SUSTAINABILITY WHITEPAPER

LNG AS MARINE FUEL

JULY 2022

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OVERVIEW

The adoption of the "Initial International Maritime Organization (IMO) Strategy on Reduction of Greenhouse Gas (GHG) Emissions from Ships" by IMO Resolution MEPC.304(72) in April 2018 demonstrates IMO's commitment to support the Paris Agreement. The IMO strategy includes initial targets to reduce (as compared to 2008 levels) the average carbon dioxide (CO_2) emissions per "transport work" by at least 40 percent by 2030, aiming to pursue 70 percent reduction by 2050; and an ambition to reduce the total annual GHG emissions from shipping by at least 50 percent by 2050. Technical approaches, operational approaches and alternative fuels may be used to achieve these goals.

The near-term regulatory changes and the future impact of the IMO's GHG targets for 2030 and 2050 should be considered when making the long-term decision on fuel selection. Liquefied natural gas (LNG) is a relatively mature low-carbon fuel, comprised primarily of methane. Its carbon to hydrogen (C/H) ratio offers a reduction in CO_2 emissions of up to 20 percent compared to baseline heavy fuel oil (HFO). In combination with latest technological improvements and/or operational measures, LNG may be a viable option to meet the 2030 emission reduction goals.

This paper focuses on selected practical considerations for LNG as a marine fuel and summarizes the relevant vessel design and operational aspects with reference also made to relevant technological advancements.

The information provided can support the decision-making process for future ship designs, propulsion systems, and fueling strategies. It is an overview of the key aspects considered for LNG as fuel, addressing bunkering, vessel arrangements, fuel containment, fuel gas supply systems, single gas and dual-fuel (DF) main engines. The adaptation of LNG as fuel depends on case-specific requirements and therefore the information provided in this paper concentrates on the areas that apply broadly to LNG as fuel installations.

This document provides practical pointers in the use of LNG as marine fuel and is intended to supplement the ABS *Advisory on Gas and Other Low Flashpoint Fuels*. Information provided in this document is generic in nature. For specific guidance on LNG as marine fuel the local ABS office may be contacted.

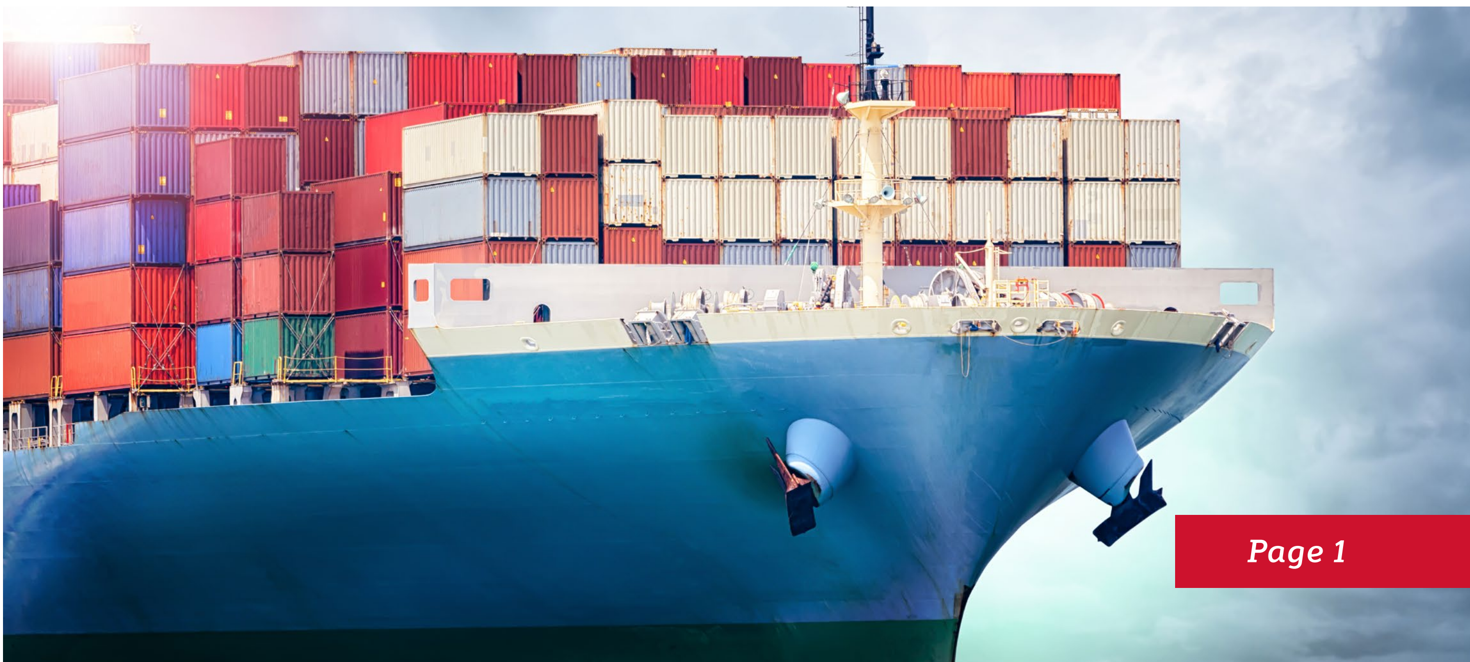
LNG AS FUEL FOR THE REDUCTION OF GREENHOUSE GAS

LNG as a fuel is one of the options that an owner might use in combination with technological and operational improvements to meet IMO 2030 CO_2 reduction targets.

In a comprehensive approach, the first step would be to benchmark where an owner's fleet is currently in its emissions reduction plans. Then look at the intended operating profile of the vessel/s and determine how an LNG fueled vessel would fit into the company's plans and what savings they could expect.

The operating profile impact is not to be underestimated, as depending on the fuel system selected a vessel may not get the expected 20 percent reduction. Burning of natural gas in boilers to control tank pressure has been used as a convenient means of controlling LNG tank pressures and temperatures and maintain them within acceptable limits. However, this excess consumption simply to control and maintain pressures affects the overall carbon footprint.

Type of containment system used, boil-off gas (BOG) management system in place and combustion process adopted have an impact on total GHG emissions.



INITIAL LNG CONSIDERATIONS

IMPACT OF OPERATIONAL PROFILES AND ROUTES ON VESSEL DESIGN

Most vessels are designed based on a defined operating profile. Hull form has also typically been a significant influencer on vessel design. For liquefied natural gas (LNG) fueled ships, the design of the LNG fuel containment system needs to consider both the optimal operating profile while the vessel is in transit and the undesirable conditions such as when the vessel stops, loads, awaits orders, etc.

For example, a sample aframax tanker in the European sector spends 30 percent of its time idle with no main propulsion power with an average speed of only 10 knots compared to a design speed of 14.5 knots. Very large ore carriers/bulk carriers often spend about three weeks in port waiting to load and about another three weeks in a destination port waiting to discharge. Along with operating profiles, designs are to consider the dynamic characteristics of LNG fuel properties and that the associated fuel containment system can cope with these extended periods with low rates of gas consumption.

This change in thinking may mean that the first fuel system proposed may not be the one that is best suited to everyday operations. The design is to be flexible enough and well suited to meet normal trading patterns.

In-depth voyage and vessel operations profile analysis is required to establish likely parameters and guide system design and equipment specifications (for example, matching tank maximum allowable relief valve setting of a cargo tank [MARVS] to meet likely fuel supply saturated pressure).

OWNERSHIP COST CONSIDERATIONS DURING CONCEPTUALIZATION

Actual operating profile and fuel to be used for each part of the journey needs to be considered during cost analysis.

There are multiple different configurations that could be utilized between propulsion power and electrical power supply by auxiliary generators such as single gas fuel generators coupled with dual-fuel (DF) or conventional liquid fuel generators. In certain cases, it might be better to fit LNG fuel to the main engine and have the auxiliary generators on liquid fuel.

Reliquification plants are an option, but a life-cycle cost analysis might be necessary to justify the capital expenditure (capex), operational expenditure (opex) and environmental costs.

For redundancy, having a means of replacing a pump or valve in service may be cheaper than having two pumps or valves. However, redundancy replacements might not be as straightforward in many cases. Careful attention needs to be paid towards the redundancy requirements. With regards to the International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code), essential services are to be provided by DF gas consumers since single point failure of a gas component will revert to diesel operation. For single gas fuel consumers redundancy is required for essential services.

CHARATERISTICS OF LNG

LNG is a mixture of several gases, in liquid form, principally composed of methane (CH_4), with a concentration that can vary from 70 to 99 percent by mass, depending on the origin of the natural gas. Other hydrocarbon constituents commonly found in LNG are ethane (C_2H_5), propane (C3H8), and butane (C_4H_{10}). Small amounts of other gases, such as nitrogen (N_2), may also be present. Natural gas reserves are significant; with the International Energy Agency (IEA) estimating reserves at current usage rates (January 2011) are over 250 years.

When liquefied at approximately -162° C, the volume required for natural gas is reduced to about 1/600th of that required when in the gaseous state. In this condition, LNG is stored in tanks where the heat ingress leads to the generation of boil-off gas (BOG). The BOG is consumed by the engines or is re-liquified in order to maintain the LNG tank pressure within acceptable limits. The LNG saturation vapor curve and its effect on bunkering is to be fully comprehended to improve bunkering.

Both marine slow-speed two-stroke engine manufacturers, MAN Energy Solutions and Winterthur Gas & Diesel (WinGD), offer DF internal combustion engines. However, each manufacturer has selected a completely different combustion process for when the engine operates in gas mode. The two different gas mode combustion concepts are low-pressure (LP) gas engines using the Otto cycle and high-pressure (HP) gas engines using the Diesel cycle.

The WinGD LP DF engines (X-DF) utilize the Otto process in gas mode and the conventional Diesel process when in oil mode. The MAN HP DF engines (ME-GI) use the Diesel combustion process in both oil and gas modes. For both concepts, the gas is ignited by a pilot injection of liquid fuel from the conventional fuel injection system, or a dedicated pilot fuel system. The point during the combustion cycle where the gas is injected dictates the required gas supply pressure.

The WinGD X-DF is designed to operate at a gas supply pressure of up to 13 bar, and the high-pressure MAN ME-GI uses gas delivered by a direct injection system at approximately 300 bar. The two different designs lead to different combustion concepts, Otto cycle for the X-DF and Diesel cycle for the ME-GI, and therefore have different performance and emissions characteristics. A recent announcement by MAN involved the development of their low-pressure DF engine, ME-GA.

Table 2 highlights some of the key similarities and differences between the slow speed DF concepts. The similarities are limited to, the pilot fuel oil quantities required to start the gas combustion process, the minimum engine load that the engine can achieve when operating in gas mode, and the fact that both concepts are sulfur oxides (SOx) compliant when using sulfur compliant fuel for the pilot fuel.

Overall, the suitability of a specific concept, or engine type, to a ship is very much a case-specific decision. For some, it may simply be that they are not comfortable with HP gas or the increased complexity and cost associated with HP fuel gas supply systems. For others, it may be the concerns with Otto cycle being sensitive to a number of operating parameters (Methane Number, Ambient Conditions), or the GHG impact of methane slip.

Table 1: Otto vs Diesel Slow Speed 2-Stroke DF Engine Comparison

	WinGD X-DF	MAN ME-GI
Cycle Type (in Gas Mode)	Otto	Diesel
Gas Supply Pressure [bar]	< 13	300
BMEP [bar]	17.3	19.0-21.5
IMO NOx Compliance (in Gas Mode)	Tier III	Tier II
Liquid pilot % @ 30% MCR	~1.0	3.0-5.0
Methane Number Sensitive	< 80	No
Knock/Misfire Sensitive	Yes	No
Methane Slip	Yes	Not significant
Development Status [Type (Year)]	XDF 2.0 (2020)	Mk 2.0 (2019)

Note: All Figures are approximations, based on Manufacturers' updates, and may change

REGULATORY COMPLIANCE

Regulatory and classification requirements are in place for the use of natural gas fuel in marine applications. The specific gas fueled ship (GFS) arrangements depend on the fuel containment, the fuel gas supply system (FGSS), and selected prime mover technologies. The link between fuel storage, fuel preparation and gas consumer is much more interdependent as compared to conventional fuels. Critical equipment and system design decisions cannot be made in isolation. The following sections are to be considered for the use of liquefied natural gas (LNG) as a marine fuel.

IMO REGULATIONS

The adoption of the Initial International Maritime Organization Strategy on Reduction of Greenhouse Gas Emissions from Ships by the Resolution MEPC.304(72) in April 2018 demonstrates the IMO's commitment to support the Paris Agreement. It includes a vision to phase out GHG emissions from international shipping within the century and may be an active driver for member States to initiate decarbonization and reduction of GHGs using policies and procedures.

The IMO's International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) applies to ships to which the SOLAS Part G Chapter II-1 applies and contains only detailed prescriptive requirements for LNG under Part A-1 of the Code. Other low-flashpoint fuels may also be used as marine fuels on ships falling under the scope of the IGF Code, provided they meet the intent of the goals and functional requirements of the IGF Code and provide an equivalent level of safety. This equivalency is to be demonstrated by applying the Alternative Design risk assessment process and SOLAS novel concepts approval procedure of SOLAS regulationII-1/55, and as required by 2.3 of the IGF Code.

RISK ASSESSMENT

The following basic operations and routing items are to be considered:

- Type of vessel and associated cargo operations (e.g., offshore support vessel (OSV), tug, container carrier, bulk carrier)
- Expected trade route (including roundtrip or one way).
- Where to bunker the vessel, how often to bunker, bunker providers, bunkering time duration.
- Vessel bunker tank sizes have increased considerably. Larger tank sizes require careful planning for cargo transfer operations as the operation might take weeks in port.
- Vessel build location and maintenance/ repair locations which might influence scheduled and unscheduled delays. Choice of fuel between these locations and plan to manage operating expenditure (opex) costs.

These basic considerations can impact on choices and selections for a vessel and in determining engine choice, gas fuel handling system and amount of redundancy needed.

Contingency planning is necessary to account for unexpected vessel repairs (emergency drydocking, hull inspection, engine repair, major damage) to accommodate tank emptying, gas freeing and subsequent return to service.

Extensive prior planning for integration of LNG fuel, methods and procedures with crews, fuel suppliers, transporters, port authorities and regulators is necessary.

DESIGN CONSIDERATIONS

VESSEL ARRANGEMENTS

For liquefied natural gas (LNG) fueled ships, the main systems to be accommodated in a design concept that are different, or additional, to conventional ship designs are the LNG fuel containment system, associated LNG bunker station and transfer piping, a fuel gas supply system, the double-wall fuel gas distribution piping, gas valve unit (which may be located in a gas valve unit [GVU] room), gas consumers, nitrogen generating plant, vent piping systems and mast(s), and for some LNG tank types, additional equipment for managing tank temperatures and pressure.

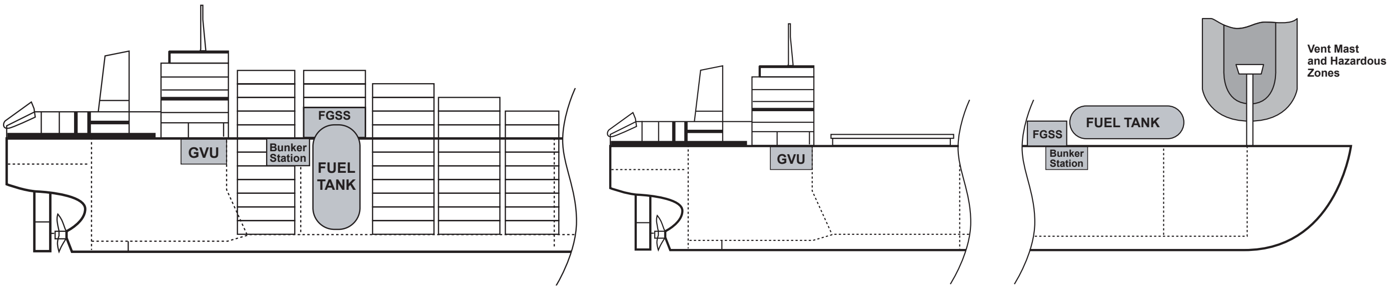


Figure 1: Typical Examples for the location of LNG tanks and main equipment

The protective LNG tank location criteria can be based on a deterministic approach considering tank volume or a probabilistic method. The International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) provides a third alternative, where the ship's hull is specifically designed and reinforced in the way of the LNG tank, therefore minimizing the impact from a collision and so allowing the tank located closer to the ship's side shell. The probabilistic method requires the input of a number of ship and tank parameters to calculate the required "fCN" value, which must be below 0.04 for cargo ships and 0.02 for passenger ships. Figure 1 shows some typical examples for the location of the LNG tanks and main equipment.

The "Emergency Shutdown (ESD)-Protected machinery space" concept introduces additional measures to provide an equivalent level of safety to the conventional non-hazardous machinery space. Application of the ESD-Protected machinery space has been limited so far because of the growing availability of engines that can be supplied meeting the double barrier criteria and perhaps because of the additional vessel complexity and cost that meeting the ESD machinery space concept brings. The non-hazardous machinery space concept is based on the use of double barriers for all gas-containing components such that a failure in a single barrier cannot lead to a fuel gas release into the space. The main differences between the two machinery space concepts are shown in the Figures 2 and 3. The non-hazardous machinery space also shows the GVU room. This may be a separate space outside of the machinery space, or may be a GVU unit, which is a self-contained unit that is essentially an extension of the double barrier piping system and may be located within the non-hazardous machinery space.

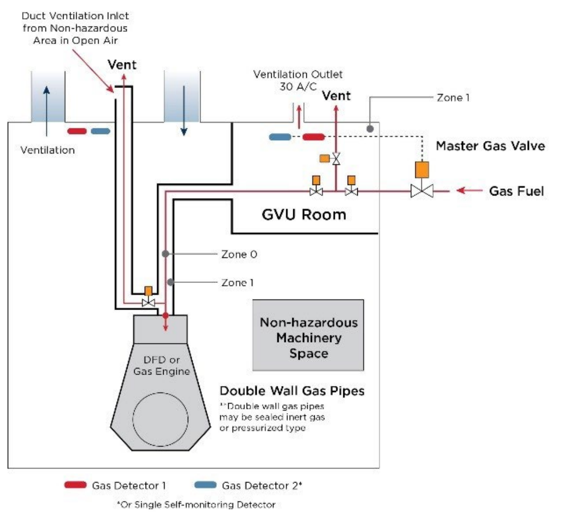


Figure 2: IGF Non-Hazardous Machinery Space Concept

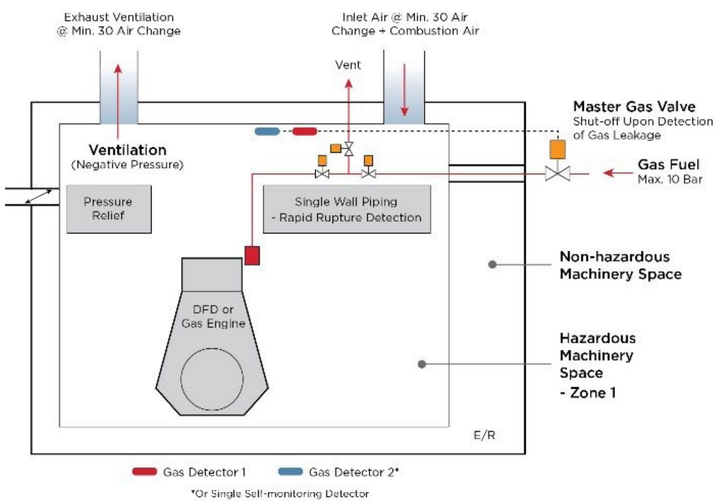


Figure 3: IGF ESD Machinery Space Concept

Vessels also have to find practical locations that meet the prescriptive requirements for the fuel preparation room, vent mast, and the nitrogen generating equipment, as per the ABS *Guide for LNG Fuel Ready Vessels*. The LNG fuel containment system vent mast location can be a particular challenge because of the requirements on hazardous area zones around the vent mast exit and the physical location criteria for the LNG tank pressure relief valve vents. These need to be at least 10 meters (m) from any air intake, air outlet or opening to accommodation, service and control spaces or other non-hazardous area and any exhaust system outlet. Vent heights shall normally not be less than B/3 or 6 m. The ABS *Guidance Notes on Gas Dispersion Studies of Gas Fueled Vessels* may be referenced for additional guidance on gas dispersion studies associated with alternative vent termination locations and proposed hazardous areas. Hazardous areas are also a challenge with location of tanks, fuel gas piping systems, fuel gas supply system (FGSS) and gas consumers.

Table 2: IMO LNG Fuel Containment System Comparison

ITEM	TYPE B	MEMBRANE	TYPE C
Secondary Barrier	Partial secondary barrier required	Complete secondary barrier required	No secondary barrier required
Volume Efficiency	Medium as it can follow the compartment shape, however space for inspection to be provided around the tank	Maximum effectiveness as the whole hold is utilized	Least space efficient. Independent tanks, simple cylindrical shape, frequently located on deck. Bi-lobe and tri-lobe give improved space efficiency
Fabrication	Similar to ship normal structures (skilled welders)	Requires high skills and accuracy (special licenses provided by the designer)	Pressure vessel construction (skilled welders)
Inerting Requirements	Hold can be filled with dry air, but sufficient inert system should be available onboard	Additional systems for pressurizing and inerting the interbarrier spaces are necessary	Hold can be filled with dry air if condensation and icing is an issue (non-vacuum tanks)
Sloshing	In general, it is not an issue due to tank internal structure	May be a serious issue, in particular for large tanks, but specially designed reinforcements are used	In general, it is not an issue
Capability to Retain Boil-off Inside the Tank	Design pressure not higher than 0.7 bar according to the Codes, therefore they cannot withstand the pressure developed by the boil-off for a long time	Design pressure not higher than 0.7 bar according to the Codes, therefore they cannot withstand the pressure developed by the boil-off for a long time	High pressure accumulation capability; e.g. LNG tanks 10 bar and LPG 18 bar
Inspections	Inspection relatively easy as the tanks are fully accessible on both sides	Inspections may be difficult as certain parts are not accessible and require special testing or inspection procedures	Inspection relatively easy as the tanks are fully accessible on both sides, smaller tanks through man or remote access holes
Maintenance and Repairs	Similar to normal ship structures, though insulation can restrict access	Specialized workers required and usually time-consuming	Similar to normal ship structures, though insulation can restrict access

FUEL STORAGE

There are four main types of LNG tanks, namely independent tank types A, B and C, and integrated membrane tanks. Types A, B and membrane are low pressure, nominally "atmospheric" tanks, whereas Type C are pressurized tanks. Type A, B and membrane tanks require a secondary barrier to protect in case of leak from the primary barrier. Type A and membrane systems require a full secondary barrier. Type B requires a partial secondary barrier since these are designed using advanced fatigue analysis tools and a "leak before failure" concept, for which small leaks can be managed with partial cryogenic barrier protection and inert gas management of the interbarrier space. Type C tanks are designed using pressure vessel code criteria and conservative stress limits; therefore, they do not require a secondary barrier.

Most gas fueled ships (GFS) in operation at present have the International Maritime Organization (IMO) Type C pressurized fuel tanks. This is because these are relatively inexpensive to manufacture and simple compared to the other fuel containment types, particularly in the smaller sizes required by the current gas fueled fleet. Type C tanks can also simplify the required boil-off gas (BOG) management equipment because of their pressure accumulation capability; however, these tanks might not be the most space-efficient option.

Large deep-sea vessels would likely specify membrane fuel containment systems to limit the loss of cargo space compared to conventional fueled ships. Sloshing can be an issue that requires special consideration for membrane tanks. LNG membrane tanks for GFS need to be designed to accommodate all LNG liquid levels as in service. Therefore, the tanks will be designed with higher density insulation materials and membrane reinforcement in critical areas.

BOIL-OFF GAS

For GFS, the amount of BOG available in certain instances might not be sufficient to sustain the ship's power demands at maximum continuous rating, so the fuel gas supply systems need to force vaporize the LNG into conditions suitable for the engines. In some cases, the designers may prefer to force vaporize LNG and send it to the main engines because it might be cheaper and more efficient to boost pressure on LNG and vaporize it on a high-pressure vaporizer rather than use a compressor. But the ship will still need to manage the BOG and LNG tank pressures at all times, including times where there is no gas consumption by propulsion related consumers, which can lead to many potential combinations for fuel supply and BOG management equipment.

Vapor returns need to be considered during design when the bunker supplier has the capability of receiving and handling vapor returns. Vapor return does assist with reducing heat transfer while loading the LNG tank with liquid from the bottom in lieu of using top spray
to manage pressure accumulation while loading. Vapor return also assists with reducing the duration of the bunker evolution since liquid can be filled in the bottom of the tank and any vapor pressure accumulated during loading can be returned to the supplier.

The LNG fuel containment system selected will influence the installed equipment for BOG management and also have an operational impact on tank filling levels and how bunkering (tank pressure and vapor return) is managed in service. The complexity of LNG bunker vessels is greater than conventional fuel oil bunker vessels and introduces specific compatibility challenges.

The IGF Code permits a number of ways to manage the BOG, including consumption, reliquefication, cooling and pressure accumulation. The IGF Code sets criteria for controlling tank pressure and temperature at all times and for maintaining tank pressure below the relief valve setting for 15 days when the vessel is idle with domestic load only. The 15-day criteria may be difficult for atmospheric tanks to achieve on domestic (hotel) load only and may therefore necessitate the fitting of additional BOG management equipment, such as reliquefication systems.

FUEL GAS SUPPLY SYSTEMS

The purpose of the FGSS is to deliver fuel to the engine or consumer at the required temperature and pressure. For gaseous fuels using cryogenic/pressurized liquefied storage, the fuel may be pumped or pressure fed, directly in liquid form, such as LNG, from the tank and vaporized to a gaseous state for the consumer, or supplied in combination with the use of compressed gas from the natural tank BOG

For dual-fuel (DF) engines, typically there is no requirement for FGSS redundancy since the basic safety concept is that the primary fuel remains the fuel oil and seamless transition back to oil mode is required in the event of a safety system trip of the gas fuel system. In those cases where gas is the means of Tier III NOx compliance, MARPOL Annex VI/ NOx Technical Code (NTC) permits transit to the next port in Tier II mode. However, for practical reasons, duplication of rotating and reciprocating FGSS equipment, such as submerged LNG pumps or high-pressure cryogenic pumps, is often specified by ship owners and operators for redundancy, reliability and maintenance purposes.

Two common engine and FGSS options are:

1. MAN's ME-GI High-Pressure DF Engine, operating on Diesel cycle where the gas is supplied to this engine at high pressure (300 bar) therefore the FGSS involves high-pressure pumps, evaporators and high-pressure compressors and
2. WinGD's X-DF Low-Pressure Engine, operating on Otto and Diesel cycle where the gas is supplied to this engine at low pressure (13 bar), therefore the FGSS involves low-pressure pumps, evaporators and low-pressure compressors.

Common issues reported so far involve the main engines and the relevant FGSS. However, this was expected as these technologies are relatively new to the marine industry. The problems reported on both types of main engines involve mainly the components related to gas mode operation. Based on the service experience being collected, engine designers have improved their designs to minimize operational issues. Problems were initially reported with FGSS operation. However, the suppliers of this equipment have also developed and improved the designs further to eliminate issues during operation. Overall, the development process of DF engines and FGSS is still ongoing. Yanmar produces auxiliary LNG DF generators in its EY35 series lineup which operates at a mean effective pressure of 20 bar. Wartsila's 20DF (21 bar) and 31DF (27 bar) genset series can also be used as LNG auxiliary generators.

Note: All Figures are approximations, based on manufacturers' updates, and may change.

TOTAL COST OF OWNERSHIP

MAN & WinGD's DF engines cover the entire rating field (power/speed) already covered by their Diesel engine versions, satisfying the powerdemand of all types of vessels. However, the different technologies and designs for their DF engines affect the cost of the engine, the cost of the FGSS and the exhaust emission abatement equipment required for each of the design concepts differently.

The two categories that play an important role in the decision-making process of a DF engine are financial aspects such as capital expenditure (capex) and operational expenditure (opex) (derived by life-cycle cost analysis studies, on case-by-case basis) and technical aspects such as up to date service experience and feedback for the two engines/FGSS (which affect opex).

The total cost of ownership is equal to the aggregated sum of the capex and all the annual costs during the lifetime of the vessel. The selection of an engine and accompanied Tier III technologies, where applicable, affect capex and opex and therefore the total cost of ownership. In order to identify the effects a specific engine selection has on total cost of ownership; a life-cycle cost analysis is required that takes into account a specific vessel and specific operating profile (case-by-case).

DUAL FUEL ENGINE CONVERSION

Operation with gas as fuel requires specific FGSS to feed the DF engine with gas at the required pressure and temperature. In addition, the main DF engine, the components of which are generally based on the conventional Diesel engine design, require some key base engine components in order to operate in gas mode.

Furthermore, the ability of a Diesel engine to be easily converted to a DF engine in the future may also be an important decision, for example, if an owner is selecting a "Ready" notation in preparation for converting the ship to burn natural gas at some point after vessel delivery.

The fundamental engine design of MAN ME-GI is kept unchanged when compared to ME engines. The GI (Gas Injection) term refers to all gas-related components that are necessary to make an ME engine to operate on gas. As the GI concept is practically an add-on to the existing ME engine, one may consider ME engines as "Gas ready."

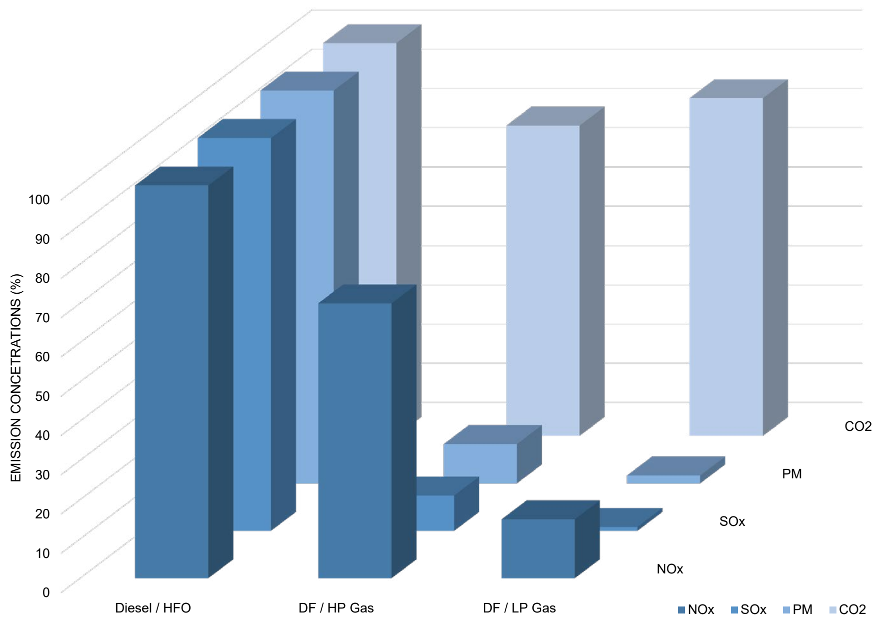
The WinGD's X-DF engine is based on the general design of the standard X-engine (Diesel). However, apart from the key gas related components that are needed to make the engine capable to run on gas, several other base engine components are different between the two engine types.

DUAL FUEL ENGINE EMISSION PROFILES

The use of natural gas and other low-flashpoint fuels, which are inherently low in sulfur, are a means of complying with the SOx emissions limits of MARPOL Annex VI, but also offer significant further reductions in the SOx and the sulphate portion of PM, since the sulfur content of these fuels is typically less than 30ppm (parts per million). Nitrogen oxides (NOx) formation is linked to peak combustion temperatures, and these are significantly higher for Diesel engines in general compared to gas engines.

Similarly, DF engines using the lean burn Otto process to burn natural gas have much lower NOx emissions than those using the Diesel diffusion combustion process. A comparison of the general emission profiles for current marine DF low and high-pressure engine technologies, when operating on natural gas, compared to the same engine using diesel or residual fuels, is shown in Figure 5. The LP DF engines can meet the current IMO NOx limits without any emissions abatement equipment when operating in gas mode.

Figure 4: Dual-Fuel Engine Emissions



BUNKERING SYSTEM

BUNKERING CONSIDERATIONS DURING CONCEPTUAL DESIGN

Bunkering is to be considered at the beginning of a design project to ensure optimum design. If during the design stage the trading route is known and the potential bunker supplier along the route identified, measures/contracts can be established to ensure the parameters of the LNG vessel during bunkering and the supplier/bunker vessel are aligned and procedures of bunkering standardized. If trading routes and suppliers are unknown during design stage, then it might be beneficial to increase the equipment limits on the ship to ensure issues arising from bunkering are handled correctly.

Temperature of bunkers and pressure control are two issues of concern.

- The colder the LNG from the LNG supplier the better it is for the GFS. This means there is more time to manage pressure control in the tanks. If the bunker vessel supplies warm LNG, this might result in handling increased boil-off/pressure which may lead to an increase in fuel consumption just to handle pressure.
- Linked to temperature, an additional concern is understanding if the LNG gas carriers/bunker vessels' vapor return system has been evaluated for conducting vapor balancing in a compatibility study/assessment with the gas fueled vessel. Vapor balancing design compatibility between supplier and receiver is to be verified. As we look at larger bunker tanks, an owner needs to consider what happens during the cool down of the bunker tank prior to full rate loading and how to handle the associated flash gas that will be generated If this is not considered, then this will impact the duration of the bunkering operation evolution, which in results may impact on the expected operating profile.

In addition to verifying the vapor balancing design compatibility between supplier and receiver, there could be challenges with documenting custody transfers. In addition to measuring quantities of LNG supplied to the GFS, the amount of vapor returned may need to be measured. Credits for gas vapor return need to be included into the overall price during custody transfer.

Other areas such as bunker station location and bunker vessel compatibility are to be considered.

DIFFERENCES IN DESIGN BETWEEN GAS AND FUEL OIL SYSTEM

LNG fueled vessels are to be thought from the bunker tank point of view. This concept is new to most owners although more familiar within the LNG/liquefied petroleum gas (LPG) cargo community. The design thought process needs to shift from handling a static liquid fuel that does not significantly alter if left alone to that of a dynamic liquefied gas fuel which is actively trying to get back into a gaseous state.

It is typical to think about consumptions or flows in metric tons (tonnes) and cubic meters (m3) and although this can also be done for LNG it is not to be forgotten that LNG is an energy source that has different characteristics depending on pressure and temperature and is constantly changing. Factors such as loading capacity, energy value received and measuring the amount of energy received need to be considered when bunkering.

KEY LEARNINGS FROM EXISTING VESSELS

LNG fuel vessel ordering has grown steadily but the vessel types are changing to include large container vessels, tankers and bulk carriers. These vessel types and sizes will bring with them some new challenges which will need to be addressed, both at the design and operational stages.

- Bunker tanks are now much bigger which brings high boil-off rates (BOR). Maintenance of tank pressure for intending operating profile needs to be carefully evaluated. Larger sizes also correspond to greater surface are to cool down during loading thus having more flash gas.
- The time between bunkering operations for large vessels will be in weeks whereas for the small vessels it was a few days. This results in warmer tanks when loaded and thereby increased flash gas.
- Location of the GFS bunkering station is to be close to the fuel containment system. This results in less lines to cool down and lowers associated heat ingress during loading.
- Many LNG vessel designs have large Type C containment tanks with outer surfaces exposed on deck. As these tanks are exposed to radiant heat from the sun, changes in ambient temperature affect the temperatures and pressures within the LNG tanks.
- Rolling motions will increase sloshing. Sloshing collapses the pressure within the fuel containment system as an initial effect. Ultimately sloshing increases the rate of heat ingress thereby increasing rate of pressure build up in the tank.
- Designs therefore need to consider that the installed equipment matches the operating conditions and profile so that LNG tank temperature and pressure can be managed at all times; the IGF Code criteria is applicable but may not be robust enough for many ship types and operating profiles.
- Designs also need to consider provision of fuel supply system redundancy, or carriage of sufficient spare parts, to avoid being unable to burn LNG when required. Many arrangements have full redundancy of fuel oil systems to meet SOLAS requirements, but single pumps or equipment for the LNG fuel supply system. This can limit operation on LNG.
- LNG fuel supply systems also need to have sufficient filtration to meet the equipment manufacturer's specifications and avoid debris or contamination related equipment failures.

IMPACT OF ONBOARD GAS CONTAINMENT SYSTEM ON CONCEPT/DESIGN

There are several containment options for the bunker tank. Considerations for selecting containment options include:

- Range in terms of energy and volume
- Fuel containment system locations
- Single or multiple tanks
- Required LNG BOR for generating power
- Impact on cargo capacity
- Matching the fuel containment system to the FGSS and engines
- Purging, cool down, filling and warm up procedures of tanks
- Volume/space efficiency
- Maximum design vapor pressure
- Requirement for secondary barrier
- Typical BOR values for the containment type/design
- Sloshing impact (whether extra reinforcement is required and impact on BOR)
- Tank weight (impact on ship's deadweight, stability and strength)
- Production cost and shipyard's capability/license to build containment
- Service experience and reliability
- Maintenance, testing and inspection requirements

SUPPLY CHAIN

Fuel availability is one of the challenges to widespread take-up; however, there are initiatives underway to develop new marine fuel supply chains. In all cases, the three basic routes to supply are truck-to-ship, ship-to-ship and tank-to-ship.

Truck-to-ship is usually the first bunkering method applied but is only suitable for delivering small quantities. Truck-to ship provides most versatility as observed with ferries. They can be driven on board the vessel to provide bunker operations similar to existing conventional fuel bunkering operations. Capacities/transfer rates can be increased by introducing loading manifolds/skids.

Land-based tank infrastructure can require significant investment and take many years to develop and obtain the necessary approvals. However, examples of land-based tank infrastructure exist. For instance, Harvey Gulf International Marine (HGIM) Port Fourchon facility and Eagle LNG facility in Jacksonville, Florida.

The use of dedicated bunker vessels is expected to be a preferred option for many operators. However, the most viable option depends on the GFS operating profile and the regional LNG supply infrastructure where bunker may occur.

ABS PUBLICATIONS ON LNG BUNKERING

ABS published an LNG Bunkering Study titled "Bunkering of Liquefied Natural Gas-fueled Marine Vessels in North America" to provide comprehensive information on LNG, bunkering, training, risk assessment, etc. for GFS operators, bunker suppliers and state and port authorities. This document also provides detailed generic information applicable to all considering LNG as a marine fuel.

ABS has also published an advisory titled "LNG Bunkering: Technical and Operational Advisory" to provide information on tank capacity, compatibility, operational issues, monitoring, bunkering and custody transfer.

In January 2017, ABS published the ABS *Guide for LNG Bunkering* to outline the LNG bunkering requirements for the design, construction, and survey of liquefied gas carriers and barges fitted with dedicated LNG transfer arrangements and intended to operate in regular LNG bunkering service. Among other safety topics, the guide addresses bunkering station safety, lifting and hose handling equipment, control, monitoring and ESD safety systems and emergency release systems.

OPERATIONAL CONSIDERATIONS

LOADING LIMIT

Reference temperature is the temperature corresponding to the liquefied natural gas (LNG) vapor pressure at the set pressure of the pressure relief valves.

Loading limit is defined as the maximum allowable liquid volume relative to the tank volume.

$$LL = FL \frac{\rho_R}{\rho_L}$$

Per ABS Marine Vessel Rules (MVR) 5C-13-6/8.1,
LL = loading limit, in percent tank volume
FL = filling limit, 98 percent
ρ_R = relative density of the fuel at the reference temperature
ρ_L = density of LNG at the loading temperature

Tanks typically cannot be loaded beyond the agreed loading limit.

However, as per MVR 5C-13-6/8.2, "In cases where the tank insulation and tank location make the probability very small for the tank contents to be heated up due to external fire, special considerations may be made to allow a higher loading limit than calculated using the reference temperature, but never above 95 percent. This also applies in cases where a second system for pressure maintenance is installed, (refer to MVR 5C-13-6/9). However, if the pressure can only be maintained/ controlled by fuel consumers, the loading limit as calculated in MVR 5C-13-6/8.1 shall be used. The alternative loading limit option given under 5C-13-6/8.2 is understood to be an alternative to 5C-13-6/8.1 and should only be applicable when the calculated loading limit using the formulae in 5C-13-6/8.1, gives a lower value than 95 percent."

Most gas fuel vessels fitted with Type C tanks request a loading limit of 95 percent. The risk associated with external fire resulting in heating tanks, increased liquefied gas vaporization and over pressurization should be addressed by a risk assessment.

HANDLING RISK

A risk analysis will help identify possible risks and consider the safety mitigating measures that may need to be implemented during design and operational procedures. The International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) and class require specific areas of ship design to be risk assessed as shown in Table 3.

In addition to the design of the vessel, the operations associated with bunkering the vessel may need to be further assessed for risk based on the specific operation concept and the stakeholders. Handling risk is a shared responsibility amongst all stakeholders. Typically, the shipowner/operator will take the lead in developing risk and safety studies as they are in control of the vessel operations and procedures, with the added expectation of operation specific knowledge combined with access to LNG safety and technical expertise from the earlier concept development phase.

Table 3: Risk Assessment

ABS MARINE VESSEL RULES	SECTION TITLE
5C-13-5/10.5	Capacity of Drip Trays
5C-13-5/12.3	Separation of Spaces by Airlocks
5C-13-6/4.1.1	Containment System – Integration to Overall Design
5C-13-6/4.15.4.7.2	Design Load for Membrane Tanks – Accidental Scenarios
5C-13-8/3.1.1	Closed or Semi-Enclosed Bunkering Stations
5C-13-13/4.1	Alternative Ventilation Capacity for tank connection spaces
5C-13-13/7	Ventilation System for Bunkering Station not on Open Deck
5C-13-15/8.1.10	Gas Detectors for Ventilation Inlets
5C-13-6/4.4	Novel Containment Systems – Alternative Design Factor
5C-13-6/6.8	Novel Containment Systems – Accidental Scenarios

Once the initial studies have been completed, ship operators have to ensure that the resulting mitigations and safety measures that reduce the risk of LNG fuel and bunkering operations into the acceptable range are fully implemented within their safety management system process, communicated to crew and other stakeholders and consistently implemented. A key element of consistent implementation to reduce risk to as low as reasonably practical (ALARP) level relies on the capability of persons in charge of bunkering to recognize on-scene, site and condition specific risks to the LNG fuel vessel or bunkering operation and take effective measures to eliminate or reduce it, including canceling, postponing or halting the operation.

SHIP PROCEDURES

During the initial design stage of the project, it is essential to establish a comprehensive and detailed concept of operations. This should include participation of all identified stakeholders and parties that may have input to or be impacted by operation of the gas fueled ship (GFS). Detailed operations concept development is to account for actual and practical performance of all activities related to using LNG as marine fuel.

Shipboard procedures must incorporate the risk control and safety measures already required within their company and ship Safety Management System under the International Safety Management (ISM Code). This requires effective understanding of the hazards that LNG fuel presents, the necessary precautions, ship and equipment design and the operating parameters of the containment and fuel gas supply system (FGSS).

Specific operational challenges arise around managing the LNG fuel supply on board – port call scheduling and voyage management may become more challenging depending on the ship's service. Point to point or return to base operations are more easily managed than a ship in global trading on spot charters. Vessel masters and chief engineers may have to adjust speed/power or otherwise manage fuel consumption and boil-off gas (BOG) generation for pressure control/reduction to accommodate scheduled bunkering's, slow speed passages in port and idle time alongside or at anchor.

SIMULTANEOUS OPERATIONS

Charterers will need to be conscious of available fueling infrastructure when issuing voyage orders. Scheduling bunkering operations for before or after cargo operations will be necessary unless a Simultaneous Operations (SIMOPS) study shows an acceptable risk level permitting both operation at once. Some ports or terminals may not permit LNG bunkering within the port or restrict it to certain locations that may require the ship to shift to receive bunkers.

The specific operating procedures need to be documented in the "fuel handling manual" (vessel operations manual) as specified in the IGF Code, and should also include the results of all the safety measures and recommendations from the risk and safety studies that were performed as part of IGF Code, class and administration compliance. This would include SIMOPS evaluations and any other risk studies done for specific locations by the bunker supplier.

MAINTENANCE

The maintenance regime change is dependent on the technology, systems and equipment chosen for the LNG fueled vessel. It is expected that maintenance activities related to inspection and cleaning of fuel supply and exhaust systems may be reduced and perhaps lead to increased intervals between propulsion system overhauls, but there may be increased requirement for inspection, maintenance and repair of other elements of the vessel systems and equipment, including heat exchangers, control, monitoring systems and safety systems, and bunker transfer equipment.

TRAINING AND QUALIFICATION

Seamanship and good marine practices need to be followed on all vessels including LNG fueled vessels. It is important not to be complacent. This knowledge relies on good foundational training as specified in the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) table of competence but also should be underpinned by a robust onboard training program that allows crew members to fully familiarize themselves with the operation of the vessel prior to assuming their duties and responsibilities. This is a fundamental requirement for all ships specified in SOLAS, including a focus on the different risks and consequences resulting from use of a different fuel.

Crew members will have to become skilled at recognizing risks to the safety of a bunkering operation using on the scene analysis consistent with their training and with the hazard elements identified in a location specific risk assessment. Training is required for crew, shore staff and commercial teams including charterers on LNG fueled vessels. The STCW Part A, Chapter V, Section A-V/3 lists the mandatory minimum requirements for the training and qualification of masters, officers, ratings and other personnel on ships subject to the IGF Code.

Some important aspects of training and education for GFS operation include:

- LNG safety, awareness and risk management for executives
- Technical and operational training for supervisors and shore staff, including bunker supplier
- STCW and Administration compliant training for seafarers aboard GFS
- STCW and Administration compliant training for seafarers aboard bunker ships
- Regulatory Marine Inspectors, port authorities, emergency responders, other port and terminal stakeholders impacted by LNG bunkering operations

CHARTER PARTIES, CONTRACTS AND BUNKERING AGREEMENTS

Shipowners must specify fuel supply contracts that reflect the requirements for safely storing and holding LNG fuel within the operating parameters of their ship containment and FGSS. For example, tank operating pressure limits should reflect the expected condition at the time of bunkering, not the tank maker specified design minimum temperature. The LNG supply contract should specify, for example, a maximum acceptable saturated vapor pressure. The Society for Gas as a Marine Fuel (SGMF) contractual guidelines may be used as a resource.

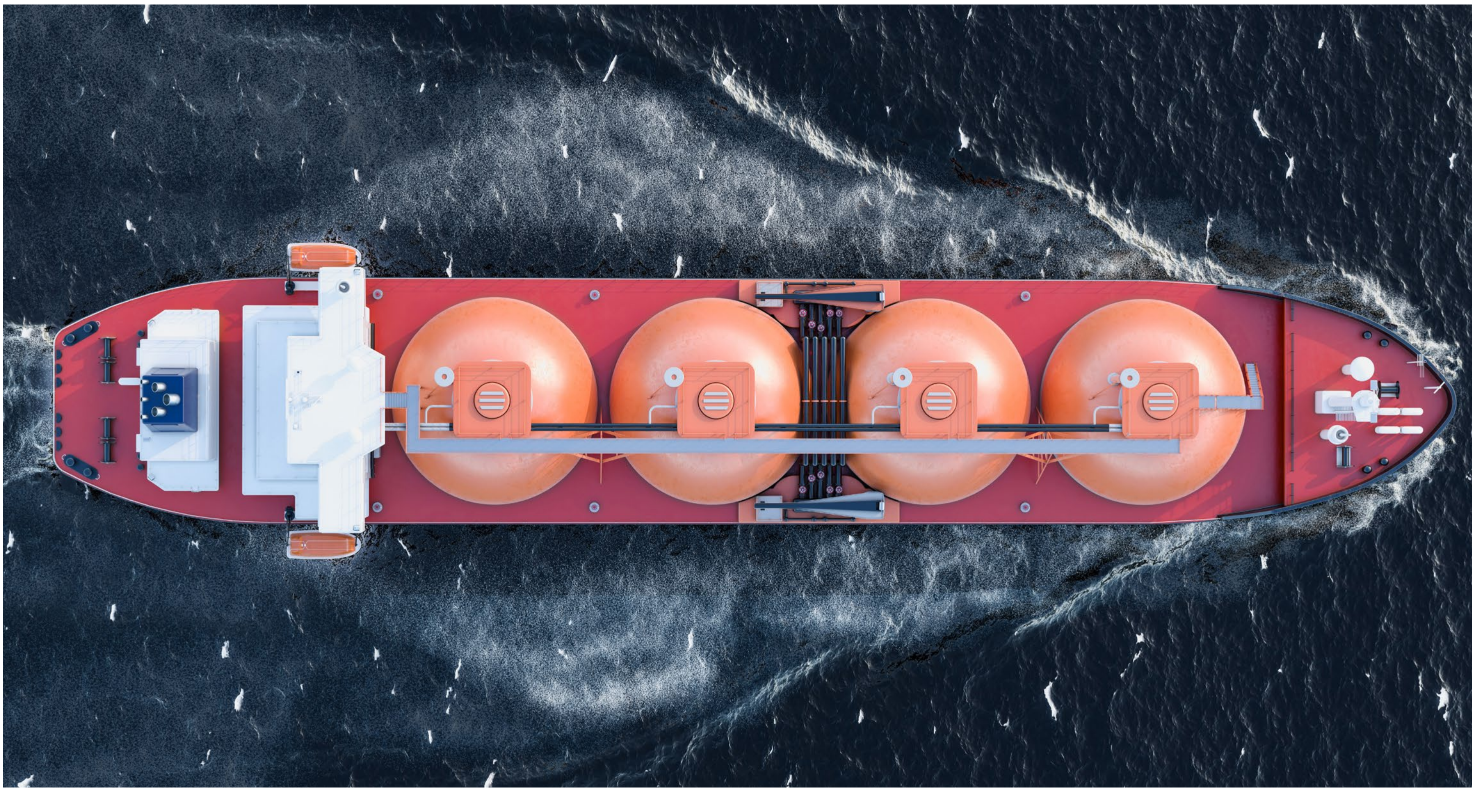
Charter party terms should account for potential voyage management issues that facilitate fuel tank conditioning prior to bunkering that fits with the vessel port schedule and minimizes fuel waste, delay or results in fuel management issues that adversely affect ship performance. LNG fuel operations, technical and safety management training/familiarization should be conducted for shore staff, managers and executives that may be in a decision-making capacity to ensure they are familiar with the specific contract terms and more importantly the implications for safe operation of the GFS. This links to risk management and crew safety awareness by ensuring that masters and chief engineers have decision-making tools that facilitate safe and efficient LNG bunkering and LNG fuel operation.

Detailed instructions/specifications/contractual terms to vendors, shipyards and system designers are required to ensure that all required pre-planning, design integration and equipment specifications are relevant for the true vessel operational profile (from builder's yard to first drydocking) and within the operating specifications of the LNG fuel handling systems.

DRY DOCKING

Steps and actions needed for scheduled or unscheduled dry docking is an integral concept of operations planning. System, equipment capabilities and modifications can be incorporated through initial design to facilitate smooth dry-docking operations. These may include additional piping, spool pieces, blind flanges, etc. within the FGSS. Modular construction of components and critical spares inventory may simplify replacement and repair during scheduled dockings.

Risk and safety studies can look at a variety of contingencies and requirements for safe management. This may require input from fuel suppliers, service providers, shipyards, equipment makers and port authorities/regulators. Dry dock planning must include a procedure for emptying, inerting and gas freeing the tanks. Shipboard planning for such operations must include risk and safety training in addition to detailed procedural steps to minimize risk. Work planning for survey, maintenance, overhaul, replacement, repair needs to included long lead ordering and arrangement of specialized technicians if needed for servicing gas fuel equipment.



ONGOING RESEARCH

METHANE SLIP

Methane slip is the escape of methane gas from production, processing, transport, operation or combustion. In terms of internal combustion (IC) engines, "methane slip" refers to the unburned methane present in IC engine exhaust emissions. The amount of methane contained in the IC engine exhaust varies greatly between engine combustion types (Otto or Diesel), specific engine designs and engine loads.

Methane is of primary concern due to its increased Global Warming Potential (GWP) over other greenhouse gases (GHGs). There are various studies on the life-cycle GHG emissions, the results of which are typically shown on a 100-year or 20-year GWP basis. It is known that methane emissions in the atmosphere can trap solar radiation more than carbon dioxide (CO_2). Methane emissions are estimated to be 84 times more severe than CO_2 on a 20-year basis and 28 times more severe than CO_2 over the 100-year basis by the IPCC AR5 report.

There are three primary causes of methane slip: scavenging leakage, incomplete combustion and trapped methane in the combustion chamber crevices. Scavenging leakage occurs when the methane and air mixture passes directly to the exhaust, for example when gas injection to the cylinder occurs prior to closing the exhaust valve. Incomplete combustion occurs in all IC engine types but is primarily an issue for lean burn Otto process gas engines.

Incomplete combustion can occur for many reasons (including trapped methane, detailed below) but it is typically due to flame quenching close to the cylinder walls and extinguishing of the combustion flame at low pressure and temperature. This is effectively fuel quenching at the coldest part of the combustion chamber while the engine is running. This results in increased methane emissions during transient operation and operation at low engine loads. To keep combustion stable and reduce methane slip, lean burn Otto engines need to accurately control combustion between knock and misfire conditions.

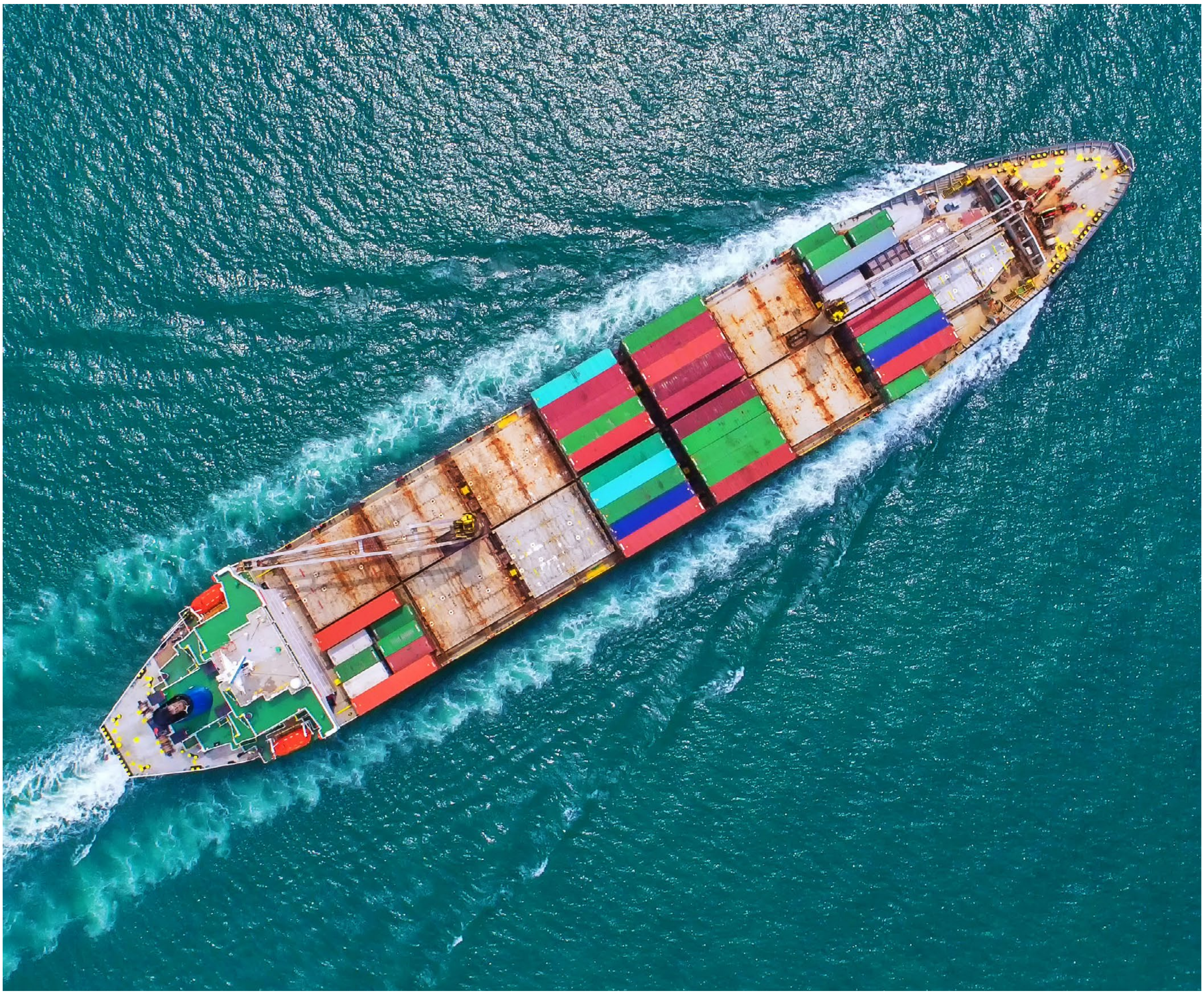
Dead volumes, or crevices, within an IC engine cylinder and combustion chamber are also a source for incomplete combustion and an opportunity for methane to leak directly to the exhaust. The amount of methane slip emitted is highly dependent on the installed engine technology. For example, high-pressure gas injection engines using the diesel combustion process in gas mode can reduce levels of methane slip to the engine exhaust more so than low-pressure engines applying the Otto combustion process in gas mode. A two-stroke engine, when compared to a four-stroke engine, is also typically more effective at reducing methane slip due to the reduced quantities of geometric gas traps.

Methane slip can be reduced by running engines at higher power output. While this is not possible in all ship propulsion and power generation arrangements, it can be used in power generation load sharing to optimize power plant operation to reduce methane emissions.

The IMO's Intersessional Working Group on Reduction of GHG Emissions from Ships continues to consider approaches to control methane slip, which is part of the 37 Candidate Measure Proposals submitted to IMO for adoption. Options to address methane slip include direct methane emission controls or indirect means through fuel carbon factors. The engine manufacturers' latest specifications and latest updates on the dual-fuel (DF) engine concepts regarding possible primary reductions of methane slip, should be referenced.

ABS SUPPORT

- ABS can assist owners and operators as they consider the practical implications of the use of LNG fuel. Services offered include:
- Life-cycle and cost analysis of LNG fueled vessels
- Methane slip calculation and identification of methane slip reduction options
- Vessel/fleet benchmarking and identification of improvement options
- EEDI verification and identification of improvement options
- Econometer and calculation of minimum propulsion power
- Optimum voyage planning
- Alternative fuel adoption strategy
- Technoeconomic studies
- Regulatory and statutory compliance
- Advanced analysis including structural analysis
- Cyber safety notations and assessments
- Risk assessments
- Contingency arrangement planning and investigations
- Classification services for LNG vessels (LNG-Ready notation)
- New technology qualifications



APPENDIX 1: LIST OF ITEMS TO CONSIDER

A. Concern: Design for liquid fuel replacement

1. Most designs are based on at sea nominal continuous rating speed condition. However, oil is passive but LNG which is active. Design needs to account for this change.
2. Existing approvals/codes might be based on static conditions and not dynamic conditions
3. Lack of consumer capacity to reduce pressure when main engine is not at full load

B. Concern: Boil-off Rate – not as expected

4. Ambient conditions – consider direct sunlight/tank color
5. Vessel motions increase pressure and energy in tank
6. Insulation material degradation

C. Concern: Bunkering and Supply

7. Cool down of pipes/return gas can be an issue
8. Bunkers supplied at too high temperature
9. Bunkers have been on board bunker vessel too long
10. Time between bunkering operations

D. Concern: Range and Tank Pressure Control

11. Tank pressure control operates below MARVS – Pressure control designed to be automatic
12. Tank filling limits based on temperature and pressure not volume – Reference temperatures to be understood
13. Conflict between range and allowable filling level – Can reduce time for pressure increase if filling level too high

E. Concern: Vessel Operational Profile

14. At sea, idle, in port – Consider this from an LNG fuel tank perspective

F. Concern: What is the expect/needed operational features for new vessel

15. Range on gas

G. Concern: Location of Bunker

16. Time between bunkering operations
17. Time allowed to bunker
18. Is the bunker supplier looking after your interests/how do they maintain/supply the LNG

H. Concern: Fuel system not matching operating profile

19. Consider the means of handling tank pressure
20. Consumption of each fuel user over full operating profile
21. Scenarios of lesser speed or greater idle time than planned
22. How to consume excess boil-off gas/reduce tank pressure quickly
23. Ensure dynamic approach and not static approval

I. Concern: Getting the boil-off rate needed

24. Be aware of ambient temperature conditions but consider extremes and exposure to direct sunlight
25. Tank location and vessel motions
26. Consider multiple scenarios when approving – Approvals are often based on theoretical temperature and start points, not actuals
27. Tank pressure control arrangements versus MARVS settings
28. Insulation material degradation

J. Concern: Range vs Filling Levels

29. Consider range needed and various pressure in tank scenarios
30. Consider accepting amount of fuel needed without compromising filling level.

K. Concern: capex vs opex considerations

31. Determine if gas will be a primary or secondary fuel
32. Evaluate need for redundancy versus maintainability. Consider spare parts for maintainability instead of redundancy where appropriate.

APPENDIX 2: REFERENCES

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APPENDIX 3: LIST OF ACRONYMS AND ABBREVIATIONS

ABS	American Bureau of Shipping
BOG	boil-off gas
capex	capital expenditure
ESD	Emergency Shutdown
FGSS	fuel gas supply system
GFS	gas fueled ship
GHG	greenhouse gas
GVU	gas valve unit
IACS	International Association of Classification Societies
IGF	International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels
IMO	International Maritime Organization
ISO	International Organization for Standardization
LNG	liquified natural gas
MARPOL	The International Convention for the Prevention of Pollution from Ships
MARVS	Maximum allowable relief valve setting of a cargo tank (gauge pressure)
ME-GI	MAN engine identifier – M series Electronic Gas Injection
MEPC	Marine Environment Protection Committee (IMO)
MSC	Maritime Safety Committee (IMO)
MVR	Marine Vessel Rules
NIST	National Institute of Standards and Technology
NOx	nitrogen oxides
OPEX	operating expenditures
SIMOPS	Simultaneous Operations
SOLAS	International Convention for the Safety of Life at Sea, 1974, as amended
SOx	sulfur oxides
STCW	The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
USCG	United States Coast Guard
WinGD	Winterthur Gas and Diesel

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