel tanks begins to mix too much with fuel [36]. Ammonia fuels would not have water in the tanks and, therefore, could be used until they were empty.[3] However, this benefit has strategic limits. If the USS Cole had adequate fuel levels, it would not have been necessary to stop at the Port of Aden (a port with high levels of terrorist activity), the ship could have proceeded to Bahrain or a more friendly port. However, miscalculations led to the required stop, placing them at risk of attack, a risk that materialized and could have been avoided [38]. This lesson has led commanders to rarely let fuel levels fall below 50%. Ultimately, the operational environment supersedes the technical limitations, negating this potential benefit. However, it is worth mentioning.

In summary, ammonia fuel has the best properties for storage on a naval vessel among nonfossil fuel options. This is due to the temperature and pressure at which it can be stored and the favorable behavior of ammonia and water mixtures.

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[2] It is still important to note that ammonia does react in the presence of zinc, copper and brass, and these materials should be avoided. Chlorine and other acids should also be avoided as the alkali nature of ammonia will react in the presence of acids [23].

[3] If there was a desire to keep the tanks cool for rapid refilling some fuel would be required to stay in the tank, this level is known as the tank heels and it is usually about 4% by volume [37].

2.1.3 Carbon Free Energy Production

The chemical energy stored in ammonia is released in two ways, either through a fuel cell or as a working fluid in a cycle. Since ammonia has no carbon in its chemical formula, both result in zero carbon production. Several life cycle analyses (LCAs) have been conducted to the total carbon emissions of ammonia use. Bicer and Dincer found that a green ammonia power plant would have lifecycle emissions 97% less than an equivalent natural gas power plant [39]. In another paper, the same authors reported that ammonia powered vehicles fueled by green ammonia produce 40% less greenhouse gases than a gasoline vehicle [40]. When Al-Breiki and Bicer evaluated the entire ammonia supply chain, it was found that lifetime (production to use) greenhouse gas emissions for ammonia were lower than those of all other fuel types, except hydrogen [41].

Opponents of ammonia will argue that the industry is not carbon neutral. They are correct that current production methods are carbon-intensive. For one, hydrogen is currently sourced from steam methane reforming, and the energy for heating and pressurizing the plants is fueled by a fossil fuel-dependent grid. Current ammonia production is estimated to consume 1.8-3.0% of global energy, making it one of the largest single producers of carbon dioxide since the electricity grid and heating methods are dependent on fossil fuels [23].

Despite this challenge, the Haber-Bosch process is not necessarily carbon-intensive. Both hydrogen and electricity, the two vectors required for the production of ammonia with the highest carbon concentration, can be replaced with the use of green electricity. Fuel cells for hydrogen and direct catalysis from pure nitrogen are two options under investigation [42]. The economics also argues that green ammonia is feasible. In 2008, a financial analysis performed by Jeffrey Bartels found that the reduction in the costs of renewables would allow carbon-free methods of production to be comparable to current methods [31]. A more recent analysis found that, while still costly, green ammonia is becoming more bankable [43].

2.1.4 High Volumetric Energy Density

The final upside of ammonia is its high volumetric energy density. Energy density is an important engineering metric for fuel usability. Ammonia has the highest volumetric density among carbon-free fuel options (see Table 2.2). However, the energy density of ammonia is low compared to that of diesel.[4]

Table 2.2: Volumetric Energy Densities

	Diesel	**LNG**	**Methanol**	**Hydrogen**	**Ammonia**
Volumetric Energy Density (GJ/m^3)	36.6	23.4	15.8	8.5	12.7

Therefore, the rest of the section presents the history of energy density in warships. It argues that a lower energy density should not be viewed as a nonstarter.

In the days of sailing, space was left for additional water, crew rations, and extra sails. The mass and space requirements for a 14-week voyage for a fifth-rate ship of the line in the Royal Navy exceeded 400 tons and [45]. A visual representation, seen in Figure 2.1 [46], shows that more than half of the space on the ships was reserved for stores. The bottom two decks (of five total) would have been the largest and were reserved for stores and backup equipment to make the ship seaworthy. Only in the last 200 years have we seen ships with small propulsion plants.

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[4] Although ammonia is energy dense when compared to renewable fuel options, it still requires more than 2.5 times more ammonia by volume to obtain the same energy from a fossil-based fuel [44].

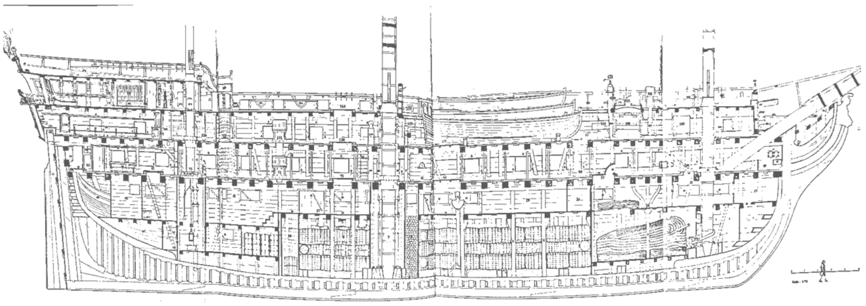

Figure 2.1: Fifth Rate Ship of the Line

Coal eventually took over. It was chosen for strategic reasons. Coal allowed ships to sail faster, without wind, and in a straight line. It did not, however, take up less space or mass, and it certainly took more people. A fifth-rate ship of the line in the 18th century had a crew of just over 200, and the ship built for the same purpose in the late 19th century had an engineering (just engineering!) complement of 600 [47]. Large crew sizes and the added space for coal led to larger ships [47]. Here, a less dense and more expensive fuel was selected in order to gain navigational freedom.

Oil came onto the scene next and would provide a more energy dense fuel, faster fueling times, and smaller engineering crews (100 vs 600) than coal ships. However, oil-powered ships did not initially replace coal in the UK, because the UK lacked sufficient oil resources to fuel them [47]. In this case, the naval board in the UK adhered to a strategic imperative reminiscent of the Mahan epigraph that begins Chapter 1 [4]. Here a more dense fuel was not used because of strategic availability.

Nuclear power was the next logical step in the search for a high energy density, with an energy density 2.5 times higher than that of a steam turbine-driven gas-powered ship [48]. However, aircraft carriers and submarines are the only nuclear powered vessels in modern naval fleets [49]. This is due to the costs associated with training crews and geopolitical sensitivity [50].

The history of energy density aboard warships shows that though energy density has powerful benefits, it can be neglected if the fuel offers greater navigational freedom, better strategic availability, preferential geopolitics, or lower costs. Fuel selection is therefore a multifaceted endeavor.

2.2 Challenges to Ammonia Implementation

Ammonia use faces several challenges, some of which have already been discussed. Challenges already discussed are: pollution related to the supply chain (2.1.3), corrosion (2.1.2), and a decrease in energy density compared to fossil fuels (2.1.4). Other challenges include: difficulty with combustion (including the production of NOx), the toxic nature of ammonia, and the potential stability of ships.

2.2.1 Combustion Challenges

Ammonia faces a two-fold challenge with combustion; the first relates to the reaction kinetics and the second to the reaction products. Engine designers are faced with slow flame speeds that can easily blow out, high ignition temperatures, and slow reaction speed. These problems are usually solved by blending the fuel with hydrogen or another fuel [51]. This requires additional equipment and catalysts that are combined in devices called crackers.

The products of combustion pose another challenge. NOx production during ammonia combustion is a potential challenge for ammonia use [23, 51]. NOx is a common product of most combustion reactions and increased concentration of nitrogen in ammonia in addition to air leads to greater NOx production. The production of NOx is unfavorable because it leads to acid rain and other environmental concerns [52]. This problem has been solved by mixing ammonia with other fuels and also through scrubbing the exhaust [23, 51]. These methods increase the footprint of the engineering spaces, raising concerns about the use of ammonia in vessels limited by space.

2.2.2 Human Health

Another challenge facing ammonia is the toxicity of ammonia fumes and their effects on human health. These range from skin dehydration, frostbite, chemical burns, and death from inhalation. The likelihood of death and harm increases with time of exposure and concentration. The risk is mitigated because ammonia is easily detected.[5]

A review of safety challenges by Duong et al. found that dangerous situations arise from the rapid release of ammonia gas or vapor [54]. A medical review by Vadysinghe et al. describes six exposures to ammonia and the range of possible injuries in detail. They show that the leading cause of death is inhalation and not corrosive burns [55]. They recommend good ventilation and respirators to reduce risks. This conclusion is supported by a wide spread of medical literature dating back to the 1800s [55, 53, 56, 57].

Fire-related risks are less of a concern compared to other fuels due to the high ignition temperature of ammonia and the high and narrow flammability limit (the description of fuel concentration in which combustion is possible).[6] The lower risk is quantitatively shown using Bayseian networks by Fan et al. [58], and is further supported by assessments conducted by Maersk, de Vries, and Duong et al. [59, 30, 54].

2.2.3 Ballast

An additional challenge unique to the implementation of ammonia in warships is that smaller combatants, such as those discussed in this thesis, replace the fuel in their tanks with water [36]. This is possible because diesel fuel is mostly immiscible with water. Filling the fuel tanks with water ensures that the center of gravity of the ship does not rise as fuel is used, making ship handling easier. Because ammonia is hydrophilic and cryogenic, fuel tanks cannot be used for ballast. Therefore, additional tanks would be required to provide ballast for the ship.

This increases the space burden of ammonia, which includes added material for scrubbing catalysts, cracking equipment to enhance combustion, and additional fuel tanks to compensate for the lower energy density than diesel fuel. A summary of the advantages and disadvantages discussed in these first two sections are presented in Table 2.3.

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[5] Ammonia is detectable at 53 parts per million (ppm), humans can survive at levels of 100 ppm for several hours [53].

[6] 15-28% for ammonia, and 4-17% for natural gas.

Table 2.3: Summary of Advantages and Disadvantages of Ammonia Adoption

Advantages	**Challenges**
Carbon free combustion	Current production methods are carbon intensive
Highest energy density among no carbon fuels	Low energy density compared to fossil fuels
Fuel is produced globally and at scale	Fatal if inhaled
Storage and transport processes are well known	Large additional space requirements
Non-corrosive properties in nautical environment	Non-ideal combustion characteristics

2.3 State of Ammonia Adoption on Ships

2.3.1 Commercial Shipping

The desire to reduce carbon output has materialized in a mandate from the International Maritime Organization (IMO) that seeks to limit the amount of fossil-fueled vessels. By 2030 they hope to reduce carbon emissions by 40% and 70% by 2050 [11]. To reach this goal, the strategy recommends that efficiency efforts should continue in the short term, but in the medium to long term alternative fuels should be considered. In 2022, a survey conducted by the Global Maritime Forum with a sample size of 29 companies and 20% of the global shipping tonnage found that 95% ships ran internal combustion engines on petroleum-based fuels [60]. This shows that the current fuel profile is heavily dominated by fossil fuels but will need to change if the IMO is to reach its goals.

In the same study, the global maritime forum asked respondents what fuel they perceived as dominant in the 2050 market. The responses varied widely, but, with 17%, ammonia was predicted to be the most dominant, tied only to fuel oils already in use [60]. Additionally, the International Energy Agency predicts that an additional 203 million tons of ammonia production will be required to supply 45% of maritime shipping in 2050 [22].

Despite high levels of interest and several projects underway, there have been zero successful applications as of writing. Chapter 5 discusses the maturity of the technology in more detail.

2.3.2 Military Use

There are currently no uses of ammonia on warships. However, the military industrial complex is generally interested in ammonia and alternative fuels. In the 1960s the US army commissioned a study to determine the feasibility of running a gas turbine on ammonia [44]. As of November 2022, the Office of Naval Research was funding efforts to research ammonia fuels [20]. More generally, the US military and its partners are interested in alternative fuels. In 2016, the US Navy operated a fleet on biofuels, and the Netherlands (a NATO partner) is considering a vessel that operates on two fuels [61, 62]. Increased efforts are also being made to use smaller, unmanned assets that are powered by batteries and solar panels and optimized for long duration journeys. There are new multinational task forces dedicated to these vessels in both the Caribbean and the Middle East [63]. These platforms promote a more efficient use of fuel and allow larger capital assets, such as ships, to be used only when necessary.

All ships in the US navy operate on diesel, nuclear power, or special blend jet fuel known as JP-8 [2].

2.4 Ship Design

The next section discusses ship design. This is important if the fuel's feasibility is to be analyzed. Recognizing that ammonia has a place as a maritime fuel, it is constructive to return to the first principles of Naval Architecture to set the stage for further analysis.

First, some terms and boundaries must be set. The terms destroyer and frigate are used throughout this thesis in accordance with their use among modern ship classes in the US Navy. More generally, the definition supplied in Oxford's Companion to Ships and the Sea of a *destroyer* appropriately captures the class of ships of interest here.[7] Similarly, the vague label of *frigate* described in the Companion is equally applicable.[8]

2.4.1 Requirements of a Modern Naval Vessel

When designing the power system of this class of ship, the main factors that must be examined are the type of war anticipated, the tactics expected, the enemy's ships, force compatibility, budgetary requirements and social and political constraints [48]. A review of the current national defense strategy would suggest that future conflict would require ships capable of deterring aggression and assets that are resilient to a changing environment [65]. The US Navy's procurement plan projects a growing fleet to a larger than 300-ship navy by the end of the 2030s [12]. Gains are split between destroyers and submarines. The intent is too have greater specialization in the missions sets of vessels [66]. Larger destroyers (DDG) will have one role, while smaller frigates (FFG) will take on other roles. The main difference between these two is the power requirements, with FFGs having lower power requirements. These user requirements can be refined into two engineering requirements: shaft power and range.

Over time, the top-end power requirements of ships have increased dramatically, while the average has remained more consistent. This is because, despite the capability to move at faster speeds, this comes with costs in fuel and range. This trend is likely to continue, especially in a time of peace [50, 2]. The plot in Figure 2.2 demonstrates this trend. The values presented are the power for a River Class destroyer, a Gleaves Class destroyer, and an Arleigh- Burke Class destroyer [67, 68, 2]. As time moves forward, the increasing trend is likely to continue as armaments shift to energy-based systems such as lasers and railguns, in place of legacy chemically powered kinetic armaments. Additionally, electronic spoofing, high-powered detection radars, and communication equipment will lead to larger energy requirements.

Therefore, the design requirements for a destroyer must be considered to be at least 78 MW. Future designs will likely have increased efficiencies but also increased demands if the Jevons effect is believed. This effect can be seen in the newest class of US destroyers (Zumwalt class), which is 24% more efficient than the Arliegh Burke class it replaces but has the same power plant [2].

The other requirement that must be considered in the power system is the range. Ranges for destroyers are typically on the order of 3000-6000 nautical miles [49]. These ranges should be able to be extended with easy refueling and resupply. Liquid fuels offer an advantage in that they can be easily transferred from ship to ship while underway at a rate of 3000-6000 gallons per minute (1000 gpm for each of the six tanks) [36]. Therefore, an alternative fuel option must be capable of refueling at sea.

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[7] A light, fast warship developed in the last decades of the 19th century... with a tonnage of 2000-5000 tonnes [64].

[8] The generic term for smaller warships in all navies with an anti-submarine, anti-aircraft, aircraft-direction, or general purpose capability [64].

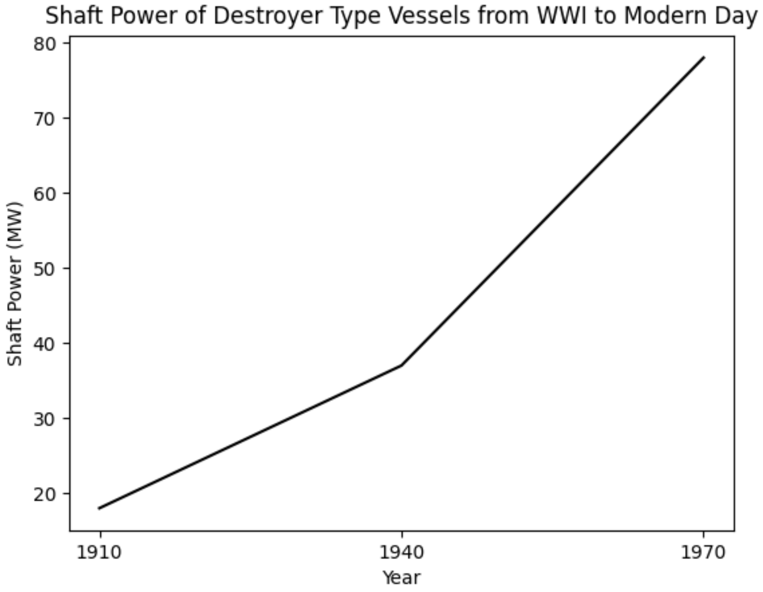

Figure 2.2: Change in Ship Power Over Time

2.4.2 Propulsion Plants

Modern naval vessels are propelled with a variety of different movers. Namely, the Brayton Cycle, the Rankine Cycle, the diesel cycle, the integrated power system (a combination of prime movers and Electric Motors), and nuclear power. For completeness, each will be briefly discussed here.[9] This section aims to provide context so that applications with ammonia can be discussed in further detail in chapter 5, as well as to justify decisions made in models.

Destroyers in the US Navy use four 20 MW gas turbine engines as the prime movers. These are modified Rolls Royce engines that were used on the Boeing 747, and are used in more than 15 other navies around the world. In the most fuel efficient mode, one engine runs one propeller and the blades of the other are set to reduce drag. This is called trail shaft and is often used as a test case, since it is the most common state of an engineering plant [13, 19].

Benefits

- Quick start-up (Minutes)
- Compact Size (Shipping Container $\sim$ 12 m)
- Limited Maintenance Crew ($\sim$ 30 people)
- Modular Power Capacity

Challenges

- Poor fuel efficiency

Prior to the wide-spread adoption of the Brayton cycle in the 1960s and 1970s, ships were driven by the Rankine cycle. These ships use high-pressure steam from boilers to spin the propellers. Some ships today are still driven by the Rankine cycle. The US Navy contains some larger ships, loosely called

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[9] Information on specific ship power systems is drawn from *Jane's Book of Fighting Ships* [49].

helicopter carriers, that use a Rankine steam cycle. The Chinese and Russian navies also have some Rankine cycle ships.

Benefits

- Cheap (1/3 the Cost of Nuclear)
- Large Power Capacity (>100 MW)

Challenges

- Personnel Intense Engineering Plant ($\sim$ 125 people)
- Larger Size ($\sim$ 80 m)
- Long Start Time (Hours)

The diesel cycle is widely used in smaller vessels in the destroyer class, but is almost always paired with a gas turbine. Diesel engines are prevalent in many European naval vessels, namely the navies of Spain, Germany, and the Netherlands.

Benefits

- Cheap (1/3 the Cost of Nuclear)
- Fuel Efficient

Challenges

- Heavy ($\sim$ 80 tons vs $\sim$ 30 tons for a GT)

The integrated power system is based on the combination of prime movers. Instead of using gearboxes to drive the propeller, motors and generators are used. The integrated power system takes any prime mover and then uses it to generate electricity that powers the motors and the rest of the ship. This technology can be seen on the latest class of US destroyer and also on board Australian, British, Spanish, Japanese, and Chinese vessels.

Benefits

- Fuel Efficient
- Quieter (No Reduction Gear)
- Smaller Heat Signature

Challenges

- Requires a Computer Based Control System

The final option is nuclear. Nuclear power uses steam to drive turbines in a manner similar to the Rankine cycle or, in some ships, to turn generators in an integrated power system. Only six nations in the world have nuclear powered ships in their fleet (US, UK, France, Russia, The Peoples Republic of China, and India), although this list is growing (Brazil and Australia plan to add nuclear powered submarines to their fleet). Most of these nations only have nuclear submarines, but three navies have nuclear surface vessels. The French, the US and Russia operate nuclear-powered surface vessels.

Benefits

- Infinite Range

- Large Power Capacity (700MW)

Challenges

- Geopolitically Sensitive
- Expensive (Most Expensive Ship Ever Built is the Nuclear Powered Gerald R Ford at 12.8 Billion USD [69])

2.5 Fuel Storage

Cryogenic fluids are typically those with a boiling point below -150°C. Ammonia boils at -33° C, but it faces many of the same challenges as cryogenic fluids. Namely, heat ingress into the tanks causing vaporization.

Modeling ammonia behavior while underway is a serious challenge that involves heat transfer and fluid dynamics. Sloshing, a constantly draining tank from evaporating liquid held at a constant pressure, and demand for fuel make the problem difficult to model. This section presents the literature on fuel tank models as one will be developed later in the report.

To the authors' knowledge, only a couple ammonia-specific models exist. Lee et al. produced a model for a power and fuel system for a tanker vessel, but assumed a constant boil off rate of 0.04% [70]. Imhoff et al. modeled a cuboid fuel tank and chose an insulation thickness that allowed him to obtain the boil off rate he needed to fuel his engines and also a vapor-liquid temperature equilibrium [19]. Both of these models assert that there is room for improvement.

LPG, which has a boiling point similar to that of ammonia,[10] also shows a small number of studies. Shameki and Ashouri present a model to calculate the BOG for loading, unloading, and storage of a tank [71].

The widest-ranging literature that exists is on LNG tanks. Luckily the ammonia model is less complex than the LNG which is never pure methane but a composite of other fuels in equilibrium. Ammonia can be modeled as a pure substance.

LNG models are in two general categories the numerical/ analytical model, or full Computational fluid Dynamics models in multiple dimensions. Models have evolved over time, becoming more computationally demanding. Initial models attempted to determine the natural gas composition using Peng Robinson equations of state [72]. Then the vapor-liquid interaction under non-equilibrium conditions was added [73]. This showed the limited role of convection inside the vapor phase. The next evolution incorporated a temperature gradient in the vapor in lieu of an average like the previous models [74]. With each iteration, marginal improvements to the realism were made. The general model was also shared in a paper on pure compounds and could easily be applied to ammonia [74]. The most recent iteration from this set of authors is a CFD model that confirms their previous work [75]. Although the research mentioned here is largely the work of one research group, it was built from older models compiled by Miana et al., who assembled one of the first thermodynamic and mass balance models of a fuel tank [76].

Another approach is to use industry measurements and processes to experimentally determine boil off gas (BOG). Kirkkis uses this approach, his model is based on experimental values from an LNG voyage [77]. Unfortunately, the limited data points were a challenge to his model. Similarly, Qu et al. developed

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[10] LPG has a boiling point of -42°C.

a model for industrial shipping applications that attempts to quantify sloshing in the estimation of BOG [78].

The final category of models involves bunkering. This is a particularly difficult model because of the heat entering from the new fuel. Wang and Ju modeled the difference between the top and bottom filling of the tank and showed the impact of pressure build-up in the tank [79]. Another study by Lee et al. presents a model of ship-to-ship bunkering of LNG [80].

2.6 US Navy Education System

The purpose of this section is to provide a brief overview of the literature available on the US Navy's education system. This is included in order to provide a basis for the subsequent discussion in Section 5.2.

Michael Besch presents an evaluation of the Navy's training apparatus during the first world war in his book *Navy Second to None: The History of U.S. Naval Training in World War I.* The rapid technological advances that occurred in the lead up to the first world war [81], the first war in which oil and coal ships were used, and the first war to include radio, represent a motif not too different than contemporary challenges. Then, just as now, new technologies required new skills from operators. The book describes how the navy successfully adpated to these challenges and created new instituions to handle the technology. However, the book is dated, and many of the structures discussed by Besch have shifted or were changed by the National Security Act of 1947.

More contemporary literature does not focus on the effectiveness of the training infrastructure in the same way as Besch. There is one excpetion in a study of aviation and the incorporation of simulators. Judy et al. found that time in the aircraft was a better predictor of success than time in a simulator [82].

Instead, the bulk of the literature focuses on attrition and costs, rather than effectiveness. This can be seen in studies by Vasquez et al., Laing and Buclatin, McDonald et al. and Campion, which all focus on predicting the attrition rate of different schools based on recruitment statistics [83, 84, 85, 86].

With the rise in information technology and personalized computers, the focus shifted to cost savings using virtual learning. This can be seen in research done at the Naval Postgraduate School by Nathaniel Robbins, Jessica Eisen, Roy Ezel and Bell et al. [87, 88, 89, 90].

An outlier study was found that looked at the perceived preparedness of Naval Officers in their jobs. Titled *The Education and Development of Strategic Planners in the Navy*, the author Michael Weiss surveys people with Strategic Planning codes [91].[11] Weiss concludes by writing: "it is the knowledge gained from first-hand experience that the warrior brings to the strategy formation arena that is so valuable" [91]. In a sense, the format of training is less important than time on board ships or the books an officer reads during certain events. Here, Weiss argues that experiences shape the policies created by strategic planners.

2.7 Ammonia Economics

Many studies on the economics of ammonia focus on its production and not its use as a marine fuel. A study already mentioned by Bartels [31] reviewed the economic feasibility of ammonia production.

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[11] The Navy assigns numerical indicators to individuals that describe what training they have, for example, upon completion of this course with an engineering graduate degree, I will be assigned code 5000P.

Another study by Eric Morgan found that ammonia could be produced using offshore wind in the United States for 580-1280 USD [92]. Ikaheimo et al. reported on the economic feasibility of green hydrogen in northern Europe [93].

Several papers were found that discussed ammonia as a maritime fuel. The first by Lee et al. discussed the economics of BOG liquefaction equipment on board an ammonia tanker [70]. A paper by de Vries argues that ammonia vessels are 3.5 times more expensive than diesel due to high fuel costs [30]. Both Harvarth et al. and Korberg et al. produced a techno-economic analysis on a variety of ship designs and found that fuel cost is the driving factor and that fuel cells are currently not cost competitive [94, 95]. Kistner et al. argue that if environmental costs are included, then fuel cells perform better than internal combustion engines [96]. However, Kistner et al. argue that fuel costs are still the driving factor when it comes to cost competitiveness [96].

No studies were found on the economic feasibility of the use of ammonia on board warships.

3 | Methodology

This section explains the reasoning behind the methodologies used in the subsequent chapters. The respective chapters detail specifics on the analysis, so this chapter exists to defend the chosen approach.

3.1 Chapter 4: Fuel

The fuel section seeks to answer three questions:

- Is ammonia accessible for warships?
- Can ammonia be transferred between ships?
- What happens to ammonia in the fuel tank?

The first question is asked because it is widely stated as true using averages, but the reality could be more complex. The second question was investigated because underway replenishment is a requirement for warships, and the third question was asked because contemporary models are in the early stages and large contributions to the accuracy and understanding could be made.

The first question is answered with a geospatial analysis. This is useful because it is a visual tool that can be used to understand whether ammonia is actually available where it is needed or if the averages are hiding the details.

The second question is answered with a review of the literature. Without performing an at-sea replenishment, it is difficult to know if this would work any differently than the current replenishment. Therefore, the analysis is comparative in nature.

The third question is answered using a model. Due to the lack of ammonia fuel tank models, this was an area where the field could be advanced relatively easily. Analytical models were used because a full computational fluid dynamics (CFD) analysis would jump ahead of current research progress. This model would allow deeper questions to be answered like: How fast does ammonia boil off? How will the fuel tanks fit in the hull? Will extra equipment be required?

3.2 Chapter 5: Powertrains

The powertrain section seeks to answer two questions:

- Are ammonia powertrains available?
- Is it possible for sailors to learn how to use ammonia safely?

The first question impacts the feasibility because the Navy is not in the business of building engines. This activity is contracted out. For commercial systems (such as powertrains), it is mandatory that the technology is proven [97]. Answering this question determines whether the Navy will consider ammonia fuel. The second question is important because it dictates the size of the crew and has a cost associated with it.

The availability question is answered by taking a survey of current projects. This method shows the current potential of the technology and the feasibility of adoption in a naval vessel without speculating on ship design too much. The goal is not to discuss engineering details such as flame speed or fuel consumption or fuel mixtures, as this can only be addressed when more details of the ship design are available.

The education question uses anecdotal examples to discuss the flexibility of the Naval education system. Anecdotal examples are used in the same vain as Weiss [91], as he shows that experience is a large indicator of perceived success. In the absence of recent data on the Navy's education system, these anecdotes are the best tool available.

3.3 Chapter 6: Safety, Environmental, and Social

Chapter six is a very broad chapter, and an applied literature review is used to answer all of the following questions:

- How safe is ammonia under standard operating procedures?
- How safe is ammonia in the event of a casualty?[1]
- Is the release of ammonia into the environment a greater challenge than an oil spill?
- Does the US Navy follow environmental standards?
- Does the citizenry of the US have the power to influence naval policy?

The first two questions are important to answer in the feasibility study because the first is something every reasonable person would ask. If it is not safe to work around, the Navy would have a hard time employing sailors and, therefore, be unable to carry out its mission. The second question is more complicated because the Navy is unique in that its ships are designed to survive casualties. Understanding the resiliency of ammonia in the event of a casualty is important for a warship.

Questions on the environment are included to ensure that the analysis is well rounded but also to determine if the environment should be viewed as a design constraint.

Social feasibility is analyzed mainly because there is a lot of grey in this realm. There are many unknowns to include the level of care, and if people care what impact can they have. The US military is ultimately civilian led, a unique feature of the US military. Understanding the role the State interferes with the Soldier and visa versa is a question that has been routinely asked, most famously by Samuel Huntington [98]. It is important to see the implications for fuel use.

An applied literature review is used in tandem with web scraping of the New York Times Web site to measure public sentiment to answer these questions. From these data, conclusions were drawn on the environmental, social, and safety of ammonia in a defense application. Much research on environmental and safety issues has already been conducted due to the ubiquity of ammonia so literature consultation was deemed sufficient.[2] Additionally, the New York Times is widely recognized as a "News Paper of Record" and representative of the facts that people might know or care to know about [99], therefore, it was considered to be a fair place to assess public sentiment.[3]

3.4 Chapter 7: Techno-economic analysis

This chapter determines the total cost of ownership of an ammonia propulsion plant versus a diesel fueled propulsion plant for a destroyer and compares the two. This was required for the feasibility study, as without it the affordability motivation discussed in Section 1.1 would be a moot point.

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[1] Here casualty is used to describe a fire, collision, or attack that causes the release of ammonia.

[2] As already discussed research dates back to the 1800s on Safety.

[3] 10 million people read the NYTs every day [100].

4 | Ammonia Fuel: From Generation to Use

This chapter aims to present the location of current ammonia depots and highlight the overlap between major US bases. It also discusses the status of refueling at sea and applies a model for an ammonia fuel tank on board a destroyer.

4.1 Fuel Availability in Port

The background section takes the position that ammonia is widely available in the commercial sector. This is by and large true. However, the unique defense requirements are different from those of farmers, who are the main commercial users today. This section offers a review of the available ammonia plants and their location.

4.1.1 Methodology

A list of plants was assembled by consulting lists of the largest ammonia producing companies in the world and determining where they operated (BASF SE, CF Industries, CSBP Limited, EuroChem, Group DF, Gujarat State Fertilizer & Chemicals, IFFCO, Koch Industries, Nutrien, OCI Nitrogen, PJSC Togliattiazot, PT Pupuk Sriwidjaja Palembang, Qatar Fertilizer Co, Rashtriya Chemicals and Fertilizers Limited, SABIC, and YARA). The list was further developed by researching major ammonia plant constructors, namely: KBR, Whessoe (Samsung), Thyssenkrupp Uhde, and Linde Engineering, who all list their project experience on their websites. Finally, the list was supplemented with industry reports to understand which ports were capable of both import and export [101]. The pipeline routes were placed on the map using information from their operators (NuStar and Transammiak).

It is important to note a gap in this data set, namely the lack of information on China. China is repeatedly cited as the largest producer of ammonia [22]. Information on Chinese plants in English is difficult to find, but the IEA reports that 30% of global ammonia production occurs in China and 85% of production occurs using coal in the upper Mongolia region [22]. However, reports in Chinese paint a different picture. China outlawed the construction of new Natural Gas Plants in 2012, due to the dependence on European and American natural gas imports. China also does not introduce its ammonia onto the global market, and due to falling ammonia profits, in the past few years, they have actually reduced their ammonia generation capacity [102]. These actions make Chinese ammonia less relevant for this review, especially given the current reductions in ammonia production in China and geopolitical tensions.

4.1.2 Discussion

Ammonia production facilities are generally located in two locations. They are near natural resources (coal or natural gas) or near farms that would use ammonia. The abundance of ammonia plants in the Middle East not only suggests a desire of these nations to diversify their exports but also shows that the current production method is highly carbon intensive. This is not unique to just the Middle East though, the trend can also be seen in the South Pacific (mainly in Indonesia), but also in Scandinavia as well. The US seemed more willing to build plants in the Corn Belt, but plants are prevalent in the Gulf of Mexico, where there are petroleum reserves.

The geospatial availability of ammonia makes it less feasible as a marine fuel than the broad numbers might initially suggest. Figure 4.1 shows the main ammonia infrastructure in the US as well as the location of the major US naval bases. The only port on the east coast capable of exporting ammonia is in Louisiana, far from naval bases in Florida and Virginia ($\sim$ 400 and $\sim$ 1000 mi respectively). On the west coast, Portland has production capacity, but is more than 200 miles from Everett Washington and the Naval Base located there. The largest base on the west coast, in San Diego (25% of the Navy), has an import capacity in LA (∼ 120 miles away), but does not have the facilities required to offload the fuel onto a ship. This is because the US is a net importer of ammonia and does not have widely developed export facilities [26].

It is not just a production problem, transport and storage are also a problem. Even though the US has 10,000 ammonia storage tanks; almost all of them are located along the pipelines in the Midwest. This shows that in order for ammonia to be used as a defense fuel, changes to both the transport infrastructure and production would need to occur.

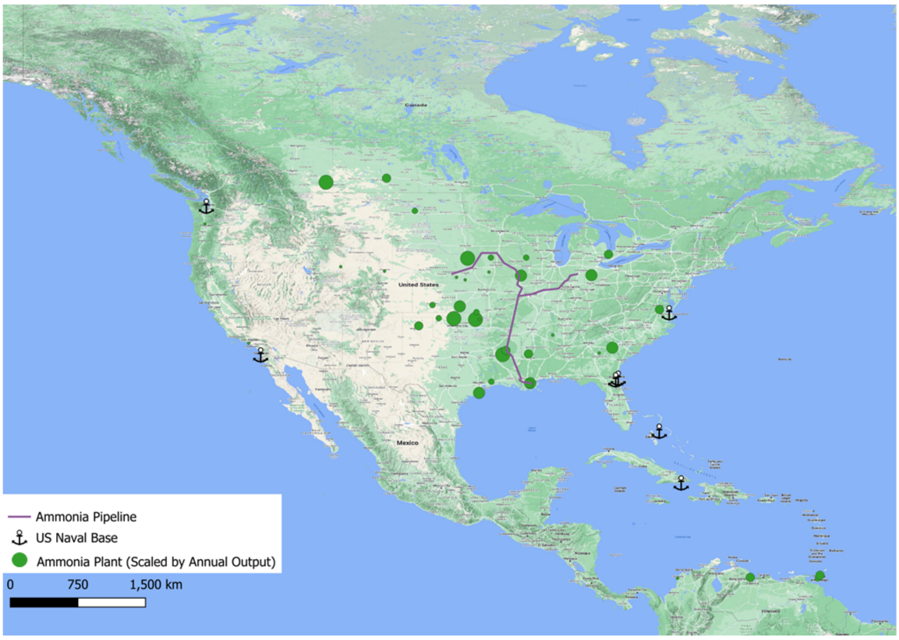

Figure 4.1: Location of Ammonia Infrastructure and US Naval Bases

In the international arena, ammonia is faced with many of the same geospatial problems as it faces in the US. Figure 4.2 shows the location of global ammonia production facilities, as well as the location of forward deployed US naval bases. Ammonia has the greatest availability in the Middle East and northern Europe for US and NATO countries. This is because in the Mediterranean and Central Europe ammonia is imported via pipeline from Russia.[1] If ammonia is to become a more important fuel in the energy system and, particularly, in defense, then a more secure supply in the Mediterranean would be desirable, since just under 100,000 active duty service members are stationed there [104].[2] Unlike central and southern Europe, the Pacific Ocean, Arabian Gulf and Indian Ocean theaters offer a diverse collection of suppliers, making these regions more strategically sound. Since diversity of supply makes choke points harder to apply. In northern Europe, long-standing alliances in the UK and Norway make ammonia a safer option but they do not have the required capacity to support a navy, even though the plants are well situated along the coast.

The average age of the infrastructure was also found to be misleading. The average global age of a plant is 25 years, but the average age of European and American plants is closer to 40 years (the lifespan of a plant is 50 years) [22]. This means that plants in Asia and the Middle East are newer. If ammonia is to become a defense fuel. America and NATO's production infrastructure lag behind the rest of the world, making it vulnerable to price shocks.

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[1] The value of ammonia as a fertilizer has been exploited in the current conflict with Ukraine, where ammonia pipelines have become the target of attacks [103].

[2] This is 7.6% of Active Duty Service Members, 3 times the number stationed in the Middle East. Only Japan has a greater number of US troops stationed there.

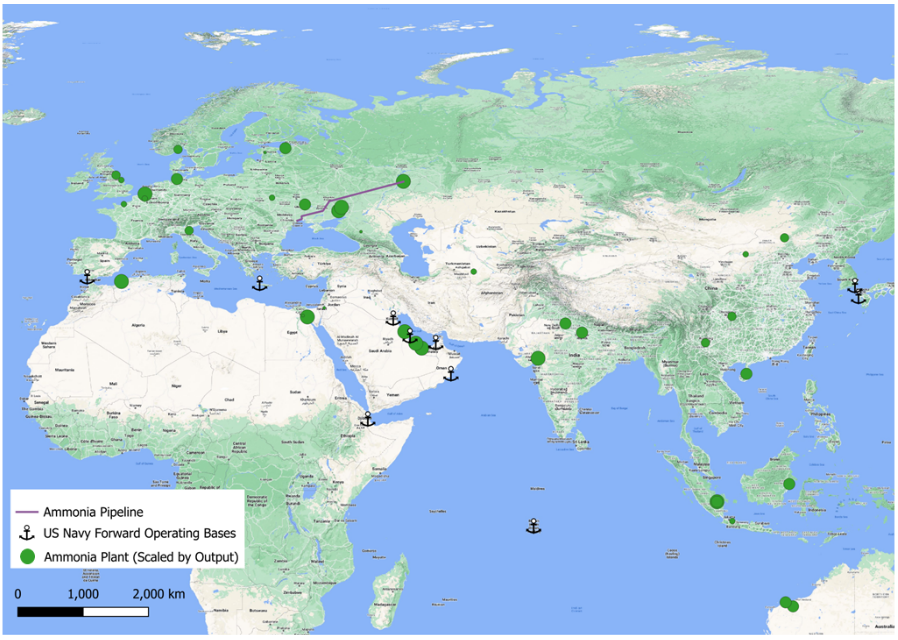

Figure 4.2: Location of Ammonia Infrastructure and US Naval Bases

From a forward-looking perspective, green ammonia plants will continue to be built in areas with cheap energy. If the ammonia industry is electrified, as many hope it will be, production can be paired closer to use cases, such as maritime defense. The typical new ammonia plant generates in excess of 2000 tons per day or enough to fill an Arleigh Burke class destroyer's current diesel tanks with ammonia twice. An active base would require at least one dedicated plant, as well as storage facilities. The time scale to develop this production capacity is approximately 3-5 years according to the project timelines available in stockholder releases from Thyssenkupp [105]. The cost of building a plant of this size is about 2 billion dollars (for green ammonia) [106].

4.1.3 Conclusions

Ammonia is currently not feasible given its proximity to defense assets in the continental United States. In Europe, the ammonia industry is strategically vulnerable to Russia, much like the natural gas industry. The areas where ammonia fuel currently makes the most sense as a defense fuel are the Middle East and the Indian Ocean, where the market has a diverse cohort of suppliers. The age of the infrastructure is also a concern. For ammonia to become feasible, new production infrastructure in strategic locations would need to be built at a cost of at least 2 billion dollars per base and a timeline of 3-5 years.

4.2 Fuel Availability at Sea

As discussed, a requirement for a modern naval vessel includes the ability to remain on station without returning to port for prolonged periods of time. This requires the ability to refuel at sea. This section presents the current status of ship-to-ship bunkering of cryogenic fuels and the current capabilities of the US Sealift Command's tanker fleet and its ability to supply cryogenic fuels. [3]

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[3] The US Sealift Command is the part of the US government that supplies the Navy's warships with fuel while underway

4.2.1 Technological Feasibility

As already mentioned in a previous section (2.5), some models for bunkering exist. These mainly aim to define the most efficient process. In many ways, ammonia bunkering is simpler than LNG. For one, the temperatures are less dramatic. Another difference comes from the composition of LNG. LNG settles into many components, while ammonia is homogeneous. These different components lead to a phenomenon called rollover, in which the tank pressure increases uncontrollably due to the different component densities. This leads to tank damage and excess boil off gas at a rate of 8-10 times higher than normal storage [70]. Ammonia would not face this challenge.

Furthermore, industry has developed guidelines for LNG bunkering from ship to ship in ports, and there are more than two dozen bunkering vessels in ports that transfer fuel at a rate of 1400 gpm (half of the 3000-6000 gpm currently used by the Navy) [107]. This low rate is to reduce rollover and could be avoided for ammonia. Of greater concern would be the feasibility of ship-to-ship bunkering at sea. This is a defense-specific activity and one that does not have any corollary to LNG.

4.2.2 Logistical Likelihood

Though it may be technically possible, at sea ammonia bunkering would face significant logistical hurdles. In 2019, the US Sealift Command and the US Navy started the process of acquiring new oilers to replace the current fleet. They have preemptively ordered 20 of these vessels and have already completed 6 and are set to keep building 2 per year as long as the budget allows. With a useful life of 35 years, these ships represent a sunk cost (559 million USD per ship or 2% of the annual ship building budget) that will challenge the willingness of the Navy to switch fuels [69]. In the commercial shipping sector, the conversion of vessels is common.[4] Therefore, this offers a potential option for the Navy to utilize capital assets.

4.3 Fuel Storage on Board

Once the fuel is on board, the behavior of the fuel is of interest. In this section, a model for the fuel tank is presented. This model is particularly tailored to a defense application and also to ammonia. This section discusses the results of the model and then compares the results with the powertrain analysis conducted by Imhoff et al. [19].

4.3.1 Methodology

The model was based on the model for pure cryogenic fluids created by Huerta and Vesovic [108]. The ammonia properties were looked up using the CoolProps package in Python [109]. The tank was assumed to be cylindrical and of the same volume as one of the 6 tanks that make up the fuel storage system on an Arliegh Burke Class Destroyer. A 3D rendering of the tank is presented in the Figure 4.3. This shows one of six tanks required to meet the same fuel volume as a destroyer.

The tank was assumed to have an internal diameter of 15 meters and a wall thickness of .025 m (composed of insulation and steel– for typical anhydrous ammonia tanks [110]), and a 1.4 meter height. Insulation (k = $0.033\frac{W}{mK}$) was assumed to be 0.013m thick and bracketed with steel of thickness 0.006 m thick (k=$14\frac{W}{mK}$) [19, 72]. These dimensions were chosen to mirror the volume of the current 260 m^3 tanks present on ships and also to have a similar height. The beam (width) of an Arleigh Burke class

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[4] About a quarter of the LNG bunkering fleet is a conversion [107].

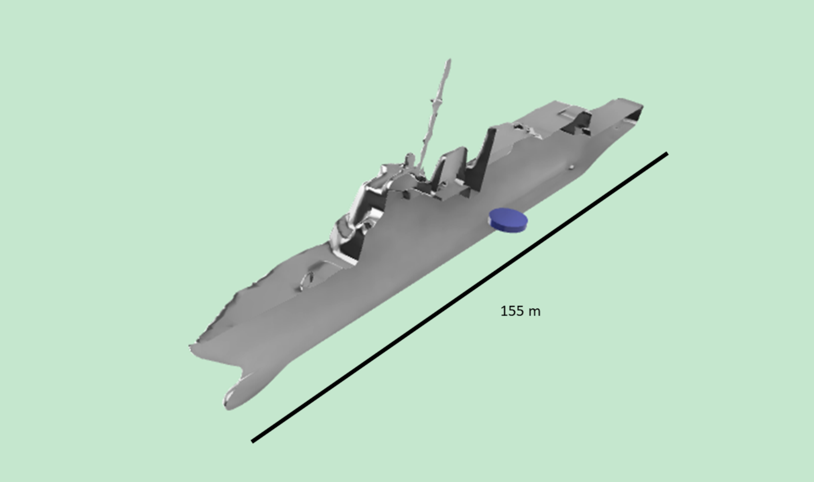

Figure 4.3: 3D Rendering of a Tank in an Arliegh Burke Destroyer Model

destroyer is about 20 meters, but narrows at the waterline, meaning that only one tank can fit centered on the keel. This differs from the current design, which has tanks side by side. However, there is plenty of room to spread tanks along the keel because of the overall length of 155 meters. The tank model was run with an tank level of 97%. This fill level was chosen because attempting to fill the tank to 100% could result in an environmental or safety concern.

The tank heat transfer model is the same as those developed by Huerta and Vesovic [108]. Modifications for tank size and fluid type were applied, and the commented Python code is available in Appendix B. The assumptions made in the model can be understood best pictorially using the Figure 4.4. The model assumes a constant liquid temperature and constant pressure. The pressure is maintained constant by allowing boil off gas to leave the tank as the ammonia evaporates. There is a temperature gradient in the vapor due to cooling of the liquid, which is based on the substantial evidence presented by Huerta and Vesovic for a wide range of tank sizes and cryogens [108]. Heat transfer between the liquid and the vapor stages is driven by conduction. This assumption is validated by the results of another paper by Huerta and Vesovic [74].

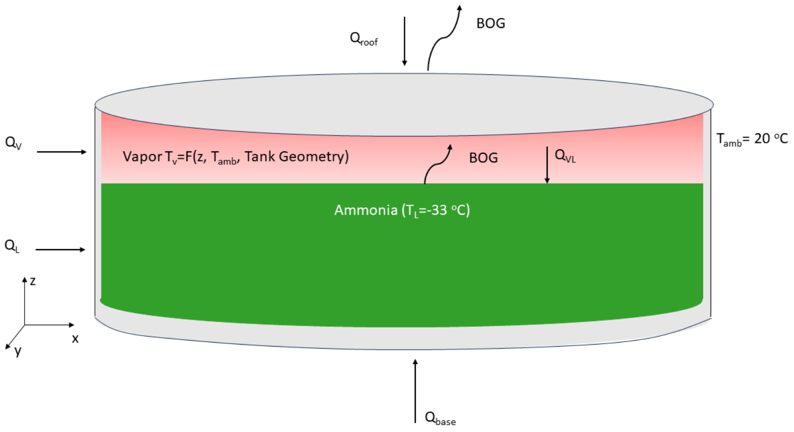

Figure 4.4: Conceptual Schematic of Thermodynamic Model

The heat transfer coefficients were calculated using the commented Python code and the constants described in Appendix C. The same heat transfer coefficients for the tank walls were considered equal in the liquid and vapor portions of the tank. This assumption was valid as the percent difference between the two coefficients was 1.39e-6%. A value of 2.53 $\frac{W}{m^2*K}$ was used for the overall heat coefficient (U) for the walls of the tanks. The base was assumed to have a heat transfer coefficient of 1.18 $\frac{W}{m^2*K}$. These values were calculated using the Churchill-Chu correlation (equation 4.1) for free convection for vertical plates on the sides. The correlation used for the horizontal base of the tank is seen in equation 4.2 [111, 19].

$$Nu = \left(0.825 + \frac{0.387Ra^{1/6}}{\left(1 + (0.492/Pr)^{9/16}\right)^{8/27}}\right)^2 \tag{4.1}$$

$$Nu = 0.52 \times Ra^{1/5} \tag{4.2}$$

The Rayleigh numbers were calculated using equation 4.3. Where L is 1.4 meters for the sides of the tank and $L = A_s/p$ for the base (A_s is the surface area, p is the perimeter); T_s and T_{bulk} are the surface and ambient temperature, respectively.

$$Ra = \frac{g\beta(T_s - T_{bulk})L^3}{\nu^2 Pr} \tag{4.3}$$

The heat ingress from the roof was modeled with the Robin boundary condition, which was shown to be more accurate for tanks of small and medium size (like this one) [108]. A constant heat flux into the tank of 11051 W was assumed for the base. This was calculated using the equation 4.4, where A is the area of the base, T_{amb} was 20° C and T_L was -33°C. Throughout all calculations, the tank pressure was set to 101000 Pa.

$$Q_{base} = U * A(T_{amb} - T_L) \tag{4.4}$$

4.3.2 Discussion

Before discussing the results of the model, it is worth noting the size requirements of the tanks and the space constraints they create. As can be seen in Figure 4.3 which shows the modeled tank inside the hull of a Arliegh Burke class destroyer, the tank does not fit well. Fitting six of them would take up substantial space. Dead space due to tank shape could be used for the ballast tanks. However, if a range similar to that of the diesel-fueled ship was desired, twice the volume would be required, with additional tanks required for ballast. This highlights the conclusion made by Imhoff et al. that it is difficult to imagine an ammonia-fueled powertrain fitting on a modern naval vessel. Not just from a powertrain perspective, but from a fuel storage perspective. A complete redesign of the vessel would be required in order to make storage feasible.

Using the tank specifications, it would take 21 weeks for the tank to empty. The scope of this boil off can be seen in Figure 4.5. This represents a boil off rate of around 3%-6%. This is a large boil off rate for a tank (typical values for tankers are 0.04%). However, the tanks in storage vessels are much larger (480 times larger) and designed to store fuel for long periods of time. The tanks on a destroyer would be built for consuming fuel, and therefore a higher boil off rate would be desirable. The dramatic boil off rates are due to the insulation thickness, which if doubled increases the emptying time to 25 weeks. It is also a function of the tank dimensions, which have large surface areas that allow heat to enter. In terms of strategy, a boil off time of 21 weeks is sufficient to sustain a destroyer with a typical deployment of 6 months.

Boil off is not an inherent bad thing, as it is required to move the ship. In the powertrain analysis of Imhoff et al., a gas turbine powered ship requires a flow rate of 201 mols/s for a gas turbine in trail shaft

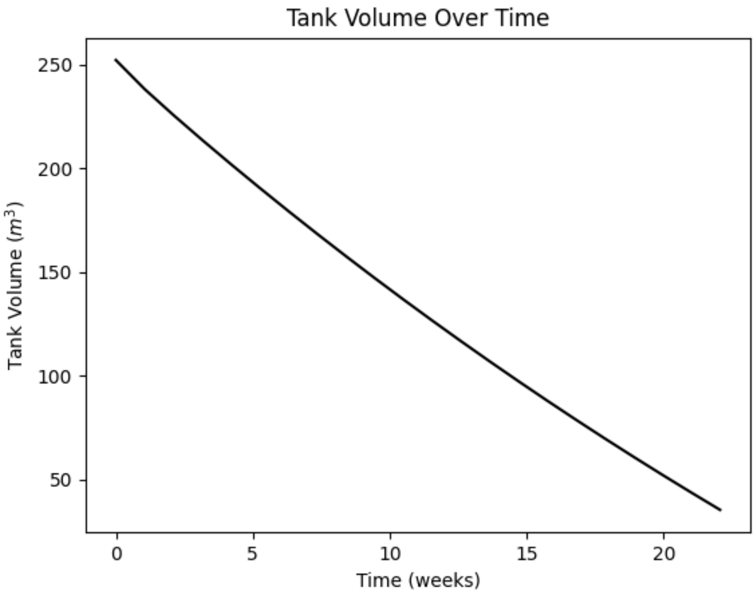

Figure 4.5: Tank Volume Over Time

mode [19]. Six of the fuel tanks modeled here produce an average flow rate from boil-off gas of 4.68 mols/s. This means that some form of external heater would be required to produce the required flow. This would make the system more inefficient, as it would be heating the fuel to create boil off. It is also worth noting that the natural boil off is not consistent and decreases over time.

4.4 Conclusions

From Generation to on ship storage, ammonia fuel poses challenges that will need to be addressed if ammonia is to be used in defense. The current location of the ammonia infrastructure is not strategically placed. The US would need to build new ammonia plants near naval bases, a process that could take 5-10 years and billions of dollars (although the cost would be born by industry). Additionally, sunk cots in cargo ships will need to be addressed if ammonia becomes the next defense fuel. Finally, fuel storage on board would require heaters to increase boil off and increased space provided to both ammonia tanks and ballast.

In summary, the fuel supply chain and current ship layout make ammonia use aboard a warship a poor strategic decision.

5 | Powertrains: Technology Maturity and Skills

This chapter seeks to explore two main sections through research. The first section compiles a list of different ship-based engines and power systems and presents their current maturity. In the second section, the adaptability of the Navy's sailors' skills is evaluated.

5.1 Available Powertrains

Discussed in Section 2.4.2, there are a range of different prime movers available to ships. Almost all of them have the potential to be powered by ammonia. There is a collection of papers that describe the current trends in combustion engines powered by ammonia. Valera-Medina et al. produced a comprehensive review [23], Manigandan et al. discussed diesel engine technology [112], Chiong et al. and Xu et al. discussed ammonia combustion and fuel mixing in a host of engines [113, 114]. Manigdan et al. also discuss the emission reduction strategy [112] and the need to reduce costs, a topic Chiong et al. also examines [113, 112]. All of these papers conclude that further research is required but that ammonia is a viable alternative to carbon-based fuels in combustion engines.

The alternative to an engine is a Rankine cycle. As discussed in Section 2.4.2, the maritime application of Rankine cycles is not common. However, Mitsubishi Heavy Industries patents have been found for ammonia-powered furnaces and boilers [115, 116], and press releases signal that research on ammonia boilers is ongoing [117]. The establishment of shore-based boilers is not an indication of future maritime applications, but it is worth reporting here given the continued history of ships moved with Rankine cycles.

Fuel cells offer a non-combustion alternative. Directly fed ammonia fuel cells are present in the literature by Wang et al. and Afif et al. [21, 118]. Although their position for commercialization is slightly less mature than combustion methods, fuel cells are a vector that should not be overlooked. The challenges lie primarily in optimizing catalysts, material structure, and system integration [21]. An alternative to the direct fed ammonia fuel cell is an external decomposition model that cracks the ammonia and feeds it into a hydrogen powered fuel cell. This adds system complexity but uses already available and understood processes. The process of cracking ammonia is well known, as is the process of using hydrogen in a fuel cell [119]. The external decomposition model is the technology used by Amogy, the company aiming to produce the first ammonia-powered ship [120].

A synthesis of the current commercial projects is presented in the Table 5.1. This table does not include approvals in principle or vessels that are conventionally fueled and have the ability to be retrofitted for ammonia use at a later date. Only the vessels that are being built are included.[1] The table shows that ammonia powertrains have not been tested on the commercial scale at the required powers discussed in Section 2.4.1. The US Navy requires that the power systems of its ships be commercially operational for 2 years unless paperwork for a waiver is submitted [97]. As these technologies demonstrate their commercial viability, they become more palatable to a defense customer.

5.2 Skills

The US Navy maintains its equipment while at sea and in port using the skills of enlisted sailor taught at collection of different schoolhouses across the US. The Navy has an integrated education mechanism to train service members on the skills required for their job. This includes schools that teach mechanical or

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[1] The list is compiled primarily from press releases, but additional information is available from the Global Maritime Forums Map of Zero Emission Pilots: https://www.globalmaritimeforum.org/publications/mapping-of-zero-emission-pilots-and-demonstration-projects

Table 5.1: Current Publicly Available Commericial Ammonia Projects

Company	Powertrain	Year	Notes	Source
Ships and Ship Systems				
Wartsila	4 Stroke	2023	Built for Cargo Vessels (Powertrain Only)	[121]
MAN Energy Systems	2 Stroke	2024	Built for Cargo Vessels (Powertrain Only)	[122]
Amogy	Fuel Cell	2023	1 MW Tug boat Conversion	[120]
Eidesvik Offshore Viking Energy	Fuel Cell	2024	2 MW Retrofitted Energy Carrier	[123]
Other Power Generation Activities				
Mitsubishi Heavy Industry	Brayton	2025	40 MW Ammonia Fueled Turbine for Power Generation	[124]
Mitsubishi Heavy Industry	Rankine	No Date	Creation and testing of ammonia fueled boilers	[117]

technical skills (welding, machining, strategy, acquisitions, etc.) as well as higher education institutions (that provide general degrees in engineering, English, management, etc.). This robust and diverse infrastructure is equipped to design and implement training changes that may be required. Modern studies on this topic are not present in the literature (as shown in Section 2.6); however, recent technology adoptions of AM, Unmanned Systems, and changes in the understanding of physical fitness can be taken as examples of what might occur with a fuel switch.

The rise of additive manufacturing (AM) is the first example. As the technology began to be discussed broadly, there was increased interest from the research arm of the Department of Defense, as reports were written discussing it as an area of interest [125]. The Naval Academy noticed the technology and began teaching it to engineering students; now all students receive a two-day introduction to AM, even English and Political Science majors [126]. The officers then shared the technology with dental technicians (enlisted sailors), who use it to make molds for fillings. Showing how the technology can make a full circle [127].

Another example is unmanned systems (robotics). Autonomy is becoming increasingly important in defense, with the Deputy Secretary of Defense calling for 1000s unmanned platforms [128]. With this trend, departments have changed their names. At the US Naval Academy, the *Department of Weapons* was rebranded as the *Department of Weapons, Robotics and Control Engineering* in 2017. Before 1975 the department was called the Department of Ordinance and Gunnery, in 1975 new technologies such as guided munitions, radar, and sonar were being incorporated into the curriculum and the name was deemed to be too narrow [129]. Evidently, the Navy adopts what it teaches to meet the strategic needs. These changes trickle down into the fleet where officers work with the enlisted, who can now be seen installing Starlink Dishes and Silvus Radio Mesh- Network devices, both critical for contemporary robotics [130].

Another example of this phenomenon is the changes made to the annual physical fitness test. Researchers found that the old test was a poor measure of fitness [131]. A new test was created and was first applied to the training institutions before the test was implemented in the larger fleet [132].

Ammonia powertrains would likely first appear in the engineering curriculum all future officers are exposed to. In time, this information would trickle through the fleet. It should be noted that this change is not overnight; the Navy released its first AM guidance in 2016 and it took 3 years to establish a robust center at USNA 2019 [125, 127], and articles were written in 2015 on the physical fitness test before changes were made in 2020 [131, 132].

Note:

Beyond the literal ease and flexibility of the training arm of the Navy, the required skills are familiar to sailors already (with the exception of fuel cells). Diesel engines, gas turbines, boilers, and the associated maintenance with each of these systems is well known, as they are already on ships. Sailors already understand the work and maintenance that may be required, and little adaptation would be required.

5.3 Conclusions

Ammonia powertains are just entering the commercial market. As the technologies prove themselves, the interest of the Navy will likely grow. This makes the powertrains feasible for a defense application.

Injecting new education into the Navy is possible and has several examples from the past. Education should not be seen as a challenge.

6 | Safety, Environmental, and Social Considerations

Though the safety of ammonia fuel has been briefly discussed in Section 2.2.2, a further analysis will be conducted here from the perspective of a defense application. Additionally, the environmental and social feasibility of ammonia adoption will be analyzed.

6.1 Safety

6.1.1 In Port

In order for ammonia to be feasible it must be judged against current fuels.

The analysis carried out by Duijm et al. for a cradle-to-use case for an automotive application estimated that unintentional ammonia releases were ten times higher during maintenance and transport [133]. However, they concluded that even with these occurrences, certain safety measures (such as transporting the fuel in refrigerated vice-pressurized containers) reduce the risks to the same level as conventional fuels. The risks surrounding the generation of ammonia are also very low. A study by Liu et al. found that fatal accidents were only likely to occur once every ten years [134]. In contrast, in the 18 years between 2000 and 2018, there was an average of 6 accidents per year in which more than 2000 people died from oil extraction and transport [135]. This argument is limited due to the size of the ammonia industry, but with the appropriate safety measures and maintenance, there is no reason to believe that ammonia is more dangerous than the oil industry.

From a defense perspective, these risks would be even further reduced given the ability to restrict traffic on bases and to run pipelines directly to the piers from potential storage and generation facilities. Maintenance procedures could be written so that unintentional ammonia releases are avoided. This would not be unfamiliar to the Navy, which adopts a "Tag-Out" procedure to perform maintenance on energized components [136].

6.1.2 At Sea

At sea different challenges exist due to the confined space and the need to save or fight the ship in response to a casualty.

A study by Maersk found three main factors that increase risk: number of leak sources, flow pressure and ammonia volume in the section of interest, and chance of escape [137, 59]. Their model reduced the risk to less than 1 in 10,000.[1] The engineers lowered the risk by creating segregated living and engineering spaces, easy-to-access life boats and ensuring that the fuel remains at low pressures. They also suggested water curtains around fuel tanks and double-walled piping in some areas. This shows that on a normal vessel ammonia is feasible from a safety perspective, because the ship can be designed so that it is easy to abandon.

In a defense application, the ship cannot be abandoned. Warships do not have lifeboats, and space dictates that tanks be spread along the keel; this makes segregation difficult. Therefore, instead of abandonment saving the ship is important.

A pipe rupture and a fire are two of the most threatening casualties that can occur on a ship. With petroleum leaks, pipes can be sealed with a plug, a waxed cord, and a skilled sailor. In the event of a damaged ammonia pipe, the toxicity of the fuel becomes a serious concern. Respirators would be

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[1] This is the standard used by insurers such as Lloyds.

required and a system similar to what is on board submarines could offer an effective risk management strategy.[2]

In terms of fire, ammonia has a lower risk of explosion or ignition than petroleum because its flash point is 120° C (higher than diesel). However, in a serious fire, both fuels would burn. An ammonia fire would offer the additional challenge of freezing water due to the cryogenic nature of the fuel. Current fire suppression systems are water-based to ensure that people in spaces fighting the fire are not suffocated. This decision would need to be re-evaluated for ammonia.

Ammonia offers unique risks in the defense field. Both firefighting and pipe ruptures require different damage control systems. More research on shipboard risk management would be required before implementation since commercial strategies do not align with a warship's mission. This makes the current state of ammonia unfeasible.

6.2 Environmental

Similar to ammonia safety, the environmental impact should not exceed that of fossil fuels. The possible environmental effects of ammonia include: leaks and spills, carbon emissions from generation, and NOx from combustion.

Ammonia, like all chemicals, can have an impact on the environment. A comprehensive review of the effect of ammonia concentration on Canadian fish showed the damaging effect of elevated ammonia levels [138]. However, the ecological concern also applies to fossil fuels. After the BP Deepwater Horizons oil spill, 4768 dead animals were recovered, and of the 346 projects that started to help with environmental recovery, 28 have been completed since 2010, and the rest are still ongoing [139]. The Deepwater Horizons was just one of many disasters that have taken place in the oil and gas industry. Other big accidents include the Exxon Valdez spill, the Amoco Cadiz Spill, and the Persian Gulf War Oil Spill all of which led to similar devastation. There are no comparable examples like this with ammonia, even though it is a widely used chemical. A report by the Environmental Defense fund supports this conclusion, citing a negligent effect on fauna, a short, but large, impact on fish in the vicinity of a spill, and a limited effect on flora [140].

The leakage of ammonia tanks into groundwater is another concern, but one that already has solutions. Ammonia contamination is commonly seen in leaking landfills or near farms. To combat this problem, water treatment plants already use electrodes to treat water [141].

The carbon emissions associated with ammonia generation exist because it is currently generated using fossil fuels and is energy-intensive to produce. This places ammonia generation as one of the largest carbon dioxide emitters [23]. Although this is a concern, solutions exist in electrification, and the industry is in the process of transformation. A report assembled in 2021 found that 9 green ammonia plants were under construction or finished [142].

Combustion troubles were briefly mentioned in Section 2.2.1. The effect of NOx on the environment is mainly acid rain and poor air quality [143]. This concern is mitigated with different catalysts in exhaust scrubbers [52]. However, the concern about NOx is particularly relevant for US naval vessels due to the large amount of space scrubbers require. Imhoff et al. suggested that for a destroyer in the US Navy, a total of 2.5 tonnes of catalyst would be required [19].

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[2] On board submarines there are respirator closets in every compartment and an isolated clean air system. Each respirator has a hood and gloves to ensure that the skin is not showing. This equipment would provide safety in the event of an ammonia leak and allow a sailor to patch a pipe.

In summary, beyond the space concerns for scrubbers, ammonia is already more environmentally feasible than oil.

6.2.1 Note: The Navy's Perspective on the Environment

The Navy does not think of carbon or the natural environment as a constraint. Therefore, the emissions from burning fuel, or damage to the natural habitat, are a lower priority. The operation-first, environment-second mentality is clearly seen in a report from the Environmental Protection Agency (EPA) that discusses the practice of discharging contaminated ballast water by the Navy. In the report, the conclusion is explicit in stating the environmental harm. Regardless of the statement, the Department of Defense in the 1992 National Defense Authorization Act received an amendment to the EPA standards to allow the Navy to continue the process to this day [144]. Another example of this prevailing mentality is the DoD's continued use of burn pits to dispose of toxic materials. The burning of trash in open spaces is obviously not the most sustainable activity, and the practice was banned by the EPA in the 1980s and a waiver was again obtained by the military [145]. However, burn pits continue to be used in contemporary conflicts in the Middle East, where hundreds of thousands have received disability benefits from the fumes [146]. Given the current attitude toward environmental concerns, it is unlikely that the Navy will change course unless some external pressure is placed on them.

6.3 Social

The social feasibility of ammonia only matters if the public cares about the fuel that the navy uses and has the power to change its course. To establish that the public does not care about naval fuel use, a small selection (100 Relevant articles) of the New York Times (NYT) was scraped using the search term "Navy" to show that there is limited interest. The second question is addressed with a historical case that shows the impact people can have on the system.

The preliminary web scraping was done to gauge sentiment. Of the 100 most relavent articles published in the NYT since the year 2000 the words oil and fuel are mentioned 17 and 9 times, respectively. Meanwhile, the word SEALs and Chief Gallagher appear over 200 times.[3] A word map of the most common phrases is shown in Figure 6.1. This search shows that the public is more interested in war crimes and killing terrorists than they are in the Navy's fuel use.

If this sentiment were to shift, it is important to show that the public can have an impact on Naval Strategy. To show this, a case study is presented from the pre-World War One era. Some of the historical context in the case study is based on a history of the US Navy Fuel strategy from 1898-1925 by John Maurer [147].

In the years before world war one, President Roosevelt had goals to make the Caribbean the "American Mediterranean," goals that he formally reiterated in the Roosevelt Corollary to the Monroe Doctrine.[4] This contrasts the relationship Roosevelt had with Japan. Teddy Roosevelt's "Gentleman's Agreement" in 1907 with Japan was a mutual agreement to limit immigration and stay on peaceful terms; it was an agreement built on mutual trust and respect. Meanwhile Roosevelt was building a Great White Fleet to show Europe the strength of America. Roosevelt's desire to combat Europe however was foiled by a

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[3] Since 2000 the SEALs have been responsible for killing Bin Laden, and some have written bestselling books that became block buster movies. Additionally, the SEALs were also the center of several scandals, including President Trump involving himself in the case of Chief Gallagher, a SEAL accused of War Crimes.

[4] The Monroe Doctrine, named after President James Monroe, stated the US policy that the Western Hemisphere should be free of European colonialism.

Figure 6.1: Word Map of 100 Most Relevant NYT Articles Since 2000 with the Search Query: "Navy"

series of racist laws passed in California and a subsequently hostile response from Japan. This forced Roosevelt and his naval planners to spread resources across both the Pacific and the Atlantic. Something that did not align with the best strategy.

This example shows that a populist movement changed naval strategy. The president and his strategists rightly believed that the greatest threat to America was Germany or Britain. At the time these two nations represented the strongest and most capable navies in the world, and both were interfering with the US completion of the Panama Canal and establishing fueling stations in the Caribbean. If the Germans had been successful in either front WWI may have looked very different, or if US control over the Panama Canal (a critical shipping channel controlled by the US until the Carter administration) was lost to the British, the US may not have risen to power so meteorically. Regardless of the strategic sense, xenophobia towards Japan led the navy to deploy ships to the Pacific Ocean. In spite of friendly politics evidenced in the "Gentleman's Agreement," Roosevelt was forced to use the navy in a way that appeased the American people.

If the past is any indication, all that is required is enough public sentiment in America to decarbonize the fleet or to switch to ammonia. For example, if California threatened to expel the US base in San Diego (highly unlikely) or if an ally barred US ships from entering the port if they burned fossil fuels (more likely), then these social effects could make ammonia-fueled naval vessels more of a possibility. Ammonia provides certain challenges, just like operating a two-ocean Navy as planners at the turn of the last century were forced to do, but with the right political and social pressures it could become feasible.

6.4 Conclusions

This chapter looked at three broad topics: safety, environmental, and social. Through an applied literature review and webscraping the following conclusions were reached:

- Ammonia fuel is likely safer on a naval base than in other ports.
- The risk of ammonia accidents is already low (<1 every ten years vs oil's 6 per year).
- Ammonia casualties would require different tools than diesel casualties.
- Environmental challenges come with well understood and long standing solutions.
- The Navy does not prioritize environmental standards.
- The public is more interested in Navy SEALs than Naval Fuel Use (by a factor of $\sim$10).
- Examples exist of the Navy changing policy in response to social pressure.

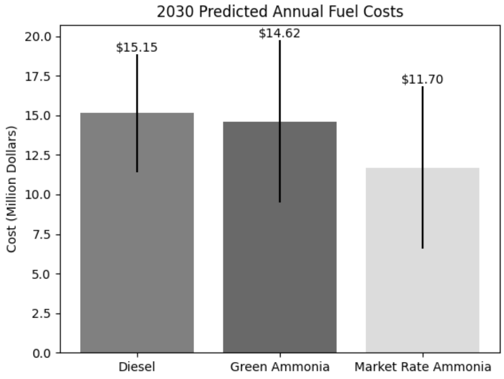
7 | Techno-economic Analysis

This chapter begins with fuel costs, discusses capital investment, and concludes with a comparison of the total cost of ownership. The analysis is done in 2023 dollars and uses predicted prices in 2030 based on the cited sources.

7.1 Production, Storage and Use

Production, storage and annual usage is explored in the following section. In Figure 7.1 the annual cost of green ammonia for a single ship is compared [148, 149]. On a per-ton basis, ammonia is predicted to be cheaper than diesel. This cost savings accounts for the increased fuel use. To calculate this increase, a scaled value was used based on an efficiency of 60% for the diesel plant and 57.4% for the ammonia powered plant. The difference comes from losses as a result of cracking of the fuel. The fuel usage factor also takes into account the energy densities to ensure that the fuels are compared fairly on a ton-to-ton basis. In general, the annual fuel consumption of the ammonia power system is 2.4 times the fuel required on a mass bases. On average savings of about 0.5-3 million dollars (per ship per year) can be expected if ammonia fuel is used.

However, this analysis does not account for more frequent at sea replenishment. This information was not included because the only available data is from a small data set that was highly inconsistent. Other researchers showed that no statistical trends could be derived from the data set [150]. Another challenge with this analysis is the difficulty in predicting future fuel costs. The error bars for the estimates are around 60% of the costs due to the unknown cost of fuels and electricity in the future. Despite these challenges, ammonia is on average expected to be cheaper than diesel.



Fuel Production		
	Cost ($/ton)	Source
Diesel	1477	[149]
Green Ammonia	590	[148]
2023 Market Methods	472	[148]
Annual Usage		
	Tons	Source
Diesel	10256	[13]
Ammonia	24784	Calculated

Figure 7.1: Fuel Production Costs

7.2 Capital Costs

Beyond fuel there is variation in the prime movers required. Generally, the capital costs for these systems are predicted to be the same in the literature [148]. However, some additional technologies are required to burn ammonia. These technologies include fuel crackers and exhaust scrubbers. The cost of the gearbox is also considered, as ICE engines do not require gearboxes, but fuel cells and GTs do. Ammonia fueled ships are also expected to be at least 2.5 tones larger to accommodate additional components [19]. The Congressional Budget Office estimates that a warship costs 1.23 million USD per ton [151] and this cost is accounted for in the analysis. The final comparison of capital costs is presented in Figure 7.2. These values are calculated using mid-range estimates from the literature and an interest in the 3% annuity, and equation 7.1 to determine annual capital costs over an anticipated 30-year lifetime. Here P is the initial cost, i is the interest, and t is the lifetime of the equipment.

$$C = \frac{P * i}{1 - \frac{1}{(1+i)^t}} \tag{7.1}$$

Diesel technologies are predicted to be only slightly more competitive due to the absence of crackers, post-processing, and larger ship size. For ICEs the cost savings in a diesel powertrain are estimated to be 18%, while the savings for a GTs are slightly lower at 16%. Fuel cells are not remotely competitive with established options; this is reflected in the literature [148, 95]. The added capital costs are 600,000 USD per year, a very small amount (∼1% over the lifetime for a 1.8 billion dollar destroyer) compared to the total ship cost.

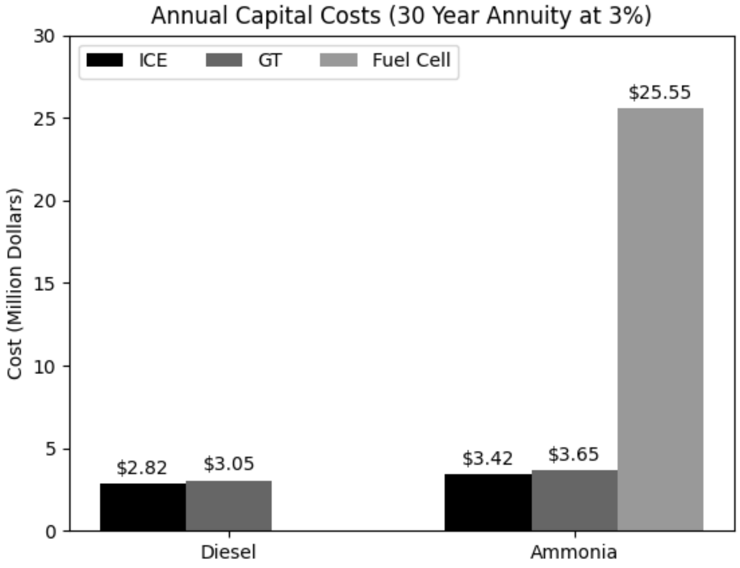


Figure 7.2: Annualized Capital Costs at Predicted 2030 Levels

7.3 Conclusions on Total Cost of Ownership

The analysis presented above shows that there is relatively little variation in the capital costs of these technologies, with the exception of fuel cells, which require further research before they are economically competitive. This means that the fuel price will largely drive the economic feasibility of ammonia-powered warships.

The limitations in this analysis surround the added logistic cost of more frequent refueling at sea. The lack of substantial data sets on tanker activity and inconsistent cost assessments in the literature make costing these events difficult [150].

In summary, the difference in capital costs is marginal (600,000 USD per year), meaning that future fuel costs will determine the economic competitiveness of ammonia powered warships.

8 | Conclusions

This report sought to answer the general question: Can ammonia be used as fuel aboard warships? To answer this question a whole systems approach was taken and the report sought to answer the following questions:

Table 8.1: Summary of Conclusions

Question	**Answer**
Is fuel accessible for warships?	Fuel is regionally available. In the Continental US it is not, but in the Middle East and the Indian Ocean there are sufficient fuel supplies.
Can fuel be transferred between ships?	Technically this is possible, but it would require conversion of tankers.
What happens to the fuel in the fuel tank?	Fuel sustains itself below use requirements and would require additional equipment to reach the required flow rate.
Are ammonia powertrains available?	Yes. Small (<10 MW) ships being built now with completion expected by 2025. DoD will require at least 2 years of commercial application at higher power capacity.
Is it possible for sailors to learn to use ammonia?	Yes. Examples of new skill transfer exists with robotics, AM and physical training.
How safe is ammonia under standard operating procedures?	Safer than fossil fuels (<1 accident every ten years vs oil's 6 accidents per year).
How safe is ammonia in the event of a casualty?	Manageable but would require different damage control methods.
Is the release of ammonia into the environment a greater challenge than an oil spill?	Ammonia has well known abatement methods, and has a short term effect on an ecosystem.
Does the US Navy follow environmental standards?	No, waivers exist for dumping fuel oil into the ocean and burn pits.
Does the citizenry of the US have the power to influence naval policy ?	Yes, they have done so under president Roosevelt, but do not have interest in the fuel discussion.
Is ammonia cost competitive?	Marginally higher capital costs (600,000 USD per year) therefore cost competitiveness is reliant on future fuel cost.

With all of these conclusions in mind, it is clear that ammonia is technically feasible but not strategically likely due to the lack of pressure to change.

8.1 Recommendations for Future Work

Future work should model sloshing in the fuel tanks, analyze the effectiveness of new ammonia powertrains, develop methods of fighting ship board ammonia fires, and further assess public opinion regarding naval fuel use.

There is also much lower hanging fruit that can be targeted before surface combatants are redesigned. Heating and cooling of the DoD's buildings alone require monumental amounts of energy (3.5 billion dollars worth) the pentagon alone emitted 24,650 metric tons of CO_2 in 2013 [1]. Regardless, work in both fields will need to continue should the Navy wish to reduce its impact on the environment, lower the number of conflicts, and save lives and dollars in the process.

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A | Ammonia Plant Locations and Sizes

Location	**Output (1000 metric Tons)**	**Lattitude**	**Longitude**	**Source**
Donaldson LA	4335	32.7886	-92.9764	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Port Neal IA	1148	42.4253	-96.5015	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Verdigris OK	1098	36.3059	-95.7136	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Enid OK	1016	36.3956	-97.8784	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Wever IA	914	40.6995	-91.1559	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Waggaman LA	800	29.9314	-90.2405	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Augusta GA	765	33.4735	-82.0105	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Freeport TX	726	28.9544	-95.3561	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Lima OH	725	40.7426	-84.1052	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Hopewell VA	535	37.3043	-77.2872	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Yazoo City MS	513	32.8554	-90.4052	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Faustine LA	508	29.8895	-90.3744	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Borger TX	450	35.6677	-101.3959	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
El Dorado AK	447	33.2077	-92.6666	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Wodward OK	435	36.4337	-99.3904	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Coffeyville KS	425	37.0373	-95.6175	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Belulah ND	365	47.1806	-101.7828	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
E. Dubuque IL	350	42.4976	-90.6336	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Beaumont TX	331	30.0802	-94.1266	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Fort Dodge IA	300	42.4975	-94.168	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Dodge City KS	280	37.7529	-100.0171	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Beatrice NE	248	40.2687	-96.7461	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Pryor OK	223	36.3061	-95.3165	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Rock Spring WY	210	41.5875	-109.2029	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Cheyenne WY	173	41.1399	-104.8202	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Cherokee AL	171	34.7526	-87.9723	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
St Helens OR	100	45.8572	-122.8044	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Geneva NE	91	40.5272	-97.6077	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Creston IA	32	41.0534	-94.3636	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Gordon GA	30	32.9455	-83.3247	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
El Secundo CA	24	33.9192	-118.4165	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/
Medicine Hat Alberta	1230	50.0379	-110.6767	https://www.cfindustries.com/what-we-do/ammonia-production
Billingham UK	590	54.6132	-1.2726	https://www.cfindustries.com/what-we-do/ammonia-production
Courtright Ontario	480	42.8183	-82.3953	https://www.cfindustries.com/what-we-do/ammonia-production
Point Lisas Trinidad	360	10.3874	-61.4486	https://www.cfindustries.com/what-we-do/ammonia-production
Kwinana	255	-32.2389	115.7644	https://csbp.com.au/products/ammonia/
Nevinnomyssk	100	44.6339	41.9445	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:62021TJ0126
Kingisepp	1000	59.3671	28.6136	https://www.dentons.com/en/about-dentons/news-events-and-awards/news/2021/july/dentons-advises-eurochem
Cherkasy	963	49.4285	32.0621	http://ostchem.com/en/o-kompanii/proizvodstvo/azot
Horlivka	1470	48.3136	38.0176	http://www.ostchem.com/en/o-kompanii/proizvodstvo/stirol
Severodonetsk	1020	48.9475	38.4904	http://www.ostchem.com/en/o-kompanii/proizvodstvo/sever
Rivne	420	50.6199	26.2516	http://www.ostchem.com/en/o-kompanii/proizvodstvo/rovno
Estonia	180	58.5953	25.0136	http://www.ostchem.com/en/o-kompanii/proizvodstvo/nitrofert
Vadodara	1450	22.3072	73.1812	https://www.gsfclimited.com/vadodara-unit
Uttar Pradesh	1000	26.8467	80.9462	https://www.tatachemicals.com/News-room/Articles/Babrala,-northern-exposure
Arzew Industrial Zone	1629	35.8482	-0.3193	https://fertiglobe.com/wp-content/uploads/2022/03/Fertiglobe-AR-2021-vF.pdf
Ain Al Sokhna	1624	29.5965	32.4906	https://fertiglobe.com/wp-content/uploads/2022/03/Fertiglobe-AR-2021-vF.pdf
Ruwais	1205	24.0955	52.6476	https://fertiglobe.com/wp-content/uploads/2022/03/Fertiglobe-AR-2021-vF.pdf
Togliatti	3000	53.5078	49.4204	https://www.toaz.ru/en/about-the-company
Kota Palembang	1800	-2.9888	104.7567	https://www.iamm.green/ammonia-producing-companies/
Mesaieed Industrial Area	3800	24.9591	51.614	https://www.iamm.green/ammonia-producing-companies/
Jubail	3400	27.006	49.6625	https://www.iamm.green/ammonia-producing-companies/
Porsgrunn	500	59.135	9.6648	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Buettel Germany	839	53.9194	9.4723	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Regina Canada	678	50.4452	-104.6189	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Pilbara	800	-21.4422	118.1673	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Cartegna	100	10.391	-75.4794	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Ferrara Italy	600	44.8345	11.618	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Hull	300	53.7457	-0.3367	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Sluiskill	1900	51.2753	3.8324	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Lifeco	200	29.8328	31.7071	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Tertre	400	50.4605	3.7954	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Belle Plaine	700	37.619	-97.2814	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Babrala	700	28.4442	78.0211	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Cubatao	200	-23.8986	-46.4246	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Le Havre	400	49.4944	0.1079	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Trinidad and Tobago	500	10.6918	-61.2225	https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/
Yunnan, China	605	25.0389	102.7183	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-8
Hainan Island	985	19.5664	109.9497	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-9
Inner Mongolia, China	594	43.556	116.6709	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-10
Fuling China	547	29.7022	107.3874	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-11
Bontang Indonesia	985	0.1333	117.5	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-12
Mary Turkmenistan	438	37.5925	61.8309	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-13
Palembang Indonesia	730	-2.9909	104.7569	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-14
Burrup Peninsula Australia	800	-20.7282	116.8585	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-15
Cikampek Indonesia	365	-6.3932	107.4556	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-16
Moron Venezuela	657	10.4816	-68.1971	https://www.kbr.com/en/experience#group=kbr-projects-group&markets-filter=3&solutions-filter=0&locations-filter=1&status-filter=0&paginationprojects=2-17
Mishor Rotem	100	31.2015	35.4562	https://www.haifa-group.com/news/haifa-group-and-saipem-signed-contract-building-ammonia-plant-israel
Baotou	390	40.6522	109.8223	https://www.chemanager-online.com/en/news/topsoe-wins-china-green-ammonia-project

B | Fuel Tank Code

```python
# Analytical solutions for the isobaric evaporation of pure cryogens in storage tanks

# Largely Influenced by Felipe Huerta and Velisa Vesovic
# Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK

# James Potticay Contributions: Incorporated Coolprops, changed the fuel tank parameters,
# and changed the heat transfer coefficients (see appendix C)


# Import relevant packages
import numpy as np
import matplotlib.pyplot as plt
import copy # Copy constructor
import CoolProp.CoolProp as cp


## Storage tank class
# The storage tank class contains information on the geometrical and thermal properties of a vertical cylindrical storage tank

class Tank:
    """ Class to be used as a container for the
    evaporation of pure cryogens"""
    def __init__(self, d_i, d_o, V):
        """ Class constructor """
        # Compulsory parameters
        self.d_i = d_i # [m] Tank internal diameter
        self.d_o = d_o # [m] Tank external diameter
        self.V = V     # [m^3] Tank volume
        self.A_T = np.pi*d_i**2/4 # [m^2] Area of the surface
        # perpendicular to the vertical axis
        self.l = V/self.A_T # [m] Tank height
        self.roof_BC = ’Robin’ # Roof Temperature boundary condition,
        # "Neumann" or "Robin"
        self.thermophysical_it =  True # Thermophysical iteration
        # switch for the non-eq model
        pass

    def set_HeatTransProps(self, U_L, U_V, Q_b, Q_roof, T_air):
        """Set separately tank heat transfer properties
        Usage: set_HeatTransProps(self, U_L, U_V, Q_b, Q_roof, T_air)"""
        self.U_L = U_L # [W*m^-2*K^-1]Overall heat transfer coefficient
        # for the liquid phase stored in the tank
        self.U_V = U_V # [W*m^-2*K^-1] Overall heat transfer coefficient
        # for the vapour phase stored in the tank
        self.Q_b = Q_b # [W] Heat ingress through the bottom / W
        self.Q_roof = Q_roof # [W] Heat ingress through the roof
        self.T_air = T_air # [K] Temperature of the surrounding air /K
        pass

    def set_LF(self, LF):
        """Update liquid filling and vapour length"""
        self.LF = LF # [-] set tank liquid filling
        self.l_V = self.l * (1-LF) # [m] sets vapour length
        pass
```

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    def set_advective_v(self):
        """Update advective velocity with respect to tank liquid filling"""
        # Area of the tank walls in contact with the liquid phase
        A_L = np.pi * self.d_o * self.l * self.LF
        # Initial wall heat ingress
        Q_L0 = self.U_V * A_L * (self.T_air-self.cryogen.T_sat)
        # Initial evaporation rate mol/s
        BL_0 = (Q_L0 + self.Q_b)/((self.cryogen.h_V-self.cryogen.h_L))
        self.v_z = 4*BL_0/(self.cryogen.rho_V*np.pi*self.d_i**2)
        pass
class Cryogen:
    """ Class which contains a cryogen thermodynamic
    and thermophysical properties """
    def __init__(self, name, P, T_sat, rho_L, rho_V, h_L, h_V, k_V, cp_V):
        """Constructor"""
        self.name = name
        self.P = P # Pressure / Pa
        self.T_sat = T_sat # Saturation temperature / K
        self.rho_L = rho_L # Liquid Density / mol*m^-3
        self.rho_V = rho_V # Vapour density / mol*m^-3
        self.rho_V_sat = rho_V # Initialize vapour density at the interface
        self.h_L = h_L # Liquid enthalpy J/mol
        self.h_V = h_V # Vapour enthalpy J/mol
        self.k_V = k_V # Thermal conductivity of the vapour W/mK
        self.k_int = k_V # Thermal conductivity at the vapour-liquid interface
        self.cp_V = cp_V # Heat capacity at constant pressure / J/molK

def equilibrium_sols(tank):
    """Calculates coefficients C and D in the analytical solution

    Return values:    C, D, V_L0    """
    C = -4*tank.d_o/tank.d_i**2 * \
    (tank.T_air - tank.cryogen.T_sat) / \
    (tank.cryogen.rho_L*(tank.cryogen.h_V - tank.cryogen.h_L)) * \
    (tank.U_L - tank.U_V)

    D = -1 /(tank.cryogen.rho_L*(tank.cryogen.h_V - tank.cryogen.h_L)) * \
    ( 4*tank.d_o/tank.d_i**2 * (tank.T_air - tank.cryogen.T_sat) * \
    tank.U_V * tank.V + tank.Q_b )

    V_L0 = tank.V*tank.LF

    return C, D, V_L0

def V_L(t, C, D, V_L0):
    """Analytical solution for the liquid volume"""
    if (C != 0):
        V_L = D/C * ( np.exp(C*t)-1 ) + V_L0*np.exp(C*t)
    else:
        V_L = D*t + V_L0
    return V_L

# We can also define the BOG rate
def BOG(t, cryogen, C, D, V_L0):
    """BOG"""
    return (cryogen.rho_V - cryogen.rho_L) * ( C*V_L(t, C,D,V_L0) + D)

```

```
def tau_evap(C,D,V_L0):
    """tau_evap(C,D,V_L0) estimates the evaporation time"""
    if C != 0:
        tau_evap = -1/C * np.log (1 + V_L0 * C/D)
    else:
        tau_evap = - V_L0/D
    return tau_evap

# Cryogen thermophysical properties obtained from DOI: 10.1063/1.555579

# Ammonia at 1 Bar

k_V = .02096   #  W/(mK)
k_V_roof = k_V # Assume k_V_roof = k_V
rho_V = 51.59664 # mol/m^3
rho_L = 40041.64331  # mol/m^3
cp_V = 38.0217    # J/molK
T_L = 239.55     # /K
h_V = 7757.96   # J/mol
h_L = -15580.64  # J/mol
P = 101000        # Pa

ammonia = Cryogen("ammonia", P, T_L, rho_L, rho_V, h_L, h_V, k_V, cp_V)

# PDE coefficients
def analytical_T_neq(tank):
    """ Calculates the parameters for the vapour temperature
    profile & vapour to liquid heat transfer rate

    Return values:
    chi_minus, chi_plus, c_1, c_2
    """

    name_BC = tank.roof_BC
    cryo = tank.cryogen
    H = cryo.rho_V*cryo.cp_V*tank.v_z
    S = 4*tank.U_V*tank.d_o/tank.d_i**2
    E = S*tank.T_air
    # Temperature gradient at the tank roof, if defined
    try:
        gradT_roof = tank.Q_roof/(tank.k_V_roof*tank.A_T)
    except:
        gradT_roof = tank.Q_roof/(cryo.k_V*tank.A_T)
    # Chi plus minus
    chi_plus = (H + np.sqrt(H**2+4*cryo.k_V*S))/(2*cryo.k_V)
    chi_minus = (H - np.sqrt(H**2+4*cryo.k_V*S))/(2*cryo.k_V)

    b_plus = np.exp(tank.l_V*chi_plus)
    b_minus = np.exp(tank.l_V*chi_minus)

    a_plus = chi_plus*b_plus
    a_minus = chi_minus*b_minus

    if(name_BC == "Neumann"):
        c_1 = (a_plus*(cryo.T_sat-tank.T_air) - gradT_roof)/(a_plus-a_minus)
        c_2 = (a_minus*(tank.T_air-cryo.T_sat) + gradT_roof)/(a_plus-a_minus)
    elif (name_BC == "Robin"):
        try:
```

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            gamma = U_roof / k_V_roof
        except:
            gamma = tank.U_V / k_V_roof
        c_1 = (cryo.T_sat-tank.T_air)*(a_plus + gamma*b_plus)/ \
        ( (a_plus+gamma*b_plus)-(a_minus + gamma*b_minus))
        c_2 = (tank.T_air-cryo.T_sat)*(a_minus + gamma*b_minus) /\
        ((a_plus + gamma*b_plus) - (a_minus + gamma*b_minus))
    else:
        raise Exception("Unsupported BC, use Neumann or Robin")
    return chi_minus, chi_plus, c_1, c_2

def T_V(z, c_1, c_2, chi_minus, chi_plus, T_air):
    """Outputs the vapour temperature profile.
    z must be a length vector with 0 < z < l_V.
    The coefficients of the vapour T profile are also inputs"""
    TV = c_1*np.exp(z*chi_minus) + c_2 * np.exp(z*chi_plus) + T_air
    return TV

def Q_VL(tank):
    """Calculates the vapour to liquid heat ingress"""
    chi_minus, chi_plus, c_1, c_2 = analytical_T_neq(tank)
    Q = np.pi * tank.d_i **2/4 * tank.cryogen.k_int * (c_1*chi_minus + c_2*chi_plus)
    return Q

def Tv_avg(tank):
    """Calculates the average vapour temperature
    for the non-equilibrium model"""
    chi_minus, chi_plus, c_1, c_2 = analytical_T_neq(tank)
    Tv_avg = tank.T_air + 1/tank.l_V * \
    (c_1/chi_minus * (np.exp(tank.l_V*chi_minus)-1) + \
     c_2/chi_plus * (np.exp(tank.l_V*chi_plus)-1))
    return Tv_avg

def analytical_neq(tank):
    """Calculates C_neq and D_neq coefficients"""
    C_neq = -4*tank.d_o/tank.d_i**2 * \
    (tank.T_air - tank.cryogen.T_sat) / \
    (tank.cryogen.rho_L * (tank.cryogen.h_V - tank.cryogen.h_L))* \
    tank.U_L

    D_neq = - (tank.Q_b + tank.Q_VL)/\
    (tank.cryogen.rho_L * (tank.cryogen.h_V - tank.cryogen.h_L))
    return C_neq, D_neq

def Tv_plot(tank):
    """Function to plot vapour temperature profile"""
    zspan = np.linspace(0,tank.l_V,100)
    chi_minus, chi_plus, c_1, c_2 = analytical_T_neq(tank)
    plt.plot(zspan, T_V(zspan, c_1=c_1, c_2=c_2, chi_minus=chi_minus, \
                        chi_plus = chi_plus, T_air = tank.T_air), ’r’)
    plt.xlabel("Height")
    plt.ylabel("Vapour Temperature")



# Actual Tank: Destroyer
# Tank properties
```

```
d_i = 15 # [m]
d_o = 15.05 # [m]
V_tank = 260 # [m^3]
LF = 0.97
T_air = 292.15 # [K]
U_V = 2.1959 # W/[m^2*K]
Q_roof = 0 # [W]
Q_b =  11051 # [W], heat ingress from the bottom (Area of bottom* Uv* (Tair-TL))

des_tank = Tank(d_i, d_o, V_tank)
des_tank.set_HeatTransProps(U_V, U_V, Q_b, Q_roof, T_air)
des_tank.set_LF(LF)
des_tank.cryogen = ammonia
des_tank.set_advective_v()
des_tank.Q_VL = 0
des_tank.roof_BC = "Robin"

# Build the analytical solutions
C, D, V_L0 = equilibrium_sols(des_tank)
# Tv_plot(des_tank)
def direct(tank, timespan):
    C_neq, D_neq = analytical_neq(tank)
    my_tank = copy.deepcopy(tank)
    V_L_direct = V_L(timespan, C=C_neq, D=D_neq, V_L0 = my_tank.V*my_tank.LF)
    BOG_direct = BOG(timespan, ammonia, C=C_neq, D=D_neq, V_L0 = my_tank.V*my_tank.LF)
    Q_VL_direct = np.zeros(len(V_L_direct))
    for i in range(0,len(V_L_direct),1):
        my_tank.set_LF(V_L_direct[i]/my_tank.V)
        # Get the temperature profile
        chi_minus, chi_plus, c_1r, c_2r = analytical_T_neq(my_tank)
        # Update Q_VL
        my_tank.Q_VL = Q_VL(my_tank)
        Q_VL_direct[i] = my_tank.Q_VL
        my_tank.set_advective_v()
        # Update advective velocity

    return V_L_direct, Q_VL_direct, BOG_direct

def k_V(T, cryogen_name):
    k_V=cp.PropsSI("L","T",T,"P",101300, cryogen_name) # W*m^-1*K^-1
    return k_V

def rho_V(T, cryogen_name):
    rho_V = cp.PropsSI("Dmolar","T",T,"P",101300, cryogen_name) # mol*m^-3
    return rho_V

def cp_V(T, cryogen_name):
    """ Vapour specific heat capacity in J/[mol*K] """
    cp_V = cp.PropsSI("Cpmolar","T",T,"P",101300, cryogen_name)
    return cp_V

def thermophysprops(T,cryogen_name):
    return k_V(T,cryogen_name), rho_V(T, cryogen_name), cp_V(T, cryogen_name)

def thermophysical_iteration(tank):
    """Update k_V, rho_V and cp_V
    for a given liquid filling"""
```

```
    # Initialise old vapour temperature
    T_old = 0
    T_new = Tv_avg(tank)
    while abs(T_old-T_new) > 1e-2:
        T_old = T_new
        # Unpack thermophysical properties
        k, rho, cp = thermophysprops(T_old, tank.cryogen.name)
        # Update thermophysical properties
        tank.cryogen.k_V = k
        tank.cryogen.rho_V = rho
        tank.cryogen.cp_V = cp
        T_new = Tv_avg(tank)

def sequential_proc(tank, delta_t = 3600*24*7):
    """ Default timestep delta_t is a week
    delta_t must be in seconds

    Returns

    timespan: np.array, timestamps
    V_L_analytical: np.array, liquid volume
    Q_VL_analytical: np.array, vapour to liquid heat ingress
    T_V_analytical: np.array of i*j dimensions.
    T_V_analytical[i,j] corresponds to the
    temperature profile of the j node in the vapour
    at timespan[i], while     T_V_analytical[i,:]
    is the whole vapour temperature profile at timespan[i]
    """
    # Initialize Q_VL for the tank
    tank.set_advective_v()
    tank.Q_VL = Q_VL(tank)

    # Obtain C and D
    C_neq, D_neq = analytical_neq(tank)

    # Estimate evaporation time
    tau_neq = tau_evap(C_neq,D_neq,tank.V*tank.LF)

    # get n_timesteps approximating to
    # the highest nearest integer
    n_t = int(np.floor(tau_neq/(delta_t)))
    timespan = np.linspace(0,tau_neq,n_t)

    # Initialize V_L and Q_VL
    V_L_analytical = np.zeros(n_t)
    Q_VL_analytical = np.zeros(n_t)
    BOG_analytical=np.zeros(n_t)

    V_L_analytical[0] = tank.V*tank.LF
    Q_VL_analytical[0] = tank.Q_VL


    LF = copy.deepcopy(tank.LF)
    my_tank = copy.deepcopy(tank)

    # Initialize vapour temperature
    n_z = 100 # Number of nodes in the vapour domain
    T_V_analytical = np.zeros([n_t, n_z])
```

```
    chi_minus, chi_plus, c_1, c_2 = analytical_T_neq(my_tank)
    z = np.linspace(0,my_tank.l_V,n_z)
    T_V_analytical[0,:] = T_V(z, c_1, c_2, chi_minus, chi_plus, T_air)


    for i in range(1, n_t,1):
        # Get V_L at t_0 + delta_t
        V_L_analytical[i] = V_L(delta_t, C=C_neq, D=D_neq,\
                                V_L0 = my_tank.V*my_tank.LF)
        # Update the liquid filling
        my_tank.set_LF(V_L_analytical[i]/my_tank.V)
        my_tank.set_advective_v()
        # If activated, update thermophysical properties
        if tank.thermophysical_it == True:
            thermophysical_iteration(my_tank)
        # Get the temperature profile for each time step
        chi_minus, chi_plus, c_1, c_2 = analytical_T_neq(my_tank)
        z = np.linspace(0,my_tank.l_V,n_z)
        T_V_analytical[i,:] = T_V(z, c_1, c_2, chi_minus, chi_plus, T_air)
        # Update Q_VL
        my_tank.Q_VL = Q_VL(my_tank)
        Q_VL_analytical[i] = my_tank.Q_VL
        BOG_analytical[i]=BOG(delta_t, ammonia, C=C_neq, D=D_neq, V_L0= my_tank.V*
   my_tank.LF)
        # Update C_neq, D_neq
        C_neq, D_neq = analytical_neq(my_tank)
    return timespan, V_L_analytical, Q_VL_analytical, T_V_analytical,
   BOG_analytical

# We can set on or off the update of thermophysical properties

# Set Q_VL at the initial liquid filling
des_tank.Q_VL = Q_VL(des_tank)
C_neq, D_neq = analytical_neq(des_tank)

# Thermophysical iteration and sequential procedure
des_tank.thermophysical_it = True
timespan, V_L_analytical, Q_VL_analytical, T_V_analytical, BOG_analytical = \
sequential_proc(des_tank, delta_t = 3600*24*7)

# Sequential procedure only
des_tank.thermophysical_it = False
timespan, V_L_analytical_s, Q_VL_analytical_s, T_V_analytical_s, BOG_analytical =
   \
sequential_proc(des_tank, delta_t = 3600*24*7)

# Direct calculation
V_L_direct, Q_VL_direct, BOG_direct = direct(des_tank, timespan)

plt.style.use(’grayscale’)
fig, ax= plt.subplots()
ax.plot(timespan/(3600*24*7), V_L_analytical)
ax.set (xlabel=’Time (weeks)’, ylabel=’Tank Volume ($m^3$)’,
        title=’Tank Volume Over Time’)

plt.show()
```

C | Heat Transfer Coefficients

```
    g=9.81 #m/s^2
def rayleigh(Pr,L,beta,v,dT):
    Ra=Pr*g*beta*dT*L**3/v**2
    return Ra
def nuesselt_wall(Ra,Pr):
    Nu=.0825+((.387*Ra)/(1+(.492/Pr)**(9/16))**(8/27))
    return Nu
def nuesselt_top_bottom(Ra):
    Nut=.52*Ra**(1/5)
    Nub= .15*Ra**(1/3)
    return Nut, Nub
def h(Nu,L,k):
    h=Nu*k/L
    return h


Ls=1.4 #m
Ltb=(3.14*15**2/4)/(3.14*15) #m

tsteel=.006 #m
tins=.015   #m

Pr_air=.71
Pr_la= 1.71 # Liquid ammonia
Pr_ga= 0.881 # gaseous ammonia

v_air=0.1516e-6 #m^2/s
v_la= 0.3758e-6 #m^2/s
v_ga= 9.156e-6 #m^2/s

Tair=293.15 # K
Tamm=240 # K

beta_amm=0.00245
beta_air=1/(Tair)

kair=0.02587 #W/mK
kla=0.6666 #W/mK liquid ammonia
kva=0.02096 #W/mK vapor ammonia
kins=0.033  #W/mK
ksteel=14.0 #W/mK

Ra_out_side=rayleigh(Pr_air,Ls,beta_air,v_air,Tair-Tamm)
Ra_out_side_t=rayleigh(Pr_air,Ltb,beta_air,v_air,Tair-Tamm)
Ra_in_side_l=rayleigh(Pr_la,Ls,beta_amm,v_la,Tair-Tamm)
Ra_in_side_v=rayleigh(Pr_ga,Ls,beta_amm,v_ga,Tair-Tamm)

Nu_out_side=nuesselt_wall(Ra_out_side, Pr_air)
Nu_in_side=nuesselt_wall(Ra_in_side_l, Pr_la)
Nu_in_side_g= nuesselt_wall(Ra_in_side_v, Pr_ga)
Nut_ou,Nub_ou=nuesselt_top_bottom(Ra_out_side_t)

ho=h(Nu_out_side,Ls,kair)
hil=h(Nu_in_side,Ls,kla)
hiv=h(Nu_in_side_g,Ls,kva)
ht=h(Nut_ou,Ltb,kair)
```

```
Uls=1/(1/(ho)+2*tsteel/(ksteel)+tins/(kins)+1/(hil))
Uvs=1/(1/(ho)+2*tsteel/(ksteel)+tins/(kins)+1/(hiv))

pd=100*(Uls-Uvs)/Uls
```