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LIQUID NATURAL GAS STORAGE INTEGRATION INTO FUTURE COMBATANTS

by

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June 2023

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**LIQUID NATURAL GAS STORAGE INTEGRATION INTO FUTURE
COMBATANTS**

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ABSTRACT

The goal of this research is to approximate the Defense Acquisition System process for an acquisition category I program through the Milestone A decision to provide a high-level design and determine the impacts of implementing liquid natural gas (LNG) fuel on a baseline combatant ship. The motivation to explore alternative fuels for military application is provided from the 2022 National Security Strategy and other political, economic, and industrial factors to maintain energy security and combat the threat of climate change. An analysis of alternatives is conducted to determine the most viable alternative fuel from the most promising energy transition fuels. LNG is selected based on its alignment with the political, economic, and industrial factors. LNG poses significant design difficulties due to its cryogenic ($-160\text{ }^{\circ}\text{C}$) storage conditions. The primary components of the fuel storage and transfer system are designed based on industry standards using a 1-D heat transfer model to meet a target boil off rate. The impacts to the baseline DDG-51 Flight I ship are modeled using the Parent-Design ship method for estimating surface ship weights. A parametric cost analysis and qualitative survivability analysis are performed. The results of the analysis reveal the baseline ship must increase in length and lightship weight by 22 percent to incorporate LNG as a fuel. The cost to produce the design ship is estimated to be 86 percent greater than the baseline with a lower survivability.

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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	Analysis of Alternatives
BOG	Boil Off Gas
CNO	Chief of Naval Operations
DAS	Defense Acquisition System
DDG	Guided Missile Destroyer
DOD	Department of Defense
EIA	Energy Information Administration
IEA	International Energy Agency
IMO	International Maritime Organization
JCIDS	Joint Capabilities Integration and Development System
LNG	Liquid Natural Gas
LSNG	Liquid Synthetic Natural Gas
NATO	North Atlantic Treaty Organization
NFPA	National Fire Protection Association
NO _x	Nitrogen Oxides
NSS	National Security Strategy
NZE	Net Zero Emissions
OPEC	Organization of the Petroleum Exporting Countries
SO _x	Sulfur Oxides
USN	United States Navy

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I. INTRODUCTION

A. BACKGROUND

As the world and the United States progress further into the 21st century, the transition from fossil fuels to cleaner, renewable energy sources remains at the forefront of the political, socioeconomic, and environmental agendas. Numerous governments, including the United States, and agencies are requiring energy consumers (e.g., industry, household, etc.) to lower and eventually eliminate all carbon-based electrical generation and net-zero carbon emissions from facilities and vehicles with many initial and final completion dates by the years of 2030 and 2050, respectively. The most prominent recent issuance of guidance towards this energy transition is from the International Energy Agency (IEA) [1] to provide major achievable lines of effort worldwide. The United States agrees and has identified climate change and energy security as two major factors in determining the 2022 National Security Strategy (NSS) [2]. The significance of these two factors is explored further with numerous publications by the U.S. government and the DOD on accomplishment plans and risk mitigation including executive orders, the National Defense Strategy (NDS), DOD Climate Risk Analysis, the DOD Climate Adaptation Plan, and the DOD Sustainability Plan. This push currently has no direct requirement to be instituted by military forces, as they are excluded for their role in national security. However, the DOD is striving to have all facilities and non-tactical vehicles meet this goal [3], and the DOD has been developing alternative fuels [4].

Fossil fuels relied upon by the military (gasoline and diesel derivatives) provide a potential key weakness in logistics and defense capability, as seen most recently, in cost alone, with the Russian aggression into Ukraine. Excluding the temporary drop in response to the COVID-19 pandemic, the average price of WTI crude oil nearly doubled from 2019 to 2022 [5]. The price surged as Russia, the world's second largest oil and natural gas producer [6], was placed under economic sanctions from many nations that previously were importers of Russian oil products, drastically affecting the supply. The cost of F-76 fuel for ships is historically about twice the price of WTI crude [7], which resulted in significantly increased prices likely not accounted for in the fiscal budget. The price of

WTI crude oil and therefore F-76 is only expected to increase in the future, potentially reaching as high as \$165 and \$330 per barrel, respectively [8]. If oil consumption remains constant at the average over the seven-year span from FY 14 through FY 20, oil expenditure would increase from an average of \$10.6 billion to the high estimate of \$27.9 billion [4]. Although the U.S. has increased its fossil fuel production to try and be energy independent, the U.S. is a net importer of crude oil and is expected to remain so through 2050 [8]. The U.S. natural gas production is more sustainable than crude oil based on production rate and proven reserves. Following proven reserve and production rate projections, the U.S. has enough dry natural gas to last at least 60 years [9] and enough crude oil to last about 10 years [10].

The 2022 NDS is “one stamped by dramatic changes in geopolitics, technology, economics, and our environment” [11]. As such, the U.S. must secure its energy future to maintain the ability to ensure NSS goals are met when faced with the reality of our resource availability and production. The United States, in conjunction with NATO, has used the “single fuel concept” since 1988 [12] to minimize fuel types for logistical and design simplicity. The concept has been successful in its goal; however, the policy creates unintended consequences on the future force and acquisition as it disincentivizes alternative fuel and related product generation. Although the U.S. oil supply will likely stretch due to the transition towards renewable and cleaner energy sources, it is prudent to explore alternative fuels for military assets.

Despite the incentivization of alternative fuels by the military-industrial complex, the U.S. Navy (USN) has used the Navy Research Laboratory (NRL) to explore alternative fuels and synthetic fuel production. In its efforts, the Navy has produced and used biofuels (developed from algae and animal byproducts) in the Great Green Fleet initiative [13] and developed methods to extract carbon dioxide and hydrogen gas from seawater for hydrocarbon fuel synthesis [14]. The hydrocarbon production from seawater is an exciting technology as seawater covers most of the Earth’s surface and is the vast majority of water. The ability to power the Navy’s ships from its operational areas throughout the world provides the potential for complete energy independence and security.

B. PROBLEM STATEMENT

The USN needs to be energy independent with reliable logistics to continue to meet its primary missions with the future fleet: be capable of winning wars, deterring aggression, and maintaining freedom of the seas. The U.S. is projected to maintain its status as a net importer of crude oil through at least 2050 with dwindling domestic proven reserves [8], which provides inherent risk to the military logistically. Ultimate energy independence and security for the U.S. Navy is contained in the waters it sails. Fortunately, the NRL has developed proven methods to produce potentially net-zero hydrocarbon fuel from seawater [14], such as synthetic natural gas (SNG). In accordance with the high-level strategy documents, the USN needs to continue innovating, modernizing, and building on our strengths to develop capabilities to maintain superior strength and capability. Developing a true energy independence capability capitalizes on every aspect of our current NSS and NDS while taking positive action toward the “greatest and potentially existential” [2] threat to the world.

C. THESIS OBJECTIVES

The line of research contained in this thesis is aimed at developing and determining the feasibility of using LNG and LSNG as an alternate fuel source to power the USN non-nuclear surface fleet via an examination of the DDG class. The feasibility analysis is developed beginning with the high-level economic-socio-political basis starting with the NSS and subsequently filtering down to the engineering analysis level to the final physical system recommendations. The thesis provides recommendations on changes to the DDG class as a baseline to incorporate LNG, specifically, the fuel storage and transfer system and the naval architecture related implications before concluding with a final recommendation on the validity and feasibility of LNG as an alternative fuel source. The primary design process goal is to minimize the impact of the recommended changes to the baseline DDG; specifically, maintain operational capability, maintain survivability, minimize impact to the configuration of the ship, and minimize impact to the size of the ship.

The scope of the work acknowledges, as appropriate, but does not incorporate related thermodynamic, hydraulic, or turbomachinery concerns or analysis such as machinery or concepts for engine conversion. The extent of this analysis is limited to a hydrostatic analysis for the required net positive suction head for the fuel transfer pumps and a heat transfer analysis based on specified boil-off gas production rate to determine the thickness of the storage system layers.

D. THESIS OVERVIEW

Chapter II organizes the multiple strings of information being used to determine the validity of using an alternative fuel source. The primary avenues of research approximate the JCIDS process to determine a new capability-based solution. The section provides a historical perspective and aligns the NSS, NDS, CNO NAVPLAN, and other high-level documents with input from U.S. and international industrial-economic factors to develop a basis for requiring an alternative fuel option.

Chapter III provides an analysis of alternatives (AoA) to determine the best alternative fuel source for the current non-nuclear surface fleet. The analysis compares major factors for the viability of each fuel against each other and to the baseline F-76 fuel. The key baseline parameters focus on fuel-related ship performance factors (e.g., range, displacement) and industrial viability. The analysis concludes with a fuel selection of LNG.

Chapter IV provides a comprehensive review of current and future capabilities and technology to validate the alternate fuel source selected in the AoA section. The section provides relevant DDG capabilities for baseline comparison. The key technologies required for implementation on a DDG are explored with a specific focus on the fuel storage tank and transfer system design.

Chapter V covers four main areas critical to determining the requirements of implementing the alternative fuel on a DDG. These areas cover the method of analysis and design of the baseline and updated DDG, with differences as necessary.

1. Fuel Storage System Design. The process for developing the fuel storage tank design as a survivable part of the ship requires understanding and

weighing risk associated with the type and shape of the storage tank, material selection, and sizing of the tank.

2. Fuel Transfer System Design. The fuel transfer system design process is discussed with a specific emphasis on materials, system design, and the fuel transfer process.
3. Fuel Storage and Transfer System Integration. The process for integrating the fuel storage tank is explored to minimize changes to the existing DDG baseline in terms of physical specifications, functionality of the ship's organization, and overall ship capability.
4. Modeling. The modeling section discusses the results of the surface ship weight estimation analyses for comparison between the baseline and design ship.

Chapter VI provides the results of the analyses outlined in Section V with relevant graphs, figures, and tables. The different aspects of the design are discussed regarding comparison between the alternative fuel and baseline DDG for advantages, disadvantages, and concerns with emphasis placed on capability gaps, risk, and survivability.

Chapter VII provides final conclusions on the feasibility analysis of implementing the alternative fuel source for non-nuclear USN surface ships. The conclusions summarize the recommended changes to modify the baseline DDG to the alternative fuel variant, summarize key differences and associated risk, and provide a final recommendation on the viability of the selected alternative fuel as a military fuel choice for further investigation.

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II. MOTIVATION

A. INTRODUCTION

The U.S. shapes its current and future force based on the NSS and its derivative documents (NDS, NMS, CNO NAVPLAN, etc.) to drive short and long-term strategy. The long-term strategy is based off 20–30-year future projections of the socio-economic-political landscape and the force capabilities of the U.S., its allies, and other near peer adversaries. This assessment helps drive the Defense Acquisition System (DAS) in determining if new material capabilities and non-material solutions are required via the Joint Capability Integrated Defense System (JCIDS). If a new material capability is warranted, it is provided with initial capability requirements and assigned to the appropriate track on the Adaptive Acquisition Framework (AAF). Figure 1 displays the AAF flow path for DAS projects following the completion of the JCIDS process.

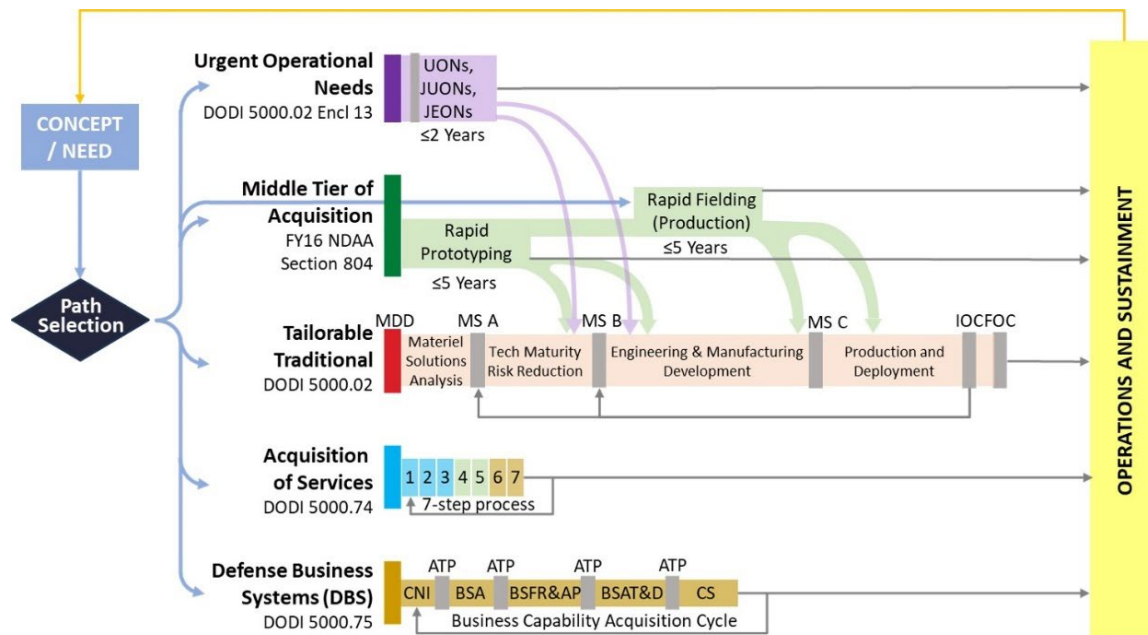


Figure 1. Source: AAF Diagram. Source: [15].

This section provides a framework for the reasonable motivation of the acquisition of an alternative fuel for USN non-nuclear surface combatants using a DDG-51 as a model

by deriving requirements flow down from the NSS down to the proposed alternative fuel solution. The motivation section approximates the JCIDS and DAS processes with a capability and need based assessment to determine the motivation for a new fuel, provide the basis for an analysis of alternatives of potential new fuels, and then provide the basis for the viability of the alternative fuel as a military marine fuel using supporting evidence from the current and projected estimates for alternative fuel technology and availability of resources and infrastructure.

B. HISTORICAL VIEW

Sea power has historically been a primary indicator for the strength of a nation by enabling its economy and people to prosper while deterring enemies and rivals. This indicator is evident throughout the ages and has shaped the world for thousands of years from the Punic Wars of Carthage and Rome, the Seven Year's War, to World War II. Sea Power has always been predicated on having the greatest power projection capability by maintaining the military technology advantage, strongest political-industrial-economic base, and location of operations as discussed by Mahan [16] and Stavridis [17]. Transcending location, resource availability and supply drive the nation and the technology. A primary aspect of sea power in a military sense is propulsion and the means of propulsion. Propulsion determines many basic ship characteristics and capabilities including speed and range, which directly affect the ability to project power and deter enemies. The navy with the greatest ability to propel their ships often had the most powerful ships, as propulsion is the basis of ship survivability and lethality.

Ship propulsion has evolved over time due to evolving technology and resource availability beginning with basic buoyant vessels with human powered propulsion, such as the galley. As civilization developed, the need for greater shipping capabilities required larger ships, which require greater propulsion. Shipping vessels carry large quantities of important cargo for the time period, such as copper during the Bronze Age, and provide vulnerable and valuable targets. Military vessels are required to deter the pirating and raiding of shipping vessels and trade ports to enable economic growth. The cycle of civilian and military naval capability development directly improved sea power and helped drive

the world forward. Naval propulsion has evolved from human oar-driven, to sail powered, to steam powered, to direct engine powered (diesel and gas turbine), to nuclear powered.

Since the beginning of recorded naval history in the Bronze Age, the nation with the most capable ships and fleet was typically the dominant nation in the region. The evolution of technology and the early adoption thereof commonly defined the rise and fall of nations. Often, the evolution of technology was simply the ability to build larger ships. For example, the Phoenicians were one of the few cultures to survive the late Bronze Age [18] and established themselves as a preeminent sea power due to their extensive colony network, commercial fleet, and military naval technology. The Phoenicians led military innovation with the development of the bireme and trireme galleys, which were two and three level, respectively, primarily oar-powered vessels designed to ram other ships in combat. The Phoenician legacy was carried on by their former colony, Carthage, who developed larger versions of the design known as quadriremes and quinqueremes [19]. The Carthaginians formed a colonial empire and had the largest, most powerful ships and fleet until their defeat by the Romans in the Punic Wars. The Roman Empire remained the dominant naval power until its fall and the subsequent development of centralized nation states that evolved in the Middle Ages. These basic galley design ships were the dominant naval vessel design well into the 16th century and even remained in use until the 18th century [20]. After the introduction of naval cannons, galleys would install these batteries in the forward area as the sides were dominated by oarsmen. The galley dominated in part by its simplicity, high maneuverability, high sprint speed, manufacturability, and applicability to its design operational region, the Mediterranean Sea. However, the galley design required a large length to beam ratio to allow for effective rowing by the oarsmen. The narrow ratio disabled the galley design from being used outside of relatively calm waters.

The galley is a unique outlier example in naval history, as the basic design maintained its relevance and dominance with only minor modifications for about 2,000 years. Despite the galley's success, sail driven vessels eventually caused the abandonment of the galley because of the eventual capabilities enabled by their propulsion system. Sail powered ships enabled the ship to allocate more space towards its cargo or armament, as

the propulsion system internal size was now minimized to the masts and rigging. Additionally, sail powered ships could be built with a larger beam. Sail powered ship development eventually allowed for transoceanic travel, which required a highly stable ship large enough to carry necessary stores for the lengthy trips. Following the cycle, military ships grew in size and capability to protect these commercial vessels. Eventually, the ocean-going sail powered military vessels simply outclassed the previous oar powered ships in almost every category. Sail powered ship designs rapidly developed from the basic merchant vessel cog in the North Atlantic of the early Middle Ages to the ships of the line of the 17th century and beyond [21] during the Age of Sail. This period existed until around the mid-19th century after the development of steam power during the Industrial Revolution.

The steam power age of naval history is relatively short in its entirety, only about 100 years [22]. The revolutionary coal powered steam engine developed in the 1760s by James Watt helped spark the Industrial Revolution [23]. Robert Fulton, an American pioneer, invented the first steam powered naval vessel: a coal fired steam powered paddle wheel river passenger boat in 1807 [24]. The USN launched the USS *Demologos* eight years later as the world's first steam powered warship during the close of the War of 1812 [25]. Although never used in combat, the ship was an important step in realizing the emergence of a new, revolutionary propulsion method. Steam power provided one irrefutable, significant advantage over sail powered ships - independent power. Steam ships could sail anywhere at any time making them reliably faster. However, early steam ships were highly dangerous and impractical as the naval technology had not caught up with the propulsion technology; for example, boiler explosions were common, paddle wheels were unreliable, and larger crews were required to handle coal. Over time, the technologies converged as screw driven propellers were developed and wooden ships became metal ships such as the USS *Monitor* and the USS *Merrimack* [26]. The previous weak survivability aspects of steam power (e.g., exposed paddle wheel, vulnerable boiler, etc.) were removed or made less vulnerable. The rapid growth of the industrial-economic base fueled by coal naturally allowed for the growth and full adoption of the steam ship. Additionally, the U.S. had an unexpected resource advantage, as the U.S. is home to the

largest coal reserves in the world [23]. Despite the numerous advantages and proven technology, the USN did not officially transition from sail to coal powered steam until the 1890s [27]. The steam power age ended the glorious Age of Sail but was itself very short-lived with the discovery and growth of the oil industry in the second half of the 20th century.

Heavy fuel oils have been the dominant fuel for marine vessels both commercial and military since the transition from coal power over 100 years ago. However, the transition period from initial discovery to primary propulsion method in the U.S. took decades and was the result of a confluence of the major factors discussed. Oil was first discovered in the U.S. in Titusville, PA in 1859, but its primary uses were simplistic due to technology limitations, political events, and minimal industrial footprint. Following the conclusion of the American Civil War, the USN commissioned a study in 1866 to evaluate petroleum as a replacement fuel for coal, even though steam-only powered ships were few. Despite several advantages (deemed insignificant at the time), oil was declared a “hopeless” endeavor and not pursued again until 1880 and then in the 1890s with similar conclusions [28]. Despite the USN reluctance or inability to fully transition from sail to steam and to recognize oil’s superiority, the British and French were on the cutting edge and began to commission oil powered vessels in the late 1880s despite having the most robust coal supply chains for its ships. Further significant political-military events (e.g., Battle of Tsushima Strait in the Russo-Japanese War and the *USS Maine* explosion in the Spanish-American) coupled with the advent of the U.S. oil and petroleum industry boom in the early 1900s with the discovery of the Spindletop oil field [29], spurred the rapid development and subsequent adoption of oil over coal.

Oil was a known resource for decades but became the dominant energy source due to the convergence of the political, industrial, and economic aspects in the early 20th century. The official USN transition from coal to oil occurred in 1910. The final coal powered U.S. battleship, the *USS Texas*, was commissioned in 1914 and transitioned to burn fuel oil in 1925 [22]. Coal powered ships were a brief phase in naval history lasting only about fifty years in the late 19th and early 20th centuries. Coal was quickly replaced with oil due its numerous advantages including higher specific energy (27 vs. 44.8 MJ/kg)

with comparable energy density (36,450 vs. 37,184 MJ/m³) [30], better propulsion characteristics, higher health and safety factor, greater survivability, easier refuel process, and were less crew intensive. The Spanish-American War was a major catalyst in driving the USN to transition from coal to oil due to the emergence of major oil reserves, demonstrated tactical shortcomings of coal fired vessels, and the explosion of the *USS Maine* reinforced safety and reliability concerns. The USN with an oil-fired fleet could now build ships to focus more on survivability and warfighting than storage space for fuel, and ships now effectively had larger range with the ability to refuel at sea enabled.

From this brief historical review, the USN should always be looking for the next fuel to provide advantages to further its mission set. With the external pressures of political goals (e.g., carbon emission initiatives), shifting economic bases, and dwindling proven oil reserves, the Navy should again be identifying and preparing for the next fuel, which is likely already known as the case in the coal to oil transition. The best benchmarking source for alternative marine fuels from heavy fuel oils is the marine shipping industry, which continually identifies methods and resources to improve its capacity and ability within the external pressures exerted.

C. ANALYSIS

The primary factors in determining the feasibility of a primary resource transition are political, economic, and industrial in nature. Each of these factors overlap and influence each other so it is difficult, if not impossible, to separate them. The following sections attempt to provide logical supported evidence and reasonable projections within these three main factors individually. Synthesizing the evidence in each thread provides a reasonable conclusion with justification. The alignment of these three factors indicates a change is necessary, or at least worthy of further review. The three factors are sorted in a tiered method from highest to lowest level in their influence, and they are defined in the following ways to provide a basis for the supporting evidence and discussion.

The political discussion is focused on the overall strategy and direction of the U.S., its allies, and the world in general. Examples of information include policies, initiatives, goals, and the political environment.

The economy is often the strongest indicator of the strength of a political system. The economic lens provides the operational frame of reference. Examples of information include general trends, projections, and costs.

Industry is directly tied into the economy, as it is the prime mover of economic growth. As such, the industry is viewed as the tactical frame of reference. Examples of information are limited to the concepts of primary and secondary industry. Primary industry is the sector of a nation's economy that produces and extracts resources [31]. Secondary industry is the manufacturing sector that uses the resources to provide goods [31].

Primary influences for analyzing evidence for the motivation of an alternative fuel are drawn from military theorists Carl von Clausewitz, Alfred Thayer Mahan, and Julian Corbett. These theorists provide themes on important aspects of the origins of this work, the evidential analysis, and the conclusions from the combined and overlapping political, economic, industrial, and military lenses. Clausewitz's work *On War* [32] provides an overview on military strategy stressing the interaction of diverse factors, the military as an extension of the political body, and the three elements of war (the government, the army, and the people). Mahan's work *The Influence of Sea Power upon History* [16] outlines general tenets and examples of developing, supporting, and achieving sea power. Corbett's work *Some Principles of Maritime Strategy* [33] provides strategies on leveraging sea power, importance of joint operations, and the concept of limited or indirect war.

1. Political

As the world and the United States progress further into the 21st century, the transition from fossil fuels to cleaner, renewable energy sources remains at the forefront of the political, socioeconomic, and environmental agendas. Numerous governments, including the United States, and agencies are requiring energy consumers (e.g., industry, residential, etc.) to lower and eventually eliminate all carbon-based electrical generation and replace with net-zero carbon emissions from facilities and vehicles with most final completion dates between the years of 2030 and 2050 in support of the IEA Net Zero by 2050 initiative (NZE). The NZE's goal is to provide major achievable lines of effort

worldwide to prevent global temperatures rising more than 1.5 °C. This temperature benchmark was estimated to occur around 2031, with no significant action and expected global economy increase [34]. The NZE's major benchmarks to ensure the goal is met include a decrease of carbon dioxide emission by 40% between 2020 and 2030 with net zero by 2050, wind and solar provide 70% of global energy, coal demand decreases by 90%, oil decreases by 75%, and natural gas declines by 55% [1]. These benchmarks are aimed at the economic uses of carbon including transportation, residential, and industrial, which excludes the military as an instrument of national security. The United States agrees and has thus identified climate change and energy security as two major factors in determining the 2022 NSS [2] to safeguard the U.S. long into the future.

The significance of these two factors is explored further with numerous NSS derivative documents by the U.S. government, its agencies, and the DOD on accomplishment plans and risk mitigation including executive orders, the National Defense Strategy, DOD Climate Risk Analysis (CRA), the DOD Climate Adaptation Plan (CAP), and the DOD Sustainability Plan. This effort currently has no direct requirement to be instituted by military forces, as they are excluded for their role in national security. However, the DOD is striving to have all facilities and non-tactical vehicles meet this goal [3] and the DOD has been developing alternative fuels: fuel mixtures and clean alternatives [4]. For example, the 2021 CRA determined climate change will potentially generate significant climate hazards including increased drought and flooding risk; these risks pose direct threats to water supply, critical asset inundation, reduced food supply, and damage to infrastructure [35]. All of these risks (and others) posed by climate change provide direct national security risks to the citizens in the homeland and forward operating bases throughout the world, as shown in Figure 2. These risks would provide significant strain on the world with less habitable areas and lower availability of critical resources, resulting in a more competitive and dangerous world.

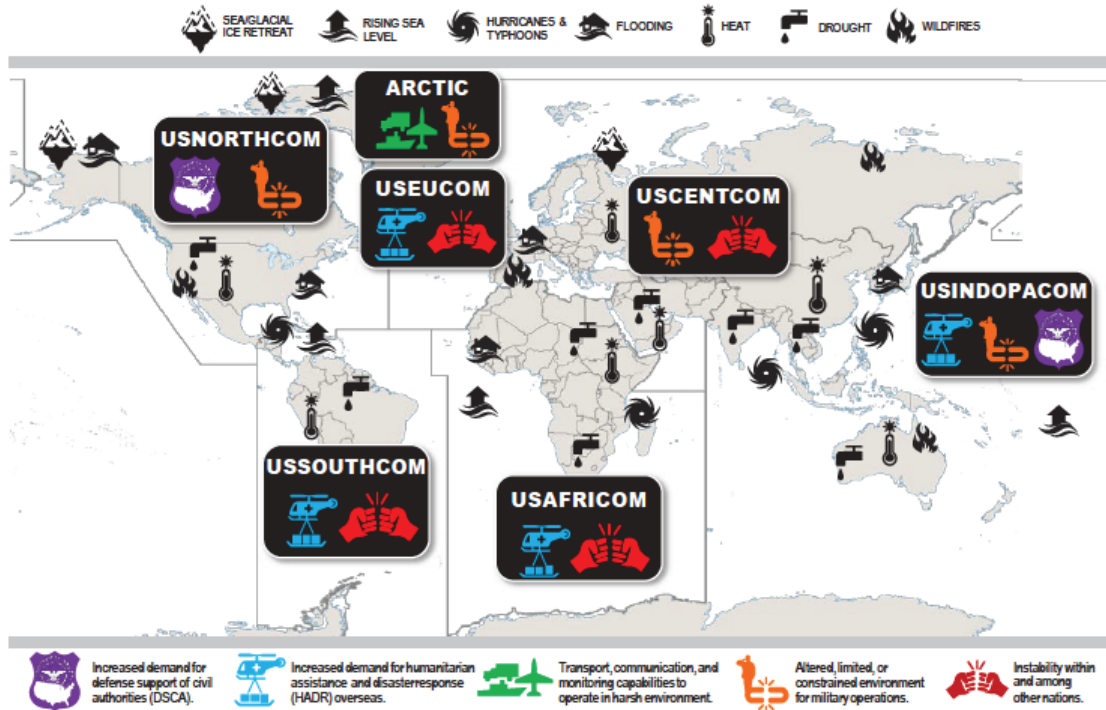


Figure 2. Potential Regional Hazards and Security Implications due to Climate Change. Source: [35].

Energy has always been a leading factor in the power competition of the world, as energy is the driver of industrial economies and militaries. The energy factor has only increased as the world becomes increasingly reliant on electricity while the traditional energy sources decrease. At the current consumption and proven reserve levels worldwide, the world has enough oil to supply the total oil demand for 47 more years [36]. Even though the world supply is sufficient to support the world economy, the primary oil reserves are limited to a few countries. The nations supplying the majority of crude oil are in the Organization of the Petroleum Exporting Countries (OPEC), the expanded affiliation OPEC+, and some nations remaining major independent producers (see Table 1). The OPEC and OPEC+ nations control 70% and 79%, respectively, of all proven oil reserves [37]. As a result, the OPEC community can and has exerted economic pressure for political and strategic purposes. Compounding this ability is the geographic centrality of these nations and the potential resulting impact of instability in the region.

Table 1. Significant Oil Producing Countries by Affiliation. Adapted from [38].

OPEC	OPEC+	Non-OPEC
Algeria	Azerbaijan	Brazil
Angola	Bahrain	Canada
Congo	Brunei	China
Equatorial Guinea	Kazakhstan	Norway
Gabon	Malaysia	Qatar
Iran	Mexico	United States
Iraq	Oman	
Kuwait	Russia	
Libya	South Sudan	
Nigeria	Sudan	
Saudi Arabia		
United Arab Emirates		
Venezuela		

The relationship between the U.S. and many of the OPEC and OPEC+ countries can often be characterized as tenuous over the last century due to economic dependence struggles, significant differences in political and social ideologies, and various military interventions. Significant events that have shaped the relationships include the U.S. Mandatory Oil Import Program, the Suez Canal Crisis, the Arab Oil Embargoes, the Tehran and Tripoli Agreements, the Iranian Revolution, the First Gulf War, the Iraq War, the COVID-19 Pandemic, and the Russia-Ukraine War [39]. Many of these events occurred during the Cold War while the U.S. and its allies fought proxy wars against the Soviet Union for economic and political leverage in the battleground regions of the Middle East, Africa, Southeast Asia, and the Americas. These

events and disputes have led to relation strains and even the severance of ties such as the U.S.-Iran [40] and U.S.-Venezuela [41] relations. In part to the inconsistent and often stressed relations with these various OPEC nations, the U.S. imports over 70% of its crude oil from its direct neighbors, Canada and Mexico [42].

Ongoing and future political turmoil and instability pose significant threats to the U.S. energy supply, as the U.S. is a net importer of crude oil and expected to remain so through 2050 [8]. The U.S. and other first world countries are increasingly dependent on modern technology which is primarily powered by fossil fuels and electricity. The lack of these resources can lead to energy insecurity which may have significant negative effects on the stability of a country, as the social, economic, political, and industrial centers are no longer supported.

As a case study for the political impact of energy insecurity, South Africa, the continent's most developed economy, has experienced an energy insecurity crisis for the last 15 years [43]. Over this time, the nation has experienced non-constant electrical power output resulting in rolling blackouts disrupting the lives of millions of people at a time. In 2022, the nation experienced twice as many rolling blackouts than any year up to that point. These blackouts last for as many as 12 hours a day, which have a profound effect on the economy, daily life, and ultimately the stability of the nation. These effects range from the decline of the economy, inability of critical infrastructure to work, a rise in crime and corruption, and even the appearance of civil war conditions [44]. South Africa's President declared a national state of disaster in February 2023 with the goal of restoring energy security to prevent the systematic collapse of the country. The issue is ongoing with multiple national and international partners working to resolve the national disaster. Although the South Africa case of energy insecurity is largely due to inadequate infrastructure, instead of the potential political and strategic ramifications of energy dependence, it highlights the potential multi-dimensional threat of energy insecurity.

The United States, in conjunction with NATO, has used the "single fuel concept" since 1988 [12] to minimize fuel types for logistical and design simplicity. The primary fuels used in this paradigm include JP-5, JP-8, and F-76 for all tactical vehicles. The concept has been successful in its goal; however, the policy had unintended consequences on the future force

and acquisition as it disincentivized alternative fuel and related product generation. Despite the implications of the single fuel concept, the USN has used NRL to research and develop alternative fuels to power its forces. The ultimate achievement in this vein of research would be a method to provide complete energy independence and security of the fleet. Recently, the NRL has developed the capability to produce hydrocarbon fuels from seawater [14]. This capability offers the ability to produce fuel from the ocean, which covers 71% of the globe and contains about 96% of all water. The reliance on primarily imported crude oil to produce F-76 would be reduced or eliminated with a fuel that could be produced sustainably.

2. Economic

Fossil fuels relied upon by the military, primarily JP-5, JP-8, and F-76, provide a potential key weakness in logistics and defense capability, as seen most recently, in cost alone, with the Russian aggression into Ukraine. Excluding the temporary drop in response to the COVID-19 pandemic, the price of WTI crude oil went from an average price of \$57 per barrel in 2019 to \$103.71 per barrel in 2022 [5]. The price surged as Russia, the world's second largest oil and natural gas producer [6], was placed under economic sanctions from many nations that previously were importers of Russian oil products. The cost of F-76 fuel for ships in 2019 was \$126 [45] and raised to \$174.30 in 2022 [7] (the price ratio between F-76 has historically been approximately twice the price of WTI crude per barrel). The price of WTI crude oil is expected to increase to \$87 per barrel (range from \$44 to \$165 for the 2045–2050 timeline [8]). Based on this projection, the cost of F-76 fuel would likely be between \$90 and \$330 with the predicted price at \$174. If oil consumption remains constant at the average over the seven-year span from FY 14 through FY 20 [4], oil expenditure would increase from an average of \$10.6 billion to \$16 billion (range from \$7.4 to \$27.9 billion). These oil prices assume a 2020 real dollar value and a compound growth of 2.9 percent.

Most alternative fuel choices to petroleum products are more expensive as they are less developed technologies, have smaller economies of scale (lower supply, lower demand, and smaller supply chain), and have fewer applications. Inversely to the oil prices discussed, multiple alternative fuel technologies should grow in economies of scale and become less expensive and more attainable. Economically, the fuel must be comparable to F-76 or better to

be a viable alternative since the U.S. still maintains a significant petroleum reserve. With the growth of the alternative fuels used to power the world, it is expected petroleum dependence will decrease in alignment with the NZE 2050 goal.

3. Industrial

The U.S. has been blessed with its strategic, diverse geography and the vast amount of important raw resources within its borders. These features have helped power the U.S. from its European colonial days to the global superpower it is today on the back of energy supplying resources such as wood, coal, oil, and natural gas, primarily. With advances in technology and the vast amounts of energy consumed by the nation and its military, the energy sources of today and tomorrow must be identified and developed.

Although the U.S. has increased its fossil fuel production in an attempt to be energy independent, the U.S. is a net importer of crude oil and is expected to remain so through 2050 [8]. The U.S. natural gas production is more sustainable than crude oil based on production rate and proven reserves. Following proven reserve and production rate projections, the U.S. has enough dry natural gas to last at least 60 years [9] and enough crude oil to last about 10 years [10]. Multiple alternative fuel options for marine applications use natural gas as a feedstock and an energy source to synthesize fuel such as methanol and ammonia. Therefore, natural gas posits itself to be influential in the next major marine fuel regardless of if it is used directly or indirectly.

The historical perspective discussed and the influence of the great strategists of sea power provide the reasons for a strong industrial base. The industrial base converts all natural resources into the products used and provides the supply chain infrastructure. The alternative fuel must have or have the potential for a significant industrial base to ensure the resources required are available, the infrastructure (extraction, processing, manufacturing) exists and grows, and the international supply chain exists to provide fuel on demand throughout the globe. Effectively, the new alternative fuel and associated infrastructure must be able to fill the gap of petroleum quickly and seamlessly, most similar to the transition from coal to oil powered ships in the late 19th and early 20th century.

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III. ANALYSIS OF ALTERNATIVES

A. INTRODUCTION

The section provides an analysis of alternatives to F-76 fuel for use in the non-nuclear surface fleet. The basis for selecting these alternative fuels is discussed and the capabilities of each is compared to determine the most viable fuel from a performance, industrial, and political-economic viewpoint. The alternative fuels explored are based off the marine shipping industry's most promising fuels LNG, LPG, methanol, hydrogen, battery, ammonia, and nuclear [46].

B. ANALYSIS CRITERIA OVERVIEW

In determining the ideal replacement to F-76 for the non-nuclear surface fleet, each viable alternative must be reviewed individually on their merits then compared against each other and the baseline. The primary factors for consideration are derived from the overall political, economic, and industrial impacts that drove the initial decision. The determining factors include fuel performance metrics, alignment with political and strategic direction, economy for the fuel, and the industrial base of the fuel. The analysis is primarily qualitative in nature for this initial overview. Following the initial analysis, the remaining alternatives are reviewed in depth prior to determining the fuel selection and its integration requirements and impacts.

The fuel performance metrics determine how effective and compatible the fuel is for propulsion in a surface vessel and provide a measure of survivability. Primary fuel performance metrics include energy density, fuel density, and engine compatibility. The energy density of the fuel drives the volume of the fuel and the size of the storage tank. The fuel density combined with the energy density determines the mass of fuel and its effect on ship displacement and stability. The fuel is analyzed on its impact to ship survivability based on its ignition temperature, combustibility, damage control, and effect to crew if released. Additionally, the maintainability of the fuel and its associated system are reviewed.

The fuel's economic impact and industrial base is analyzed to provide an overall measure of feasibility. The ideal fuel must have an established and projected growth in its industrial base in the U.S. and abroad. Without a robust industrial base (current and projected), fuel will be too risky for the proposed replacement of F-76 due to the strategic importance of resources on the sea power of the nation. The fuel technology and resource cost should be comparable or less expensive to the current F-76 for financial impact.

Overarching all these parameters, is the ability of the fuel to align with the political and strategic goal of fuel independence, energy security, and ability to execute strategic goals. A primary strategic concern to measure is the ability of the new fuel to execute the concept of Distributed Maritime Operations (DMO) and its associated shipbuilding schedule and force structure through 2050. Although achieving the NZE goal with a replacement fuel is ideal, this metric is secondary and subject to compromise.

C. ANALYSIS OF ALTERNATIVE FUELS

The following sections provide an overview of each of the primary alternatives and the baseline fuel F-76. Figure 3 displays volumetric and gravimetric energy density of multiple alternative and non-alternative fuels and is referenced frequently in this section for these metrics and their potential impact to the implementation of the fuel as the alternative to F-76 fuel. F-76, as a heavy sulfur distillate fuel [47], is overlaid with a blue marking for convenience on Figure 3 at its approximate location based on diesel fuel energy densities [30]. The diesel approximation to F-76 is used throughout this section.

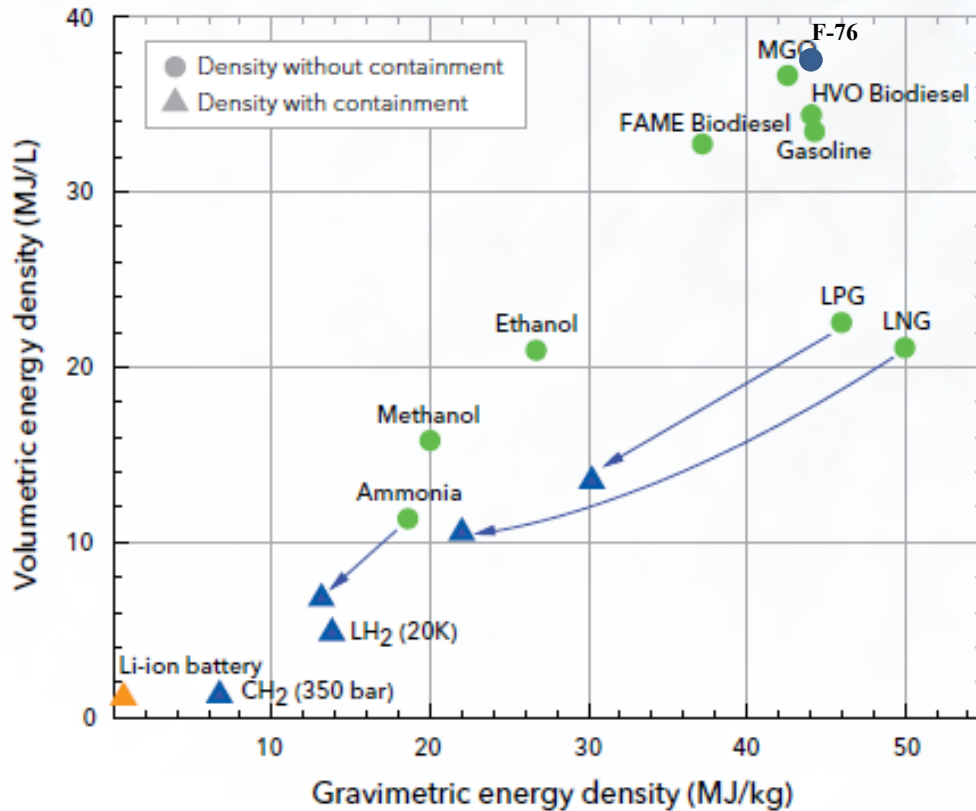


Figure 3. Energy Density of Alternative Fuels with and without Containment. Adapted from [48].

1. F-76

F-76 is the current standard military diesel fuel for non-nuclear surface ships. The fuel is an amber colored liquid at room temperature, which provides simple storage and transport methods. The fuel is highly stable chemically, non-reactive, and non-hazardous in standard conditions. Outside of standard conditions, the fuel provides a significant hazard, as a liquid or vapor, due to its toxicity and flammability, as shown in Figure 4. The fuel must be stored in closed containers in a cool, well-ventilated area. The fuel has a narrow flammability limit between 0.6% and 6.5%, a flash point of 129°F, and a boiling point of 540°F [47]. Despite the narrow flammability limit, the lower limit provides a minimal threshold for vapors to ignite. The flash point provides one of the higher thresholds for ignition. In an ignition event, the flame may be extinguished with multiple media

depending on the size of the flame. As a fuel, it has the highest volumetric energy density allowing for more compact storage solutions.



Figure 4. F-76 NFPA Rating. Source: [47].

F-76 has the most established infrastructure currently on all levels of industry (extraction, processing, distribution) in the U.S. and abroad. F-76 has an average API of 37 [47], meaning it can be processed using much of the oil in the U.S. oil reserves [49]. Conventional oil powered naval ships remain the dominant option for the near future which is reinforced by the USN shipbuilding plans [50] indicating no change in fuel. Figure 5 displays the Defense Logistics Agency (DLA) petroleum supply chain throughout the world.



Figure 5. DLA Bulk Petroleum Supply Chain Services. Source: [51].

2. Liquid Natural Gas

Liquid Natural Gas (LNG) is the liquefied form of natural gas, which is composed primarily of methane. Natural gas usage has the longest usage history stretching thousands of years [52]. LNG is produced from raw natural gas following a natural gas refining process and then the liquefaction at about -260°F [53]. The liquefaction of natural gas increases its volumetric energy density by approximately 600 times to allow for more efficient non-pipeline transport and storage [53]. Contrasting the liquefaction and high storage requirements, LNG maintains a relatively high volumetric and gravimetric energy density for the alternatives examined (see Figure 6). LNG has been a commercial shipping fuel beginning in the 1950s with the *Methane Pioneer* [54]. LNG commercial transport use was first formalized under the International Maritime Organization's (IMO) International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) in 1986 and has been updated numerous times (most recently in 2019) as technology and knowledge improves [55]. The U.S. and the international community have extensive experience with LNG and the commercial shipping industry, moreover than any other alternative fuel examined.

From a safety and survivability standpoint, LNG is often misunderstood as the properties of LNG are different from its gaseous state. Regardless, the properties of natural gas in its liquid and gaseous states are examined since LNGs boiling point is approximately -260°F, so the transition from liquid to gas will occur in a leak or damage control scenario. For clarity, natural gas is the term used for the gaseous state and LNG for the liquid state. Natural gas' NFPA rating is shown in Figure 6. LNG is odorless, colorless, non-corrosive, non-flammable, and non-toxic [56]. As a cryogenic fluid, LNG handling requires cold insulating personal protection equipment. Although natural gas is flammable, LNG is not since there is no oxygen in the liquid. However, the low boiling point results in vaporization in the presence of a heat source. Methane, the primary compound in natural gas and LNG, has a flammability range between five and 15 percent. If a leak occurs in a well-ventilated space, the conditions for flames would likely only exist in the local region of the leak as the relative density of natural gas is less than air [57]. The auto-ignition temperature of LNG is 599°C, which is significantly higher than diesel's 260–371°C [56]. Additionally,

if natural gas vapors combust into a flame, the flame speed of methane is low (about four meters per second) making an explosion unlikely; however, if a tank is breached from an intentional attack, a fire is likely [58]. If LNG spills into water, two results may occur: first, no fire will occur due to a combination of local conditions, LNG spread and pooling, high vaporization rate, and dilution due to wind; second, a rapid phase transition (RPT) may occur resulting in a sonic boom and localized over pressurization [58]. The conditions for a RPT are not clearly defined, but the results of measured RPT overpressure events on an LNG ship or pier are insufficient to cause more than minor damage to either [58].



Figure 6. Natural Gas NFPA Rating. Source: [57].

The LNG industry has established standard practices to prevent and mitigate leaks from material selection, monitoring and control systems, passive and active fire protection, and proven operator procedures. The LNG industry has only had one significant safety event which happened in the early days of the industry in Cleveland, OH 1944. The gas leak event resulted in fires and an explosion killing 130 people and destroying a large area with an estimated 100 million gallons of LNG [58]. Furthermore, the safety record of the LNG record is outstanding with only eight events: six minor spills all occurring during fuel transfer events and two collisions with jetties resulting in minor damage and no LNG release. The industry learned a lot from its early major failure and subsequent minor events resulting in the LNG industry's approach to defense in depth for safety, as shown in Figure 7.

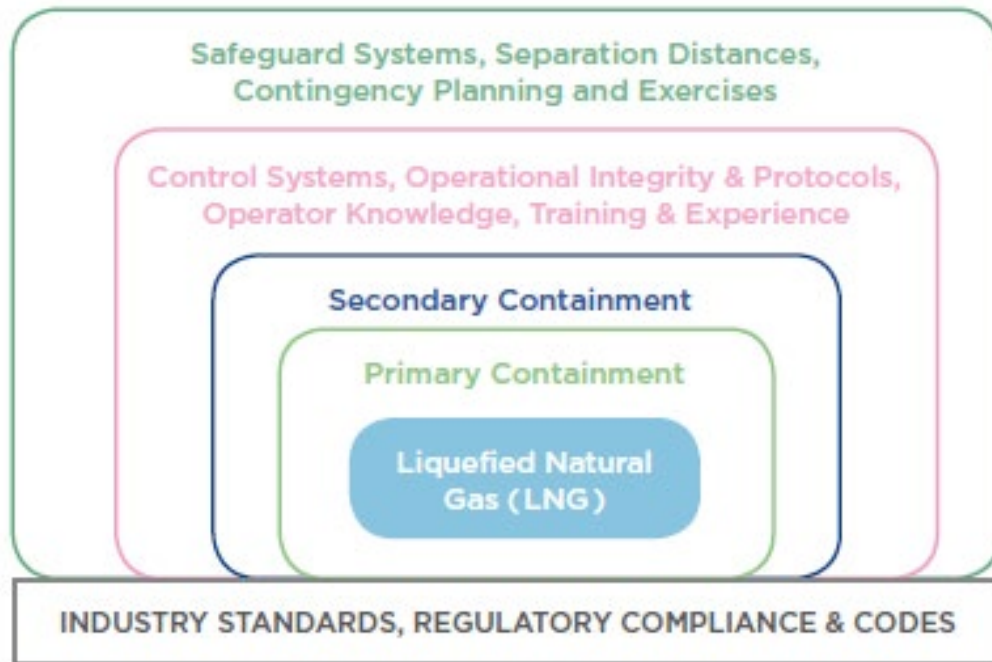


Figure 7. LNG Defense in Depth Diagram. Source: [59].

Economically, LNG is a popular fuel for commercial shipping due to the relatively low price of LNG. The January 2023 energy-equivalent price per million BTU of LNG was \$36.99 and \$35.59 for diesel (F-76) [60] as displayed in Table 2. However, LNG is typically a less expensive alternative as shown in Figure 8. The SEA-LNG organization reports LNG as the only commercially viable deep-sea alternative fuel with capital expenditure return on investment periods of no more than five years [61].

Table 2. National Average Retail Fuel Prices on an Energy Equivalent Basis, January 2023. Source: [60].

	Per Gasoline Gallon Equivalent (\$/GGE)	Per Diesel Gallon Equivalent (\$/DGE)	Per Million British Thermal Units (\$/MBtu)
Gasoline	\$3.31	\$3.74	\$28.96
Diesel	\$4.08	\$4.58	\$35.59
CNG	\$3.25	\$3.67	\$28.43
LNG	\$4.23	\$4.76	\$36.99
Ethanol (E85)	\$3.60	\$4.07	\$41.10
Propane**	\$5.02	\$5.64	\$60.12
Biodiesel (B20)	\$4.01	\$4.55	\$31.72
Biodiesel (B99/B100)	\$5.11	\$5.74	\$43.64

*Includes public and private stations

**Includes primary and secondary stations

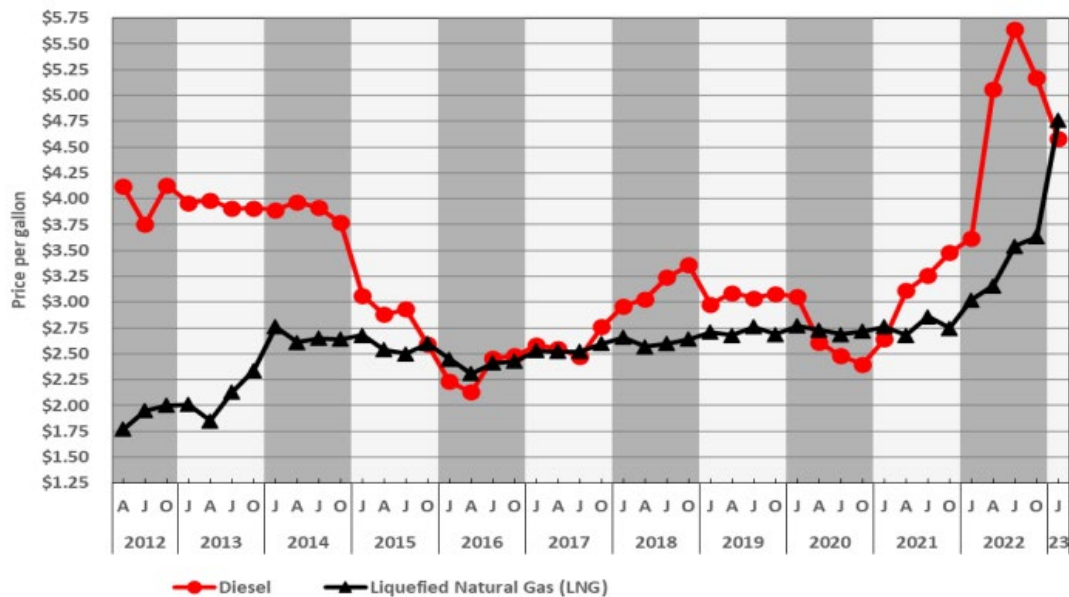


Figure 8. Historical LNG Prices vs. Diesel. Source: [60].

Natural gas is a raw resource the U.S. has an extensive supply of ranking fourth in the world in proven reserves at 589 trillion cubic feet and an estimated technically

recoverable resource amount of 2,926 trillion cubic feet, as of the end of 2022 [62]. Assuming the 2022 annual production rate of roughly 43 trillion cubic feet is maintained, the U.S. has about 67 years of TRR reserves [62]. The 2022 EIA Annual Energy Report estimates the natural gas production rate will follow the trend as shown in Figure 9. Additionally, several significant U.S. allies and strategic partners such as Australia, Qatar, Canada, and Indonesia are significant LNG producers and suppliers in various regions providing additional resource security.

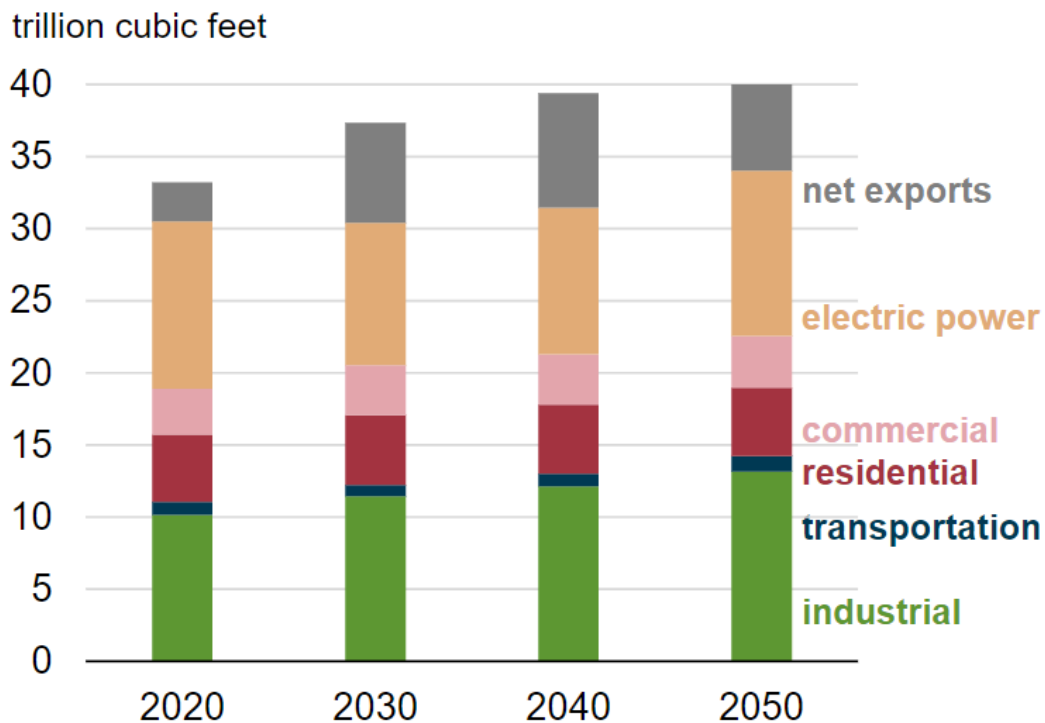


Figure 9. U.S. Energy Information Administration 2022 Annual Energy Outlook Production Estimates and Distribution. Source: [8].

Industrially, LNG is second only to F-76 as a petroleum-based fuel in terms of supporting infrastructure in the U.S. and internationally. The map in Figure 10 displays the major LNG shipping routes currently used along with natural gas liquefaction plants (dark green), LNG bunkering ports (light blue), and bunkering vessels (white). As of the end of 2021, the U.S., Australia, and Qatar have the three largest LNG liquefaction capacities in the world accounting for 18.7%, 19%, and 16.8%, respectively, for a total of 54.4% of the

459.9 million tons per year (MTPA) [63]. The world liquefaction capacity is expected to grow by 138.5 MTPA with current final investment decision (FID) and under construction projects with 1034.5 MTPA of pre-FID projects scheduled [63]. The lack of domestic LNG infrastructure may be addressed by these projects of which the U.S. has 19.4 MTPA approved and 387.6 MTPA proposed [63].

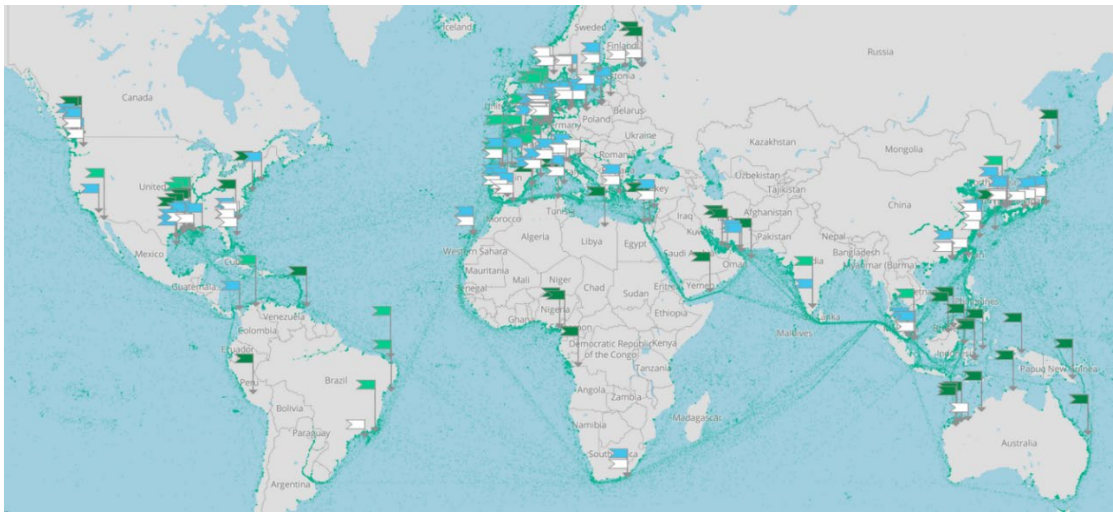


Figure 10. Map of LNG Major Shipping Routes, Liquefaction Plants (Dark Green), Bunkering Ports (Light Blue), and Bunkering Vessels (White).
Source: [64].

Despite the significant domestic LNG infrastructure, the domestic LNG capabilities are primarily focused in the Gulf Coast region where most of the natural gas operations are conducted. Additional liquefaction and bunkering facilities would be required in key fleet concentration areas such as Washington, California, Hawaii, and Virginia to provide full coverage for non-nuclear surface ships. The U.S. natural gas pipeline infrastructure is robust (shown in Figure 11) but may require additional redundancy or dedicated lines for national defense.

Map of U.S. interstate and intrastate natural gas pipelines

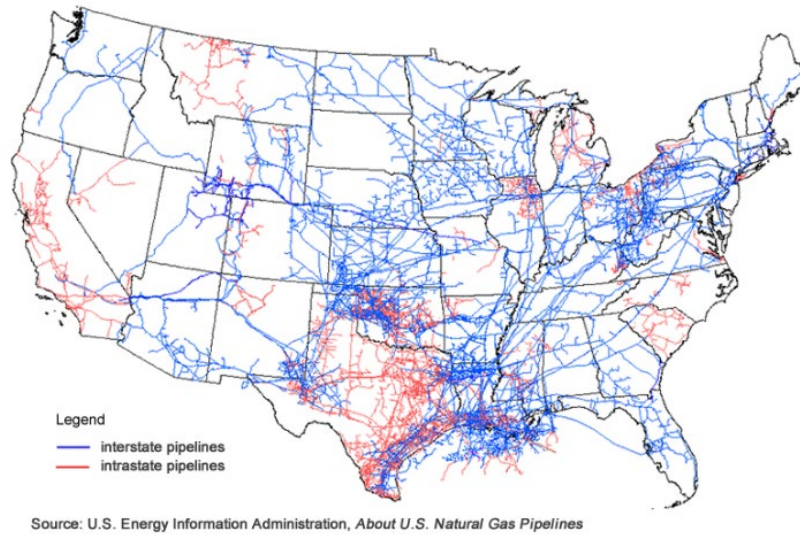


Figure 11. Map of U.S. Natural Gas Pipelines. Source: [65].

The global LNG commercial shipping fleet consists of 641 active vessels including 45 floating storage and regasification units (FSRU) and five floating storage units (FSU) with 216 more vessels under construction as of April 2022 [63]. The commercial fleet is also relatively young with approximately 90% of the fleet constructed in the last 20 years in conjunction with the rapid increase in LNG demand. Modern LNG vessels are designed for a nominal operational life of 40 years [63]. The size of the fleet and the recency of construction provide a significant amount of knowledge on producing LNG capable ships, which would be beneficial when determining how to best integrate the containment and propulsion system technology into warships. Furthermore, South Korea (a key U.S. ally) is the top LNG shipbuilder between its “Big Three” of Hyundai Heavy Industries Group, Samsung Heavy Industries, and Daewoo Shipbuilding and Marine Engineering. Of the 216 vessels under construction, these three companies are building 82, 54, and 35 units, respectively, which is approximately 80% [63]. Most LNG vessels are significantly larger than a DDG-51: LNG vessel average construction to delivery time is 30–40 months [63], which is less than the average four-year construction period of a DDG-51 [66]. Although not a direct comparison, due to the higher complexity of military vessels with significantly

more survivability features, typical LNG carriers (as shown in Figure 12) are primarily dedicated to LNG cargo storage which demonstrates the industrial capacity to construct maritime LNG storage.

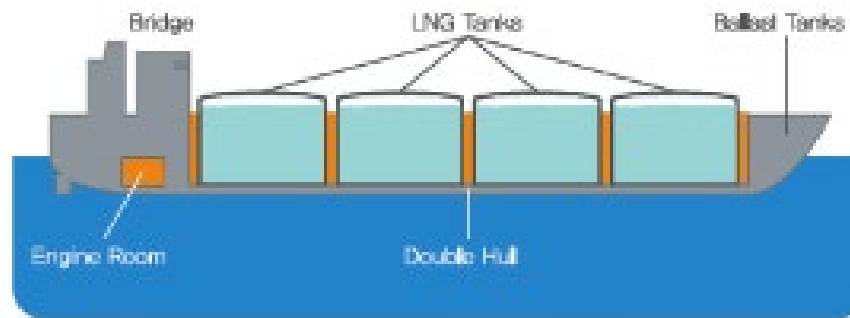


Figure 12. LNG Membrane Carrier Diagram. Source: [67].

A unique feature LNG has over the other alternative fuels is the ability to be created synthetically as a renewable and net zero carbon fuel. The Navy Research Laboratory developed a method to convert seawater into hydrogen and carbon dioxide gases [14]. These products can then undergo a methanation process to produce synthetic natural gas (SNG), which is simply pure methane [68]. The SNG may then undergo liquefaction just like natural gas to produce liquid SNG (LSNG). The production and usage of LSNG in many ways is advantageous over LNG including the ability to have a potentially unlimited fuel source, LSNG has better safety characteristics, and LSNG is a cleaner fuel than LNG. The production of LSNG from seawater would only be viable using nuclear power or a renewable energy source, such as wind, solar, or ocean thermal energy conversion. The Naval Postgraduate School recently conducted a study and produced a high-level preliminary design for a nuclear-powered aircraft carrier capable of producing, storing, and transferring LSNG made from seawater [69]. This vessel would be capable of creating completely independent strike groups and truly enabling the DMO strategy.

LNG accomplishes all of the goals in this alternative fuel analysis from a political, strategic, industrial, and economic viewpoint. The U.S. and its strategic partners have significant natural gas resources, production capability, and infrastructure ensuring energy independence and security. LNG's volumetric energy density is significantly offset by its

high storage requirements leaving it the fourth most energy dense behind F-76, LPG, and methanol. This lower effective volumetric fuel density would require significant modification and redesign of existing non-nuclear surface ships to incorporate the LNG storage system creating new classes of ships. LNG provides attractive economic considerations in terms of fuel cost, as it is competitive with diesel currently and historically lower. The LNG shipbuilding industry is strong with South Korea as the industry leader, which could provide another means to further the NSS by deepening alliances and partnerships. Additionally, the possibility of an unlimited carbon neutral fuel from the ocean is an exciting prospect that would completely provide energy security and independence.

3. Liquid Petroleum Gas

Liquid Petroleum Gas (LPG) is a mixture of propane and butane in liquid form [70] but is commonly referred to or identified as simply propane. LPG is primarily produced as a product of refining crude oil and natural gas processing. Therefore, all industrial and economic aspects of LPG closely resemble natural gas with higher costs; for example, the cost of natural gas was approximately 40% lower than propane for the average price per BTU to residential homes [71] [72]. In ambient conditions, propane is a gas with a boiling point of -42°C and can be liquefied at various conditions (e.g., 122 psi at 20°C). Butane is commonly found in two forms: n-butane and isobutane. These two forms have boiling points of -5°C and -12°C , respectively. The two forms of butane having higher boiling points may be liquefied at lower pressures, which makes propane the limiting factor.

LPG is typically stored in three different conditions: (1) pressurized at ambient temperature, (2) fully refrigerated (-30°C to -48°C) at atmospheric pressure, or (3) semi-refrigerated allowing for warmer temperatures with higher pressures. These three different conditions drastically alter the storage vessel design, which affects the impact to the size and space efficiency of the tank. Option one (ambient temperature), requires the fuel to be pressurized at a minimum of between 35 [73] and 136 psi [74], assuming 25°C for pure n-butane and pure propane, respectively. This option requires the LPG to be stored in a cylindrical or spherical pressure vessel, which would be the least space efficient. Option

two (fully refrigerated) allows the LPG to be stored at atmospheric pressures in an insulated storage tank. The storage tank, similar to LNG, could be integrated to the hull or independent of the hull. Since LPG has non-cryogenic storage conditions, the tank would require significantly less insulation and be smaller. Option three (semi-refrigerated) would be similar to storage tanks for option one.

LPG is about 2/3 as volumetrically energy dense as diesel at an average heating value of 87,750 BTU per gallon [75], slightly higher than LNG's value of 84,450 BTU per gallon. Figure 13 shows the significant effect of the storage and containment on the effective energy density of LPG which equates to roughly 40% lower volumetric energy density and 35% lower gravimetric energy density. Despite the decrease due to containment requirements, LPG is the most energy dense alternative fuel considered.

From a safety and survivability standpoint, LPG is known as an extremely flammable gas and may explode when heated, based on its rating of four in Figure 13 [76]. LPG is colorless with no distinct odor, which would require an additory agent for identification or sensors for detection. LPG has a low flashpoint of -156°F and a boiling point of -44°F. When LPG changes phase to gas, it has a higher density than air which poses an asphyxiation risk to personnel and much higher risk of combustion conditions. Propane has a flammability range of 1.8 to 9.6% [77], the lowest flammability of all fuels evaluated. LPG does not have specific regulations determined by the International Maritime Organization (IMO) for LPG fueled ships, as many alternatives do, but it does provide guidance with the International Code of Safety for Ship Using Gases or Other Low-Flashpoint Fuels based off the commercial success of LNG [78]. Currently, LPG and other low flashpoint fuels (excluding LNG) may only be used “if their safety, reliability, and dependability of the systems can be shown to be equivalent to those achieved by new and comparable conventionally fueled main and auxiliary machinery,” which can be a time-consuming and costly process [79]. LPG poses the greatest safety and survivability risk among all the alternative fuels, which may be too much risk despite its advantages.

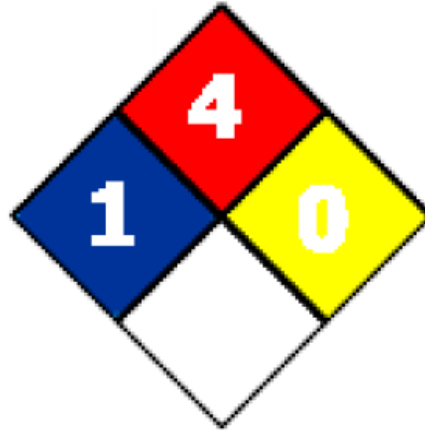


Figure 13. LPG NFPA Rating. Source: [76].

LPG has attractive features, similar to LNG, including its large industrial base, competitive economic basis, and high volumetric energy density. However, the low combustion limit and high relative density make LPG the most dangerous fuel in the event of a casualty.

4. Methanol

Methanol (CH_3OH) is a water soluble, biodegradable, colorless liquid at atmospheric conditions commonly used to help create plastics, paints, pharmaceuticals, and more [80]. Methanol is typically produced using fossil fuel feedstock and has been identified as one of the best potential fuels for NZE goals since it drastically lowers NO_x , SO_x , and particulate emissions. Since it is produced renewably or from fossil fuels, the methanol fuel supply would be secure. Similar to LNG and LPG, methanol is a fuel already being used in the marine industry with 22 methanol powered ships according to DNV [81]. Methanol's primary advantage over other popular alternative fuel options is its lack of extensive storage and handling requirements as an atmospheric condition liquid – similar to current fuels. Methanol's volumetric energy density is about half of diesel fuel at 18.2 MJ/L, requiring fuel tank capacity about 2.5 times larger than diesel or 1.3 times larger than LNG tanks. Although methanol is less energy dense than LNG or LPG, it requires no significant storage and handling precautions which would help lower cost and size of storage system (no cryogenic insulation). The lack of significant storage requirements

allows methanol to be comparable to LNG and LPG in gravimetric and volumetric energy density (see Figure 3).

From a safety and survivability standpoint, methanol is highly flammable and acutely toxic as shown by Figure 14. Methanol is heavier than air in gaseous form with a flammability range of 6–36%, a flash point of 54°F (evaporates easily), and an autoignition temperature of 897°F [82]. Methanol is similarly toxic to gasoline and diesel [83]. However, methanol powered ships are mature enough to already have commercial regulations for reference during potential design.

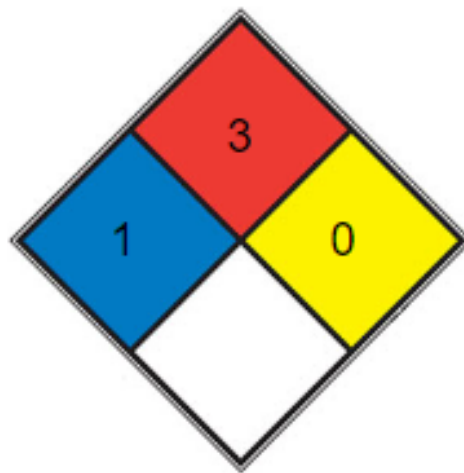


Figure 14. Methanol NFPA Rating. Source: [84].

Industrially, methanol is a well-known and available liquid that has been shipped internationally for decades, and it is currently among the top five chemical commodities [85]. Additionally, the world has over 100 ports with existing methanol infrastructure allowing for a highly available fuel [81]. Since methanol requires no special storage or handling requirements (similar to oil and gasoline), any port location with a methanol terminal or an oil bunkering facility could be modified with minimal investment to provide methanol as a marine fuel. In addition to the wide port availability, more than 30 production sites are planned worldwide to provide three megatons of supply [81]; however, much of the increased production is occurring outside of the United States. [86]. Nevertheless,

methanol production facilities are reasonably inexpensive at a capital investment price of \$1,000 per installed ton of production [87]. The capital investment to incorporate a methanol propulsion system is between the cost of a traditional diesel system and an LNG system [85]. Methanol is produced primarily using natural gas as a feedstock and process heat but much of the supply is expected to shift towards renewable sources in support of NZE. However, methanol may be produced synthetically from a two-stage chemical reaction using carbon dioxide and hydrogen gas as reactants [88]. The ability to produce methanol from these two basic reactants provides the future capability to produce methanol renewably at home, abroad, and at sea, assuming a platform capable of implementing a scaled up NRL patented process [14].

Economically, methanol contract prices vary significantly depending on the region. The contract price, as shown in Figure 15, is \$575, \$514, and \$332 per metric ton in the United States Gulf Coast, Rotterdam, and China, respectively [89]. As a comparison, diesel fuel costs about \$1,330 per metric ton and \$842 per metric ton at retail price and wholesale, respectively [90]. Keeping in mind the energy density differences (1 gallon methanol = .45 diesel gas equivalent) [75], the cost of methanol currently is competitive. If the United States can sufficiently optimize the balance of methanol production, demand, and export, this cost could become less than diesel fuel.

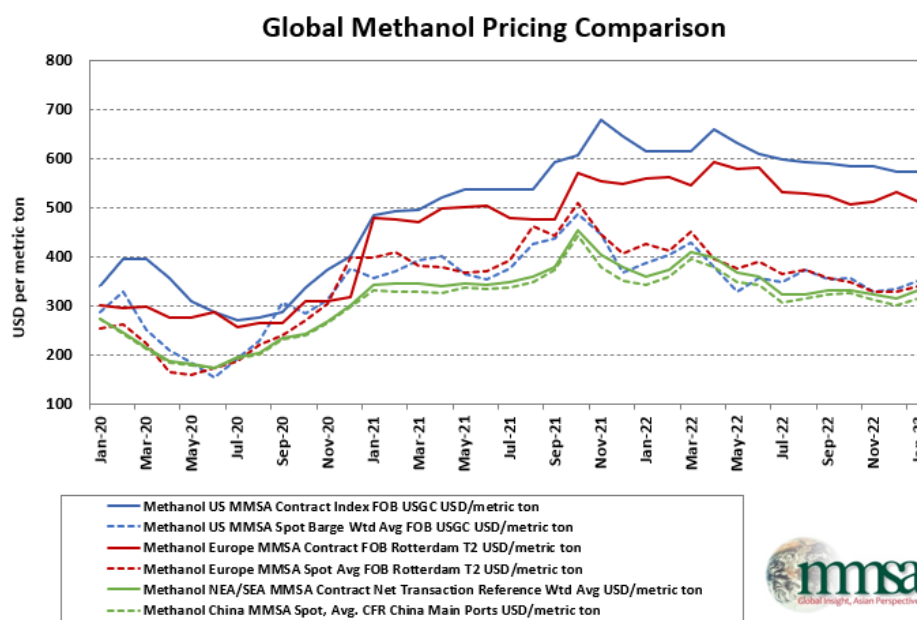


Figure 15. Methanol Market Services Asia Global Methanol Price Comparison. Source: [89].

The Asia-Pacific region is currently the world's leading methanol producer and consumer with over half of global production and 65% of demand [91]. Since the 2000s, the United States has been an importer of methanol, but it has recently increased its domestic production to become a net exporter of methanol and one of the top five exporters, as shown by Figure 16 [92].

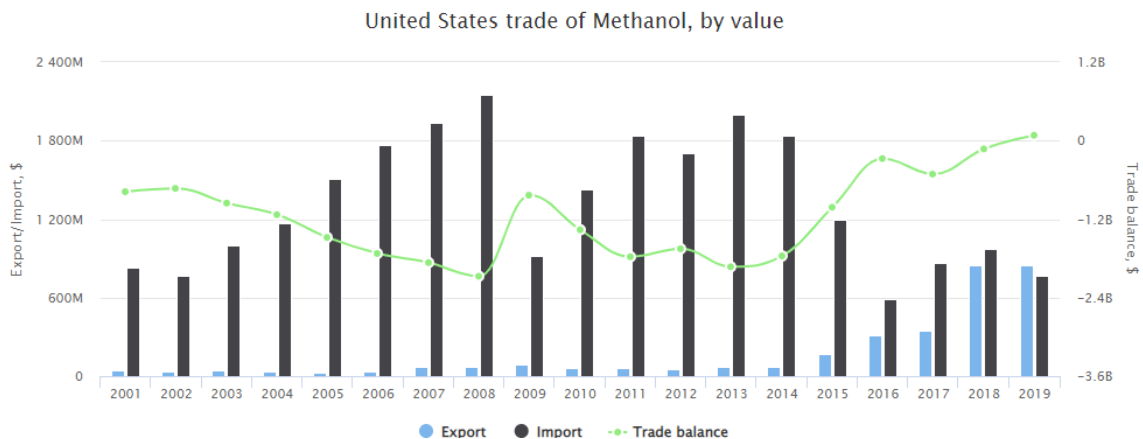


Figure 16. U.S. Export and Import of Methanol by Value. Source: [91].

Methanol provides a strong case among the alternative fuels as a replacement for F-76. Methanol, unlike most of the alternative fuels, does not require significant storage and handling requirements, similar to current diesel and gasoline fuels. The tradeoffs between storage requirements and energy capacity compared to LNG and LPG require closer inspection. Current methanol production and distribution facilities is limited within the United States primarily to the Gulf Coast region, which would require significant industrial scaling to be used as a fuel for the USN. However, the expansion of the industrial base is viable, especially since bunkering facilities are effectively the same as gasoline and diesel facilities at ports. Economically, methanol is already competitively priced and has strong potential to become even more favorable. Methanol is produced primarily using natural gas but may also be produced synthetically and from renewable energy sources, which would support the strategic goal of energy security and independence.

5. Hydrogen

Hydrogen power is often viewed as the holy grail of fuels since it has the highest molar energy density of non-nuclear fuels, it is the cleanest burning fuel, and it is the most abundant resource on Earth. Hydrogen power provides promise for the NZE goal, but hydrogen does not show promise as a marine fuel. The DNV Energy Transition Outlook does not project hydrogen to be used as a marine fuel through 2050 [46]. Hydrogen is ill-suited for current and near-future naval applications because of its extensive storage requirements and low volumetric energy density. Gaseous hydrogen is approximately 1/800th and 1/840th the density and volumetric energy density of liquid hydrogen, respectively [93]. Therefore, hydrogen must be liquified to provide the most viable solution. In its liquid state, hydrogen must be maintained below -252.8°C at atmospheric pressure to prevent boiling [94]. Despite the significantly larger volumetric energy density of liquid over gaseous hydrogen, it is only about 24% the density of F-76. On a naval vessel, space utilization and size are major considerations in design. By volumetric energy density alone, liquid hydrogen storage capacity must be approximately four times greater than F-76. The storage tank must be significantly larger to maintain the fuel at the necessary cryogenic temperature with minimal boil off gas to prevent tank over pressurization. Most common hydrogen storage tanks are pressure vessels, but this design is highly space

inefficient. Storage tanks of this design can easily be 30% larger than the internal fuel storage volume to account for the cryogenic storage requirements [93].

Hydrogen has a promising future for many energy applications, but it is not a feasible option for the USN.

6. Battery

Electric batteries are an emerging power source for the transportation industry for cars and ships. Modern batteries are primarily lithium-ion based as lithium has the highest theoretical capacity and lowest potential among known anode materials [95]. Battery powered vehicles have the ability to be powered by green electricity, which directly works towards achieving the NZE goal. Ships running on lithium-ion battery power will be quieter, odorless, and require less maintenance, manning, and labor to operate. Lead-acid batteries have an extensive history in naval applications for powering submarines since World War One, as a means to enhance survivability by providing greater stealth capability and an emergency backup power source. Lead-acid batteries have worked effectively for submarines and are still employed today for their maturity and reliability, but lithium-ion batteries represent a potential improvement for the future with advances in energy density and thermal management.

A recent study in 2022, performed by Naval Postgraduate Students, explored the potential cost efficiency of battery-powered warships vs. conventional warships. Their study revealed mechanic and electric manning decreases resulting in \$435M in annual savings, ship conversion costs would be between \$138M and \$256M, and \$38M to \$156M annual savings from converting the propulsion method [96]. Converting from conventional to battery powered would change the layout of a ship significantly, as there would no longer be a need for significant amounts of machinery or fuel storage – resulting in manning reductions.

Between 2008 and 2020, lithium-ion battery energy density has increased from 55 to 450 Wh/L [97]. Despite this significant advancement in a relatively short time frame, this volumetric energy density is insignificant in comparison to F-76 and the other fuels. Compared to F-76, the best battery capacity of 450 Wh/L is less than five percent of the

equivalent volumetric energy density. Similar to hydrogen, this volumetric energy density is insufficient as it would require a battery bank 20 times larger than the F-76 fuel capacity. The largest battery powered ship is a 100-m long and 16.3-m wide river cruise ship in China with a battery capacity of 7,500 kWh designed to travel up to 100 km on a single charge [98]. For comparison, a DDG at sprint speed will use its full 100,000 SHP engine capacity. Assuming the DDG sprints for one hour, the energy consumed would be about ten times greater than the capacity of the slower, smaller, and less capable cruise ship.

Battery power and technology have made significant strides, primarily due to the NZE initiative and its application to the transportation industry. Battery power has a strong future for commercial and industrial applications where volumetric energy density and space are not major concerns. However, naval engineering places a premium on space optimization and size as major drivers of cost. Unless battery power can continue its optimization growth, battery power has no future in the USN as the prime energy source for its large surface combatants.

7. Ammonia

Ammonia (NH_3) is a carbon free colorless gas under ambient conditions with a lower density than air [48]. As a result, ammonia must be cooled to a liquid state. As a liquid, ammonia has a low boiling point of -33.3°C at atmospheric pressure; at moderate pressures and room temperature conditions, the density is 0.61-0.68 metric tons per cubic meter with a lower heating value of 18.6 MJ/kg. Compared to conventional fuel, liquid ammonia has less than half the energy density by mass and about a third by volume. As a result, fuel storage tanks would be at least three times as large in volume requiring significant changes to ship design. Furthermore, ammonia propulsion is immature with gas burning engines only recently being developed for commercial application with the first market available engine in 2024 [99]. Ammonia burning engines are just now emerging due to specific fuel burning challenges including slow flame propagation and high auto ignition temperatures, which makes sustained internal combustion difficult. These challenges are most likely to be overcome using a dual fuel mixture of primarily ammonia (95%) and marine gas oil.

Ammonia has a distinct pungent, suffocating odor with a typical human concentration limit above the limit considered dangerous [48], which would require the use of detectors. OSHA sets exposure limits of 8-hours at 25 ppm and 15 minutes at 35 ppm [48]. High exposure as a gas or liquid can have irreversible health effects (as shown by Figure 17) and is a highly soluble molecule enabling the absorption by bodily fluids. Typical safety equipment and systems include water spray, emergency eye and body shower stations, and more robust ventilation systems. Additionally, ammonia provides material science and engineering concerns with zinc, copper, and steel alloys relating to corrosion and material performance. However, many of these material engineering concerns are known and may be minimized with proper material selection and storage conditions. Ammonia combustion eliminates sulfur emissions, particulate matter, and black carbon emissions, but ammonia will likely produce nitrogen oxide compounds and nitrous oxide. The nitrogen oxide emissions are expected to be similar to current fuels. Nitrous oxide provides a global warming potential of 265 (for reference carbon dioxide's potential is one) [48].

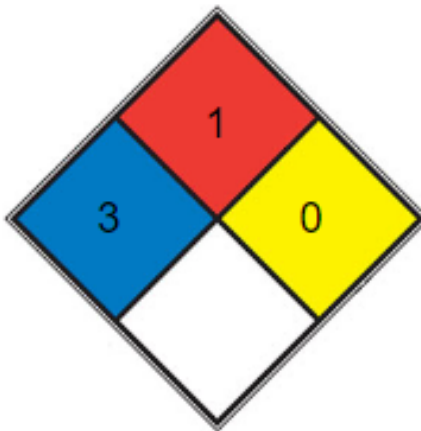


Figure 17. Ammonia NFPA Rating. Source: [100].

From an industrial standpoint, ammonia is primarily produced using Haber-Bosch processes requiring fossil fuel feedstock of natural gas, coal, and oil with respective percentages of 68%, 28%, and 4%. As of 2020, the United States is the third highest

ammonia producer at almost nine percent behind China (31%) and Russia (10%). Ammonia is primarily used for fertilizer (80%), so the agriculture sector provides a major resource competitor with significant socio-economic ramifications. In ports, there is little to no infrastructure beyond short term discharge storage from tankers as shown in Figure 18.



Figure 18. Worldwide Ammonia Ports. Source: [48].

Economically, ammonia is significantly more expensive at about \$1600 per metric ton [101] while LNG was \$10.33 per thousand cubic feet in April 2022 [102]. For a direct unit comparison, this equates to almost \$31,000 per thousand cubic feet of ammonia, which is almost 3,000 times more expensive. Ammonia production and cost are highly correlated with the global natural gas price despite the low cost of U.S. natural gas. The U.S. currently supplies about 86% of its ammonia demand, which means it likely has the potential to ramp up and meet expanded demand with internal resources if the cost per volume could be lowered.

Overall, ammonia provides a fuel with relatively strong fuel performance and storage metrics compared to other renewable sources. Ammonia poses significant safety and material concerns towards the survivability of the ship due to toxicity and corrosivity (especially regarding stress corrosion cracking). Furthermore, the economic and industrial perspectives provide significant concern due to the immature technology of ammonia

powered propulsion, lower commercial familiarity of marine ammonia handling than with fuels such as LNG and LPG, high dependence of agriculture on ammonia, and high cost per volume of the fuel. For these negative reasons, ammonia does not provide a strong alternative in the near future.

8. Nuclear

The USN has employed nuclear power since the 1950s beginning with the *USS Nautilus* and has maintained an impeccable safety record. During the Cold War, the nuclear navy expanded to the surface fleet with the introduction of the *USS Enterprise* (CVN-65) and the *USS Long Beach* (CGN-9). Based on the naming convention for naval reactors, the USN also had plans to extend nuclear power to the DDG class. The nuclear powered DDGs never materialized and most of the CGNs were retired early due to high costs in construction and life cycle support. For example, the *USS California* (CGN-36) had a crew of approximately 600 and the *USS Ticonderoga* (CG-47) had a crew of 330 despite similar combat capabilities [103]. Ultimately, the surface combatant fleet nuclear concept was relinquished for a conventional fleet of similar capability.

Nuclear power provides numerous unparalleled advantages such as near unlimited endurance, greater power production, and higher speed. These inherent design advantages provide strategic, operational, and tactical benefits other surface ships cannot match. However, nuclear power has many disadvantages including high capital cost, greater manning and training requirements over conventional Sailors, and limited capability for production and maintenance. Despite the higher initial cost, reactors are commonly designed to last at least as long as the ship; therefore, the ship only requires maintenance.

The USN has four public shipyards capable of life cycle support of nuclear-powered vessels and two shipyards capable of building nuclear-powered vessels [104]. As of 2022, the public shipyards all had been experiencing significant delays in completing submarine maintenance and these delays are expected to continue for the next 30 years [105]. As it stands, the U.S. does not have the capability to expand its nuclear-powered vessel construction and support without a significant investment of resources. The U.S. Navy's 2023 Shipbuilding Plan already has an aggressive plan to increase the fleet size

from 292 today to 316–367 ships by 2052 with the assumption the aforementioned delays will be resolved this decade [50]. The USN simply does not have the financial capability or Congressional confidence to deviate from this plan by replacing proposed conventional surface ships to nuclear powered. According to the most recent CBO analysis of the nuclear cost effectiveness in 2011, a nuclear-powered fleet of destroyers would become cost effective if oil prices increased to at least \$223 (\$290 in 2022-dollar value) in 2040 [106]. The 2022 EIA's highest estimate has oil prices in 2040 at about \$155, almost half of the needed breakeven price [8]. Additionally, the CBO estimated the life cycle support costs of a nuclear fleet would be 19% higher than a conventional fleet and the cost of constructing a nuclear DDG would also be 19% higher [106]. Applying this estimate to today's shipbuilding costs for a DDG results in a nuclear DDG costing at least \$2.6B instead of \$2.2B [107].

In addition to higher capital and life cycle support costs of nuclear vessels, the manpower and training aspect is significantly more expensive for nuclear trained personnel in comparison to conventional. Reviewing pay and allowances of enlisted personnel only, there is a significant difference in bonuses between nuclear trained personnel and their conventional contemporaries. Based on enlistment bonuses, the three nuclear trained rates are each authorized up to \$38,000 whereas most other ratings are capped at \$15,000 [108]. Based on reenlistment bonuses, the nuclear trained ratings are authorized up to \$100,000 and the highest conventional equivalent is capped at \$75,000 with most less than \$60,000 [109]. Based on the FY22 U.S. Navy President's budget submission, \$26.6 billion of the total \$211.7 billion budget (12.6%) was allocated to personnel pay [110]. Without access to detailed manpower information, an accurate estimate of the change in personnel pay would be impossible. Qualitatively, the transition to a primarily nuclear-powered force with no conventional combatants would be a significant increase in personnel funding. Based on the 2021 force structure, 154 non-nuclear surface combatants (e.g., DDG, CG, LHD, LHA) and their appropriate crews would need to be transitioned to nuclear equivalent.

The future may still be nuclear with the evolution of the nuclear industry towards small modular reactors (SMR). These systems have only been designed for commercial

use and thus far have not been built. The NuScale SMR is a 77 MWe module and is the only Nuclear Regulatory Commission approved SMR. The estimated cost of a single NuScale SMR module has risen by 75% in one year from \$880M to \$1.55B [111]. Industry and Naval Reactors must develop a relatively inexpensive reactor plant requiring less training and manning before nuclear can make fiscal sense. Despite the great benefits provided by nuclear power, transitioning the surface fleet to nuclear power is untenable by financial analysis alone.

D. CONCLUSION

All the alternative fuels have their strengths, weaknesses, and applications for the future to secure energy independence and achieve goals set forth by the NSS and NZE 2050. Any naval marine fuel replacement to petroleum will require compromise due to its importance to the U.S. and the world based on its political, economic, and industrial significance. Most of the alternative fuel options have common weaknesses such as lower volumetric energy density (Figure 3), smaller infrastructure base, and smaller economies of scale. Petroleum (F-76) is the ideal option to continue to power the U.S. non-nuclear surface fleet, but it provides the shortest outlook for use based on the oil reserves and production rate. As a result, an alternative fuel for tomorrow's fleet must be explored.

Weighing the political, industrial, economic, and fuel performance characteristics immediately eliminates several alternatives including hydrogen, battery, ammonia, and nuclear power. Hydrogen and battery simply are not volumetrically energy dense enough to provide a viable alternative as the volume dedicated to the fuel would increase by at least a factor of seven. Nuclear is a great alternative in many aspects except the economic case: the operational support cost increases by a minimum of 20 percent, the capital expenditure only becomes viable after oil reaches prices far exceeding the high estimate, and personnel costs for recruiting and retention would drastically increase. Ammonia offers great potential as a commercial shipping fuel for NZE 2050 goals, but it is significantly more expensive than the alternatives with lower fuel performance.

The remaining fuels (LNG, LPG, and methanol) require a more stringent review to filter and select the best option. All three fuels have comparable volumetric energy and

gravimetric energy densities, have potential to be significant energy sources for commercial shipping, currently have high technology readiness levels, and have strong industrial bases with the ability to grow. All three fuels are also more dangerous than diesel fuel based on their NFPA ratings.

Methanol is a significant synthetic chemical used throughout the world relying primarily on natural gas but aligns with the NZE 2050 goals with fuel combustion byproducts. Methanol is primarily used as a building block for the production of a wide array of products with a growing interest as a clean, sustainable fuel for land and marine vehicles. Methanol is the only liquid at room temperature allowing for the highest volumetric energy density (~16 MJ/L), simplifying the storage requirements on ships and at bunkering facilities. Methanol infrastructure would likely require a significant increase for production, transport, and storage to support the USN domestically and abroad. Methanol poses a significant threat to safety and survivability as it is highly flammable and heavier than air creating a significant risk for explosion.

LPG and LNG share many political, economic, industrial, and fuel performance qualities with a few key differences. The primary advantage LPG holds is the higher volumetric energy density due to its less stringent storage requirements. The primary disadvantages of LPG are its significantly lower maturity as a marine fuel and greater survivability risk due to lower flammability limit and high relative density. LNG and LPG are rated similarly by the NFPA for toxicity and flammability but have significantly different material characteristics that have allowed LNG to emerge as one of the preeminent marine shipping fuels.

LNG is the most mature marine fuel of the remaining alternatives with an outstanding safety record in shipping despite its high NFPA safety ratings. LNG has the lowest volumetric energy density, due to the cryogenic storage temperatures, but may be stored at atmospheric pressure requiring the fuel storage to increase by a factor of three approximately. The fuel has significant supply and production capabilities in the U.S. and abroad leading to the lowest price for fuels. Additionally, the potential to create SNG from seawater for liquefaction provides the ability to have unlimited fuel, assuming it is cost competitive. The U.S. has a robust supply chain infrastructure of natural gas pipeline,

liquefaction facilities, and LNG bunkering domestically, but it would require expansion of liquefaction and LNG bunkering capability to major fleet concentration areas. International key strategic partners also have significant LNG primary and secondary industrial capabilities allowing for a supply chain infrastructure similar to petroleum, including the world's leading LNG vessel builder in South Korea. Until a new fuel emerges or known fuels become more competitive, LNG is the best alternative fuel option for non-nuclear surface ships as the U.S. and the world transition from oil powered ships.

IV. LITERATURE REVIEW AND SYSTEM METHODOLOGY

A. INTRODUCTION

The Literature Review section will provide a capability baseline for the DDG-51 class fueled by F-76 focused on fuel related factors and naval architecture concerns including survivability, storage, operational range, and stability. The majority of the section will focus on LNG and SNG capability and viability as an alternative fuel. A brief overview of LNG's history and industrial base will be included in addition to the information provided in the previous section. The focus will be on LNG technology and potential challenges for implementation. Due to their similarity, LNG and SNG will be considered synonymous with the exception of the production method: LNG is extracted and processed; SNG is synthesized.

B. ANALYSIS

1. DDG Baseline Characteristics

a. Ship Characteristics

The following report shown in Figure 19 displays the DDG Flight I baseline information for ship principal characteristics, weight summary, and propulsion. The primary result of the design phase will be the change in fuel related characteristics and their effect on the principal characteristics of the ship. The primary fuel characteristic from the DDG Flight I baseline is the usable fuel metric (1,145.5 metric tons (t)) as this value must be matched equivalently for LNG conversion to determine the tank storage volume, total tank volume, and impact to ship characteristics. The usable fuel metric is 40 percent of the total fuel volume. The fuel mass will be converted to determine the energy equivalent amount from the baseline to reverse engineer the weight and volume of the LNG fuel.

PRINCIPAL CHARACTERISTICS - M		WEIGHT SUMMARY - MTON	
LBP	142.0	GROUP 1 - HULL STRUCTURE	3041.4
HULL LOA	150.0	GROUP 2 - PROP PLANT	756.8
BEAM, DWL	18.0	GROUP 3 - ELECT PLANT	319.7
DEPTH @ STA 10	12.7	GROUP 4 - COMM + SURVEIL	437.5
DRAFT TO KEEL DWL	6.3	GROUP 5 - AUX SYSTEMS	842.2
DRAFT TO KEEL LWL	6.1	GROUP 6 - OUTFIT + FURN	675.9
FREEBOARD @ STA 3	8.1	GROUP 7 - ARMAMENT	320.0
GMT	1.6	-----	-----
CP	0.615	SUM GROUPS 1-7	6393.6
CX	0.822	DESIGN MARGIN	31.7
		-----	-----
SPEED(KT): MAX= 31.3 SUST= 30.0		LIGHTSHIP WEIGHT	6425.4
ENDURANCE: 3808.0 NM AT 20.0 KTS		LOADS	1710.3
		-----	-----
TRANSMISSION TYPE: MECH		FULL LOAD DISPLACEMENT	8135.7
MAIN ENG: 4 GT @ 19220.4 KW		FULL LOAD KG: M	7.2
		-----	-----
SHAFT POWER/SHAFT: 37487.0 KW		MILITARY PAYLOAD WT- MTON	1115.8
PROPELLERS: 2 - CP - 5.2 M DIA		USABLE FUEL WT - MTON	1145.5
SEP GEN: 3 GT @ 2500.0 KW			
24-HR LOAD	2412.1	OFF CPO ENL TOTAL	
MAX MARG ELECT LOAD	3666.5	MANNING 26 24 291 341	
		ACCOM 29 27 321 377	
REQUIRED AREA SUMMARY - M2		AVAILABLE AREA SUMMARY - M2	
OTHER AREA	- 5021.	HULL AREA	- 4248.
SUPERSTRUCTURE AREA	- 1284.	SUPERSTRUCTURE AREA	- 1867.
-----	-----	-----	-----
TOTAL AREA	- 6305.	TOTAL AREA	- 6115.
REQUIRED VOLUME SUMMARY - M3		AVAILABLE VOLUME SUMMARY - M3	
OTHER VOLUME	- 24744.	HULL VOLUME	- 22791.
SUPERSTRUCTURE VOLUME	- 3230.	SUPERSTRUCTURE VOLUME	- 5437.
-----	-----	-----	-----
TOTAL VOLUME	- 27974.	TOTAL VOLUME	- 28228.

Figure 19. DDG Flight I Baseline Report

b. Survivability

Combat survivability is an engineering discipline aimed to develop systems with the capability to avoid or withstand man-made hostile environments. The two main factors of survivability are susceptibility and vulnerability. These two concepts are defined as the inability to avoid or withstand, respectively, damage caused by the man-made environment [112]. Survivability must be incorporated at the beginning of a design and considered throughout, as it is difficult to improve survivability after a design is completed. Survivability of a system is improved by reducing susceptibility and vulnerability in the following twelve survivability enhancement concepts, as shown in Table 3.

Table 3. Survivability Enhancement Concepts. Adapted from [112].

	Susceptibility Reduction	Vulnerability Reduction
1	Situational Awareness / Threat Warning	Component and System Redundancy (w/ effective separation)
2	Signature Control	Component Location
3	Electronic Noise Jamming and Deceiving	Passive and Active Damage Suppression
4	Expendables	Component and System Recovery
5	Threat Suppression and Offensive Weapons	Component Elimination or Replacement
6	Mission Planning, Tactics, System Performance, Crew Training and Proficiency	Component Shielding

As the baseline ship, the DDG-51 class was designed to fulfill all forms of naval warfare: Anti-Submarine Warfare, Anti-Surface Warfare, Anti-Air Warfare, Ballistic Missile Defense, and Strike Warfare. In order to execute these types of warfare, the DDG-51 leverages its susceptibility reduction measures as the primary means of enhancing survivability through various technologies and systems including the AEGIS combat system. The following sections provide a brief discussion of the concept and an overview of how the DDG meets the survivability enhancement concept. Each section will conclude with a recommendation for analysis based on applicability to fuel selection.

(1) Susceptibility reduction concept one: Situational Awareness (Threat Warning)

This concept focuses on the ability of the system to identify threats through the use of sensors, such as radar. The DDG uses multiple radars for threat identification and tracking with the AEGIS combat system for surface, air, and sub-surface threats. AEGIS

also boasts the cooperative engagement capability to share information among multiple members of a group via the appropriate link among other capabilities. The transition to an LNG fuel system will not impact the situational awareness concept.

(2) Susceptibility reduction concept two: Signature Control

Signature control or management relates to the ability to reduce the specific signature below the weapon system's sensor threshold and the signature to background contrast [112]. The primary signatures for ships include radar cross section (RCS), the electromagnetic, sonar, infrared, and visual signature of the ship. The non-visual signature of any large surface combatant will unavoidably be significant without a revolutionary change in ship geometry. The incorporation of the LNG fuel storage system will increase the size of the ship, and any alteration to the ship geometry beyond basic parameters is outside the scope. Most of these signatures are only obtainable from complex computations or experimental testing results, so the quantitative impact will not be discussed. Qualitatively, the signatures would be expected to increase by an insignificant amount based on the size increase of the ship with all other design factors constant. Signature control will not be analyzed further.

(3) Susceptibility reduction concept three: Electronic Noise Jamming and Deceiving

This concept covers the electronic attack capabilities for contested environments. The DDG-51 houses much of its electromagnetic warfare capabilities within the ship's signal exploitation suite and associated hardware. The incorporation of LNG will have no impact on this concept.

(4) Susceptibility reduction concept four: Expendables

Expendables are the last layer of susceptibility reduction to provide false targets to weapon systems to avoid damage to the ship. The common expendables include chaff, Nulka, flares, and towed decoys. Incorporation of LNG will have no impact on this concept.

(5) Susceptibility reduction concept five: Threat Suppression and Offensive Weapons

This concept involves the use of weapons and systems to eliminate threats before or after firing to avoid potential damage. Conventional methods of eliminating a threat are achieved with anti-ship missiles (Harpoon), surface-to-surface missiles (Tomahawk), surface-to-air missiles (SM-1, SM-2, SM-3, SM-6, ESSM), and torpedoes for sub-surface threats. The surface-to-air missiles also enable the ability to destroy incoming hostile missile threats prior to requiring the use of expendables. Incorporating LNG fuel storage will have no impact on this concept.

(6) Susceptibility reduction concept six: Mission Planning, Tactics, System Performance, and Crew Training and Proficiency.

The concept will primarily relate to the crew training and proficiency aspects, as the non-fuel related ship capabilities are unchanged. Therefore, the ship will still be assumed to execute operationally as designed. Current conventional and nuclear systems are well understood with robust training programs for both. The LNG storage and transfer systems would be new and unfamiliar to current personnel. These potential effects are not possible to determine quantitatively and are difficult to project qualitatively. If the USN decided to implement LNG fueled ships, appropriate training facilities and programs would be required to train Sailors to properly operate and maintain the systems. Therefore, the qualitative impact on survivability would be negligible under the assumption the Sailors would be sufficiently trained to operate the platform they are assigned, as is the current assumption with conventional and nuclear-powered ships.

(7) Vulnerability reduction concept one: Component and System Redundancy with Effective Separation.

This concept focuses on the use of multiple devices, structural elements, parts, or mechanisms to provide redundancy. The level of redundancy can be total, partial, or functional depending on the design. Redundancy without effective separation is reliability but not actual redundancy [112].

The ship fuel storage system is a large and critical system. Similar to current designs, only one fuel storage system can be supported. For important components in the fuel storage system, as will be discussed in the following sections, the integration of LNG will follow closely with industry standards that already incorporate redundancy as part of the safe and robust design of the systems. This vulnerability reduction concept will not be affected by a fuel change with appropriate fuel system incorporation.

(8) Vulnerability reduction concept two: Component Location.

This concept is core component in vulnerability reduction and ship design as the positioning of a critical component or system may reduce the probability a damage mechanism will produce lethal damage [112]. The fuel storage system is a critical system, as the ship cannot function without fuel. The ship relies on fuel for propulsion and electrical generation and without either will be dead in the water. Space on a ship is at a premium and the fuel storage system is large. The various methods of reducing vulnerability with component location such as orientation are difficult to implement with little to no design trade space. The logical location for the system must be internal near the bottom of the ship to incorporate its large size and weight. The quantitative impact of the change in size of the fuel storage system could be calculated provided sufficient operational testing and evaluation data regarding expected hostile threats and their lethality. Qualitatively, the fuel storage system vulnerability will be analyzed primarily based on the change in size of the system and ship.

(9) Vulnerability reduction concept three: Passive and Active Damage Suppression

Passive damage suppression for current ships relies on ship design and materials. The primary dangers to ships are fire and flooding. Compartmentalization is a requirement primarily to minimize the impact of flooding on stability. Effects created by successful hostile threats, such as fragmentation, pose significant threat to personnel and ship components. DDG 51s incorporate Kevlar armor in critical spaces throughout the ship to minimize damage from cascading effects, especially to personnel.

Active damage suppression, also known as damage control, is a significant aspect of crew knowledge and proficiency to maintain the ship in combat scenarios. Damage control teams and lockers are strategically positioned throughout the ship in critical areas to react quickly to damage, primarily fire and flooding. These teams are trained and equipped to fight class Alpha, Bravo, and Charlie fires, primarily, with F-76 specifically posing a class Bravo threat. The firefighting doctrine of the USN standards are contained in the NAVSEA Industrial Ship Safety Manual for Fire Prevention and Response [113].

The passive damage suppression concepts of compartmentalization and defragmentation will not be affected except potential extension. Active damage suppression methods will need to be adapted for LNG from F-76 in the event of a leak, as the primary fire threat will change from class Bravo to class Charlie.

(10) Vulnerability reduction concept four: Component and System Recovery

Recovery is the component or system's capability to return to a functional level after sustaining damage. The method of recovery may be active or passive. An example of passive recovery may be a self-sealing tire. A fuel storage tank is primarily static in construction with a few internal passive or active systems for monitoring and control. A compromise to the integrity of the fuel tank has no means of system recovery beyond repair or replacement to recover the structural integrity of the tank. Replacement of a fuel tank is not a viable option. Repair of a diesel or LNG fuel tank, beyond a temporary patch, would require welding. Either fuel tank would need to be emptied and thoroughly inspected to repair more permanently. Due to the wide range of damage possible to the fuel tank, this concept will not be explored further.

(11) Vulnerability reduction concept five: Component Elimination or Replacement

This concept focuses on removing vulnerability by eliminating or replacing components that are unnecessary [112]. The fuel storage system is a critical system and cannot be eliminated or replaced. This concept will not be explored further.

(12) Vulnerability reduction concept six: Component Shielding

Component shielding is the use of coatings or protective materials to resist or absorb damage mechanisms [112]. The DDG-51 incorporates an all-steel construction to protect all vital internal components except for the mast superstructure, which is aluminum to minimize impact on stability. The fuel storage tank is currently constructed to maintain the fuel with no additional shielding. An LNG fuel storage system will have the same vulnerabilities to damage as an F-76 fuel tank. The primary means to reduce vulnerability are in place with the hull material, location, and damage suppression methods. The component shielding concept will not be explored further.

2. LNG Storage Tank Design

LNG storage tank design is a major design factor for an LNG fueled ship as it directly impacts the safety, survivability, and size of the vessel. The LNG storage tank requirements are highly regulated by federal and international organizations (e.g., IGC code) to ensure safe and effective storage. The IGC code contains specific regulations addressing safety and structural aspects including material selection, material testing, leak prevention and mitigation, and pressure and temperature control [114]. These requirements provide a well-documented and understood baseline for military application.

The design of an LNG storage solution has the singular of storing the LNG fuel at the specified temperature and pressure based on tank design to maintain liquid conditions. At ambient pressure conditions, the LNG must remain at -160°C or lower. As discussed in the analysis of alternatives section, LNG is an inherently dangerous fuel which poses multiple risks that must be identified, analyzed, accepted, or controlled. The design of an LNG storage tank solution requires understood regulations, multiple subsystems, and inherent overall design choices to successfully implement as illustrated by Figure 20.

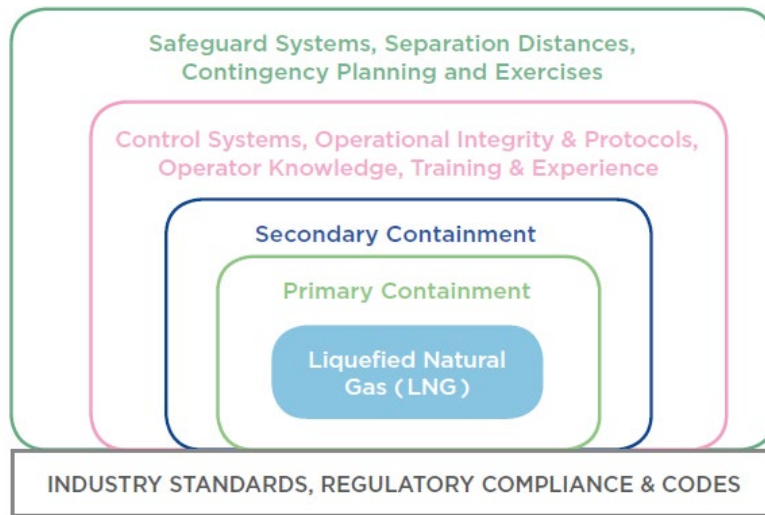


Figure 20. LNG Risk Model for Storage System Design. Source: [115].

The following sections discuss the various layers of the LNG storage system concept model working from the inside out. For the purposes of this section, the two containment levels in the diagram are condensed into one to further explore the design and tradeoff space. Additionally, the outside layer is excluded from the analysis as emergency response procedures and training are well-understood from an LNG and USN perspective.

a. Primary Layer: Containment

The first layer, containment, is primarily required to hold the liquid and maintain its liquid state conditions based on tank design. The cryogenic conditions necessary to maintain the liquid state make the fuel dangerous to the touch and susceptible to boiling into boil off gas (BOG), which inherently requires significant insulation and structural integrity with a limited material selection.

The materials for any containment level expected to potentially contain LNG must be able to withstand sustained cryogenic temperatures through direct contact. This first layer is the most important as it must withstand the stress and strains of various sea state conditions (hog and sag) with increased probability of failure due to the ductile-to-brittle transition phenomenon. The ductile-to-brittle transition is related to the temperature dependence of the measured impact energy absorption [116]. The transition temperature

characterizes the fracture mode as brittle or ductile. At lower temperatures, the metal is more likely to brittle fracture which tends to require less impact energy. Brittle fracture is characterized by its sudden and catastrophic failure, which eliminates physical warning indications.

The best internal containment material requires a low transition temperature to maintain its ductility and toughness. The industry standard for this primary internal containment layer is 9% nickel steel (Fe-9.0Ni), a specific type of 304L stainless steel [117], Invar steel, a 36% nickel-steel alloy (Invar-36) [118], or 316L stainless steel [119]. Table 4 provides the material composition of each stainless steel commonly used for primary containment. Invar-36 is commonly used for its low coefficient of thermal expansion and low tendency to fatigue in cryogenic environments [120]. 304L and 316L stainless steels are similar in performance, but the primary advantage of 316L steel is its improved corrosion resistance, especially in marine environments [121].

Table 4. Primary Containment Material Composition. Source: [120], [122].

Composition (%)	304L	316L	Invar-36
Fe	Balance	Balance	balance
Cr	18-20	16-18	0.5
Ni	8-10.5	10-14	35-37
Mo	-	2-3	-
Mn	2	2	0.5
Si	0.75	0.75	0.5
N	0.1	0.1	-
P	0.045	0.045	-
C	0.08 max	0.03 max	0.1

The modern industry standard for insulation is polyurethane foam (PUF) with plywood, if additional reinforcement is required for structural support [123]. As shown Figure 21, Fe-9.0Ni is able to maintain a relatively constant Young's Modulus over a large temperature range maximizing its toughness while maintaining its ductility. The vertical lines indicate the expected operating temperature (green) and the lowest temperature ductility requirements can be met (orange) [124].

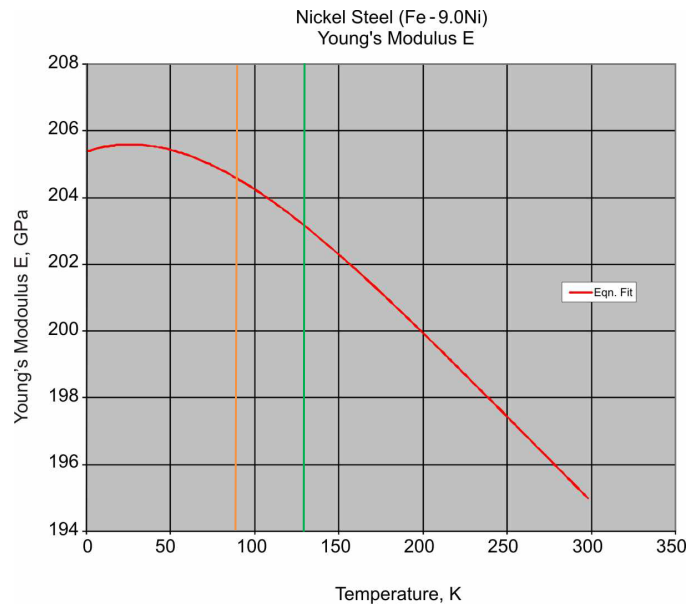


Figure 21. Young's Modulus vs. Temperature of Fe-9.0Ni. Adapted from [125].

Heat transfer from outside the fuel tank into the LNG and fuel agitation is inevitable according to the second law of thermodynamics and sea motion; therefore, insulation is required to minimize heat transfer and the subsequent production of BOG. LNG is not susceptible to combustion as a liquid, but the production of BOG makes potential leaks dangerous since the combustion range is 5–15% with an auto-ignition temperature of 599°C [56]. As a result, BOG generation must be specified appropriately to minimize risk to tank integrity from pressure buildup (depending on shape) and combustion in the event of a leak or rupture. BOG management is discussed in more detail in the following section for control systems but is typically specified at 0.1% to 0.15% of the LNG volume per day

[123]. The BOG rate is known for many tank sizes based on industry shipping standards but unique tank designs and sizes must be calculated. The shape and size has a significant impact on the BOG rate. Smaller tanks suffer from higher BOG rates due to a higher surface area to volume ratio than the large tanks used by cargo ships.

There are multiple ways to categorize the type of storage tank for the containment layer in the risk model. LNG containment relies on several interrelated tank design concepts: operational pressure range and tank shape, integrity level, and installation method.

(1) Pressure and Tank Shape

LNG is commonly stored in one of two pressure ranges: pressurized and atmospheric [115]. The pressure level and tank shape are interconnected and are determined based on the operational profile of the vessel, which is closely tied to vessel size for commercial ships. Pressurized tanks must be pressure vessels, which are spherical or cylindrical. Atmospheric pressure storage tanks are typically prismatic. Pressurized tanks are less space efficient than atmospheric pressure tanks but provide the greatest operational flexibility with greater inherent BOG management. Figure 22 demonstrates the prismatic design is 50% more space efficient than cylindrical.

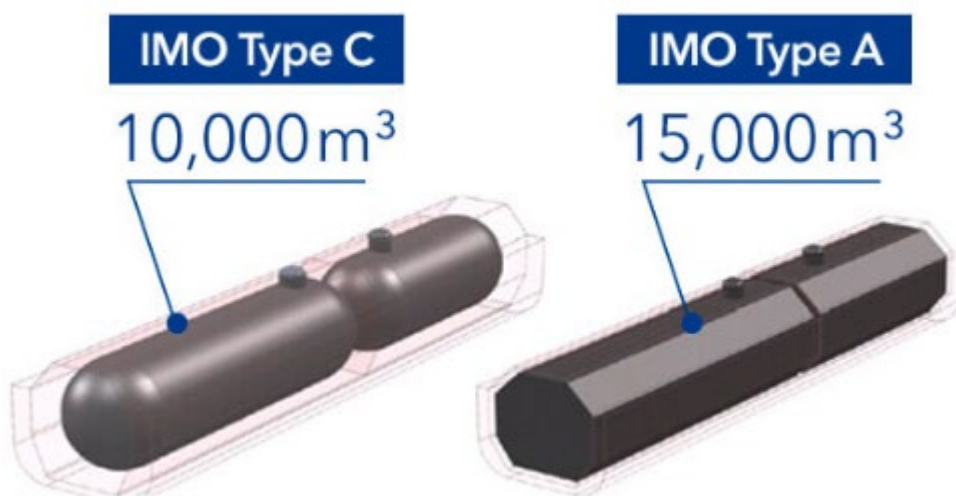


Figure 22. Cylindrical vs. Prismatic Tank Volume Efficiency. Source: [126].

(2) Integrity Level

LNG tanks have three integrity levels of containment when designing a tank: single, double, and full integrity. Single integrity tanks use a single self-supporting cryogenic steel layer to hold the liquid surrounded by an outer tank which holds insulation material in the annular space. The outer tank is designed to provide structure, protect the insulation, and contain vapor pressure, but it is incapable of containing the LNG if a leak occurs, as it is not cryogenically rated. A double integrity tank uses a cryogenically rated metal for the inner and outer tank, allowing the inner tank to be liquid and vapor tight and the outer tank to be liquid tight. The full integrity system is designed such the inner and outer tank are liquid and vapor tight [115]. Increasing the integrity level of a system increases the safety and survivability but also increases the cost. Figure 23 provides a simple flow diagram to determine the integrity classification of LNG tank designs. Using the materials discussed previously, a full integrity system would likely use the same inner layer material (304L or Invar-36) for the outer layer with PUF as insulation in between.

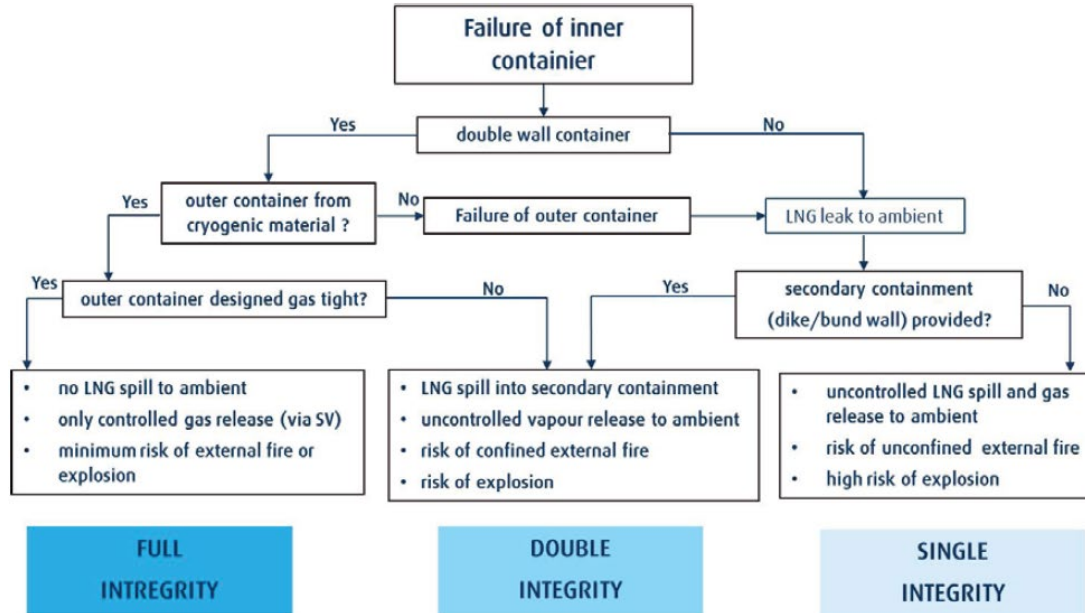


Figure 23. LNG Tank Design Integrity Classification Flow Diagram. Source: [127].

(3) Installation Method

The LNG industry uses two methods of installation that affect how the storage tank interfaces with the ship's hull: integrated and independent. Integrated tanks, commonly referred to as membrane tanks, are non-self-supported tanks, meaning they are built as part of a double hull ship structure [123]. Membrane tanks consist of alternating layers of metal barrier membranes and insulation such that stresses caused by expansion and contraction are compensated for without undue stressing of the membrane, as shown in Figure 24 [123]. Membrane tanks are exclusively prismatic in shape, so they require strict pressure (BOG) control and management. Membrane tanks are designed to withstand a maximum pressure of 0.7 barg [55], but the recent membrane Mark III tank designed by the Gaztransport and Techniaz (GTT) company may withstand up to 2 barg [128]. Since membrane tanks are built as part of the hull, they provide the lowest addition of weight.



Figure 24. Generic Membrane Tank. Source: [123].

Independent tanks are self-contained and self-supported structures that do not form a part of the ship's hull structure or contribute to the hull strength [123]. These tanks are prefabricated then installed during construction by connecting to supporters that are welded

to the ship's structure. Independent tanks are categorized into three types as defined by the IGC Code [55]: Type A, Type B, and Type C.

Type A tanks are built similar to standard oil tank design (prismatic) giving them high volume efficiency. Type A tanks are typically full integrity prismatic tank systems, similar to membrane construction, as can be shown by comparing Figure 24 and Figure 25. Type A tank systems are heavier and slightly less space efficient than membrane systems, as they are independent tanks requiring robust connectors to the hull.

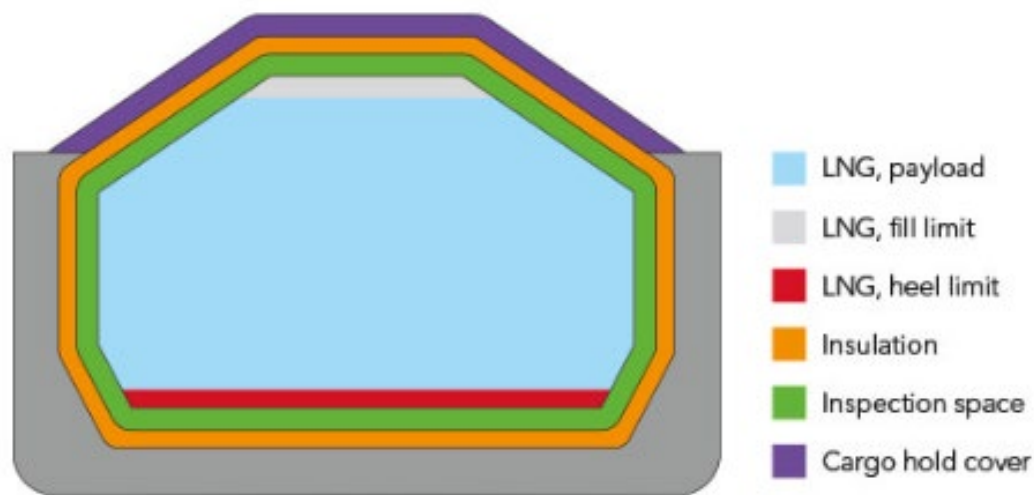


Figure 25. Torgy Type A Containment System Diagram. Source: [126].

Type C tanks are pressure vessels, typically cylindrical. Type C tanks are most commonly used on small-scale LNG carriers, which are defined as ships carrying less than 30,000 m³ of LNG as cargo or fuel [129]. The DDG baseline is classified as a small-scale LNG carrier, as it will use approximately 6,000 m³ of LNG as fuel. Type C tanks are the least space efficient but also the least expensive.

Type B tanks are any tanks that do not fall into the Type A or C category [123]. The U.S. Coast Guard considers all LNG tanks to be Type B tanks, as they inspect each tank for safety and integrity on a standard method. Type B tanks are most commonly designed using a spherical or prismatic shape.

b. Secondary Layer: Control Systems and Operations

Beyond the primary containment layers, the physical storage system includes external safety equipment and operators. The LNG industry adheres to an international network of codes and standards that specify safe technologies, materials, and designs to ensure a high level of safety. These standards provide a simple blueprint to follow for integrating an LNG containment system with appropriate secondary systems for monitoring, control, and mitigation of incidents backed up with extensive operator training, emergency procedures, and routine inspections [59]. With these regulations, codes, and standards, the LNG industry has a near flawless safety record with only one major incident early in the industry timeline and a few minor LNG spills during transfer operations [58].

A significant aspect of safeguarding a system and the ship beyond the primary containment layer involves the management of BOG. As discussed previously, LNG is not combustible but the gaseous form (natural gas) is combustible between a concentration in oxygen of 5–15% provided a sufficient heat source. BOG management directly reduces and mitigates the risk of BOG. Figure 26 expands the secondary and tertiary layers of LNG storage risk reduction and mitigation methods. The following sections expound upon each of these sublayers.

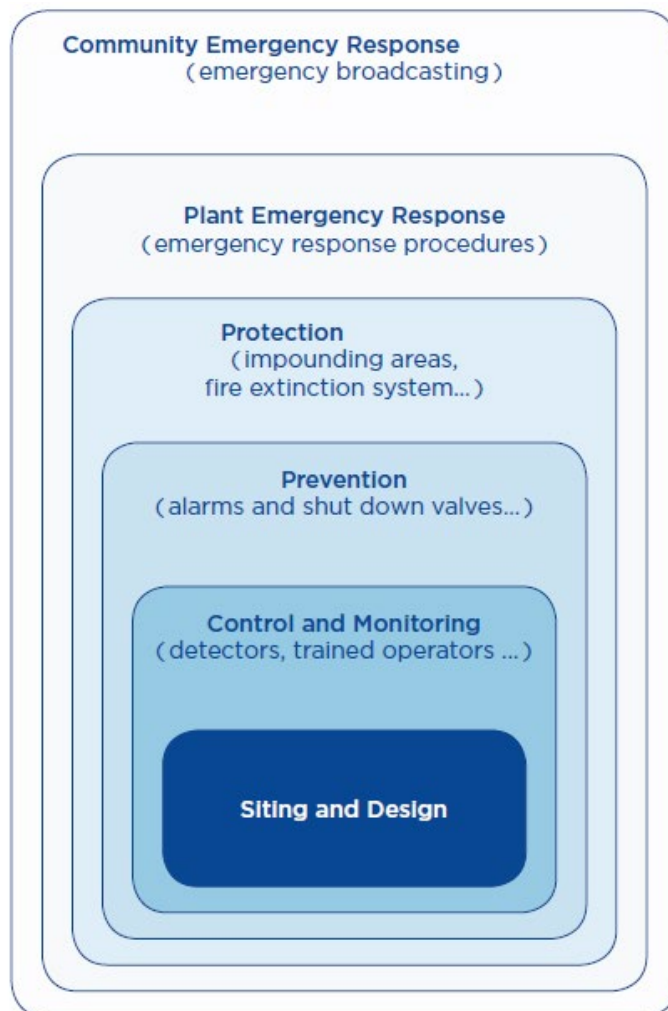


Figure 26. LNG Risk Reduction and Mitigation Layers Excluding Primary Containment. Source: [59].

As a warship, survivability of design must be incorporated from the beginning. For the most survivable design from expected hostile threats (e.g., torpedo, mine, missile, etc.), the storage system must be located internally to minimize vulnerability. Internal space aboard a ship is at a premium so compromises in ship design and layout must often be made. Regardless, best efforts should be made to isolate the storage tank space from the rest of the ship and eliminate any potential heat sources. The LNG tank placement would follow closely with conventional diesel fuel tank placement along the bottom of the ship. In the event of a leak, the BOG would have no ignition source except for battle damage scenarios. The tank should also be located in close proximity to any system fuel would be

transferred from or into. The proximity in location would minimize the transfer distance to minimize BOG formation from heat added by pump work or friction and minimize monitoring and control of the transfer system.

Next, the primary containment system must be equipped with internal systems for temperature and pressure monitoring, tank level, and pressure control. The internal monitoring systems provide the ability to detect deviation from acceptable parameters, which would allow for corrective action. These detectors are typically placed near likely LNG release or vapor accumulation locations [59]. These systems must be monitored continuously to identify and respond to undesirable scenarios such as over pressurization and leaks. The systems are equipped with alarms and automatic shutdown capabilities (passive and active).

Outside of the primary containment system, the space must be sufficiently large to allow for routine visual inspection, the installation of additional monitoring and control systems, emergency ventilation, and sprinkler systems. The monitoring and control systems include external leak detectors (gas and liquid), smoke detectors, flame detectors, alarms, and a visual detection system [59]. Sprinkler systems are used to increase the vaporization rate of LNG for two reasons: one, cause faster mixing and dilution of natural gas outside of flammable limits; two, raise temperature quickly to cause the vapor to lower its specific gravity and become buoyant, so the vapor rises away from ignition sources and personnel [59]. The emergency ventilation systems are to supplement the sprinkler systems to keep concentration outside of flammability limits and remove gas from the vicinity.

BOG serves as a potential threat if over pressurization or a leak occurs but the engines require the conversion of LNG into gas to use for combustion. If BOG exists outside of normal operating parameters, it can be managed in three ways: one, siphon the BOG to supplement the routine LNG transfer to the engines for combustion; two, siphon the gas for waste combustion; three, re-liquefaction of the BOG and return to the storage tank.

3. LNG Transfer System

LNG transfer systems follow many of the same concepts as general LNG containment, as the LNG is transferred most efficiently as a liquid instead of a gas. However, the generation of a two-phase mixture will occur due to heat added to the fluid via friction along the flow path. As discussed in tank placement, the transfer piping should be as short as possible between the primary systems involving LNG including the LNG loading site, LNG storage tank, and regasification tank. The primary components discussed for an LNG transfer system are the prime mover, piping, and the evaporator for regasification.

a. LNG Pump

The prime mover for LNG during fuel loading or fuel transfer from the onboard storage tank are pumps. Submerged motor-driven LNG pumps are the primary type of pump used some systems also utilize external reciprocating pumps [130]. This section discusses the submerged pump types to allow LNG transfer.

Submerged cryogenic motor-driven pumps are single units installed inside the storage tank that drive the LNG and are subsequently cooled by it. Depending on the application, centrifugal or reciprocating pumps may be used. The three main types of pumps used are fixed, suction vessel-mounted, and retractable [131]. Fixed pumps may only be serviced when storage tanks are empty. In terms of design, fixed pumps and retractable are nearly identical. Suction vessel-mounted pumps are an integral part of the piping system typically used for vaporizer (regasification) feed service, as shown in Figure 27 [132].

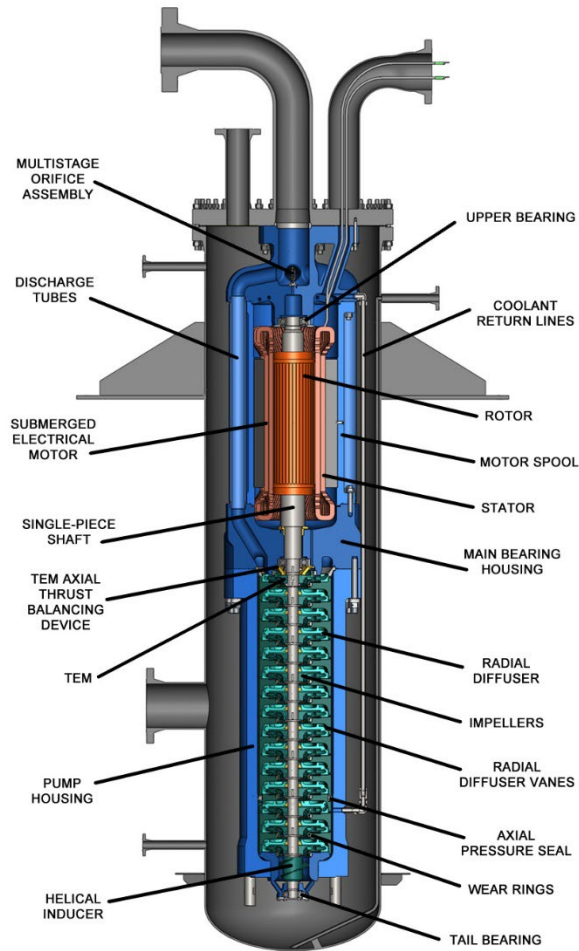


Figure 27. LNG Centrifugal Suction Vessel Mounted Pump. Source: [132].

Retractable pumps are similar in design to fixed pumps, except an additional pump column structure is included to allow the pump to be isolated and removed even when the storage tank is in use, as shown in Figure 28. Retractable pumps allow for servicing during operation, but the pump must be lifted vertically out of the storage tank [133].

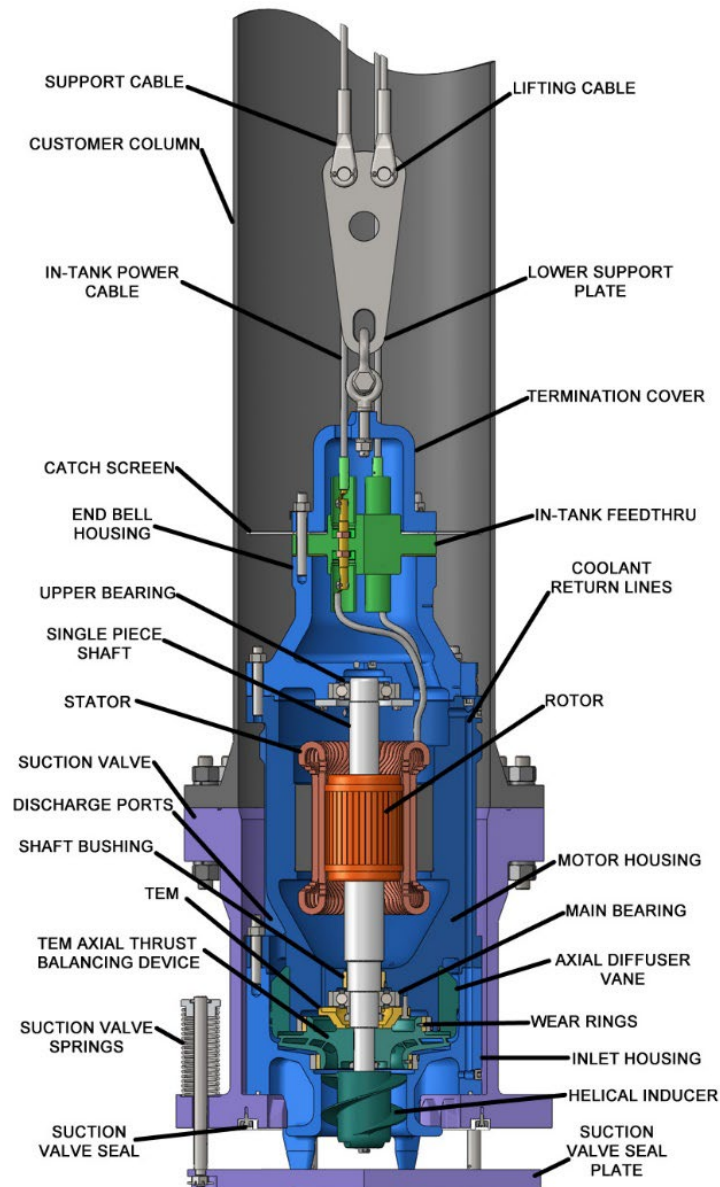


Figure 28. LNG Submerged Retractable Pump Diagram. Source: [133].

A full transfer system must determine the appropriate hydraulic considerations to determine the usable and non-usable volume of an LNG tank based on required net positive suction head (NPSH_r), flow rates, suction pressure, and other significant fluid flow parameters. The non-usable volume, occurring at a specified height in the tank, is the fuel that will remain in the tank due to pump limitations. Pump inducers and impellers may be modified to improve performance to allow operation at low NPSH.

b. LNG Piping

Piping design for LNG is similar in concept to the design for the containment of the fuel storage tank. The specific design for LNG piping is different depending on its location on the ship [119]. Overall, there are five types of piping required for LNG fuel integration: cryogenic piping for refueling, cryogenic piping from fuel tank to the evaporator, gas pipe from the evaporator to the gas valve unit (GVU), gas piping from the GVU to the engine, and vent pipes [119]. Internal cryogenic piping requires a full integrity insulated design for maximum safety and minimum heat transfer during LNG transit from the fuel tank to meet IMO 653. External cryogenic piping utilizes a single integrity insulated design, as the potential escape of BOG is significantly less dangerous since it would be open to atmosphere and rapidly dilute. Gas piping and vent piping use a standard double wall pipe for leak integrity. This section focuses on the internal cryogenic piping, as the external cryogenic piping is similar in construction.

The internal cryogenic piping is nearly identical to the materials used for the fuel storage tank with the addition of a casing of high-density polyethylene (HDPE). Following the diagram in Figure 27, the materials used in order from inside out are cryogenic steel (orange), PUR (blue), HDPE (yellow), and cryogenic steel (black).

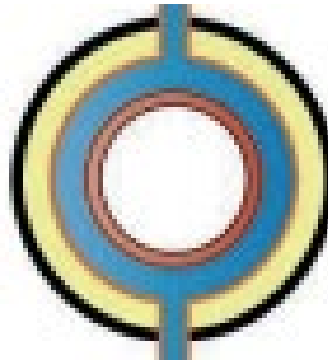


Figure 29. Cross Sectional View of Internal Cryogenic Piping. Source: [119].

The purpose of the steel and PUR are the same as the containment discussion. The HDPE is added as a casing for the PUR. The HDPE is selected for the material's toughness, UV resistance, watertightness, slow crack growth, and rapid crack propagation properties

[119]. The external cryogenic steel layer is added to provide a full integrity transfer system and ensures IMO 653 is met for low flame spread [119]. This design is watertight and robust with an operational environmental range from arctic to tropical for more than 30 years [119].

c. LNG Regasification

The final part of the LNG transfer system is the regasification stage which evaporates the LNG into natural gas for use by the engines. A simplified process diagram of an expected LNG system is shown in Figure 30. The primary component is the heat exchanger to vaporize LNG and warm up the natural gas for use in the engines. The working fluid of the vaporizer is seawater for simplicity. The excess BOG and natural gas are combined to supply the engines at the desired rate based on speed. A natural gas pressure vessel storage unit may be incorporated to act as a surge tank when the engine feed rate changes.

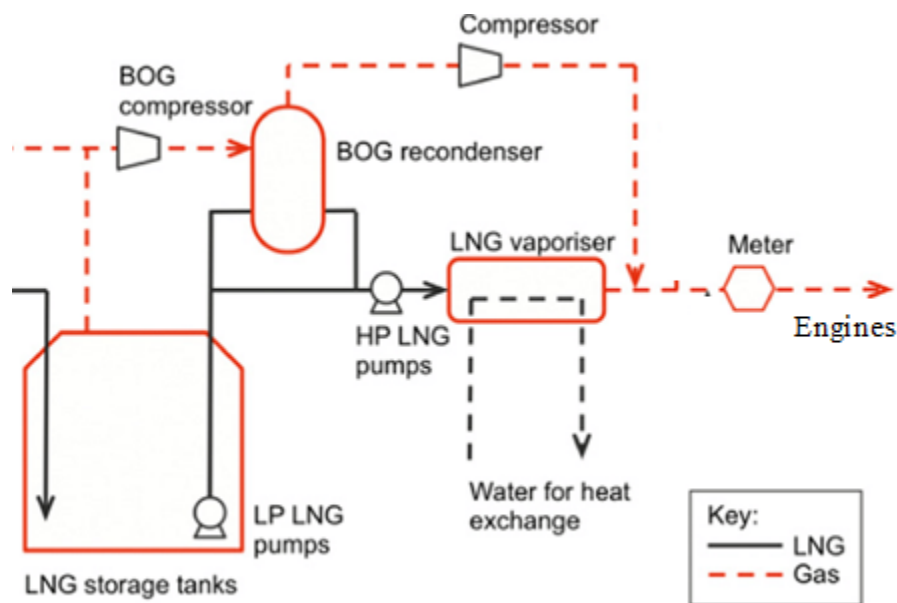


Figure 30. Process Flow of a Typical LNG Regasification System. Adapted from [134].

4. Synthetic Natural Gas

Natural Gas and SNG are effectively the same compound with the exception of their specific chemical composition and the mode of production. Natural gas is a naturally occurring gas mixture extracted from the Earth composed primarily of methane and ethane with various minor constituents. SNG is pure methane manufactured using an exothermic methanation process in fixed-bed reactors typically using carbon dioxide and hydrogen gas as feedstock, an example model is shown in Figure 28 [68]. The Wobbe Index is the main indicator of interchangeability of fuel gases and is used to compare the combustion energy output of different composition fuel gases in an appliance [135]. The average Wobbe Index value for natural gas is 51.15 MJ/m³ [135] compared to 47.5 MJ/m³ [68]. Any vehicle designed around using LNG as a fuel has a reduced operational range (~ 7% lower) if using LSNG due to the lower Wobbe Index. The difference between the two is due to the composition: natural gas contains heavier hydrocarbons in the mixture and SNG is purely methane.

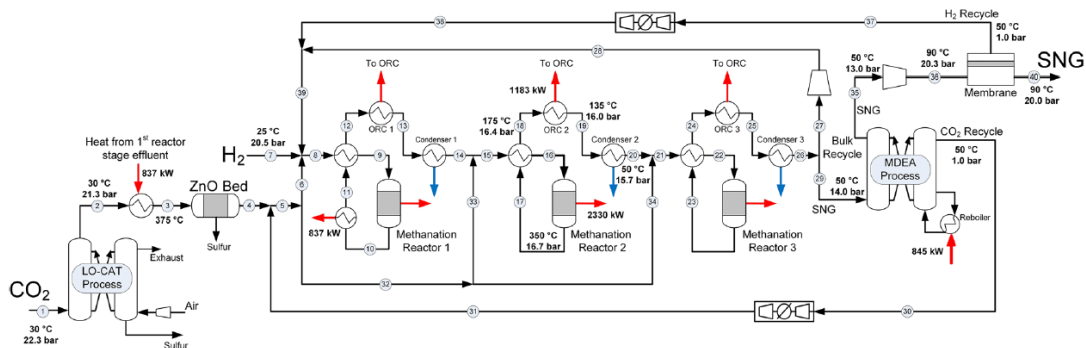


Figure 31. Becker-Braun SNG Model Plant System Design. Source: [68].

As discussed in the AoA, the NRL has developed a laboratory proven method to produce carbon dioxide and hydrogen gas from seawater [14]. If combined with a production process similar to the Becker-Braun SNG model (see Figure 28), an unlimited amount of SNG fuel could be produced, given an appropriate energy source. The most appropriate energy sources would be nuclear or a large-scale renewable energy source such as an ocean thermal energy conversion, solar, or wind farm.

C. CONCLUSION

The baseline ship characteristics from Figure 19 for the DDG-51 class provide the key ship characteristics and fuel related parameters the initial LNG fuel system is compared to. The most significant baseline parameters are the overall ship measurements and the usable fuel amount. The incorporation of LNG or LSNG requires the baseline ship size to increase due to the reduction in effective fuel energy density. The equivalent usable and total fuel for LNG conversion is determined on an energy basis.

The LNG storage system requires the use of two layers of cryogenic steel (304L or Invar-36) and a layer of PUF to provide a full integrity system. The LNG transfer system piping requires HDPE in addition to the storage system materials.

The LNG storage system commonly employed on civilian small-scale carriers is the Type C pressure vessel design. However, the need for greater space efficiency on a military vessel to minimize the impact to ship size necessitates a Type A or membrane style tank. These tank designs provide greater flexibility in the storage system's geometry.

The incorporation of LSNG further lowers the energy density provided by LNG with the same storage requirements. A storage system designed for LSNG must be larger than LNG.

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V. PROBLEM FORMULATION AND RESULTS

A. INTRODUCTION

The following sections expand upon the scope of the project by defining the method of analysis for designing the integral systems required for LNG integration onto a non-nuclear surface ship.

B. FUEL STORAGE SYSTEM DESIGN

The goals of the LNG fuel storage tank design process are to balance the ability of the ship to maintain its operational capability (e.g., range), maintain survivability, minimize impact to the ship configuration, and minimize impact to ship size. In terms of technical design of the LNG fuel storage tank, the primary considerations are the type, shape, and the materials of the storage tank. The design process goals and technical design factors of the LNG fuel storage tank are heavily interrelated and require iteration in conjunction with the integration requirements for the optimal design.

The technical design of the LNG fuel storage tank is completed based on an integral membrane style LNG storage tank for maximum volume efficiency. The storage tank materials are based on the industry standards to include 304L, 316L, or Invar-36 for the stainless-steel containment layers and PUF for the insulation layer. The general design of the storage tank is then sized to meet the usable fuel mass requirement provided by the ship baseline based on the equivalent energy. The minimum height of the fuel tank correlating with the usable fuel amount is determined to provide insight on the hydraulic requirements. The light weight and full weight of the fuel storage system is estimated based off a heat transfer analysis to determine the required layer thickness using Fourier Law and BOG generation rate equations.

The results of the fuel storage tank design section provide the technical specifications of the design to include the dimensions and weight. The results are tabulated for a 304L, 316L stainless steel and Invar-36 system using LNG fuel.

C. FUEL TRANSFER SYSTEM DESIGN

The fuel transfer system design process uses requirements and best practices from industry for LNG fuel transfer to develop a design for internal cryogenic fuel transfer pipes. The cryogenic fuel transfer pipes are based off the design from the LNG Transfer System section to include two layers of 304L stainless steel, PUF, and HDPE. The estimated weight and difference from the baseline of the internal piping are tabulated.

D. FUEL STORAGE AND TRANSFER SYSTEM INTEGRATION

The LNG fuel storage and transfer system integration process uses the primary requirements for an LNG fuel system along with the results of the previous sections to identify required system and component additions and removals from the baseline DDG.

E. MODELING

The modeling section combines the results of the previous sections to determine the impact on overall design goals and integration goals. The results of the LNG design ship and the baseline DDG are compared to determine the degree the design goals were met. The analysis follows the surface ship weight estimation method to estimate the new ship size characteristics, weights, and moments using the Parent - Design ship method [136].

VI. RESULTS AND DISCUSSION

The analyses discussed in the Methodology section are presented in the following sections. The full calculations for the analyses are contained in the appropriate section of the Appendix.

A. FUEL STORAGE SYSTEM

The design of the fuel storage system begins with determining the total and usable fuel storage volume and mass from the energy equivalent fuel volume of the baseline, as shown in Table 5. See Appendix A for the full calculations. As expected, the fuel mass of LNG for the equivalent energy is similar to the baseline F-76 and the fuel volume is significantly greater.

Table 5. Internal Storage Requirements

		Baseline F-76		LNG	
	Energy Equivalent (GJ)	Volume (m ³)	Mass (t)	Volume (m ³)	Mass (t)
Total Fuel	131,730	3,291.7	2,863.8	5,971.9	2,634.6
Usable Fuel	52,693	1,316.7	1,145.5	2,388.7	1,053.9

The approximate storage tank dimensions and placement are determined from the baseline ship characteristics. Figure 32 illustrates the cross-sectional area determination for storage tank geometry based on the waterline, station three values, half siding width (hull thickness), and full flare angle. The results of the analysis provide the geometric dimensions of the fuel volume using a trapezoidal prism volume within the bounds of the baseline cross-sectional area. The results are tabulated in Table 6. See Appendix B for specific calculations.

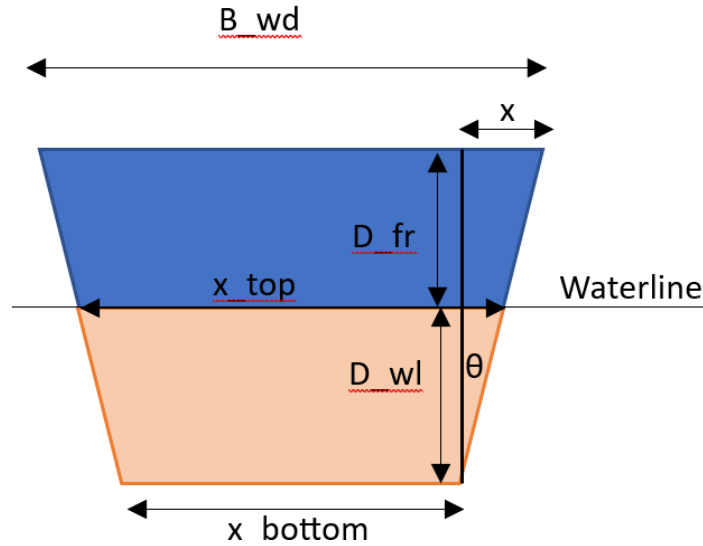


Figure 32. Diagram to Determine Tank Geometry

Table 6. Internal Tank 1-D and 2-D Geometry

1-D Parameter	Dimension (m)	2-D Parameter	Dimension (m ²)
Top Width	15.22	Top Wall	1,058.20
Bottom Width	13.08	Bottom Wall	909.4
Height	6.07	End Wall	85.9
Length	69.52	Side Wall	415.6

The dimensions of the storage tank and its three layers were determined based off the GTT Mark III [137] and GTT NO96 [118] industry standard designs using 304L, 316L, Invar-36 containment materials and PUF for insulation. The containment metal thickness was used as a known value, and the insulation thickness was iterated to meet the target BOR of $\leq 0.15\%$. The 1-D heat transfer rate through each wall of the storage tank was calculated to determine the BOR to validate the design goal was met. Table 7 contains the heat transfer rate through each wall, the total, and the BOR for the three containment systems. The full calculations are shown in Appendix C using the 304L system as an example.

Table 7. Heat Transfer Rate and BOR for Storage System

Q (kW)	Mark III with 304L	Mark III with 316L	NO96 with Invar-36
Bottom Wall	7.47	7.47	7.47
Top Wall	8.69	8.69	8.69
Side Wall	3.41	3.41	3.41
End Wall	0.71	0.71	0.71
Total	24.4	24.4	24.4
BOR	0.15%	0.15%	0.15%

The three storage systems yielded nearly identical results due to the low variation in the design. Each system used the same insulation material (PUF) and the only difference was the containment metal. The 304L and 316L thermal conductivity values as a function of temperature were used based on available literature [138], while the Invar-36 thermal conductivity remained constant at its standard temperature value. The thinness of the metal containment layers led to an insignificant impact on the heat transfer rate. The insulation layer thickness of the systems was significantly larger than the industry value due to the difference in materials used. The NO96 system uses a combination of glass-wool, foam, and plywood to provide support and insulation [118]; the Mark III system uses a higher density foam [137].

Based on the heat transfer rate calculations, the physical sizing of the storage system is calculated to determine the approximate physical geometry and weight of the system. Since the heat transfer rate calculations were nearly equal among each of the solutions, the physical dimensions are similar as well. The results of the physical sizing for the layers of the storage systems and the total dimensions are shown in Table 8. The full calculations are contained in Appendix C using the 304L system as an example.

Table 8. Physical Dimensions of Storage Tank

	Inner Layer		Insulation Layer		Outer Layer		Total	
	Mark III	NO96	Mark III	NO96	Mark III	NO96	Mark III	NO96
Thickness (mm)	1.2	0.7	720	720	1.2	0.7	722.4	721.4
Volume (m ³)	3.58	2.09	2,337.8	2,337.5	4.22	2.46	8,317.5	8,313.9
Empty Weight (t)	28.7	16.8	198.7	198.7	33.7	19.8	261.1	235.3
Full Weight (t)							2,896	2,870

The primary difference in weight between the two systems is the thickness and density of the containment layer materials. The total empty weight of the storage systems is approximately 10 percent different. The full weight with fuel loaded is less than one percent different. The percentage of total weight of the Mark III and NO96 based systems is nine and eight percent, respectively.

B. FUEL TRANSFER SYSTEM

The primary results of the fuel transfer system analysis are to determine the weight of the piping system and minimum NPSHr for the submerged cryogenic pump to operate at the usable fuel limit. A full design of the transfer system would require significant knowledge of all the fluid flow, heat transfer, and hydraulic systems. The majority of the analysis was outside the scope as an initial high-level design.

The piping design was based on the LR Marine cryogenic piping system using a nominal stiffness rating of ten for the interior cryogenic pipes [119]. Without experimental or simulated fluid flow analysis, the results of the piping system design are compared with the results of a recent study [139], shown in Figure 33. The cryogenic piping design results and the linear densities are shown in Table 9.

Table 9. Internal Cryogenic Piping Results

	Inner Layer	Insulation	Casing	Outer Layer	Total
Thickness (mm)	11.5	81.5	7	0.4	450.9
Linear Density (kg/m)	3.33	1.78	1.47	.004	6.6

The design piping has a PUF insulation thickness of 0.0815 meters and the reference plots have a PUF insulation thickness of 0.05 and 0.1 meters. The reference plots illustrate minimal difference between the two with a temperature rise in the fluid of approximately 10K over a 1000-meter distance. The baseline DDG has a total length of 142 meters. The implementation of LNG onto the DDG baseline will increase the length within the 200–400-meter window. LNG piping will not extend the entire length of the ship, so a temperature increase of less than 3K can be expected which will minimize the two-phase flow.

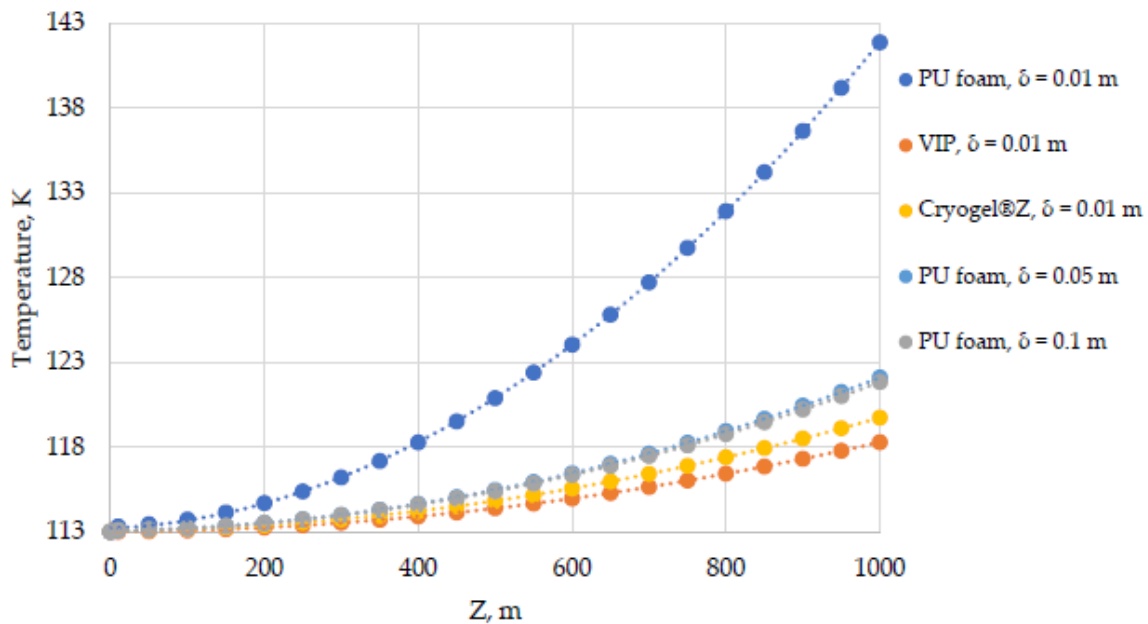


Figure 33. Extrapolated Temperature Distribution. Source: [139].

The minimum NPSHr to operate the submerged LNG transfer pumps to consume the usable fuel occurs at the storage tank level at which 60 percent of the fuel remains. As shown in Figure 32, the change in fuel level affects the height and top width in determining the remaining fuel volume based on the approximated geometry of a trapezoid. The height and top width are iterated with the length and bottom width constant to equal the target volume. The actual minimum NPSHr is specific to the pump and system characteristics so this calculation is to ensure the tank may operate with industry pumps. The minimum NPSHr for industrial pumps such as the Shinko Ind. Ltd SM350 requires at least 600 mm of LNG [140]. Table 10 displays the approximate geometry of the trapezoidal fuel volume at full capacity, after the usable fuel is consumed, and the minimum to operate.

Table 10. Fuel Geometry at Full, Partial, and Minimum Volume

1-D Parameter	Full Volume	60% Full Volume	Minimum Volume
Top Width (m)	15.22	14.78	13.29
Bottom Width (m)	13.08	13.08	13.08
Height (m)	6.07	3.7	0.6
Length (m)	69.52	69.52	69.52
Fuel Volume (m ³)	5,972	3,583	550

C. MODELING

The DDG baseline draft and beam were held constant to maintain ship characteristic coefficients and simplify the size increase estimation. Table 11 contains the principal ship characteristics of the two ships.

Table 11. Principal Characteristics of Parent and Design Ship

Parameter	Parent Ship	Design Ship
Length (m)	142	174
Beam (m)	18	18
Draft (m)	6.3	6.3

The LNG design ship was estimated to be approximately 30 meters longer than the baseline based on the additional volume of fuel required. For simplicity, the storage tank geometry for the LNG ship was assumed for the parent ship to estimate the difference in length.

The LNG modified DDG was designed using the Parent-Design ship method for estimating surface ship weights [136] after estimating the additional length from the LNG storage tank analysis. Using the estimated dimensions of the design ship, the light ship and full load weight distributions were determined with the results tabulated in Table 12 and shown in Figures 34–37.

Table 12. Parent–Design Weight Distribution Results

Group	Description	Parent Ship Weight Distribution (t)	Design Weight Distribution (t)	Percent Difference (%)
100	Hull Structure	3,041	3,961	30
200	Propulsion	757	865	14
300	Electric	320	357	12
400	Command and Surveillance	438	489	12
500	Auxiliary Systems	842	950	13
600	Outfit and Furnishings	676	836	24
700	Armament	320	320	0
F00 - F50	Full Loads	1,710	3,140	84
ACQ Weight Margin (t)		32	39	22
Total Light Weight (t)		6,426	7,817	22
Total Full Load Weight (t)		8,136	10,957	35

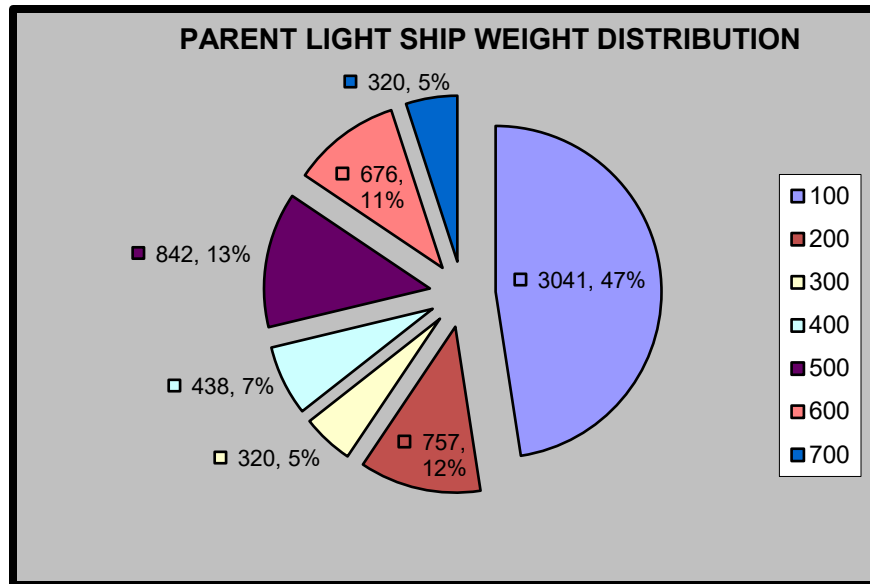


Figure 34. Parent Light Ship Weight Distribution

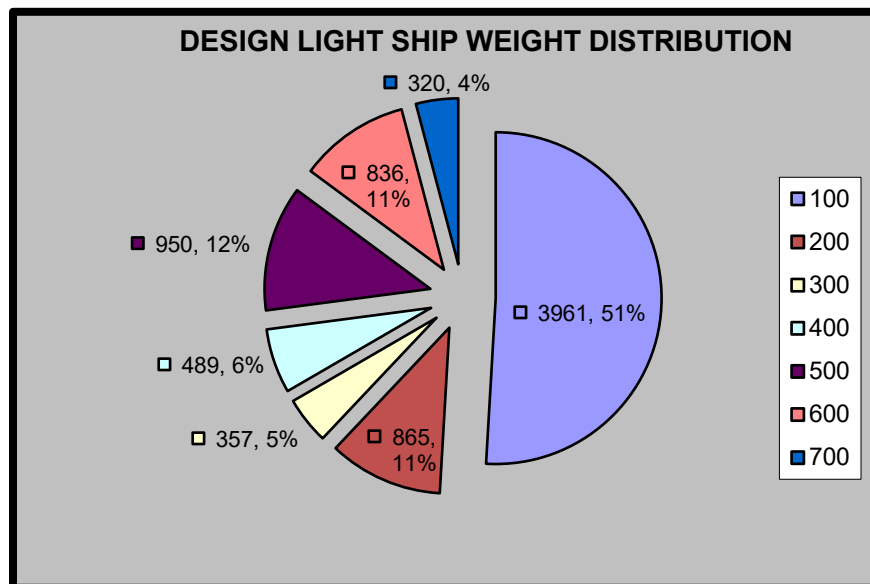


Figure 35. Design Light Ship Weight Distribution

The increased hull length requires numerous systems and components to be scaled accordingly using the Parent-Design ship method. Based on the light ship results, the LNG DDG is approximately 1,400 tons heavier largely due to the increase in hull length. As expected, the most significant weight increase was in the Hull Structure group with a 30

percent increase. The LNG storage tank was included in the Hull Structure group since the tank was modeled as a membrane tank.

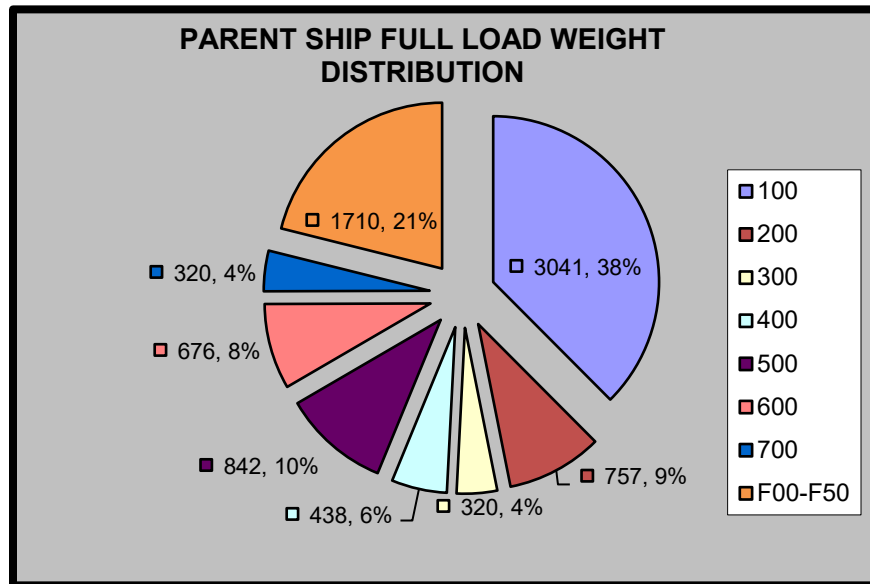


Figure 36. Parent Ship Full Load Weight Distribution

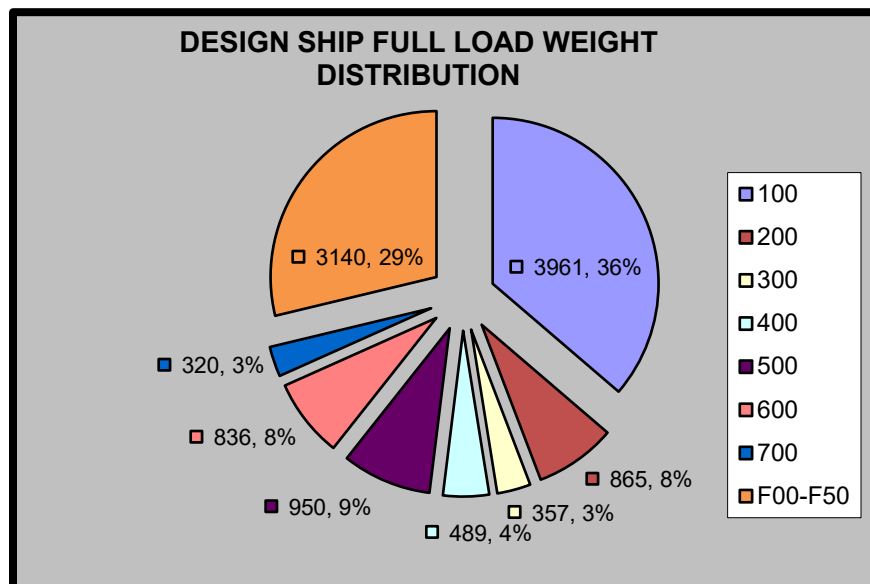


Figure 37. Design Ship Full Load Weight Distribution

The full load condition for the design LNG ship was significantly heavier than the baseline with an increase of 35 percent. This drastic increase was unexpected based on the 22 percent difference in lightship weight. The LNG ship's full load condition was expected to be greater than the parent ship due to ship size scaling factors applied to the personnel, stores, and water. The F-76 fuel mass included in the full load condition was 1205.7 tons with the usable fuel mass weight of 1145.5 tons based on the DDG report data. The total F-76 fuel mass based on usable fuel being 40 percent of total fuel was calculated as 2,864 tons. If the calculated total fuel mass is used instead of the fuel added in the full load condition, the parent ship full load displacement increases to approximately 9,800 tons and the percent difference decreases to 12 percent.

D. COST ANALYSIS

A parametric cost analysis was performed based on the Congressional Budget Office method using previous cost and displacement data of past DDG-51 ships to determine an estimated cost for the LNG DDG [141] [142] [107]. After adjusting the costs for inflation to 2022 dollars, the average cost in millions of dollars per ton for the dataset was \$0.21 M/t, with a median value of \$0.19 M/t, and an outlier of \$0.28 M/t for the lead DDG-51 ship. Using these values provides an average estimated cost of \$2.63 - \$3.12 billion compared to the current Flight III cost of \$2.2 billion [107], an increase of 20–40 percent. The difference in cost is significant, but the Flight III ship is significantly larger and more complex than the baseline Flight I ship used in this analysis. Compared to a Flight I ship and adjusted for inflation, the difference in cost is significantly greater with a percent difference of 86 percent for follow-on production. If the Flight III was used as the baseline, the cost of an LNG DDG ship would be at least \$4 billion.

E. SURVIVABILITY

The survivability assessment of the DDG-51 with LNG fuel is performed at a qualitative level to limit the scope due to the breadth of anti-ship weapons and their potential effects.

As discussed in Section IV, the DDG-51 class relies on susceptibility reduction to maximize its survivability with the high lethality weapons in use by near peer adversaries.

The susceptibility reduction components on board the ship such as sonar and the AEGIS combat system are scaled with the increased size of the ship to maintain full coverage and make use of new volumes and areas. From a susceptibility standpoint, the ship's survivability is unchanged.

From a vulnerability standpoint, the survivability of the ship is decreased primarily due to the increased size of the ship and its critical system – the fuel tank. The larger ship increases the probability of detection from visual or remote sensors. The larger fuel system and cross-sectional area increases the probability of intercept. In the event of a successful hit from an enemy weapon, the storage system has a high probability of damage since it spans approximately 70 meters (40 percent of the total length). The loss of the fuel tank system likely results in the loss of the ship. The fuel system may incorporate measures to increase its redundancy, such as backup pumps, but the system has little to no capability to recover from damage. Attempts to lower vulnerability such as increased armor thickness are unlikely to have a significant impact on the system survivability and will only increase the cost of the ship. Compared to F-76, the fuel does not pose a significantly larger threat with appropriate mitigation measures installed as required by industry standards.

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VII. CONCLUSION

The goal of this research was to approximate the DAS process for an ACAT I program through the Milestone A decision based on the justification provided for exploring alternative fuels for non-nuclear surface ships. The end product provides the most viable fuel alternative and a high-level design implementing the selected fuel on a baseline ship.

Based on the approximated acquisition process, the most viable alternative fuel for non-nuclear surface ships is LNG. The high-level design implications of incorporating LNG using a DDG-51 Flight I ship as the baseline requires the ship to increase by approximately 30 meters, increase the lightship weight by 22 percent, increase the full load condition by 12–35 percent (based on provided versus calculated total fuel mass of parent ship), and increase the production cost by nearly 90 percent. The survivability of the ship decreases with a significantly larger vulnerability area due to the larger fuel tank.

LNG and the other alternative fuels are significant contributors to powering the world's commercial maritime shipping. In commercial shipping, the economy of scale concept applies to allow for the construction of massive ships where the impact of the fuel density is significantly less than on a smaller ship. The primary constraint on these ships is size and displacement to ensure the expected ports and straits are large enough to accommodate them. Military ships are significantly more complex to ensure high performance, survivability, and lethality. These ships are designed for capability in a range of operations and mission sets compared to the single mission of a commercial ship.

This research shows the significant disadvantages of implementing LNG as a military fuel. The significant increase in cost provides a significant barrier to strategic goals of the nation. As discussed, the NZE initiative will likely increase the time militaries may utilize fossil fuels as industries and people transition to non-fossil fuels for energy. Further research for military application on this topic is not recommended based on these results.

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APPENDIX A. INTERNAL FUEL STORAGE

DDG-51 Usable Fuel (40% of total) F-76 -> Energy Equivalent -> LNG usable/total fuel equivalent mass/volume

```
clc; clear;
```

Known Values for F-76

```
UFM76t = 1145.5; % ddg-51 f-76 usable fuel (metric ton)
rho_76 = 870; % F-76 density (kg/m3)
GED76 = 46; % F-76 gravimetric energy density (MJ/kg)
VED76 = 37.2; % F-76 volumetric energy density (MJ/L)
```

Known Values for LNG

```
rho_lng = 450; % LNG density 450 (kg/m3)
GED_lng = 50; % LNG Gravimetric energy density (MJ/kg)
VED_lng = 21.5; % LNG volumetric energy density (MJ/L)
```

Conversions

```
VC = 1000; % 1000L/1m3
MC = 1000; % 1000kg/1mt
EC = 1000; % 1000MJ/1GJ
```

F-76 Usable and Total Fuel Mass/Volume

```
UFM76kg = UFM76t*MC; % f-76 usable fuel mass (kg)
UFV76 = UFM76kg/rho_76; % f-76 usable fuel density (m3)
TFM76kg = UFM76kg/.4; % f-76 total fuel mass (kg)
TFV76 = TFM76kg/rho_76; % f-76 total fuel volume (m3)
```

Energy Equivalent usable/total

```
UE = UFM76kg*GED76/EC; % usable energy (GJ)
TE = TFM76kg*GED76/EC; % total energy (GJ)
```

LNG Usable and Total Fuel Mass/Volume

```
UFMkg_lng = UE*EC/GED_lng; % LNG usable fuel mass (kg)
UFMt_lng = UFMkg_lng/MC; % LNG usable fuel mass (metric ton)
```

```
UFMt_LNG = 1.0539e+03
```

```
TFMkg_lng = UFMkg_lng/.4; % LNG total fuel mass (kg)
TFMt_lng = UFMt_lng/.4; % LNG total fuel mass (metric ton)
```

```
% Fuel volume multiplied by 1.02 since fuel tanks are typically filled to  
% max of 98% total storage volume. Factor of 1.02 allows for energy  
% equivalent calculations to remain true.
```

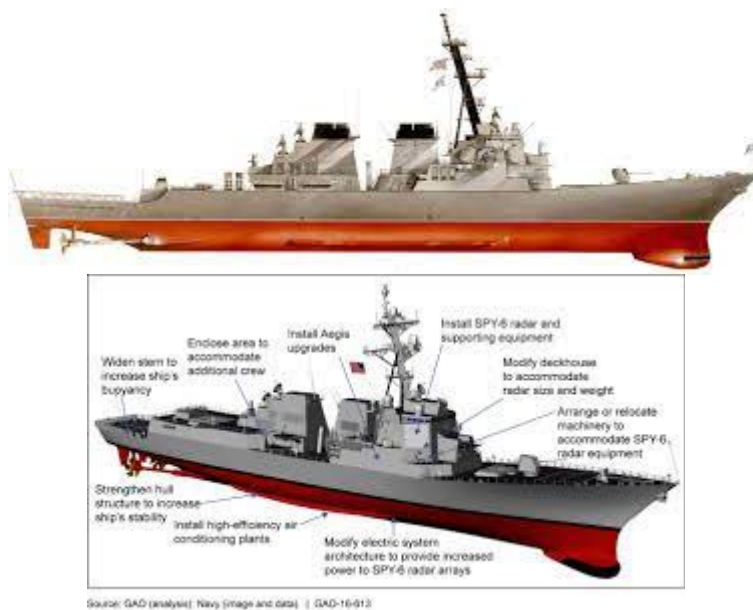
```
UFV_lng = 1.02*UFMkg_lng/rho_lng; % LNG usable fuel volume (m3)  
TFV_lng = 1.02*TFMkg_lng/rho_lng; % LNG total fuel volume (m3)
```

APPENDIX B. STORAGE TANK DESIGN

Design storage tank

A. DESIGN SPECIFICATION

- BOR = <0.15%
- LNG Total Volume = 5.9719e3 m³
- LNG Partial Volume = 2.3887e3 m³



B. RELEVANT SHIP GEOMETRY

Obtained from ship report

Use to determine area at maximum beam

```
B_wl = 17.98; % beam at waterline (m)
B_wd = 20.27; % beam at weatherdeck (m)
L_wl = 141.83; % length at waterline (m)

D_wl = 6.07; % draft at waterline (m)
D_f = 7.82; % freeboard at sta 3 (m)

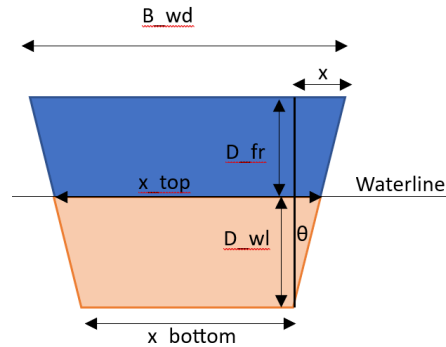
theta_deg = 10; % hull flare angle (deg)
angle = deg2rad(theta_deg); % hull flare angle (radians)
```

```
t_hull = .030; % hull thickness (m)
```

C. TANK SIZING

Model tank as trapezoid with six walls: top wall is width at waterline, bottom wall is width at beam for amidships, side walls angle up hull flare angle, end walls vertical

Calculations for internal volume of tank...figure provided for reference



```
x = (D_wl+D_f)*tan(angle)-t_hull;
x_bottom = (B_wl-2*t_hull)-2*x
```

```
x_bottom = 13.0816
```

```
x_top = x_bottom + 2*D_wl*tan(angle)
```

```
x_top = 15.2222
```

```
tA = (x_top+x_bottom)*D_wl*.5; % Tank Cross Section Area
tL = TFV_lng/tA % Tank Length
```

```
tL = 69.5194
```

```
tA_b = x_bottom*tL; % Tank Area bottom wall
tA_t = x_top*tL; % Tank area top Wall
tA_e = tA; % Tank Area End wall
tA_s = D_wl*cos(angle)*tL; % Tank Area Side Wall
```

D. MATERIAL PROPERTIES

Heat Transfer Coefficients (Conduction (k) and Convection (h))

```
k_puf = .029; % PUF conductivity (W/m-K)
k_304_in = 100*(8.116*10^-2 + T_lng*1.618*10^-4) % 304L thermal
conductivity on inner tank (W/m-K) https://www.osti.gov/servlets/purl/
4152287
k_304_out = 16.2 % 304L thermal conductivity on outer tank (W/m-K)
```

```

k_316_in = 100*(9.248*10^-2 + T_lng*1.571*10^-4) % 316L thermal
conductivity on inner tank (W/m-K) https://www.osti.gov/servlets/purl/4152287
k_316_out = 15 % 316L thermal conductivity on outer tank (W/m-K)
https://www.osti.gov/servlets/purl/4152287
k_invar = 12.8; % Invar-36 thermal conductivity (W/m-K)
https://www.slm-solutions.com/fileadmin/Content/Powder/MDS/MDS\_Fe-
Alloy\_Invar36\_0219\_EN.pdf
k_hull = 27.72; % thermal conductivity of hull based on 20C (average
surface ocean temperature)
k_sw = .6015; % thermal conductivity of seawater based on 20C (average
surface ocean temperature)

h_inner = 35; % LNG convection (W/m2-K)
h_outer = 10; % air convection (W/m2-K)

```

Thickness

```

x_invar = .7/1000; % invar36 thickness (m) based on GTT N096 design
x_304 = 1.2/1000; % 304L thickness (m) based on GTT Mark III design
x_316 = 1.2/1000; % 316L thickness (m) based on GTT Mark III design
x_puf_96 = .53; % insulation thickness (m) based on GTT N096 design
x_puf_iii = .72; % insulation thickness (m) based on Mark III design

```

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APPENDIX C. 304L STORAGE TANK DESIGN

A. 304L MODEL - BASED ON GTT MARK III DESIGN

Model tank as six flat walls with Fourier Law

$$R_{cond} = \frac{L}{Ak} \quad R_{conv} = \frac{1}{hA}$$

$$R_T = \sum(R_{conv} + R_{cond}) \quad \dot{Q} = \frac{\Delta T}{R_T}$$

$$\frac{\dot{Q}}{A} = \Delta T * h \quad \frac{\dot{Q}}{A} = \Delta T * \frac{k}{L}$$

L == thickness

B. HEAT TRANSFER

```
T_delta = T_lng - T_air;

rho_304 = 8000;
rho_316 = 7900;
rho_invar = 8050; % Invar36 density (kg/m3) https://www.americanelements.com/invar-36-alloy
rho_puf = 85; % PUF density (kg/m3) https://lrmarine.dk/wp-content/uploads/5-Double_Wall.pdf
rho_hdpe = 9545; % HDPE density (kg/m3) https://www.bpf.co.uk/plastipedia/polymers/HDPE.aspx#:~:text=PROPERTIES,low%20cost%2C%20good%20chemical%20resistance.
```

```
%Bottom Wall
R_304_lngB = 1/(h_inner*tA_b); % Convection into LNG
R_304_inB = x_304/(k_304_in*tA_b); % Conduction thru inner containment
R_puf_304B = x_puf_iii/(k_puf*tA_b); % Conduction thru insulation
R_304_outB = x_304/(k_304_out*tA_b); % Conduction thru outer containment
R_304_outerB = 1/(h_outer*tA_b); % Convection on outer surface
R_Tb_304 = R_304_lngB + R_304_inB + R_puf_304B + R_304_outB + R_304_outerB;
%Total Resistance (K/W)

Q_b_304 = (T_delta)/(R_Tb_304)/1000 % Bottom Wall Heat Transfer Rate (kW)
Q_b_304 = 3.8528

%Top Wall
R_304_lngT = 1/(h_inner*tA_t);
```

```

R_304_inT = x_304/(k_304_in*tA_t);
R_puf_304T = x_puf_iii/(k_puf*tA_t);
R_304_outT = x_304/(k_304_out*tA_t);
R_304_outerT = 1/(h_outer*tA_t);
R_Tt_304 = R_304_lngT + R_304_inT + R_puf_304T + R_304_outT + R_304_outerT;

```

```

Q_T_304 = (T_delta)/(R_Tt_304)/1000

```

```

Q_T_304 = 4.4833

```

```

%Side Walls

```

```

R_304_lngS = 1/(h_inner*tA_s);
R_304_inS = x_304/(k_304_in*tA_s);
R_puf_304S = x_puf_iii/(k_puf*tA_s);
R_304_outS = x_304/(k_304_out*tA_s);
R_304_outerS = 1/(h_outer*tA_s);
R_TS_304 = R_304_lngS + R_304_inS + R_puf_304S + R_304_outS + R_304_outerS;

```

```

Q_S_304 = (T_delta)/(R_TS_304)/1000

```

```

Q_S_304 = 1.7606

```

```

%End Walls

```

```

R_304_lngE = 1/(h_inner*tA_e);
R_304_inE = x_304/(k_304_in*tA_e);
R_puf_304E = x_puf_iii/(k_puf*tA_e);
R_304_outE = x_304/(k_304_out*tA_e);
R_304_outerE = 1/(h_outer*tA_e);
R_TE_304 = R_304_lngE + R_304_inE + R_puf_304E + R_304_outE + R_304_outerE;

```

```

Q_E_304 = (T_delta)/(R_TE_304)/1000

```

```

Q_E_304 = 0.3502

```

```

QT_304 = Q_b_304 + Q_T_304 + 2*Q_E_304 + 2*Q_S_304 % Total Heat Transfer
Rate (kW)

```

```

QT_304 = 12.5577

```

```

BOR_304 = (QT_304*3600*24)/(rho_lng*TFV_lng*Hvap) % Boil off rate per day -
Target <.15%

```

```

BOR_304 = 7.9009e-04

```

C. SIZE/DIMENSION/WEIGHT

```

Height304 = D_wl+2*(x_puf_iii+x_304+x_304)

```

Height304 = 7.5148

Bottom304 = x_bottom+2*(x_puf_iii+x_304+x_304)

Bottom304 = 14.5264

Top304 = x_top+2*(x_puf_iii+x_304+x_304)

Top304 = 16.6670

Length304 = tL+2*(x_puf_iii+x_304+x_304)

Length304 = 70.9642

Volume304 = (Bottom304+Top304)*Height304*Length304*.5

Volume304 = 8.3175e+03

% Inner containment

H304_inner = D_wl + 2*x_304; % Height of tank with inner containment layer (m)

B304_inner = x_bottom + 2*x_304; % Base length of tank with inner containment layer (m)

T304_inner = x_top + 2*x_304; % Top length of tank with inner containment layer (m)

L304_inner = tL + 2*x_304; % Length of tank with inner containment layer (m)

V304_inner = (.5*(B304_inner+T304_inner)*H304_inner*L304_inner-TFV_lng); % Volume of inner containment layer (m3)

W304_inner = V304_inner*rho_304/1000 % Weight of inner containment layer (metric ton)

W304_inner = 28.6451

% Insulation

H304_puf = H304_inner + 2*x_puf_iii; % Height of tank with insulation layer (m)

B304_puf = B304_inner + 2*x_puf_iii; % Base length of tank with insulation layer (m)

T304_puf = T304_inner + 2*x_puf_iii; % Top length of tank with insulation layer (m)

L304_puf = L304_inner + 2*x_puf_iii; % Length of tank with insulation layer (m)

V304_puf = (.5*(B304_puf+T304_puf)*H304_puf*L304_puf)-(TFV_lng+V304_inner); % Volume of insulation layer (m3)

W304_puf = V304_puf*rho_puf/1000 % Weight of insulation layer (metric ton)

W304_puf = 198.7117

% Outer containment

H304_outer = H304_puf + 2*x_304; % Height of tank with outer containment layer (m)

```

B304_outer = B304_puf + 2*x_304; % Base length of tank with outer
containment layer (m)
T304_outer = T304_puf + 2*x_304; % Top length of tank with outer containment
layer (m)
L304_outer = L304_puf + 2*x_304; % Length of tank with outer containment
layer (m)
V304_outer = (.5*(B304_outer+T304_outer)*H304_outer*L304_outer)-
(TFV_lng+V304_puf+V304_inner); % Volume of outer containment layer (m3)
W304_outer = V304_outer*rho_304/1000 % Weight of outer containment layer
(metric ton)

```

```
W304_outer = 33.7358
```

```

Weight_tank304 = (W304_inner + W304_puf + W304_outer)/1000 % Weight of empty
tank (metric ton)

```

```
Weight_tank304 = 261.7358
```

```

Weight_total304 = (TFMt_lng + Weight_tank304) % Weight of tank + LNG (metric
ton)

```

```
Weight_total304 = 2.8957e+03
```

APPENDIX D. PIPING DESIGN

Determine Piping Design

$$R_{int} = \frac{1}{\pi d_{int}^w \alpha_{int}},$$

$$R_{ext} = \frac{1}{\pi d_{ext}^{ins} \alpha_{ext}},$$

$$q_L = \frac{T_{lng} - T_{at}}{R_{int} + R_w + \sum_{i=1}^n R_{ins_i} + R_{ext}},$$

$$R_{ins} = \frac{1}{2\pi d \lambda_{ins}} \ln \frac{d_{ext}^{ins}}{d_{int}^{ins}},$$

$$R_w = \frac{1}{2\pi d \lambda_w} \ln \frac{d_{ext}^w}{d_{int}^w},$$

R_{int} = inner steel; R_w = hdpe; R_{ins} = PUF; R_{ext} = outer steel

alpha == convection coefficient (h); lambda == conduction coefficient (k)

A. PIPING THICKNESS

Assume S/N 10 for piping based on LR Marine <https://lrmarine.dk/wp-content/uploads/LNG-katalog-LRM-ver-8.pdf> using 316L. Assume thickness of metal pipe same for each metal as each have similar mechanical properties

S/N 10 is to provide a baseline. The heat transfer and fluid flow analysis outside the scope and required to fully design the system.

S/N	Stainless Steel pipe		Nominal LNG casing size	Jacket Thickness mm	HDPE Casing pipes diameter Before foaming, mm		HDPE Casing pipes diameter After foaming, mm	
	DN	Diameter [mm]			minimum	Maximum	minimum	Maximum
10	250	273	450	7	450,1	452,3	450,1	460

DN == inside diameter; Diameter == outside diameter; jacket thickness = HDPE thickness;

Parameters from BOR.m

```

ql_used = Q_used; %heat flux rate in partial tank condition (kW/m2) from
BOR.m
ql_total = Q_total; %heat flux rate in full tank condition (kW/m2) from
BOR.m
T_lng = -160+273; % LNG temperature (K)

```

```
T_at = T_air+273; % ambient temperature from BOR.m (K)
```

Diameters and Thicknesses

Inner steel layer

```
d_ss_int = 250; % interior inner steel layer diameter for each specimen (mm)
d_ss_ext = 273; % outer diameter of inner steel layer for each specimen (mm)
x_int = (d_ss_ext-d_ss_int)/2; % Inner steel layer thickness (mm) for each specimen
```

Insulation layer

```
x_puf = 7.09*x_int; % insulation thickness (mm) % manually iterate thickness factor until HDPE casing diameter after
% foaming == d_hdpe_ext = 450 mm
d_int_puf = d_ss_ext; % insulation interior diameter (mm)
d_ext_puf = d_ss_ext + 2*x_puf; % insulation exterior diameter (mm)
```

HDPE casing layer

```
xp_hdpe = 7; % HDPE thickness (mm)
d_hdpe_int = d_ext_puf; % hdpe casing interior diameter (mm)
d_hdpe_ext = d_hdpe_int + 2*xp_hdpe; % hdpe casing exterior diameter (mm)
```

Outer steel layer

```
x_ss_outer = .4; % external steel layer thickness (mm) https://lrmarine.dk/wp-content/uploads/LNG-katalog-LRM-ver-8.pdf
d_total = d_hdpe_ext + 2*x_ss_outer; % total pipe system diameter (mm)
```

Piping layer thicknesses

```
x_int
```

```
x_int = 11.5000
```

```
x_puf
```

```
x_puf = 81.5350
```

```
xp_hdpe
```

```
xp_hdpe = 7
```

```
x_ss_outer
```

```
x_ss_outer = 0.4000
```

```
d_total
```

```
d_total = 450.8700
```

B. WEIGHT PER LENGTH OF PIPE

```
rho_304 = (7.9841 - T_lng*2.6506*10^-4 - T_lng*1.1580*10^-7)*1000; % 304L SS
density (kg/m3) https://www.osti.gov/servlets/purl/4152287
rho_316 = (8.0842 - T_lng*4.2086*10^-4 - T_lng*3.8942*10^-8)*1000; % 316L SS
density (kg/m3) https://www.osti.gov/servlets/purl/4152287
rho_invar = 8050; % Invar36 density (kg/m3)
https://www.americanelements.com/invar-36-alloy
rho_puf = 85; % PUF density (kg/m3) https://lrmarine.dk/wp-content/
uploads/5-Double_Wall.pdf
rho_hdpe = 9545; % HDPE density (kg/m3) https://www.bpf.co.uk/
plastipedia/polymers/
HDPE.aspx#:~:text=PROPERTIES,low%20cost%2C%20good%20chemical%20resistance.

% Model volumes as cylinders V = pi()*(r2-r1)^2 = pi()*((d2-d1)/2)^2
% Steels have inner and outer layer cylinders
m = 1000^2; % convert from mm^2 to m^2
v_steel = (pi()*(((d_ss_ext-d_ss_int)/2)^2)...
+ pi()*(((d_total-d_hdpe_ext)/2)^2))/m; % volume of steel used for inner and
outer layers in 1m length (m3)
v_puf = pi()*(((d_ext_puf-d_int_puf)/2)^2))/m; % volume of insulation for 1m
length (m3)
v_hdpe = pi()*(((d_hdpe_ext-d_hdpe_int)/2)^2))/m; % volume of hdpe casing for
1m length (m3)

% Mass of pipe material layers per 1m
m_304 = rho_304*v_steel % mass of steel if 304L
m_304 = 3.3087

m_316 = rho_316*v_steel % mass of steel if 316L
m_316 = 3.3431

m_invar = rho_invar*v_steel % mass of steel if invar36
m_invar = 3.3486

m_puf = rho_puf*v_puf % mass of insulation
m_puf = 1.7752

m_hdpe = rho_hdpe*v_hdpe % mass of hdpe
m_hdpe = 1.4693

m_total_304 = m_304+m_puf+m_hdpe % mass of system if 304L steel
m_total_304 = 6.5533

m_total_316 = m_316+m_puf+m_hdpe % mass of system if 316L steel
m_total_316 = 6.5876
```

```
m_total_invar = m_invar+m_puf+m_hdpe % mass of system if invar36  
m_total_invar = 6.5932
```

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