Liquefied Natural Gas as Fuel Design Considerations

William J. Cotta P.E.[1] (M)**, William Alex Haugh[1], Lee Franklin P.E.[1]**
1. U.S. Coast Guard, Marine Safety Center

The global cap for airborne emissions from ships continues to grow more stringent year after year. The revised regulations within Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL Convention) have driven industry to adopt new technologies to control pollution, including the use of natural gas as fuel. To address the safety challenges presented from natural gas fueled ships, the International Maritime Organization adopted the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), which came into force January 1, 2017. The IGF Code makes special note of construction, arrangement, design, and installations, including alternatives, taking into account the unique nature of the fuel.

This paper presents the major design considerations for a natural gas fueled ship that are fundamentally different from a diesel fueled vessel. Naval architects must consider LNG design requirements early in the process because these requirements drive the arrangement and stability of a vessel more so than more traditional designs. Specific hazards unique to natural gas and LNG use on board ships outlined in this paper require special attention by ship designers to ensure safe operation. The particular design requirements to mitigate these hazards include: the requirement to conduct a risk assessment, machinery space safety concepts, the role of hazardous area classification, and fuel containment and distribution requirements. The goal of this paper is not to restate the regulations, but rather to highlight major considerations for designers weighing the use of natural gas when developing new vessel concepts.

INTRODUCTION

For over a century oil has been the dominant fuel used aboard ships, but recent interest in alternative fuels and energy sources has rapidly grown, with natural gas being the most popular option. The driving forces behind alternative fuel adoption are industry and regulatory changes, including pursuit of lower fuel costs, implementation of sulfur emissions caps, and the maturation of new technology, particularly in the case of large lithium-ion battery installations. Of all potential alternative fuels, natural gas is the most widely adopted, and has a long record of use, both as a marine fuel, and as a by-product of transporting liquefied natural gas (LNG). Described within this paper are the differences in design requirements and regulations between natural gas and oil-fueled ships. This paper is not policy or even best practices, but instead a discussion of topics and considerations that are unique to vessels using LNG as fuel and may be new to naval architects.

Oil fuel gained popularity around 1912 when it replaced coal on naval vessels. Oil greatly reduced the labor required to replenish and transfer fuel aboard ships, and enabled underway replenishments (Dahl, 2001). While naval vessels drove the transition to oil, the demand for natural gas as a marine fuel is driven primarily by the commercial industry. Natural gas has a smaller environmental footprint, particularly with regard to sulfur and particulate matter, and is seen by the maritime industry as a pathway to compliance with the IMO Emissions Control Areas Sulfur Caps, (Corbett, 2014).

Natural gas has been used as a marine fuel since the first LNG carriers used the boil off gas from cargo tanks in their engines. Liquefied natural gas has a relatively high energy per unit of mass of 21,240 BTU/lb, compared to low sulfur diesel, which has an energy per unit of mass of 18,122 BTU/lb. However, diesel has a higher density of 7.09 lbs/gal compared to 3.49 lbs/gal for LNG. Thus, a gallon of low sulfur diesel contains almost twice as much energy than a gallon of LNG (AFDC, 2017). Though diesel fuels have advantages in storage and energy per unit volume, natural gas adoption is driven by the increasing public concern about air pollution, specifically sulfur compounds and particulate matter. As IMO moves towards regulating CO2 emissions, natural gas adoption will most likely increase, as studies have shown natural gas has a lower carbon footprint (Corbett, 2011).

The design of conventional oil fueled vessels benefits from the flexibility of liquid fuels. Fuel oil can be placed low in the vessel, reducing the height of the center of gravity, and can be placed in tanks which conform to the shape of the hull. During the ship design process, naval architects typically follow a design spiral which sequentially considers owner requirements, mission requirements, hull form, size, and so on. Design constraints for fuel oil are primarily limited to endurance requirements and the storage location's effect on the stability of the vessel. The unique hazards of natural gas as a fuel result in reduced flexibility in its storage and supply to engines when compared to conventional oil fuels. Therefore, specific hazards and design considerations must be accounted for much earlier in the design spiral. Commercial vessels typically meet classification society, flag state, and international requirements. Combined class, flag state, and international regulations limit the location and type of equipment that can be used onboard a vessel. The hazards associated with natural gas use and storage as LNG have been learned through decades of LNG carrier operations, and if identified in an initial risk assessment, can be mitigated.

It is important to note that the term LNG as fuel only refers to the storage of natural gas, and not it's state when consumed. Natural gas is heated and returned to its gaseous state before being injected into an engine. Injecting natural gas in its liquid state into a combustion chamber would result in enormous thermal variations and present significant design challenges to any engine manufacturer. Though natural gas has an extremely low flashpoint (-306.4 ^{o}F) compared to diesel fuel (>120 ^{o}F), the autoignition temperature of diesel is significantly lower, 410 ^{o}F compared to 1076 ^{o}F. The compression ratios required to achieve the autoignition temperature of natural gas are exceedingly high, and typically pure gas engines require the use of a spark plug to ignite the fuel. Most natural gas engines on the market are dual-fuel engines using a small amount of diesel to ignite the gas when compressed. This dual fuel technology has eased the transition to natural gas by providing flexibility as systems are commissioned. The use of dual fuel engines has also benefits from the ability to switch fuels rather than shut down engines in the event of a leak or abnormal condition in the natural gas supply system.

The LNG carrier fleet has an excellent safety record with over 7,700 voyages and no breach of cargo containment according to the Society of International Gas Tanker and Terminal Operators (SIGTTO). LNG carriers are required to meet the International Maritime Organization's (IMO), "International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk," known as the IGC Code. These requirements were first published in 1986, though the first LNG carrier, the METHANE PIONEER, began operating in 1959. The design requirements that allow these vessels to operate safely has been applied to the use of LNG as Fuel. Safety regulations from the IMO and the U.S. Coast Guard were initially developed based on the IGC Code with the publication of the "Interim Guidelines on Safety for Natural Gas-Fuelled Engine Installations in Ships," in 2009. Standalone regulations were adopted in 2015 and came into force in 2017 for the use of LNG as fuel by the IMO in the "International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels," (IGF Code). To provide flag state guidance on the IGF Code, the Coast Guard published policy letter CG-ENG 01-12 Change-1 in 2017 which provide acceptable design alternatives which ensure that vessels operating with LNG as fuel maintain an equivalent level of safety to vessels using diesel fuel. The discussion in this paper focuses on the implications of recently published regulations and policies on the design of a vessel, in the hopes of addressing frequently asked questions and identifying potential design challenges.

In discussing various characteristics of natural gas throughout this paper, we use the properties of methane. Natural gas composition depends on source, but natural gas is typically about 94% methane by volume, as defined in the IMO Interim Guidelines. When first extracted, natural gas contains other components including heavier hydrocarbons, water, carbon dioxide and sulfur. The water, carbon dioxide, and sulfur are all removed during liquefaction. The removal of sulfur during liquefaction eliminates vessel exhaust emissions of SOx, allowing vessels using LNG as fuel to meet the most stringent IMO ECA Sulfur emission requirements.

Primary Hazards

The primary hazards to personnel are: flammability, frostbite, and asphyxiation. LNG is stored as a cryogenic liquid, which requires using appropriate materials and safety precautions to contain and handle the fluid in piping systems and storage tanks. A cryogenic liquid is defined as one that has a boiling point at atmospheric pressure below -240 °F. The boiling point of LNG at atmospheric pressure is -258.7 °F, which requires piping and containment systems to be insulated to protect personnel and maintain the temperature of the fluid. Contact with a cryogenic fluid is a serious hazard to personnel. Even short periods of contact can cause third degree frostbite. This is also a hazard to ship hull and support structures, as the typical mild steel used in the construction of ships will undergo a ductile to brittle transition at low temperatures resulting in cracking. All components on an LNG piping system must be designed for the lowest temperatures to which they may be exposed. In addition to the minimum design temperature, piping systems carrying cryogenic fluids are required to complete stress analysis accounting for the weight of the pipes, acceleration loads, internal pressure, and loads induced by the supporting structure of the ship, typically accomplished by a finite element analysis.

The design requirements and testing for piping systems mitigate the risk of a leak from piping and connections. Where piping connections are flanged or threaded, they must be provided with drip trays, which are typically made of stainless steel. Another potential leak source is the bunker station, which must be located on an open deck, and have a drip tray underneath. Vessels are required to protect surrounding hull or deck structures from a leakage of fuel. The most common method employed is a water curtain system flowing over the drip tray and discharging over the side of the vessel. The water curtain quickly moves any spilled LNG away from the vessel, while also vaporizing the LNG by heating it above its critical temperature. Natural gas disperses away from the vessel because it is lighter than air, preventing a localized flammable concentration from forming. A few areas are specifically called out as requiring drip trays to protect the ship from exposure to cryogenic temperatures, but when conducting a risk assessment, designers should be diligent in identifying potential sources of leaks.

HAZARDOUS AREAS

The flammability concerns of natural gas differ from conventional liquid fuels in that natural gas is typically odorless and disperses through a space, making it significantly more difficult to detect and contain. The flammable range for natural gas is from 5 to 15% by volume, with 5% referred to as the lower explosive limit (LEL) and 15% referred to as the upper explosive limit (UEL). Alarms typically trigger around 20% of the LEL, or 1% by volume, and machinery shutdowns can occur at 40% of LEL or 2% by volume. Regulations mitigate the danger of fire by activating protection systems before a significant quantity of natural gas can accumulate in a space.

Areas that are prone to gas leaks and developing flammable atmospheres are called hazardous areas, and are split into different categories based on the likelihood and duration of natural gas being present in an area. The purpose of establishing hazardous area classification is to prevent explosions and limit the effects resulting from an explosion. Area classification is a method of analyzing and classifying the areas where explosive gas atmospheres may occur.

Hazardous areas are much more familiar to the oil and chemical transportation world than the passenger vessel industry, but the challenges associated with designing around hazardous areas are not insurmountable; it just requires careful planning of tank location, the routing of vent piping, ventilation inlets and outlets, and the arrangement of spaces to protect from potential ignition sources.

In order to facilitate the selection of appropriate electrical apparatus and the design of suitable electrical installations, hazardous areas are divided into Zones or Divisions. Although the Division method of classification is preferred in North America, internationally the Zone method of classification is preferred and is the method used in current Coast Guard Policy for LNG. A Zone 0 location is defined as a location where concentrations of flammable gases or vapors are present continuously. A Zone 1 location is defined as a location in which ignitable concentrations of flammable gases or vapors are likely to exist under normal operating conditions. A Zone 1 and Division 1 location are not the same. Division 1 is equivalent to the combination of both Zone 0 and Zone 1. A Zone 2 location is defined as a location in which ignitable concentrations of flammable gases or vapors are not likely to occur in normal operation and, if they do occur, will exist for a short period. Zone 2 and Division 2 locations are considered the same as they have an equivalent level of risk with respect to the time a hazard may exist. Normal operations is considered the situation when equipment is operating within its design parameters. Minor releases may occur during normal operations, however intentionally releasing natural gas to control tank pressure is not allowed.

Explosion Protection

For an explosion or fire to occur, all three elements of the fire triangle must be present; fuel, oxygen, and an ignition source. Electrical equipment has the potential to become an ignition source, therefore it must meet specfied requirements based on the classification of an area. Equipment intended for use in a Zone 0 area is usually of the intrinsically safe, "ia" type. Equipment intended for use in a Zone 1 area is usually required to be flame or explosion proof, purged/pressurized, liquid immersion, increased safety, encapsulated or powder filled. Equipment that is intended for use in a Zone 2 area is usually of the nonincendive, non-sparking, restricted breathing, hermetically sealed or sealed device type. Designers should ensure that equipment selected is accepted for use based on the classification of the space.

MACHINERY SPACE SAFETY CONCEPTS

The IGF Code classifies machinery spaces in two categories: gas safe and emergency shutdown (ESD) protected spaces. The major difference between the two is that a single point of failure cannot result in a gas release in gas safe machinery spaces, while this may occur in ESD-protected spaces. Different regulations and safety provisions are required based on the safety concept selected by the shipbuilder. This section outlines the design considerations that exist for each concept.

Ventilation

An LNG-fueled ship's ventilation system is a key design element that ensures potentially explosive concentrations of vapor are dispersed in the event of a gas leak. Designers must put care into planning hazardous space ventilation systems, noting specific regulations for inlet and outlet locations, flow velocities, exchange rates, and equipment specifications. This section addresses some of the major concerns shipbuilders should be aware of when considering an LNG-fueled vessel.

Machinery space ventilation requirements are based on the selected machinery space safety concept. ESD protected machinery spaces require more elaborate designs and a minimum of 30 air exchanges per hour. Redundancy should be incorporated into the design to ensure ventilation systems remain effective even in an emergency situation. Designers should provide redundant power sources of ventilation equipment such that a failure of the main or emergency switchboard does not adversely affect ventilation capacity.

Naval architects need to design a completely independent ventilation system for all double walled piping, gas valve units, and machinery spaces. Efforts should be made to coordinate the ventilation system design with the tank and fuel supply piping designs as hazardous areas will affect locations of inlets and outlets. Ventilation inlets for non-hazardous areas must be positioned at least 1.5 meters away from hazardous boundaries. Additionally, ventilation outlets are classified based on the hazardous zone they originate from and may be subject to exclusion spaces around the outlet location. This has forced designers to come up with creative solutions to vent machinery spaces, such as using vent masts. Designers intending to utilize LNG fuel systems on smaller vessels (i.e. tugs) must consider the additional impacts of hazardous areas surrounding these entry and exit points, which can make compliance difficult. Issues such as on-deck ignition sources and machinery, limitations on tug-to-vessel contact regions, and effects on towline presentation must be addressed early on in the design process.

Gas Safe Machinery Spaces

Gas safe machinery spaces are designed based on the concept that they are inherently gas safe, i.e. vapor will not be released into the space due to a single point of failure. This requires specific considerations when addressing areas that could be prone to leaking. This primarily means the inclusion of double walled piping or ducting such that the annular space is pressurized with inert gas or the ducting is ventilated at a rate of 30 air changes per hour. Designers must also keep in mind that fuel piping must be covered up to the injection point into the engine.

Efficient machinery layouts are extremely important, as space can be restricted on LNG powered vessels. This is a significant design hurdle, which can limit the efficiency and versatility of a vessel, especially when adapting LNG powered systems for smaller vessels. IGF Code requirements mandating separation between tank storage and machinery spaces and machinery redundancy in segregated spaces will most likely drive designers to consider gas safe over ESD protected spaces for smaller vessel projects. Designers should be mindful that additional burdens may be put on the inert gas generation system if choosing to inert the annular space of the double walled fuel piping instead of venting the space. Simply modifying legacy configurations from existing vessels may not be suitable to meet regulatory standards and designers may be required to consider novel/innovative ship plans to maximize space usage.

ESD Machinery Spaces

Vessels using ESD protected machinery spaces require redundant machinery spaces in the event of a fuel supply shutdown to one space. The IGF Code requires that engines be distributed among different machinery spaces to eliminate the possibility of loss of power if one machinery space is inoperable. Due to the inherent design of ESD protected spaces, shipbuilders must also design bulkheads of adjacent machinery spaces to withstand local gas explosions that maintain the integrity of the adjacent space in order to protect against unacceptable loss of power. This adds additional complexities that are not typical in passenger vessel or RO-RO designs and must be considered early in the design process.

Designers must also consider the geometric shape of ESD protected machinery spaces due to the possibility of natural gas leakage and accumulation. Complex shapes should be addressed in the risk assessment and additional investigation, such as gas dispersion analysis or smoke testing, may be required to demonstrate proper ventilation of enclosed spaces.

Many classification societies require testing to demonstrate the effectiveness of ventilation.

FUEL CONTAINMENT

The storage tank is the most important piece of equipment in ensuring the safe use and storage of LNG onboard a vessel. A failure of the fuel containment system will result in a release of LNG that is difficult to contain and has a high probability of leading to a fire. Fortunately, based on the safety record of the industry, a fuel containment failure is a low probability scenario. LNG containment systems are split into two main types, independent and integral tanks. An independent tank has sufficient structure to support the static, sloshing, and pressure forces of the fluid within it. The ship is required to have sufficient structural support to ensure the tank is secured to the vessel, while still allowing for thermal expansion and contraction as the tank is cooled and heated. Integral tanks are also called membrane tanks and require structural support from the vessel to provide the strength that supports the forces required to contain the fuel and maintains the tank's shape. Membrane tanks consist of a liquid/vapor tight barrier insulated from the hull with a few feet of insulation that can contain the cryogenic LNG, and are popular in the LNG Carrier fleet.

Boil Off Gas

As the LNG warms over time, some of the liquid will boil off into gas, increasing the internal pressure of the fuel tank. Selecting a tank for a ship requires an understanding of how boil off gas is generated, and development of a plan to manage internal tank pressure. The internal pressure of a tank is tied to the critical temperature of the fluid in the tank. The critical temperature for any fluid is the temperature above which the fluid will not exist in a liquid state. No matter how much external pressure is applied, the fluid will remain as a vapor. Since natural gas is primarily methane, its critical temperature is generally assumed to be the same as methane at -116.2 ^{o}F. The temperature must be below the critical temperature for a gas to liquefy, but the pressure must also be above a certain level depending on the temperature of the liquid. For natural gas at -116.2 ^{o}F the pressure must be 667.17 psia, which, while possible, is energy intensive to achieve. For natural gas to be liquid at an ambient pressure of 14.7 psia, the temperature must be -260 ^{o}F. As the LNG temperature moves from -260 ^{o}F to -116.2 ^{o}F, some of the liquid changes phase into vapor, causing the increase in pressure. As the liquid changes phase it expands in volume by a factor of 600, causing internal tank pressure to increase. Tank selection must consider the insulation surrounding a tank, which will determine how fast the LNG inside warms, and the structure and design will determine what maximum internal pressure it can contain.

The tank type determines the maximum internal pressure of the tank, and the tank is protected by a valve set to relieve at this pressure. The IGF Code (6.9.1.1) requires a ship to maintain tank pressure below the relief valve set pressure for a period of 15 days with only domestic (i.e. no propulsion) loads. Therefore, the tank must either be designed to manage the full quantity of boil off gas that will be generated in 15 days or something must be done with the boil off gas to limit the pressure increase in the tank. Boil off gas has been traditionally used by LNG Carriers as a source of fuel, and the first regulations to allow shipboard use of natural gas as fuel applied to LNG Carriers burning off their boil off gas. This formed the basis of the IMO Interim Guidelines, which for the first time allowed non-LNG Carriers to use natural gas as fuel.

The rate at which boil off gas is generated is further determined by the state of the LNG when it is loaded on a vessel. The LNG must be evaluated for constituent components of the gas, and the temperature at which it is received.. A lower loading temperature corresponds to a lower starting tank pressure. The initial temperature used for the 15 day hold time calculation is reflected on the ship's Certificate of Inspection, as this will be the maximum allowable loading temperature, and thus initial internal pressure.

Independent Tanks

Independent tanks are split into two categories: prismatic and cylindrical tanks. Prismatic tanks can be formed to the shape of the hull and are made up of primarily flat surfaces. For all tanks, the maximum design pressure of the tank is equal to the relief valve setting, and the maximum allowable working pressure is 90% of the design pressure. Cylindrical tanks are limited to a maximum design pressure of 10 barg (~145 psi); however, the maximum design pressure of a prismatic tank is only 0.7 barg (10 psig). These requirements may not be exceeded regardless of additional structure or reinforcement provided to the tank. The independent tank designs can be type A, B, or C. Type A tanks are designed using deep tank standards of a classification society recognized by the Coast Guard under 46 CFR Part 8, Subpart B. Type B tanks are designed based on calculations, analysis, and model tests, and can be either prismatic or cylindrical. Type C tanks are designed as pressure vessels, the Coast Guard accepts pressure vessels designed under

46 CFR Part 54 or Section VIII of the ASME Boiler and Pressure Vessel Code (BPVC).

Independent tanks, specifically Type C pressure vessels, account for the majority of LNG fueled vessel designs in operation and on order. In the United States, we have yet to see a vessel using anything other than Type C tanks for vessels using LNG as Fuel. ASME BPVC is a well-established standard dating back over a hundred years, and there are many manufacturers building pressure vessels to this standard to transport liquefied gases. Using a Type C pressure vessel provides a clear standard to follow, and the ability to accumulate pressure, which is the simplest way to control boil off gas for the required 15 day hold time.

Integral Tanks

Integral tanks are used extensively in the LNG carrier market, accounting for 74% of the active LNG carrier fleet, and 93% of new builds (IGU, 2017). The primary design of integral tanks is a membrane system, and these two terms are often used interchangeably. These systems use the ship’s hull to provide the structural integrity of the tank against any sloshing or other loads. Membrane tanks are designed in prismatic shapes, allowing them to more efficiently occupy the space available on a ship. This allows LNG carriers and bunker vessels to maximize the amount of LNG they can carry. Insulation between the tank and the ship’s structure provides a thermal transition from the cryogenic fluid to the hull materials, such that the structure is not exposed to abnormally low temperatures. Insulation type and thickness are the primary factors in determining boil off rate. Membrane tanks have not been widely adopted on LNG fueled vessels, primarily because they require additional reliquefication or cooling equipment to maintain the internal pressure of the tank below 0.7 barg (10 psig). LNG fueled vessels have smaller tanks than LNG carriers, resulting in a larger surface area to volume ratio. A higher surface area allows higher rates of heat ingress. According to the 2017 IGU report, the average new build LNG Carrier has a capacity of 163,000 m^3. For comparison, one of the first LNG fueled vessels in the United States has a capacity of only 295 m^3. LNG Carriers have the ability to consume any boil off gas while idling in either engines or a gas combustion unit. Additionally, they have the space available to install cooling or reliquefication equipment. For smaller applications, the additional space requirements to install boil off gas management systems that can maintain tank pressure below the 10 psig maximum for 15 days is impractical. Instead, these smaller, shorter-range applications typically use cylindrical type B or C tanks that use pressure accumulation during idle periods to handle boil off gas. Designs have been proposed for larger container vessels, and with new insulation systems and cooling technologies, the use of membrane systems may grow.

RISK ASSESSMENT

The IGF Code and the CG-ENG Policy Letter both require a risk assessment to be conducted specific to the vessel and its operations. A single risk assessment is acceptable for a fleet of vessels built to the same design. The Coast Guard has not issued regulations for the use of natural gas as fuel. Instead, the policy letter provides alternative design standards that ensure a vessel using natural gas as fuel provides a level of safety equivalent to that of a vessel using diesel. The unique component of the risk assessment required by the IGF Code and the CG-ENG Policy Letter is that it must be submitted and approved by the Coast Guard prior to beginning plan approval. Once approved, the mitigating safety measures are treated as requirements for the design of the vessel. This risk-based approach allows the maritime industry to incorporate new technology faster than Coast Guard regulations can keep up by creating a custom set of requirements for each vessel unique to its design and operation. It is important to note that specific deviations from regulations or special considerations must be considered in the risk assessment, including the location of the storage tanks and a request for a higher loading limit of the LNG storage tanks. If there is a chance that a design may change and require special consideration, this should be analyzed in the risk assessment to avoid the need for a new risk assessment.

In identifying hazards to include in the risk assessment, the IGF Code specifically calls out areas that must be addressed, including drip tray size and fuel containment. Additionally, standard failure modes, including leaks, equipment failures, and collision, should be considered in addition to any deviations from the requirements, and any characteristics of the vessel that make it unique. The risk assessment must follow an industry standard technique. Typically this is conducted by a recognized classification society. The International Association of Classification Societies publishes the guidance on risk assessment techniques and scope in its recommendation “Risk Assessment as required by the IGF Code,” (IACS, 2016).

DESIGN CHALLENGES

Beyond the major decision points outlined above, there are additional design challenges that may be considered by the ship designers in the risk assessment.

Pump or Compressor Room Classification

Pump or compressor rooms are defined in the IGF Code as ‘fuel preparation rooms’, and classified as Zone 1 hazardous locations. This is a departure from the requirements in CG-521 Policy Letter 01-12 dated April 19, 2012, which classified natural gas pump or compressor rooms and associated ventilation inlet or outlets to the strictest requirements. The policy letter’s classification was established in order to bridge the gap between U.S. regulations and the IMO Interim Guidelines. This presented a design challenge given the limited electrical equipment protections allowed in cargo pump and compressor rooms under 46 CFR 111.105-31(f); intrinsically safe equipment, explosion proof lighting fixtures, and cables supplying intrinsically safe equipment in the cargo handling room. With the release of CG-521 Policy Letter 01-12 Ch.1 in 2017, the hazardous area requirements for fuel preparation rooms were harmonized with established international standards.

Vent Mast

Hazardous area classifications also impact personnel protection. For example, the outlet of an LNG storage tank relief vent is required to be located 6m or a distance equal to a third of the beam (B/3) of the vessel above the working deck, whichever is higher. This requirement aims to protect personnel from exposure to hazardous vapors in the unlikely event of unintended gas release. It should be noted that the vent mast height could be limited to a lower value as long as the arrangement demonstrates an equivalent level of safety to the requirements as stated. Consideration can be given based on the vessel’s tank release mass flow rate, pressure, and temperature; length of the tank relief vent pipe run; and fluid velocity calculated at the vent outlet.

Electrical Equipment Certifications

All electrical equipment located within the hazardous area must be protected and certified by an independent testing laboratory recognized by the Coast Guard as required in CG-521 Policy Letter 01-12. Certification under the European Union’s (EU) ATEX Directive (94/9/EC) is not acceptable. Although similar to accepted standards, the ATEX Directive allows for self-certification of equipment and test methods that are not harmonized with accepted standards. It should be noted that certification under the ATEX Directive does not limit equipment from also having certification under standards accepted in CG-521 Policy Letter 01-12 Ch-1.

Welding of Cryogenically Robust Materials

A major consideration for designers is the specific materials required for cryogenic temperatures. Examples of such materials can be found in the IGF Code (7.4), which calls out the specific requirements for the percentage of alloying elements in the steel. The alloying elements required for steel exposed to cryogenic temperatures reduce the weldability of the steel. The reduced weldability and requirements for double wall piping present challenges in fabrication, compared to the mild steels typically used in shipbuilding.

A complex LNG fuel system inherently requires strong welds throughout the piping system, which can be especially difficult to achieve in double walled piping in gas safe machinery spaces. Typically, 304L or 316L austenitic stainless steel, which is suitable for the -258.7 °F boil off temperature of LNG (Holloway & Marshall, 2005). The overall quality of the weld depends on the type of filler material used, the skill of the welder, and the welding equipment settings. In austenitic steels, achieving welds that maintain high toughness characteristics while still guaranteeing sufficient hot cracking and weld defect resistance requires low delta-ferrite (FN) levels while not exceeding a minimum threshold, usually in the 3-8 FN range (Friedrich, et. al.).

Carefully controlling consumable selection (i.e. chemical composition) and welding procedures (i.e. torch arc length) can improve overall weld quality. Not accounting for this can result in lower quality welds, significant rework, and delays during construction.

Hydrostatic vs. Pneumatic Pressure Testing

Pressure testing methodology of the fuel piping is another challenge to consider. Hydrostatic or pneumatic pressure testing is typically used to comply with section 16.7.1 of the IGF Code, both of which have advantages and disadvantages that should be addressed by shipbuilders.

Hydrostatic testing uses a liquid medium and is considered safer than pneumatic testing. Unfortunately, all excess water from testing must be removed from all piping prior to system cool down. Failure to do so can result in the formation of hydrates, a combination of water and chemical constituents that closely resembles ice (Lynch, et. al, 2014). Accumulation of hydrates can cause obstruction of fuel piping, blockages of valves, and pressure drops that can lead to equipment damage. The additional time needed to ensure all piping is clear of water after hydrostatic testing to prevent formation of hydrates can be difficult if under tight construction and delivery schedules and should be noted when planning piping test schedules. Pneumatic testing with an inert gas medium such as nitrogen can be accomplished much more quickly, but is potentially more dangerous due to the increased buildup of stored potential energy in the compressed gas, especially at higher pressures. Failure to take proper precautions can result in catastrophic brittle failure and explosive decompression of piping. More robust safety procedures and testing precautions must be taken to ensure personnel and equipment are protected and requires additional oversight and Coast Guard approval prior to conducting this type of testing.

CONCLUSIONS

LNG is quickly being adopted as a fuel source in the maritime world, and with the publication of IMO and Coast Guard policies and regulations, there are now standards in place for new projects to follow. Designing a vessel using LNG as fuel involves different safety requirements than a traditional diesel fueled ship. The classification of spaces as hazardous areas will limit the equipment that can be placed those spaces. The selection of a machinery space concept is a critical design decision that will determine the number of engine rooms required, and the piping requirements in engine rooms. Finally, the selection of a fuel containment system and boil off gas management system will determine where fuel can be placed in a vessel, and, based on the tank design, the percentage of the space that will be allocated for fuel storage. A risk assessment will address all of these design decisions, and ensure that any gaps in regulations are covered. The key to success in designing an LNG fueled vessel is an understanding of the applicable design standards provided in regulations and Coast Guard policies, and a detailed project proposal that focuses on the design decision points outlined in this document.

REFERENCES

"2017 World LNG Report." International Gas Union. 2017.

Alternative Fuels Data Center (AFDC). "Fuel Properties Comparison." U.S. Department of Energy. May 21, 2017. https://www.afdc.energy.gov/fuels/fuel_properties.php

Barron, Randall F. *Cryogenic Systems.* New York: Oxford University Press, 1985.

CG-521, "Equivalency Determination - Design Criteria for Natural Gas Fuel Systems," U.S. Coast Guard, 2012

CG-ENG, "Equivalency Determination - Design Criteria For Natural Gas Fuel Systems (Change-1)," U.S. Coast Guard, 2017.

Corbett, James J, Ph.D., Thomson, Heather, Winebrake, James J. Ph.D. "Natural Gas for Waterborne Freight Transport: A Life Cycle Emissions Assessment with Case Studies." U.S. Department of Transportation, Maritime Administration. July, 2014

Dahl, Erik. "Naval Innovation. From Coal to Oil." National Defense University, Institute for Strategic Studies. 2001.

Friedrich, Norbert, Gerhard Posch, Josef Ziegerhofer, and Walter Berger. "Welding of Austenitic Stainless Steels for Cryogenic LNG Applications." Accessed May 11, 2018. https://app.aws.org/mwf/attachments/6/240506/Friedrich_et_al.pdf.

Holloway, Graham, and Adam Marshall. "Is Welding Stainless Steel For LNG Applications Easy?" Stainless Steel World: 421-427.

International Association of Classification Societies (IACS). "Recommendation No. 146: Risk assessment as require by the IGF Code." August 2016.

International Maritime Organization (IMO). "Interim Guidelines on Safety for Natural Gas-Fuelled Engine Installations in Ships." June 1, 2009

International Maritime Organization (IMO). "International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code)." June 19, 2015

International Maritime Organization (IMO). "International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk or Other Low-Flashpoint Fuels (IGF Code)." June 19, 2015

NFPA, "NFPA 70A: National Electrical Code," NFPA, 2017