Transoceanic carriage of LNG: background and technological innovations

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1. Introduction

The Liquefied Natural Gas (LNG) industry was developed to link huge and stranded gas reserves occurring in geographically remote countries around the globe with regions needing more natural gas as an energy resource. A great part of liquefied gases are light hydrocarbons and the key property that makes hydrocarbons the world's primary energy source is the flammability, which makes all of them intrinsically hazardous. As these gases are handled and transported in huge amounts, it is necessary that all care must be taken during its transportation. The ships allocated in the LNG trades are recognized as integral parts of the major and overall projects they serve. This means that their safety and security play a very prominent role for the players involved, requiring stringent classification and certification rules and regulations for gas carriers from classifier societies[1], since their reputations are placed in this concern. This is most evident mainly when the vessels are alongside terminals in loading or discharging operations where any type of incident could reflect adversely on the owner's business.

This industry has some basic and specific characteristics that differentiate it from the others, requiring: (i) a physical chain (exploration and upstream production, liquefaction, transoceanic transportation, regasification terminals, markets), (ii) a chain ownership's structure (liquefaction, shipping and management structure) and (iii) a value chain (monetization and value creation). They are indivisible, making it a capital intensive industry, requiring strong contribution of scientific and technological development in order to make it competitive. The schematic view of all links is depicted in Fig. 1.

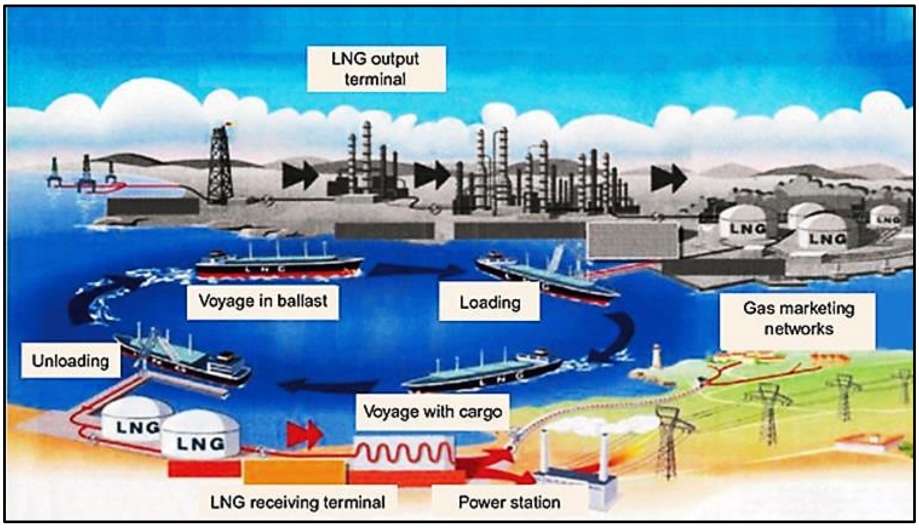

Figure 1 – The chains of the LNG industry
Available: http://www.ee.co.za/article/controlling-the-gas-flow.html Access: 19 Oct. 2015

2. Objectives of this work

LNG and its transportation all over the oceans by means of dedicated carriers are not new and the physical and value chains of this commodity are vast. As the activities of the LNG chain value are relatively new in Brazil (this industry started out in 2006), the objectives of this work is to add some approaches on the theme. It provides the

[1] ABS, Bureau Veritas, DNV, Lloyds Register, to name a few. (ABS, 2016)

basic aspects of one of the most important part of these two chains: the LNG carriers (LNGCs). They are, indeed, who makes viable the usage of this important source all over the world.

Many of the aspects of this chain are not covered here. Otherwise, they can be found elsewhere in codes, articles found in the open literature, and the sort. Some of the codes used in this research work follow ahead, and other related references are presented in the end of this report used to support this document.

The interpretation of these codes and the material used as part of this work is of the sole responsibility of the authors. The authors' belief is that this work could represent a contribution given to Brazilian LNG infant industry.

3. Codes and Maritime publications used in this work

Some of the references and additional related information from where they have been consulted internalized and used in the context of the present work can be found in:

- Code for the existing ships carrying Liquefied Gases in Bulk 1976 with Amendments and Supplements
  Available: https://searchworks.stanford.edu/view/4555379
  Access: 24 Nov 2015
- Code of Safe Working Practices
  Available:
  https://www.maritimenz.govt.nz/Publications-and-forms/Commercial-operations/Shipping-safety/Health-and-safety/Code-of-safe-working-practices-for-seafarers.pdf
  Access: 24 Nov 2015
- IMO Places of Refuge - Safe Havens for Disabled Gas Carriers, Maritime Safety Committee, 77 th Session, SIGTTO London Liaison Office, Reprinted February 2003.
  Available: http://www.sjofartsverket.se/upload/4001/77-INF2.pdf
  Access: 15 Dec 2005.
- IMO International Code for the Construction and Equipment of Ships carrying Liquefied Gases in Bulk (IGC Code) 1993, 1975.
  Available:
  http://www.imo.org/en/Publications/Documents/Supplements%20and%20CDs/English/IGC_2003sup.pdf
  Access: 24 Nov 2014
- International Convention for the Safety of Life at Sea 1974 & amendments
  Available:
  http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx
  Access: 24 Nov 2015
- International Convention on Standards of Training, Certification and Watch keeping for Seafarers
  Available:
  http://www.imo.org/en/KnowledgeCentre/InformationResourcesOnCurrentTopics/InformationResourcesOnCurrentTopicsArchives/Documents/STCW.pdf
  Access: 24 Nov 2015
- Liquefied Gas Carriers – Safety & Operational Matters
  Available:
  http://www.liquefiedgascarrier.com/index.html
  Access: 1 Dec. 2015
- OCIMF - Mooring Equipment Guidelines, 2001
  Available:
  http://joinpdf.sourceforge.net/files/ocimf-mooring-equipment-guidelines.pdf
  Access: 15 Dec 2005.
- Shipboard Oil Pollution Emergency Plan
  Available:
  http://www.imo.org/en/OurWork/Environment/PollutionPrevention/OilPollution/Pages/Shipboard-Marine-Pollution-Emergency-Plans.aspx
  Access: 25 Nov 2015
- SIGGTO International Safety Guide for Oil Tankers and Terminals
  Available http://www.isgintt.org/files/documents/isgintt062010_en.pdf
  Access: 24 Nov 2015
- SIGTTO Liquefied Gas Handling Principles On Ships And In Terminals
  Available:

http://www.sigtto.org/publications/publications-and-downloads
http://www.sgmf.info/media/5637/standards-guidelines-natural-gas-fuelled-v5k1.pdf
http://seaworm.narod.ru/2/LGHP.pdf
Access: 25 Nov 2015

- SIGTTO Ship-to-Ship Transfer Guide (Liquefied Gases) – 1995,
  Available: http://www.ocimf.org/media/8874/Publications.pdf
  Access: 15 Dec 2015.
- SIGGTO Standards and Guidelines for Natural Gas Fuelled Ship Projects
  Available: http://www.sgmf.info/media/5637/standards-guidelines-natural-gas-fuelled-v5k1.pdf
  Access: 15 Dec 2015.
- USCG Non-Tank Vessel Response Plan
  Available:
  https://homeport.uscg.mil/mycg/portal/ep/channelView.do?channelId=-30095&channelPage=%252Fep%252Fchannel%252Fdefault.jsp&pageTypeId=13489
  file:///F:/%232%C2%AABOLSA/AQUAVIARIO/PRODUTOS%20FINAIS/SP1_Item1.2_TranspTransoc/CODES/tgtntvrp20140203plan2845_2845_21555_28693_0.pdf
  Access: 25 Nov 2015.

4. The context of the problem researched

Natural gas (NG) it is increasingly present in the energy matrices of several countries, and it is considered as a ‘bridge’ between the ‘oil era’. Its use has being consolidated as a ‘clean’ renewable energetic. NG is more easily transported overseas to very distant points as LNG, being then accessible to markets, enhancing flexibility and reliability of continuous supply. It has proved to be economical, efficient and environmentally attractive ‘fuel of choice’ due to low environmental impact. This industry is experimenting continuous and accelerated growth, with global trades increasing from 8% per year since 1995 to reach 189 billion of m³ in 2005 (Tusiani & Shearer, 2007). This volume, which represents 26% of total NG (LNG and pipeline gas) traded across borders, is expected to triple by 2020 rising to 14% of world’s NG demand, compared to 7% at the present.

LNG is primarily composed of methane taking up about 1/600 the volume of the NG. This drastic reduction allows for the transport of greater quantities. Liquefaction is the process of cooling NG to -162°C, and LNG must be turned back into a gas for commercial use done at regasification plants. The raw NG also needs purification before used in homes and industries. NG, as consumed, is almost entirely methane, although it occurs associated with several components, e.g., gases and condensates, as well as with oil and water, which must be removed during production prior to liquefaction.

Most of liquefied gases are hydrocarbons and the key property that makes them one of the primary sources of energy - flammability - also makes them inherently dangerous. As these gases are handled in large quantities, it has become imperative to adopt practical measures are to make transport by sea.

Vessels involved in LNG trade are generally recognized as part of global projects. This means that security is a mandatory component for LNG players by also carrying their reputations.

The transportation of liquefied gases in bulk started in the late ’20s and the earliest vessels carried butane and propane in pressure vessels at ambient temperature. The development of refrigeration techniques and materials to support low temperatures permitted the carriage of cargoes below ambient temperatures. Later on in the late ‘50s, gases began to be transported in partially refrigerated carriers with pressure vessels made with appropriated material to resist low temperatures. By the mid-‘60s fully refrigerated LPG ships were developed to transport cargoes at atmospheric pressure, when dedicated LNG (designated from now on by LNG carriers - LNGCs) and ethylene vessels entered in operation. In this meanwhile, ammonia had become a common cargo, as well as other gases such as butadiene became commercially important as well.

In short, the liquefaction process may be obtained by one of the ways:

- Reducing the temperature by refrigeration at atmospheric pressure;
- Applying elevated pressure at ambient temperature or
- A combination of both processes above.

The first ocean transportation of LNG by ship took place in 1959 when the Methane Pioneer (a ship of the US Navy's World War II Liberty class was completely modified) loaded with 5,000 m³ of LNG going from Lake Charles, La. to Canvey Island, near London. The LNGCs Methane Princess and Methane Progress pioneered this mode of transport, being built in 1964 by shipyards in England and Northern Ireland with the same industrial specifications (Tusiani and Shearer, 2007). Historically, each was endowed with nine prismatic tanks with total capacity of 27,400 m³ per vessel carrying LNG from Algeria to Canvey Island in England, commissioned by British Gas. Each one of them operated for 28 and 22 years, respectively.

NG today is regarded as the fuel of the future. In the past when oil sought to produce oil and gas found, this finding was considered a failure. If the gas were associated, was re-injected into the formation or burned in flares. Environmental requirements began to require increasingly decreasing burning gas, forcing the application of gas for other purposes. As a result, gas production projects present attractiveness to be put in motion. Insofar as oil prices rose and production costs fall, the LNG has become feasible. With the ever-increasing demand of gas in the energy mix, to be considered a fossil fuel "cleaner", and with costs falling to the modernization of processes by technological advance, LNG has become a mature industry internationally. In this context, it includes up Brazil as a potential international supplier, at the prospect of increase in production in the pre-salt fields.

Some figures of this industry across the globe can be submitted at the end of 2014 (GIILNG, 2014):

- 110 import terminals;
- 30 importing and 19 exporting countries;
- 750 MTPA [2]capacity of the terminals;
- 298 MTPA of capacity of liquefaction plants (terrestrial majority).

The LNG LNGCs' fleet totalized 424 units is 2014 totaled 424 units in operation, with a total transport capacity of more than 61 million cubic meters, and the entry of new resulted players on the need to expand the fleet with 77 new orders ships (GIIGNL, 2014). Figure 2 shows the exponential growth trend in the cumulative amount of vessels and total capacity.

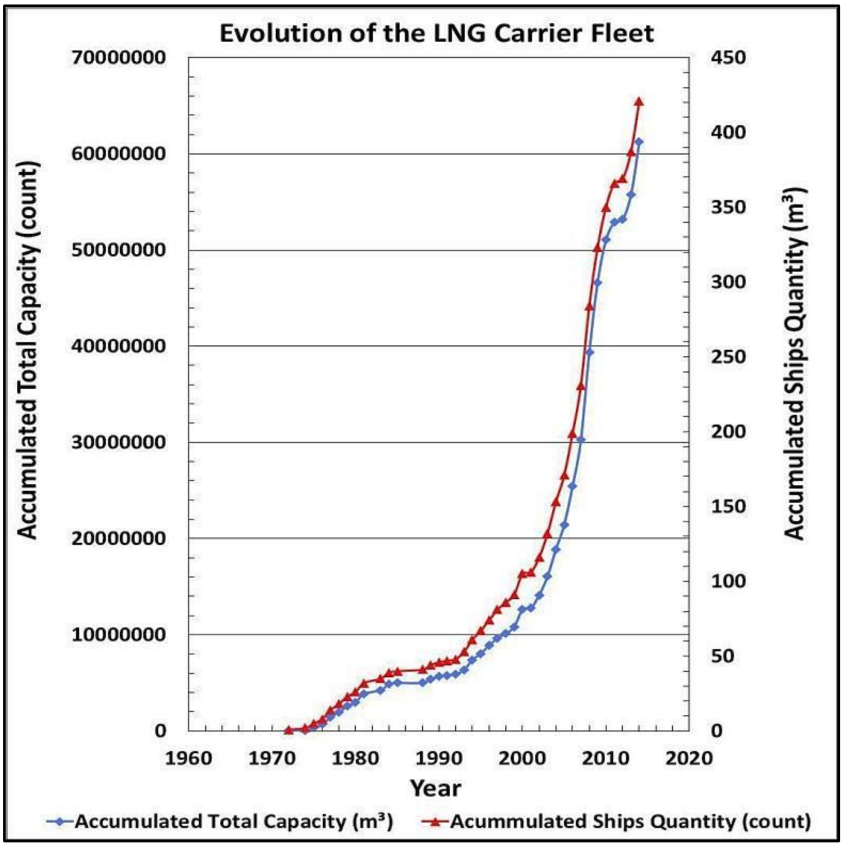

Figure 2 - Evolution of the world fleet of LNGCs.
Source: Adapted from GIIGNL (2014).

In more than 60 years in the industry, over 40,000 trips carrying LNG were made, not registering hips leaks, both at sea by collisions or by groundings (Arai, et al., 2012). The overall safety records compiled by LNG ships during the 46 years between 1964 and 2010 have been auspicious. During this period, LGNCs fleet delivered more than 30,000 LNG shipments, and traveled more than 100 million nautical miles with loaded ships (and a similar distance return trips with ballast). In all these trips and associated transfer operations (loading/unloading), no fatalities were recorded by any member of the crew of the vessel or member of the general public as a result of hazardous incidents

[2] *Millions of tonnes per annum*.

in which LNG had been involved. Indeed, there is not until 2012 no record of any fire in the operating decks (top desks) or in dispatch areas (jetties) or in the tanks of a vessel in operation (CH-IV, 2012).

Typical accidents involving LNGCs include failure of containment tanks, fractures on roofs of tanks and operation decks due to the released LNG by valves leaks, load rollover (more below), overfilling of the cargo tanks, breaking the mooring jetties, hulls cracks by fatigue, bumps, and other (Arai et al., 2012). Between the periods 2010-2014, the global fleet held 80,000 shipments, covered more than 2.8 million nautical miles, promoting inter-trading stocks over 25 countries. Figure 3 shows these numbers (GIIGNL, 2014).

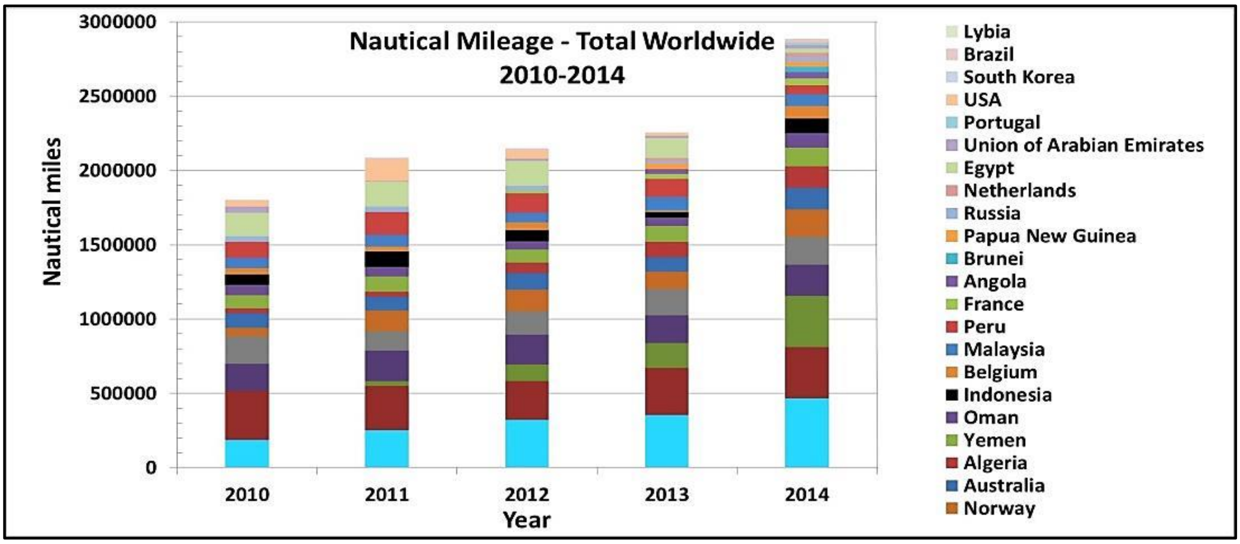

Figure 3 - Total nautical mileage and countries involved. Source: Adapted from GIIGNL (2014).

5. Origin and risks and safety issues of the products transported

LNG is produced from natural gas. LPG otherwise may be produced either from natural gas or from refining crude oil. Different forms of liquefied gas cargo require different transport modals, means and storage methods (BP, 2012). Gases and liquids have to be contained in some form. They may be stored into tank containers or flasks, or alternatively be moved without packaging in pipeline networks and dedicated LNGCs.

When gas is moved in tanks onboard ships, it is often liquefied by low temperature. This is a highly specialized form of transport demands not only expensive, purpose built carriers, but also special terminals and handling equipment. There are two forms of gas which are shipped by sea, (i) as LNG and (ii) as liquefied petroleum gas (LPG). A basic comprehension about the hazards of the LNG must start with the knowledge of its chemical and physical properties as well as the origins from where it is imported. These properties can be resumed as follows in Tables 1 and 2.

Table 1 – LNG physical average properties. Source: Wood (2014), Perry et al. (2008), Peebles (2992).

Property	Unit	Methane	Ethane	Propane	Butane	Pentane	Nitrogen
		CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	N_2
Molecular weight	-	16.042	30.068	44.094	58.120	72.150	28.016
Boiling Point (BP) (bubble point) @ 100 kPa (1 bar abs)[3]	°C	-161.5	-88.6	-42.5	-5	-36.1	-196
Liquid density @ BP	kg/m³	426.0	544.1	580.7	601.8	610.2	808.6
Vapor SG @ 15 °C and 100 100 kPa	-	0.554	1.046	1.540	2.07	2.49	0.97
Gas volume/liquid volume ratio @ BP and 100 kPa	-	-	619	413	311	311	205
Flammability limits in the air	v/v %	5.3 to 14	3 to 12.5	2.1 to 9.5	2 to 9.5	3 to 12.4	Non flamma-ble
Auto-ignition temperature	°C	595	510	510/583	510/583	-	-
Gross heating value @ 15°C Normal Iso	kJ/kg	55559	51916	50367	49530 49404	49069 48944	-
Vaporization heat @ BP	kJ/kg	510.4	589.9	426.2	385.2	357.5	199.3

[3] From now on this work will use units of Metric System only. In this context, 1 bar (= 1bar abs, or 1,000 mbar abs) is equivalent to approximately 100 kPa (kiloPascal). Ex.: bar abs = bar = barg + 1 and 1 bar abs ≅ 100 kPA. As 700 mbarg = 0.7 barg and bar = barg +1, than 0.7 barg + 1 = 1.7 bar abs = 170 kPa (Moran & Shapiro, 2010).

Table 2 – Typical composition of LNG from various liquefaction plants (ILEX, 2003)

Component in mole%	Arun LNG (Indonesia)	Atlantic LNG (Trinidad & Tobago)	Brunei LNG (Brunei)	Kenai LNG (USA)	Nigeria LNG (Nigeria)	Oman LNG (Oman)
Methane	88.48	95	89.4	99.8	87.9	90
Ethane	8.36	4.6	6.3	0.1	5.5	6.35
Propane	1.56	0.38	2.8	0	4	0.15
Butane	1.56	0	1.3	0	2.5	2.5
Nitrogen	0.04	0.02	0.2	0.1	0.1	1

The typical properties of LNG vary with its composition which depends on the original reservoir where it is produced, as well as its history of primary processing, fractioning and storage (BP, 2012). Typical LNG composition contains predominately CH_4, varying from 87 to almost 100% (99.8%), but it also includes heavier hydrocarbons, basically C_2H_6 and C_3H_8 and some heavier butanes (C_4H_{10}), N_2 and traces of $C0_2$, S or even P and Hg. So, the different compositions presented in Table 2 suggest that different mole ratio of CH_4 may reflect on weigh and volumetric properties. LNG with higher mole fractions of C_2 or higher hydrocarbons with more carbon atoms in their molecules is said to be “rich” because it has higher heat of combustion than “lean” LNG. So, it is expected that its flammability properties may vary case by case, implying that safety recommendations are average.

The critical point of CH_4 is around - 83°C (190K), so it means that it cannot be liquefied by pressure only at ambient temperature but, rather, it has to be cooled to be liquefied. At atmospheric pressure, methane has to be cooled to its boiling point of -161.5°C (Table 1) LNG is a colorless, odorless, and noncorrosive cryogenic liquid at normal atmospheric temperature and pressure, and when it is vaporized and used as natural gas fuel, it generates very low particle emissions with significantly lower carbon content emissions than other fossil fuels. Its combustion products contain, basically, almost no sulfur oxides (SO_x) and low levels of nitrogen oxides (NO_x), making the LNG is considered as a “clean” energy source when compared to other fuels.

Although LNG is nontoxic, however, as any other gaseous product, it can cause asphyxiation by the displacement of the oxygen, especially in areas with little or no ventilation, or even in confined ones. As depicted from the tables above, its normal boiling point changes with composition, being around -162°C. Its density falls in the range of 430-435 kg/m³ - therefore around half of the density of water, and the specific gravity of its vapor is 0.554 in average atmospheric weather – also about half of that of the air. It means that if LNG is spilled onto the water, its layer will float on the top of vaporize rapidly because it is lighter than the water. Initially LNG vapors are heavier than the air and will stay close to the ground, because of the ageing[4] effect. However, as vapors begin to be warmed by the surrounding air (from -162°C to -110°C or higher), the density of the vapors will be lighter than the air and the vapors become buoyant. Cold LNG with vapors below -110°C may accumulate in low areas until it begins to warm up, so LNG spills in enclosed venues may displace air, which may be dangerous to the health (difficulty to breathing due to the asphyxiation).

The boil-off vapor from LNG is lighter than air at vapor temperature above -110°C (or higher), depending on LNG composition due to the variation of density with temperature. Therefore, when vapor is vented to atmosphere, it will tend to rise above the vent outlet and will rapidly disperse. When cold vapor is mixed with ambient air, it will appear readily as a visible white cloud due to the condensation of the moisture in the air. For safety purposes, it is normally to assume that the safe flammable range to the vapor-air mixture does not extend significantly beyond the perimeter of the white cloud.

Special concerns should be given to its flammability levels, since it may ignite if mixed within this interval, if an ignition source is present with sufficient energy. As depicted in Table 1, LNG when compared to higher hydrocarbons has its auto-ignition temperature relatively high (595°C). In other words, it demands higher energy to initiate a combustion providing the lowest temperature to which the gas needs to be heated to cause self-sustained combustion without ignition by spark or flame.

Vapors released from LNG, if not vented to a flare or a safe place will mix with air and will be carried downwind, dissipating in the atmosphere to less than 5% of concentration. It may generate vapor cloud that may become flammable and explosive, if an ignition source is present, and if the cloud is within its flammability limits (5-15 % v/v in the air). Above and below these limits the mixture is said to be ‘lean’, and between these limits the mixture is ‘reach’ and will sustain the combustion (Mokhatab et al. 2014).

If the vapors are within these limits and if the ignition occurs in well-ventilated areas, the cloud will burn with low laminar combustion velocity having enough energy to other fuels. In such areas it is unlikely for NG vapors produce unconfined vapor cloud explosions (UVCE), but the same cannot be said for heavier hydrocarbons. Whether a NG fire burn back to the leakage point in a flash-fire or undergo to a UVCE, that will depend on several factors, to name a few, the degree of confinement and obstacles, chemical structure of the vapor molecules, size and concentration of the vapor cloud, energy of the ignition source (CEE, 2006; Mokhatab et al. 2014). However, if the ignition takes place

[4] Selective vaporization due to the vaporization heat: heavier hydrocarbons vaporize first, as per Table 1.

within a confined venue with some ventilation, and if the velocity of the flame front is able to accelerate, it may generate a confined explosion and build up with a velocity such that it may scale up to a detonation. Accidents such this may occur, for example, within gas pipelines after a maintenance intervention, where a welding scrap has been left within the line that has not been purged with nitrogen before re-enter into operation.

LNG is produced from NG, and it is the cryogenic form of this gas; when it is warmed, becomes NG again. However, NG cannot be liquefied into LNG unless it is cooled up to its liquefaction point. LPG (liquefied petroleum gas), otherwise, may be produced either from natural gas or from refining crude oil.

It is not possible to burn LNG by itself. LNG needs to be in vapor form and mixed with air in a given proportion to burn upon a source with a given energy. It is combustible in the range of 5% to 15% of volumetric concentrations in air. Combustible mixtures in confined space will burn explosively. As a cryogenic fluid, any physical contact or spillage poses a hazard for people and equipment.

During its loading in containment cargo tanks, the walls of the vessel are cooled very rapidly, resulting in tremendous thermal stresses for vessels and associated piping and fittings. And to avoid such damages some stringent safety procedures must to be followed. For comparison purposes with LNG (≅ methane), the liquefaction points of some products are here presented: Ammonia: -34 °C; Propane: - 42°C; Ethane: - 89°C; Methane: - 161°C; Oxygen: -182°C; Nitrogen: -196°C.

However, several metallic materials may exhibit ductile responses when subjected to very low temperatures such as those above. They can brittle and be subject to sudden breaks by brittle fracture, with a much lower tension level than the elasticity limit, causing the 'cold brittleness' (Silva Telles, 2003). As brittles propagate almost instantly to a large extent of the metallic material in several directions, these fractures are almost always catastrophic, with total loss of the containment equipment. The decrease in temperature tends to increase energy to break the material and suddenly decreases to a maximum transition point. The continuous temperature lowering may reach this maximum point, exceeding a null ductility transition temperature (NDT -Nihil Ductile Transition), leading the material to a brittle behavior, with the 100% brittle fracture with full and sudden collapse of the metal structure.

During a normal sea voyage, heat is transferred to the LNG cargo through the cargo tank insulation, causing vaporization of part of the cargo, due to the boil-off phenomena. The composition of the LNG varies because the lighter components, having lower boiling points at atmospheric pressure, vaporize first, due to the 'ageing' process. Therefore the discharged LNG has a lower percentage content of nitrogen and methane than the LNG as loaded in the beginning of the LNGC trip, and a slightly higher percentage of Ethane, Propane and Butane, due to Methane and Nitrogen boiling off in preference of the heavier gases, such propane and butane.

The flammability range of Methane in air (21% v/v of Oxygen) is approximately 5.3 to 14% v/v. To reduce this dangerous range, the air is diluted with Nitrogen until the Oxygen content is reduced to 2% v/v prior to be loaded in the LNGC after the dry-dock period. Theoretically, an explosion cannot take place, if the Oxygen content of the mixture is below 13% v/v as far as the percentage of Methane is concerned, but in the name of the safety, the purge shall continue until the Oxygen content becomes below 2% v/v (Mokhatab et al. 2014).

Different forms of liquefied gas cargo require different transport modals, means and storage methods. Gases and liquids have to be contained in some form. They may be stored into tank containers or flasks, or alternatively be moved without packaging in pipeline networks and dedicated carriers. When gas is moved in tanks onboard ships, it is often liquefied by low temperature. This is a highly specialized form of transport demands not only expensive, purpose built carriers, but also special terminals and handling equipment. There are two forms of gas which are shipped by sea, (i) as LNG and (ii) as LPG.

The advantages of cooling gases can be evidenced simply because liquid gases can be reduced by about 600% from the initial gas volume. Most liquefied gases are hydrocarbons and they have high flammability, and they are handled in large quantities, it is imperative that all practical steps are taken to minimize leakage, to limit all sources of ignition and prevent marine pollution. The majority of liquefied gases is "clean", considered as "non-polluting" chemicals and creates no danger to the marine environment. However if a certain liquefied gases spill on to the sea it should be aware that they may:

- create large quantities of vapor sea water rapidly vaporizes the liquid gas- which may cause a fire or explosion or a health hazard;
- generate toxic vapors, which can drift, sometimes over a considerable distance;
- dissolve in sea water and cause local pollution;

When carrying low temperature (or cryogenic) cargoes this introduces other potential hazards such as frostbite, posing risks of contact with very cold liquids demanding the usage of wear appropriate for low temperaturs.t) may be required. Other risks involve the rapid phase transition (RPTs) that may cause confined or semi-confined explosions.

6. Definitions and considerations about some basic concepts and glossary used in this work

In accordance with the experience consecrated by research institutes, ship owners, shipyards, the gas tankers fleet operators, naval and port authorities and classification societies, it is necessary to formally define some terms (ISSC, 2012):

- **Boil-Off Gases (BOG)** – It is the vapor generated above the surface of a boiling cargo due to evaporation. It is caused by the heat ingress or a drop in pressure[5]. It occurs during the storage of volatile liquefied gas. LNG vaporizes in about -162-163°C @ atmospheric pressure and is loaded, transported and unloaded at this temperature, requiring materials, isolation and special handling equipment. Load movements inside the tanks (sloshing) associated with the heat input inside the ship's tanks makes the cargo to boil-off. The vaporization is not homogenous though, since components with lower boiling points present in natural gas (CH_4 and N_2) tend to boil more rapidly, provoking the weathering phenomenon is known as "weathering" (or "ageing"). Consequently, the LNG composition becomes 'heavier' increasing the Wobbe Index and heating value over the time. This phenomenon is not controlled within certain limits, and it generates pressure inside the cargo tanks with increase in impact on the entire system[6]. Reid (1983, 1980) findings describes that if the concentration of C2-C3 is residual in the liquid that is vaporizing, the boil off can be approximately considered as pure methane, until its concentration is completely evaporated;
- **Boil-Off Rate (BOR)** – The vaporization rate, expressed in % of the LNG cargo within the tank per day, caused by heat inflow that during the carrier transoceanic voyage or when docked in a terminal, based on sea surface temperature of 32°C and air temperature of 45°C. Heat leaks into the tank through the insulation, warms the cargo and in turn, causes the surface layer to evaporate resulting in "boil-off". The boil-off rate depends on the tank type and application, varying from 0.02% to 0.2% of tank volume per day.
  Some LNGCs and onshore terminals are provided with re-liquefaction plants, but generally the boil-off fraction from storage tanks/cargo tanks is not re-liquefied, but treated separately. On LNGCs, the boil-off generally is used as fuel gas for the carrier driving purposes. When moored, it may be re-compressed and exported, sent to a terminal's condenser and adsorbed into the LNG export stream prior to regasification, to be used as fuel gas, or even a combination, depending on the economics. Notwithstanding, it is unusual that the BOG to be re-liquefied and send back to the terminal's storage tank, since as the lighter heavier fractions vaporizes during this process, the inventory left in that tank would increase.
- **Cargo Containment System (CCS)** in LNGCs – It is the arrangement for containment of cargo including, where fitted, primary and secondary barriers, associated insulations, inter-barrier spaces and the structure required for the support of these elements (see reference [4]). Its main purpose is to confine the LNG in a tank vessel with no air entrance, insulate the LNG load from heat influx minimizing boil-off, and avoid that the cargo at cryogenic temperature reaches the ship's hull, causing brittleness of the cargo's structure;
- **Gas Codes** - The Gas Codes are the Codes of construction and equipment of ships carrying liquefied gases in bulk. These standards are published by IMO (International Maritime Organization);
- **Rollover** - Nowadays, this phenomenon considers that LNG tanks can stratify. As tank's bottom layers always exist due to the hydraulic head above the liquid column, they are at equilibrium pressure at a given temperature above the tank's top layers. The density of the upper liquid layer can increase with time due to boil-off of Methane, which cools due to loss of latent heat. It causes the density of the surface layer to increase and the liquid to sink. Heat intake through the tank bottom/walls is sufficient to warm the lower side layers and convection current takes place, ensuring the mixture of the cryogenic liquid. The lighter fractions will boil off first, resulting in the density of the remaining liquid gradually increasing. This mechanism is known as "weathering" or "ageing", and will increase the percentage of heavier components afterwards. At a given moment the layers can invert upside down. This would bring the lower layer to the surface, and without the hydrostatic pressure gradient above it, a small fraction would go to a thermodynamic flash. Providing that the expansion ratio of liquid/vapor is about 600/1, even a small flash can generate a huge gas volume. Therefore, the sudden increase in tank pressure can exceed the capacity of pressure safety relief valves that are designed for fire exposure and threaten the tank's roof or even wall cause a failure.
  Rollover can only take place if stratification has occurred in the LNG. Stratification of LNG can happen when a LNG tank is loaded or unloaded with LNG of different densities. Stratification will occur readily if the LNG being introduced into the tank is either denser than that of the "heel" (ballast) remaining in the tank and filling is at the bottom, or if the LNG introduced is lighter than the heel and filling is into the top of the tank. This phenomenon is recognized by the major design codes EN 1473 and NFPA 59A[7] (SIGGTO, 2012). The stability of

[5] Available: http://www.pfri.uniri.hr/~bernecic/literatura/TTTT/International_documents/Lghp(siggto).pdf. Access: 11 Dez 2015.
[6] Available: https://www.pwc.com/gx/en/energy-utilities-mining/pdf/lng_glossary_final.pdf>. Access: 18 Ago. 2015.
[7] 'The Design of Onshore LNG Terminals' and 'Standards for the Production, Storage and Handling of LNG'

two stratified layers of liquid of differing relative density may be broken resulting in a spontaneous rapid mixing of the layers accompanied, in the case of liquefied gases, by violent vapor evolution (see reference 4).

During the weathering, there is "accommodation" of the layers that are being poured on each other in different LNG load and unloading in each terminal, often with different compositions depending on the exporting country. In this accommodation, LNG density gradually increases inside the tanks, and the various compositions and successive mixtures, can lead to stratification. It is characterized by two homogeneous layers of different densities and temperatures separated by a "lung" (buffer) layer called the “interface” (interface thick layer).

Nevertheless, with heat input to the process, it generates instability in the layers and enhances the movement of the heavier components of the filler background layer to the top layer, causing a sudden release of heat on the bottom of the layers increasing therefore the rate of vaporization.

Giving that a rollover took place, if the LNG in the bottom layer is superheated, depending on the conditions of the tank vapor space, it can be accompanied by a high vapor production rates that can overcome the 10 to 30 times the boil-off rate generating strong pressure inside the tank, with possibly disastrous consequences (Dobrota et al., 2013). Therefore, identify, understand, model, quantify and predict the extent of the boil-off phenomena having the cargo sloshing as backdrop, it is of fundamental importance to the proper rollover maritime management;

- **Sloshing** – It is an incident whose phenomenology arises from the random movements of tides and other meteorological and oceanic (‘metocean’) conditions of open sea (wind, tides, currents, etc.) that are transmitted to the LNGCs on a cruise overseas. This causes the ship's motion and load of LNG within the CCS, and these motions provoke damaging wave loads against inside cargo tank’s walls, especially in the case of prismatic tanks. They affect corners, edges and knuckles jeopardizing the tanks structures (Woodward & Pitblado, 2010). Violent sloshing, depending on the type of LNGC tanks can cause, e.g., complex phenomena of mutual interaction between movements of the ship, that may result in resonant dynamic response structures in the fluid-structure interaction, fatigue of structures and equipment by the repetitiveness of the movements, cargo evaporation - boil-off, limitations on filling the membrane tanks, among others. This phenomenon implies certain regulations for classification societies aiming at the LNGC vessel integrity and load. Figure 4 illustrates the sloshing phenomenon inside a membrane tank and Figure 5 exhibits different types of sloshing flows and LNG velocity fields generated in tanks of large LNGCs.

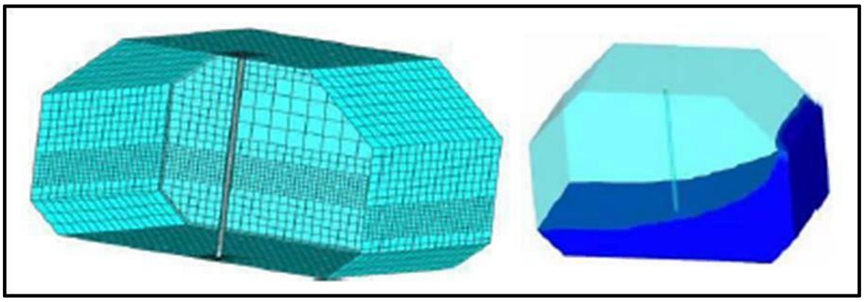

Figure 4 – Cargo sloshing. Source: ICCS (2012)

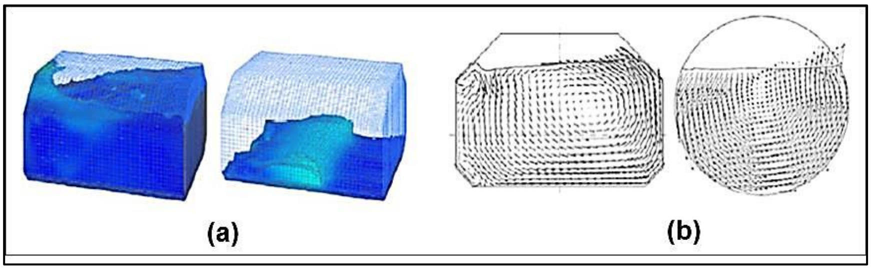

Figure 5 – (a) Typical LNG flows within a membrane tank fully loaded and partially loaded
(b) LNG velocity fields in membrane and spherical tanks. Source: Ringsberg et al (2012), Zalar et al (2006).

7. Types of gas carriers

Gas carriers range in capacity from the small pressurized ships of between 500 and 6,000 m³ for the shipment of propane, butane and the chemical gases at ambient temperature up to the fully insulated or refrigerated ships of over 100,000 m³ capacity for the transport of LNG and LPG (CCNR/OCIMF, 2010). Between these two distinct types there is a third ship type - the semi-pressurized gas carrier. These very flexible ships are able to carry many cargoes in a fully refrigerated condition at atmospheric pressure or at temperatures corresponding to carriage pressures of between 500 and 900 kPa (5 and 9 bar abs) (SIGTTO, 2000). The profiles of some of these types of ships are depicted in Fig. 6.

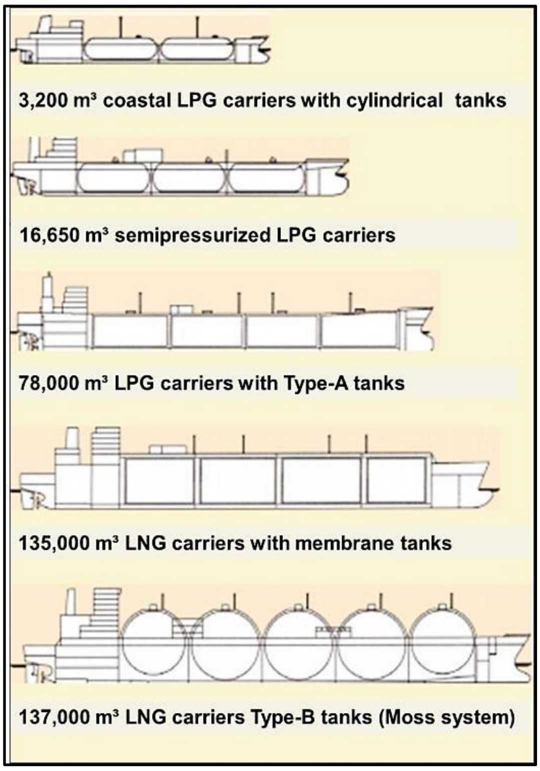

Figure 6 – Some types of gas carriers. Sources: UKPandi (2015), SIGTTO (2000)[8].
Available: http://www.ukpandi.com/fileadmin/uploads/uk-pi/LP%20Documents/Carefully_to_Carry/Carriage%20of%20liquefied%20gases.pdf.
Access: 11 Dec 2015.

The movement of liquefied gases by sea was already way back in 2000 a mature industry (SIGTTO, 2000). About 1,000 ships served its fleet, a worldwide network of export and import terminals was already in full operation and knowledge and experience have been accumulated ever since on the part of the various actors involved (SIGTTO, 2000). In 1996 this fleet transported about 62.5 Mtonnes[9] of LPG and chemical gases and over 73 Mtonnes of LNG. In the same year the ship numbers in each fleet comprised:

- LNG carriers: 105 units;
- Fully refrigerated ships: 183;
- Ethylene carriers: 100;
- Semi-pressurized ships: 276;
- Pressurized ships: 437.

Gas carriers keep some similitude of certain design features in common with other ships used for the carriage of bulk liquid, for example, oil and chemical tankers. Chemical tankers may transport their most hazardous cargoes in center tanks, while other less dangerous cargoes can be shipped in the wing tanks. New oil tankers are required to have wing and double bottom ballast tanks to protect their cargoes. They are conceived to protect against the spillage of hazardous cargo on the environment in case of groundings or collisions. This concept is equally applied to gas carriers.

As a safety requirement, the gas carriers' cargoes are kept under positive pressure to prevent from air intake to the cargo system to avoid flammable atmospheres in its interior. Consequently, all gas carriers utilize closed cargo systems for the loading/unloading operations, with no vapor vent being allowed to the atmosphere.

In the LNG industry, it is a normal accepted practice to provide a vapor return line between the carrier and shore terminal to displace the vapor generated during the maritime toil. In the LPG trades otherwise this is not seems to the

[8] The concepts of Types A and B presented here, will be discussed items 8 (The design of gas carriers), 9 [LNG Carriers (LNGCs) – An overview] and 10 (Cargo Containment Systems in Liquefied Gas Carriers).

[9] The tonne (British and SI; SI symbol: t) or metric ton (in the U.S.) is a non-SI metric unit of mass equal to 1,000 kilograms. Multiple Mtonne = 1,000,000 tonnes.

case, since under normal operation of loading and re-liquefaction it is usual to retain the vapor onboard of the ship. The main goal, in any case is to eliminate any cargo release to the atmosphere minimizing the risks.

Gas carriers must comply with the standards set by the IMO's Gas Codes, and with all safety and environmental requirements common to other carriers. The safety features inherent in the Gas Codes' ship design requirements have improved considerably the safety issues of this modal. Equipment requirements such temperature and pressure are required, as well as detection and cargo tank liquid level indicators, and all of them must be installed with alarms and dedicated instrumentation.

There is much variation in the design, construction and operation of gas carriers due to the variety of cargoes carried and the number of cargo containment purposes. Cargo containment systems may be of the independent tanks (fully pressurized, semi-pressurized or fully refrigerated) or of the membrane type as described ahead in items 7.1 to 7.5 (SIGTTO, 2000).

7.1. Fully pressurized carriers

The transportation of liquefied gases started in 1934 when international companies commenced to operate with oil/LPG tankers. Oil tankers had been converted for the carriage of LPG, enabling transport over long distances of substantial volumes of oil refinery by-products. Today, most fully pressurized LPG carriers are fitted with two or three horizontal, cylindrical or spherical cargo tanks and have capacities up to 6,000 m^3 (SIGTTO, 2000).

However, in recent years a number of larger capacity fully-pressurized ships have been built with spherical tanks, most notably with a pair of 10,000 m^3 ships, each incorporating up to five spheres in line. Fully pressurized ships are still being constructed and represent a cost-effective, simple way of moving LPG to and from smaller gas terminals.

7.2. Semi-pressurized carriers

The development of materials and metals suitable for the containment of liquefied gases at low temperatures was the great vector to the transportation of liquefied gases through the oceans. And it did not begin to grow until the early 1960s. Using special steels/alloys, insulating the cargo tanks and reducing the pressure vessels' wall thickness (consequently the weight), it turned out possible for re-liquefaction plants to be installed on board.

The first ships to use this new technology started to operate in 1961. They transported gases in a semi-pressurized/semi-refrigerated (SP/SR) state, but subsequent advances were quickly made and by the late 1960s semi-pressurized/fully refrigerated (SP/FR), or so called 'semi-pressurized carriers' had become the choice at that time.

They started to incorporate cylindrical, spherical or bi-lobe tanks, being able to load/unload gas cargoes at both refrigerated/pressurized terminals. In 2000, the existing fleet of semi-pressurized ships comprised ships ranging from 3,000 to around 15,000 m^3 of capacity range.

7.3. Ethylene and gas/chemical carriers

Ethylene ships are considered to be the most sophisticated of the semi-pressurized tankers due to the fact of ethylene have a low boiling point of –104°C @ atmospheric pressure. So these carriers have the ability to carry most of other liquefied gas cargoes above this point. The first ethylene carrier was built in 1966 and, as of 1995, there were about 100 such ships in service, with capacity ranging from 1,000 to 12,000 m^3.

Part of the ethylene carrier fleet form a special sub-group of ships able to handle a wide range of liquid chemicals and liquefied gases simultaneously. These carriers accommodate cylindrical, insulated, stainless steel cargo tanks able to transport liquid cargoes of 1.8 maximum density with temperatures varying from –104°C to +80°C and at a maximum tank pressure of 400 kPa [4 bar (abs)] according to SIGTTO (2000). As these carriers can load/unloading at virtually all pressurized/refrigerated terminals, make them to be considered the most versatile carriers in terms of cargo-handling.

7.4. Fully refrigerated carriers

In the '60s another development step was observed in the gas carriers industry: that's when the first fully refrigerated ships appeared. They were constructed to transport liquefied gases at low temperature and atmospheric pressure, since the terminals would be equipped with fully refrigerated storage tanks. The first fully refrigerated LPG carrier was built in 1962. The ship was equipped with four prismatic cargo tanks (box-like) made of 3.5 % nickel steel, allowing cargoes with temperatures as low as –48°C being transported, just below the pure propane boiling point @ normal atmosphere. This geometry enabled to maximize the transporting capacity, thus making fully refrigerated carriers suitable for carrying large volumes of cargo such as LPG, liquid ammonia and vinyl chloride over long distances. Today, fully refrigerated carriers range from 20,000 to 100,000 m^3.

7.5. LNG carriers

At about the same time LPG carriers was being developed, industry was experimenting the most demanding gas carriage challenge. The focus was the transport of LNG, a clean, non-toxic fuel that became to be the third most important energy source in the world, after oil and coal. But, but is often produced far from the centers of consumption. Because a gas in its liquefied form occupies much less space, and because of the critical temperature of liquefied methane, the ocean transport of LNG only makes sense from a commercial viewpoint if it is carried in a liquefied state at atmospheric pressure; as such, it represents a greater engineering challenge than shipping LPG, mainly because it has to be carried at a much lower temperature; its boiling point being –162°C.

The pioneering cargo of LNG was carried across the Atlantic Ocean in 1958 and by 1964 the first purpose-built LNG carriers were in service under a long-term gas purchase agreement. LNG containment system technology has developed considerably since those early days: now about one-half of the LNG carriers in service are fitted with independent cargo tanks and one-half with membrane tanks. The majority of LNG carriers are between 125,000 and 135,000 m^3 in capacity. In the modern fleet of LNG carriers, there is an interesting exception concerning ship size. This is the introduction of several smaller ships of between 18,000 and 19,000 m^3 having been built in 1994 and later to service the needs of importers of smaller volumes.

8. The design of gas carriers

The rules and regulations for the design and construction of gas carriers rely on practical ship designs codified by the International Maritime Organization (IMO). This is a root of work based on the knowledge of much expertise. However all ships from June 1986 started to be constructed according to the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (the IGC Code). This code also defines cargo properties and documentation, provided to the ship (the Certificate of Fitness for the Carriage of Liquefied Gases in Bulk), shows the cargo grades the ship can carry.

Particularly, it takes into account temperature limitations imposed by the metallurgical properties of the materials making up the cargo containment and piping systems. It also takes into account the reactions between various gases and the elements of construction not only on tanks but also related to pipeline and valve fittings.

When the IGC Code was published, an intermediate code was also developed by the IMO - the Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (the GC Code). This covers ships constructed between 1977 and 1986. As gas ships existed before IMO Code has been published, the ships constructed before 1977 were defined as ‘existing carriers’ for the purpose of the meaning of the rules, being covered then by the IMO’s Code for existing Ships Carrying Liquefied Gases in Bulk (the ‘Existing Ship Code’).

The double hull concept includes the bottom areas as a protection against grounding and, again, the designer’s experience has proven of great value in several serious grounding incidents, saving the crew, marine environment and surrounding populations from the consequences of a ruptured containment system. So a principal feature of gas carrier design is double containment and an internal hold. The cargo tanks, or as generally are referred to as the ‘cargo containment system’, are installed in the hold, often as a completely separate entity from the ship; i.e. being not as a part of the ship’s structure or its strength members. On the other side, the codes define a distinctive difference between gas carriers and other transporters such as for oil and chemicals.

Cargo tanks may be constructed with tanks independent of being of the self-supporting type or of a membrane design. The self-supporting tanks are defined in the IGC Code as being of **‘Type-A’**, **‘Type-B’** or **‘Type-C’**. Type-A comprises box shaped or prismatic tanks (i.e. shaped to fit to the hold space). Type-B is the type of tank where fatigue life and crack propagation analyses have shown improved characteristics. Such tanks are usually spherical but occasionally may be of prismatic geometry. Type-C tanks are pressure vessels, often spherical or cylindrical, but sometimes bi-lobe in shape to minimize broken stowage. The usage of one system or another depends on the type of the trade. For instance, Type-C tanks are suited to small volume carriage. They are therefore found most often on coastal or regional transportation. The large international LPG carriage is suited to the Type-A. Type-B tanks and cargo tanks following membrane principles are found in LNG fleet.

These types are discussed ahead in detail in the items 10.1 [Self-supporting independent (or free standing) cargo tanks] and 10.2 [Non self-supporting (or non-free standing or integrated) cargo tanks].

9. LNG Carriers (LNGCs) – An overview

LNG in bulk volumes is carried through the oceans by dedicated, sophisticated and specialized ships. They use insulated double-hulled cargo tanks, designed to contain the liquid cargo slightly above atmospheric pressure at a (cryogenic) temperature of about -169°C. In general, the tanks operate at 130 kPa (0.3 barg)[10], with a design pressure of 170 kPa (0.7 barg). The design of the cargo tanks must comply and ensure the integrity of the hull system and provide insulation of the LNG stored. However as the insulation cannot guarantee 100% of effectiveness, the liquid stored absorbs some heat from the exterior and boils along the trips. This gas boil-off gas has a typical rate of around 0.10%-0.15% v/v per day of the ship volume and must be vented somehow to maintain the LNGC cargo tanks at constant pressure. The vented gas can be burned to generate steam, provide fuel to the LNGC's dual engines, or even re-liquefied returning to the tanks if the ship's design allows.

LNG carriers must be robust enough to withstand the extreme cold temperatures of the liquefied gas and prevent the hull from cooling and becoming brittle. The tanks must insulate the LNG cargo from raising temperature and also prevent mixing of LNG vapor with air. Special concerns must be considered, since LNG is stored and carried at temperatures of around -162-163°C (normal boiling point at the typical storage pressure). It consists, essentially, from 85 to 96% v/v of methane, and the remainder is formed mostly of other light hydrocarbons such as ethane, propane, butane, and 1% nitrogen (ABS, 2004).

In general, LNGCs are classified in accordance with the type of LNG cargo containment system (Sandia, 2008), and most of LNGCs constructed by the industry are basically of three types of CCSs, (i) spherical independent tanks, (ii) membrane and (iii) self-supported prismatic. Figures 7 (a, b, c) depict the three LNGCs.

Figure 7: (a) LNGCs with spherical, (b) prismatic and (c) membrane cargo tanks.
Available: (a) http://www.mossww.com/technologies/lng_carriers.php,
(b) http://www.ihi.co.jp/offshore/spbmenu_e.htm
(c) http://worldmaritimenews.com/archives/50540/qatar-n-kom-inks-lng-membrane-tank-servicing-agreement/
Access: 6 Nov. 2015

As discussed above, the construction of carriers is governed by The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC, 1993, 1975) published by the International Maritime Organization (IMO), being applied to all vessels constructed after 1986. It is considered to be a leveraging mark in the international marine transportation. Table 3 presents the main characteristics of cargo tanks design. The CCSs for LNG transportation are regulated by the International Maritime Organisation (IMO) through the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code)[11] [More ahead in item 10 (Cargo Containment Systems in Liquefied Gas Carriers)].

The safety aspects to LNG transportation are linked to the handling of this cryogenic. The precautions and safety measures related to handling of LNG is mainly due to the following safety aspects:

- To carry LNG as a liquid at atmospheric pressure its temperature has to be about -162°C. Any spillage of LNG on the ship steel would be hazardous and can cause immediate damage to the ship's hull;
- Natural gas in a mixture of between of 5 to 15% v/v with air can be burned and/or explode;
- LNG contains about 1/600 times the volume of natural gas in the vapor phase;
- Its boiling temperature of about -162°C and heating LNG may cause rapid increase of gas volume and if it is enclosed the gas will cause significant pressure build up.

All carriers are constructed with full double hull to fulfill structural requirements providing, consequently, strength enough against collisions and groundings. Interspaces within the hull are of about 2-3 m, which can be used as hollows or ballast. Structural parts are usually steel to resist high tensile loads and fatigue but cannot be exposed to direct contact with LNG, since it may be subjected to brittleness due to cryogenic temperatures. The cargo containment and handling systems have to seal the cryogenic in a gas tight compartment to ensure no entrance of air and insulate the LNG from heat influx minimizing boil-off.

Besides the cargo containment systems, the carriers must load, discharge, handle, monitor, and measure the cargo's parameters such as temperature, pressure, flow rates. The equipment to handle this service must appropriated to cryogenic purposes and involves pumps, turrets, compressors, gauges, sensors, providing reliable and safe operation.

[10] barg + 1 = bar, since 1 bar ≅ 100 kPA, then 0.3 barg + 1 = 1.3 bar = 130 kPa.
[11] Available: http://www.imo.org/en/OurWork/Safety/Cargoes/CargoesInBulk/Pages/IGC-Code.aspx. Access: 17 Nov 2015.

Self-supported independent tanks are robust with heavy and rigid structures. They are constructed to support the weight of the liquid cargo. They are usually spherical and the LNGCs' hulls are designed to withstand the tank structure. On the other hand, membrane tanks are usually box-shaped, and the LNGC's hull provides the structural rigidity to the tanks. The thermal insulation is designed to support the whole membrane while contract and expand as required (Tusiani and Shearer, 2007).

In general, a cargo containment system is composed by an arrangement for containing cargo, including where applicable:

- A primary barrier (the cargo tank);
- Secondary barrier (if fitted);
- Associated thermal insulation;
- Any intervening spaces
- Adjacent structure for the support of these elements (if necessary).

If the cargoes are transported at temperatures in the range between –10°C and -55°C, the vessels' hull may act as the secondary barrier and in such cases it may be a boundary of the hold space. According to IMO IGC (1993, 1975), cargo tank types are:

- Independent 'Type A': Some other types such as:
- Independent 'Type B': Internal insulation 'Type 1'
- Independent 'Type C': Internal insulation 'Type 2'
- Membrane integrated tank.

The difference between LNGCs and the conventional oil tankers resides on the CCSs and its handling systems. IGC code classifies containment systems into two conceptual categories of CCSs:

- two self-supporting independent (or free standing) tanks with solid structures independent, being spherical and prismatic developed, respectively, by Moss Maritime of Norway and Conch International Methane Ltd, both of them constructed with 9% nickel steel or aluminum alloy, and
- two non-self-supporting (or non-free standing, or integrated), built with membranes, surrounded by a complete double structure of the ship's hull.

The schematic tree of IMO classification for LNG vessels is presented in Fig. 8[12] and the characteristics of the three main cargo tank types are presented in Table 3.

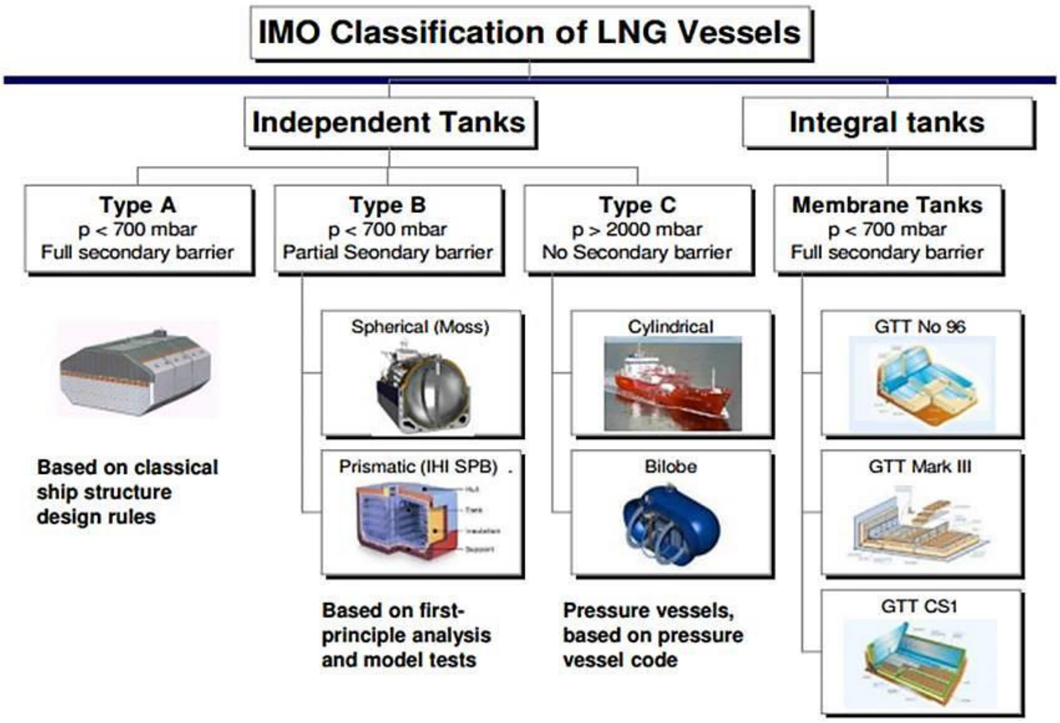

Figure 8 - LNGCs with spherical, prismatic and membrane cargo tanks. Source: ABS (2014)

[12] (i) 700 mbarg = 0.7 barg; 0.7 barg +1 = 1.7 bar = 170 kPa. (ii) 200 mbar = 0.2 barg; 0.2 bar g + 1 = 1.2 bar = 120 kPa.

Table 3 – Main tank designs [More ahead in item 10 (Cargo Containment Systems in Liquefied Gas Carriers)]

Description	Self-supporting Independent tank	Non-self-supporting Integrated tank
Type	Type-B - Partial secondary barrier Tank constructed independently of the hull	Membrane tank - Full secondary barrier The hull provides the structural strength of the tank
Containment	Kvæner (Moss Rosenberg) spherical tanks	GazTransport GTT No. 96
	IHI-SPB (self-supporting prismatic shape, independent type B tank)	Technigaz Membrane Systems Mark I and III
	Other types: Conch and Esso (small ships built in the 50's)	Technigaz & GazTransport CS-1(*)

(*) The Combined System-1, a hybrid of the Mark III and the GTT No. 69 combining the advantages of both systems, with existing technology and proven materials. Source: (Tusiani & Shearer, 2007)

However, another type of construction for tanks of the carriers was introduced in 2004 by American Ocean LNG Inc. (not in operation yet), which define the types of vessels, following, among others, the building codes for tankers ships, i.e., the Resolution Marine Environment Protection Committee, MEPC (06), of September 7, 1995, of the International Maritime Organization IMO (Esteves, 2010), namely:

- Spherical walls tanks with Kværner Moss technology, owned by the Norwegian company Aker Kværner ASA, as presented in Fig. 9

Figure 9 – Cross section and hook-up of a Kvæner Moss spherical tank Type B. Source: ABS (2006) (Courtesy)

- Self-supported tanks with prismatic structures, with technology of Japanese Ishikawagima Heavy Industries (IHI), known as SPB (Self-supporting Prismatic Shape Type B) LNG Tank System, as shown in Fig. 10

Figure 10 – Cross section and hook up of a prismatic tank type SPB
Available: http://www.ihi.co.jp/en/all_news/2014/press/2014-6-043/index.html Access: 17 Ago. 2015.

- Double membrane tanks with technology of GazTransport with GTT No. 96 System, as presented in Fig. 11

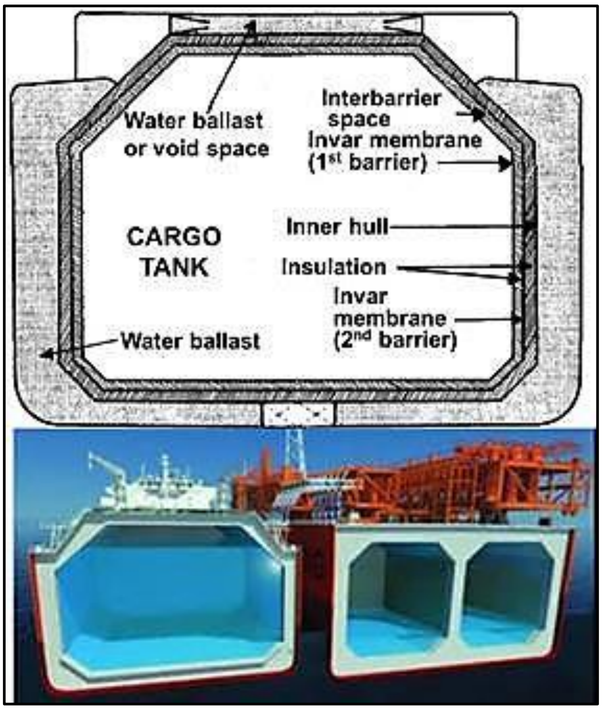

Figure 11 – Double membrane tank GTT no. 96
Available: http://www.gtt.fr/product/no96-system/http://lngsummit.com Access: 2 Dec 2015.

- Double membrane tanks with technology of TechniGaz Membrane Systems with the alternatives Mark III, as depicted in Fig. 12

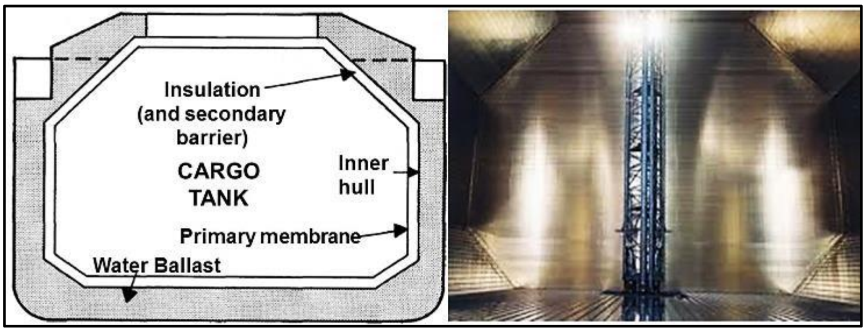

Figure 12 – Double membrane tank GTT Mark III
Available: http://www.gtt.fr/product/mark-iii-system/ Access: 17 Aug 2015.

- Double membrane tanks with technology of TechniGaz & GazTransport CS1 System, shown in Fig. 13.

Figure 13 – Double membrane cargo tank with CS1 system.
Available: http://www.gtt.fr/product/cs1-system/ Access: 2 Dec 2015.
Available: http://www.gtt.fr/product/cs1-system/http://gcaptain.com/suezs-sell-shares-fund-growth/#.VodITfkrKUk
Access: 2 Jan 2016.

- Self-supported independent tanks, with technology IMO Self-supported Type B Independent Tank, of American Ocean LNG Inc. This technology is not mature yet, but has already received the in March 30, 2004, the certificate AIP (Approved in Principle) from the Classification Society da ABS-American Bureau of Shipping, but with no ship constructed ever since. The cargo tank is presented in Fig. 14.

Figure 14 – Schematic drawing of the independent cargo tank Type B
Available: http://www.marinelog.com/DOCS/NEWSMMIV/MMIVNov30b.html Access: 17 Ago. 2015.

In summary, each one of the abovementioned types of cargo tank design or dedicated carriers have commercial and technical advantages and disadvantages.

Membrane tanks are constructed with light and flexible metals requiring rigid load-bearing insulation over the entire surface of the cargo tank surface allowing the transfer of loads from the tank to the hull. It is necessary that the insulation provide support over the membrane surface so it may expand or contract as required. Whatever the design may be cargo tanks have the main function to storage and transport huge LNG quantities close to the hull with a minimum of boil-off and no cryogenic heat transfer to the hull and structures.

In 2005 the total number of LNG ships reached 185 units. Of this total 90 (48%) were membrane tanks with GazTransport or Technigaz design, 89 (48%) were Spherical Type B (Moss), 2 (1%) were independent prismatic Type-B (IHI), and 4 (3%) for other designs. On the same year, the current order book totalized 123 ships, being 100 LNGCs of membrane type and 23 Moss (ABS, 2005). Later, SNAME (2009) presented a slight difference in favor of Moss tanks with 50% of the active fleet, as depicted in Fig. 15. In 2010, (Wang & Notteboom, 2010) based on Clarkson's[13] data report membrane tanks overcoming Moss tanks in existing fleet and in LNGCs orders as well, as shown in Figure 16.

On the other hand, a few LNGCs adopt SPB design constructed by IHI in Japan (Woodward & Pitblado, 2010).

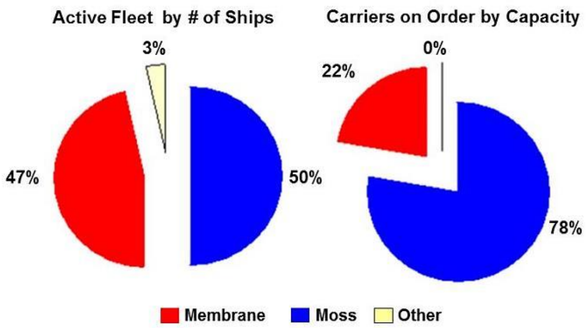

Figure 15 – Cargo containment system usage
Adapted from: SNAME (2009)

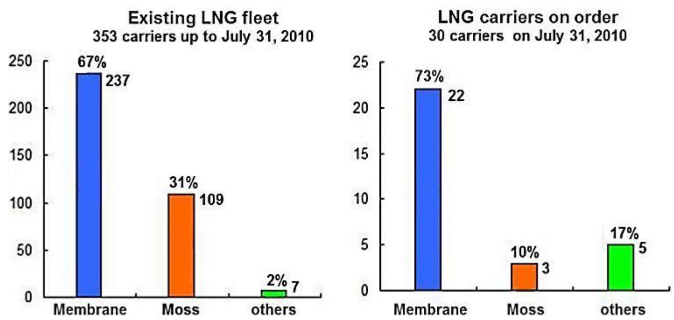

Figure 16 – Distribution of containment systems
Adapted from: Wang and Notteboom (2010)

The status computed in November 2013 for the trends for CCSs of carriers Types B and membranes, presented the following numbers (ABS, 2014), as indicated in Fig. 17.

[13] http://www.clarksons.com. Access: Nov. 12, 2015.

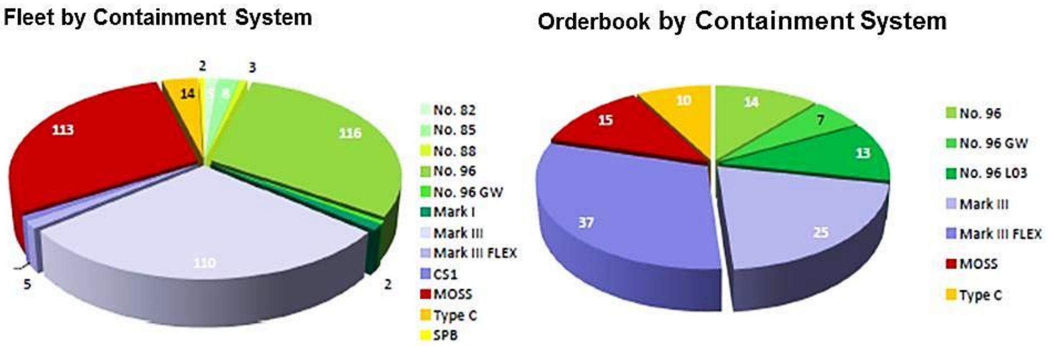

Figure 17 – (a) Fleet by containment system; (b) Order book by containment system. Adapted from: ABS (2014)

The LNG tankers are becoming larger and more efficient. The membrane design makes better use of available space on a ship and thus facilitates lighter hulls. Conventional LNG ships in service today are often in the 138-145,000 m³ range. The Q-Flex class of ships in service since 2007 reaches 210,000 m³, and the Q-Max class even 260,000 m³ since 2007. The "Q" in the name refers to the ability to dock at Qatar's LNG terminals.

These large LNG tankers are dedicated to very specific routes because most LNG terminals cannot handle such large ships. The designs differ in conception, but the first three technologies are the most internationally used on LNGCs fleets over 135,000 m³ of capacity, generally using from 4 to 6 cargo tanks. Newer vessels have been built with at least 138,000 m³, but since July 2008 the Mozah LNGC of QtarGas, is already in operation, considered to date the largest LNGC in the world, with 267,350 m³[14].

Today, the largest LNGCs are being constructed with the following capacities, according to CCS adopted (GIIGNL, 2014):

•Mark III, double membranes, over 265,000m³;
•No. 96, single membrane, with 261,700 m³;
•Moss, spherical, with 177,630 m³;
•IHI SPB, independent and self-supported prismatic, with 180,000 m³.

Table 4 presents the dimensions of current and emerging LNG LNGCs for both cargo tank designs (SANDIA, 2008).

Table 4 – Emerging LNGC size and capacity

Class	Membrane designs			
	145,000 m³	155,000 m³	215,000 m³	265,000 m³
Tanks	4	4	4	4
Length (m)	283	288	315	345
Width (m)	44	44	50	56
Draft (m)				
Class	**Kvæner Moss designs**			
	138,000 m³	**145,000 m³**	**200,000 m³**	**255,000 m³**
Tanks	5	4	5	5
Length (m)	287	290	315	345
Width (m)	46	49	50	55
Draft (m)	11	11.4	12	12.5

10. Cargo Containment Systems in Liquefied Gas Carriers

10.1. Self-supporting independent (or free standing) cargo tanks

Pursuant with Fig. 8 and in accordance with CCNR/OCIMF (2010), independent cargo tanks are integrally self-supporting, therefore do not compose the structure of the ship's hull. They do not contribute to the strength of the hull of the vessel either. As introduced previously, in accordance to the IGC (1993, 1975) code, cargo tanks are dependent on the design pressure, and three different types of independent tanks for gas carriers are possible: Tank Type-A, Type-B and Type-C. As prescribed by this code, all LNG cargo tanks types must be constructed to comply with a comparable level of safety (ISSC, 2012).

[14] Disponível em < https://www.qatargas.com/English/MediaCenter/Publications/ThePioneer/Pioneer-Jul-Aug_2008-E.pdf >. Access: 17 ago. 2015. Sources: SANDIA (2008) and Poten & Partners (2006).

10.1.1. Type-A independent tanks

The Type-A, in a general appraisal, are box-shaped or prismatic cargo tanks in order to fit to the hold space. It must have a full secondary barrier, based on classical ship structure rules. This requirement provides a redundancy to prevent any possible leakage caused by a rupture of the tank primary barrier, no matter if the leakage is caused by fatigue cracks or tank overfilling. The tank must be constructed with strength utilization similar to a deep tank in a ship structure. For Type-A tanks the hull structures are permitted to be designed for cargoes with boiling temperatures not lower than -55°C, which is not a realistic alternative for LNG purposes, being more adequate for C_3H_8, C_4H_{12} and NH_3 transportation. They are constructed basically of flat plates and surfaces. The allowable tank design pressure in the vapor space is 170 kPa (700 mbarg = 0.7 barg) as the maximum allowable, meaning that cargoes must be transported in a fully refrigerated condition at near atmospheric pressure, usually below 125 kPa (0.25 barg) as a maximum allowable (CCNR/OCIMF, 2010).

Type-A cargo tanks are self-supported tank demanding internal conventional stiffening. Usually, they are coated and surrounded by a film of foam insulation. In the regions where perlite[15] is used as insulation, it is necessary to fill the whole hold spaces. Figure 18 depicts a cross section of this type of tank usually found in the refrigerated ships used for the transportation of LPG.

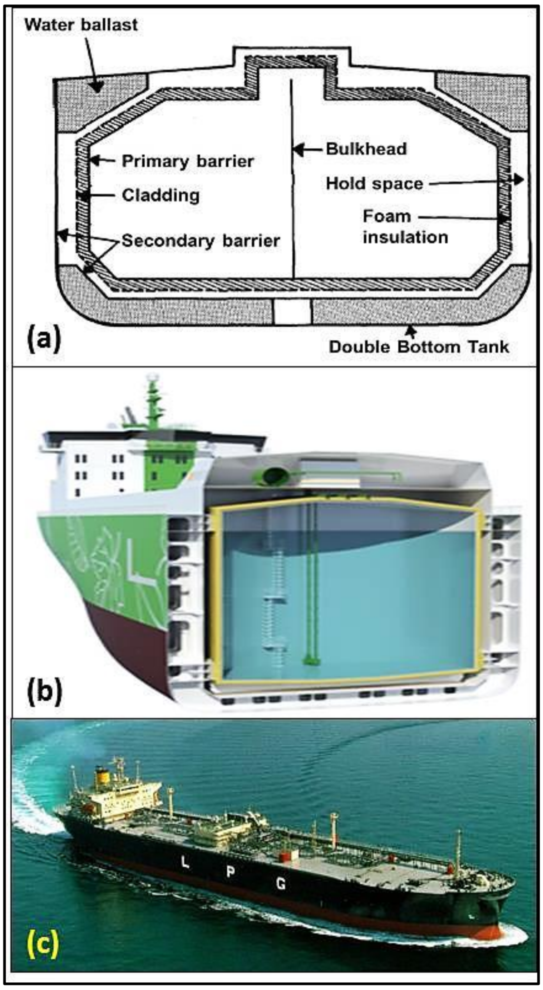

Figure 18 - Prismatic self-supporting Type-A cargo tank fully refrigerated LPG ship
(a) Adapted from: CCNR/OCIMF (2010). Available: (b) www.ship-technology.com; (c) www.dcslogistics.com Access: 4 Dec 2015

When the construction material used is not resistant to cracks, safety requires a secondary containment (barrier) for the case of an unlikely event of cargo leakage, as a feature of all vessels capable to transport cargoes below -10°C.

For these vessels, the IGC Code requires that whatever may be the secondary barrier, it must be able to hold the tank liquid for 15 days. The space between cargo tanks (known sometimes as 'primary barrier') and the secondary barrier is designated as 'hold space'. When flammable cargoes are being carried, these voids spaces must be filled with inert gas to prevent a flammable atmosphere, in case of leakage of the primary barrier.

[15] Perlite is an amorphous volcanic glass that has relatively high water content, typically formed by the hydration of obsidian. It occurs naturally and has the unusual property of greatly expanding when heated sufficiently.

Fully refrigerated LPG vessels (cargo temperatures above -55°C) require otherwise a complete barrier in order to contain the whole tank volume or, alternatively, a separate secondary barrier around each cargo tank. Parts of the hull are constructed of special steel to withstanding low temperatures. Another alternative is to construct separate barriers involving each one of the tanks. Flammable cargoes requires that either the primary or secondary barriers be filled with inert to avert flammable atmospheres in the hold space (between the cargo tank, i.e., the primary barrier, and the second barrier) if the primary barrier leaks.

10.1.2. Type-B independent tanks

The concept of these cargo tanks is such that they can be constructed using flat (prismatic IHI) or spherical plates (Moss). This last design poses otherwise more complex and detailed stresses when compared to Type-A. Therefore, the controls need to be stricter. They require fatigue investigation and crack scale up analysis during the carriers' operational life.

The Type-B needs also a partial secondary barrier that provides redundancy only to fatigue cracking. Another design redundancy is to avoid fatigue damage, except for extreme loads. The construction material used for extreme load purposes is therefore stricter than to that of Type-A, providing larger safety factors against eventual overloading.

The purpose of the Type-B (spherical or prismatic) tank's secondary barrier is to provide the cargo a temporary containment and prevent the carrier's hull from being cooled to an unsafe level. This secondary barrier must be designed to contain leakages for a given period (usually 15 days), requiring continuous monitoring to detect leakages from the primary barrier. Because of the enhanced design factors, a Type-B tank requires only a partial secondary barrier in the form of a drip tray.

The main types comprised in this category use volumes up to 135,000 m³, although larger capacities (180,000 m³) are being constructed more recently. The maximum allowed design pressure usually is 125 kPa (0.25 barg) not exceeding 170 kPa (0.70 barg). These cargo tanks usually are constructed of Aluminum 5083-0 or stainless steel grade 316/L304. The spherical design is almost exclusively dedicated to LNGCs, and seldom used in the LPG trades. As an introduction to both cargo tanks, they were presented in Figures 9 (spherical design) and 10 (prismatic design). Figures 7(a) and 7(b) represented the corresponding LNGCs.

10.1.2.1. Kvæner Moss' spherical tanks

The Norwegian Kvæner Moss developed a design of tank to transport LNG at cryogenic temperatures with pressure around the atmospheric pressure. The Type-B spherical tank was conceived, almost exclusively, to be used as LNG carriers, and seldom is used for the LPG trade. Schematic view of this tank is presented in Fig. 19.

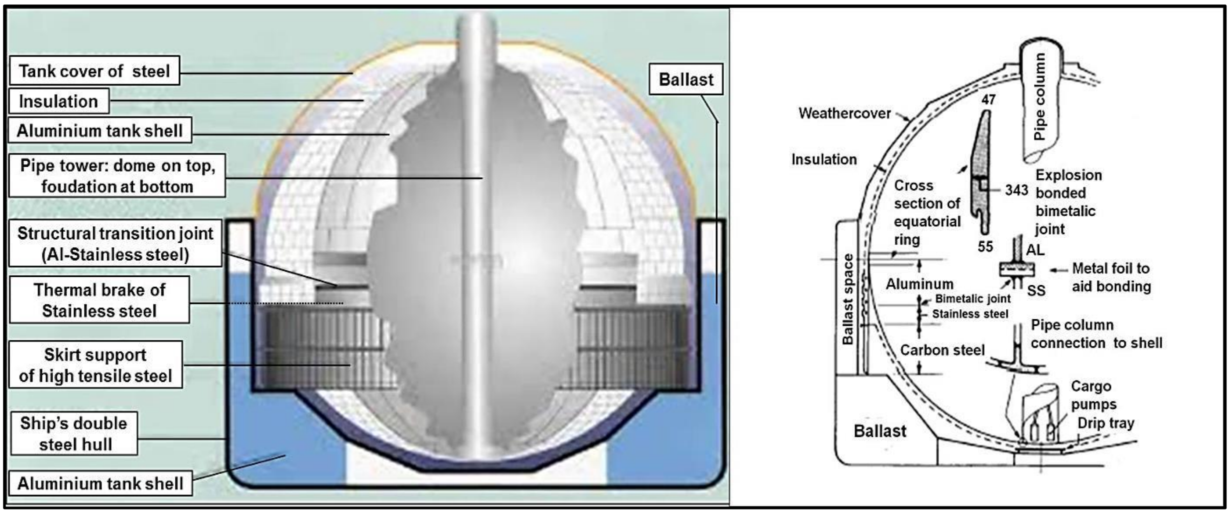

Figure 19 – Kvæner Moss' spherical tank. Available: www.marad.dot.gov. Access:18 Nov. 2015. Adapted from: CCNR/OCIMF (2010)

The enhanced design factors used in its construction makes it require a partial secondary barrier only, as a drip tray. The hold spaces are usually completed with dry inert gas or dry air providing the necessary inert void's atmosphere if the vapor detection system indicates some cargo leakage. A protective steel dome is used to cover the primary barrier above deck level and an insulation layer is applied over the outside surface of the tank. They are constructed, essentially, by supporting the independent spheres constructed from aluminum alloy with a continuous and stiffened cylinder (skirt) attached to the sphere's equator using a special extrusion process. The skirt is stiffened in the upper part by horizontal rings and the lower part by vertical corrugated stiffeners. This device transmits the weight of the tank and cargo to the lower hull. It allows the sphere to contract and expand with minimum loads transferred to the hull structure, since they are anchored to the ship's double hull using the steel skirt with a thermal brake made from a special alloy.

Spheres can accommodate the same cargo volume with the lowest tank's external area, demanding lower costs with plates, welds, etc. to construct the cargo tank. This was one of the reasons why spherical tanks were favored for containment in the early conceptual designs. However, spheres use hull space less efficiently having the disadvantage to project its upper hemisphere over the ship's main deck. The spheres are constructed using welded thick plates of Aluminum 5083-00 alloy, with thickness ranging between 29 and 57 mm, and the usual is of 50 mm. Spherical design provides a high degree of safety against failures or fractures therefore they do not require secondary barriers. Each one of the tanks is covered by a spherical steel cover in order to protect the tank and the insulation against the weather, as well as to control the void space atmosphere.

They are heavily insulated with polyurethane or polystyrene foam with thickness of 250 mm to reduce the boil-off to a minimum, and are encapsulated within the void spaces of the LNGC's hull. They are positioned in-line from bow to stern of the LNGC, and from four to six spheres are used. In this design, the supports of the spheres are provided by equatorial rings to transmit the loads to the hull using stainless steel skirts with circular shape. A special device is provided between the equator and the skirts in order to limit the transfer of cold to the skirts. Another connection is used to eliminate welding fragile points between the tanks (aluminum) and skirts (stainless steel).

The void spaces between the LNGCs' inner hull and outer hull are used for water ballast and also provide protection to the cargo tanks in case of a collision or grounding[16]. There is no secondary barrier since the tanks, due to their spherical construction, have a high degree of safety against fracture or failure. Each tank is covered by a spherical steel tank cover, the main purpose being for tank and insulation weather protection. The cover also permits control of the hold space atmosphere. The lower edge of each cover is welded to the weather deck, forming a watertight seal. Flexible rubber seals are applied at the points where the tank dome protrudes out from the cover deck. The sphere is equipped with LNG pumps inside, with no connection whatsoever in the tank bottom. The sphere maintains its own structural integrity, without the need of the ship structure for this purpose. The load is transferred to the vessel via a metal skirt connected to the sphere's equator, and there are multiple barriers between the external environment and LNG load (Woodward & Pitblado, 2010). The ship's hull is double with internal structures, and some vessels have an additional wall surrounding all spheres, which is protected by another external skirt, providing support and insulation for the sphere's wall.

In the beginning of the 2010's, Mitsubishi Heavy Industries, Ltd. (MHI) finished the development of a new-generation of LGNCs, defining evolutions of the Kvæner Moss' spherical tank. The new carrier was named 'Sayaendo' the first of a series, with the second version 'Extreme' (or 'Sayaendo 2') (Sato & Chung, 2013).

This series features a peapod-shaped continuous weather cover for the Moss spherical tanks that is integrated with the ship's hull, in lieu of a conventional hemispherical cover. It constitutes a visual and conceptual distinctive design from the classical hemispherical dished ends of the conventional Moss tanks. This new configuration allegedly enables greater structural efficiency and size and weight economies, resulting not only in improvements in fuel consumption as well as in operating economy but also in enhancements in terms of compatibility with LNG terminals and maintainability. According to ABS (2014) the 'Sayaendo' design builds on the strength (reliability) of spherical tank with lightweight, being suitable for cold navigation as a competitive differential. Figures 20 and 21 (a) and (b) depict this new concept.

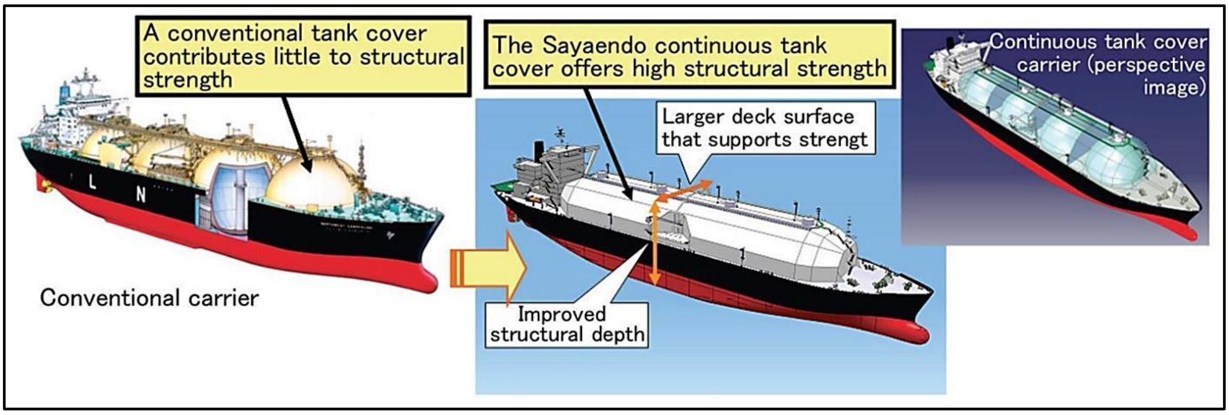

Figure 20 – Conventional and continuous tank cover comparison. Source (Courtesy): Sato & Chung (2013).

[16] Available: http://www.mossww.com/technologies/lng_carriers.php . Access: 19 Nov 2015.

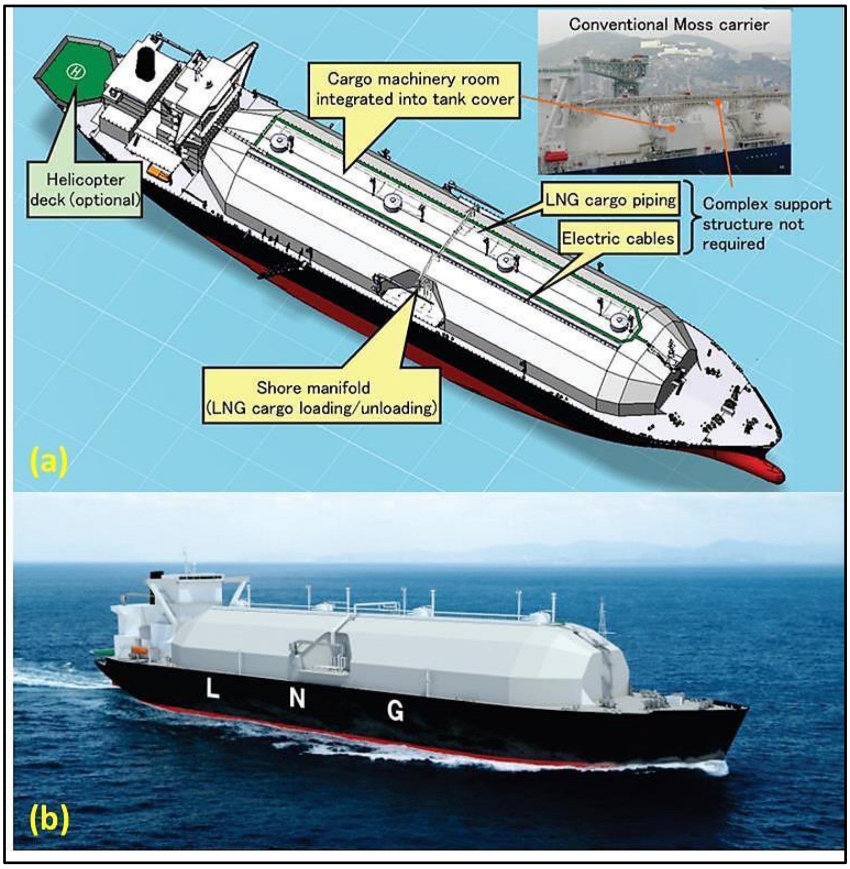

Figure 21 – (a) Conventional and continuous tank cover comparison. (b) 13,155 m³ Sayaendo
Source (Courtesy): Sato & Chung (2013).

10.1.2.2. IHI's prismatic tanks

Nevertheless, Type-B cargo tanks, not necessarily has to be of spherical geometry. There are other shape (prismatic), provided by Type-B for the LNG transportation. The prismatic tanks have some differentials as (i) maximize the carrier-hull volumetric efficiency and (ii) arrange the whole cargo tank placed beneath the main topside. When design is adopted, the maximum design pressure of the vapor space, as recommended for the Type-A cargo tanks, shall be not more than 170 kPa (0.7 barg). Schematic drawing of its design is presented in Fig. 22.

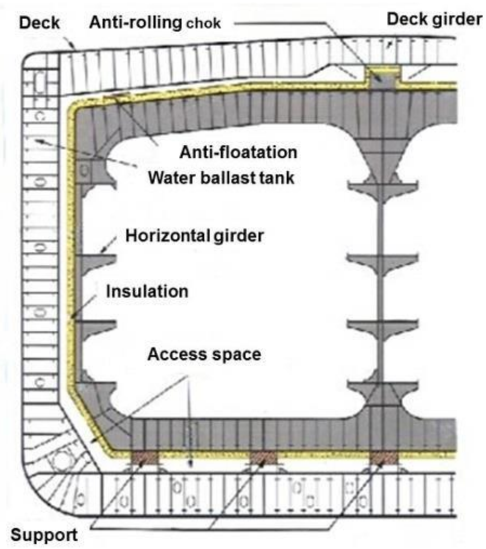

Figure 22 – IHI's self-supporting prismatic tank. Available: [www.ihi.co.jp/offshore/whatisspb_e.htm;](www.ihi.co.jp/offshore/whatisspb_e.htm)
Video movie: [https://www.youtube.com/watch?v=pVNT1gKDSH0https://www.youtube.com/watch?v=pVNT1gKDSH0](https://www.youtube.com/watch?v=pVNT1gKDSH0)

SPB LNGCs comply with IMO Type-B requirements by using Al-Alloy self-supporting prismatic tanks, proven for its reliability. These LNGCs had its development approved in 1985 by U.S. Coast Guard, launching to the water in 1993 two LNGCs of 87,000 m³, the Polar Eagle and Artic Sun[17].

According to IHI, the prismatic tank is divided into four compartments by bulkheads LNG leak proof. Thus, according to the technology, it is predicted that the local frequency of the liquid motion within the cargo tank is not affected by the vessel motion frequency. Thus, it is expected that it could not happen any resonance between the movement of the liquid cargo and the ship's movement, being supposedly possible to load the ship with any level of the cryogenic.

It also avoids, in principle, the occurrence of load stratification that may take place due to the sudden mix of LNG with different densities, compositions and heat capacities in the bottom of the ship's tanks (rollover). If this occurs with two layers of LNG the sudden mix may result in the release of large amounts of vapor.

This configuration allows to LNG be carried with the vessel partially loaded even amidships, with faster unloading when docked even to FLNG, FPSO, FSRU, etc.. The stiff tank plates are not likely to increase internal and external pressure in the vapor space, being unnecessary to control the differential pressure. This space can be accessed and used otherwise for maintenance and inspection. Additionally, according to IHI, this design has the following differential characteristics: (i) smaller pit for the suction of the dispatch pump, (ii) smaller BOGs (boil-off gases) and ballast spray formation, (iii) does not require vacuum or nitrogen purge tests in the vapor space, (iv) main deck completely plain from starboard to port side and from bow to stern without truncation of prisms or spherical caps.

One of the characteristics of the SPB prismatic tanks is its free shape, since it is constructed with stiffened plates. This allows constructing the ship's hull considering the best hull performance given a design condition (draft, beam, etc.) and designing cargo tanks to follow the hull contour afterwards, leading to a compact LNGC with reliable hull shape.

The stiffened plates used in its structure are made of aluminum alloy A5083 or 9% Ni steel SUS 304, with thickness varying between 10 mm and 50 mm, and covered by an insulation layer of polyurethane foam with thickness of 250 mm. Each cargo tank is supported by a special type of reinforced plywood, and subdivided by a tight bulkhead (working as a centerline for the liquid content) and a swash bulkhead into 4 spaces. So the natural frequency of the liquid movement inside tank is different from that of ship's motion, eliminating chances of resonance between the liquid cargo and ship movements. Consequently, no sloshing problem is expected and any level of loading within the tank is supposedly always possible. This enables partial loaded voyage, quick dispatch from the berth in emergency, making SPBs suited to FPSOs, FLNGs, FSRUs, or any other offshore structure, in which tanks are always half loaded. Because of the nature of stiffened plate structure, the tank has the same strength to support inner and outer pressures.

SPB tanks do not use pressure control devices between hold spaces and tank shell, on the contrary of membrane and Moss tanks that are susceptible to the control of outer and differential pressures. The IHI's prismatic Type-B is independent of the LNGC's structure, having some advantages when compared to spherical Moss tanks, since it maximizes the available cargo voids. The hold spaces are used for inspection and maintenance. IHI also claims for some advantages such as less fuel expense (less horsepower consumption with compact hull form), more cargo deliverability thanks to less heel of the pump well, less BOG due to the nominal lower vaporization within the cargo tanks, no spray in ballast voyage. Some other characteristics are also cited: less down time, maintenance expenses and easy operation. However, IHI's design has the inconvenient to increase weight and cost, because it includes plates and bracings keeping hull's plates from being distorted due to hydrostatic loads (Moktahab et al., 2014). One important characteristic of this design is the deck that is completely flat from side to side, with no obstacles on the deck when compared with membrane and extruded sphere on the deck of Moss LNGCs. This contributes to less wind resistance thus with less power consumption, easy maintenance and easy navigability and maneuverability.

10.1.3. Type-C independent tanks

According to CCNR/OCIMF (2010), these tanks are usually of spherical or cylindrical geometry pressure vessels with design pressure higher than 500 kPa (4 barg). If cylindrical, they may be vertically or horizontally mounted. These tanks are always used for semi-pressurized and fully pressurized gas transporters. Type C tanks are designed and built to according pressure vessel codes and, as a result, can be subjected to accurate stress analysis. Consequently, no secondary barrier is required and hold spaces can be filled with either inert gas or dry air; if the carrier is pressurized normal air can be used. If the ship is typical fully pressurized, with the cargo transported at ambient temperature, the tanks may be designed for a maximum working pressure of about 1,900 kPa[18]. (18 bar g). Figures 23 depict in (a) a gas carrier with fully pressurized double hull and double bottom, and (b) same with single hull. The geometries of Fig. 23 (a) and (b) present, comparatively, poor utilization of the hull volume.

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[17] Available: http://www.ihi.co.jp/offshore/whatisspb_e.htm. Access: 15 Nov. 2015.

[18] 19 bar abs = 18 bar g +1 = 19 x 100 kPa/1 bar = 1,900 kPa.

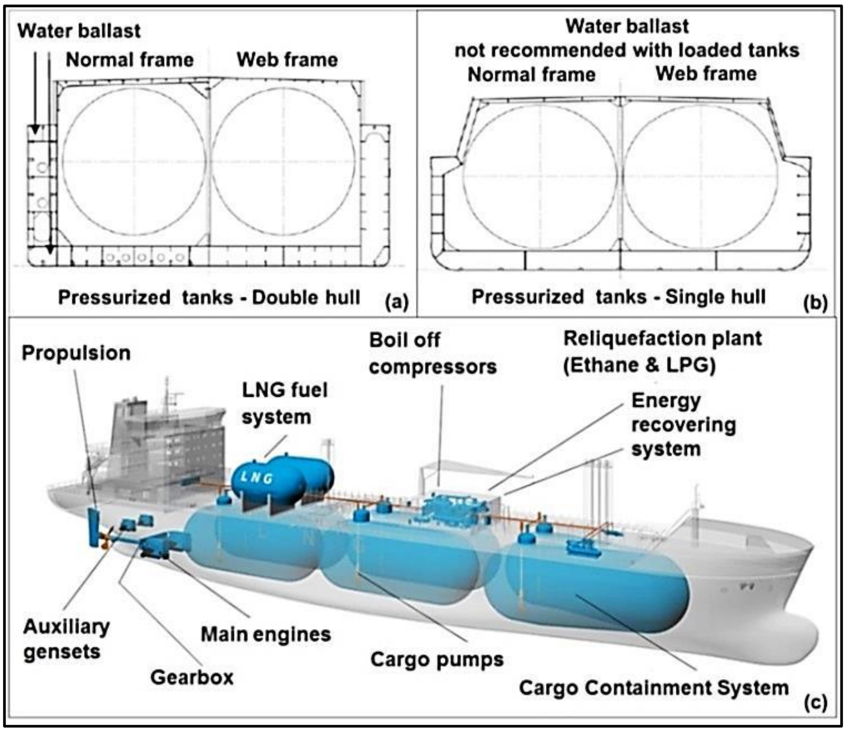


Figure 23 – Type-C cylindrical cargo tanks assembled in pressurized gas ship (a) Double hull, (b) Single hull. Adapted from: CCNR/OCIMF (2010) (c) Carrier 3D visualization. Available: www.lngworldnews.com
Courtesy of Wärtsilä and Evergas. Access: 4 Dec 2015

For a semi-pressurized ship the cargo tanks and associated equipment are designed for a working pressure of approximately 600 to 800 kPa (5 to 7 barg) and a vacuum of 140 kPa (0.3 barg). Usually, the steel applied for the semi-pressurized ships are capable of withstanding transport temperatures of -48°C for LPG or -104°C for ethylene which can be used to transport LPG. Type C tanks as fitted in a typical fully pressurized gas carrier.

These cargo tanks are constructed to a minimum design pressure, and they are not used for LNG transportation purpose except in the cases this cryogenic is carried as fuel. The advantage of Type-C is the possibility to handle the BOG, increasing the cargo tank pressure. When compared to Type-A and Type-B, this carrier presents some disadvantages due to higher containment weight and lower effective utilization of void spaces (Tusiani & Shearer, 2007).

However, improvements can be achieved with intersecting pressure vessels or bi-lobe type tanks which may be designed with a taper at the forward end of the ship, as shown in Fig. 24 (a) and (b).

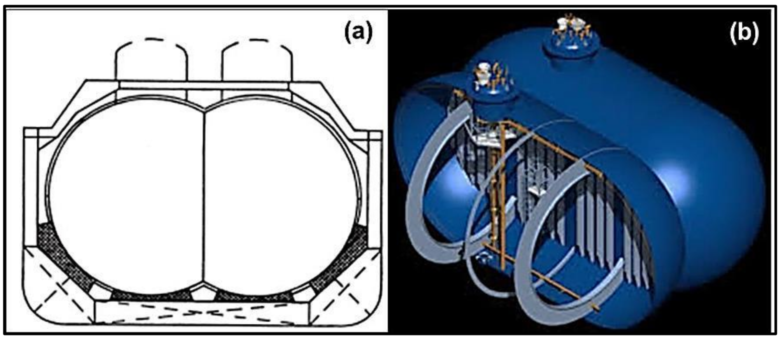


Figure 24 – Type-C cargo tanks – semi-pressurized gas carrier with bi-lobe tanks.
Adapted from: (a) SIGTTO (2000); (b) Bi-lobe cargo tank 3D visualization Available: www.lngbunkering.org. Access: 4 Dec 2015

10.2. Non self-supporting (or non-free standing or integrated) cargo tanks

Non self-supporting membrane tanks are, otherwise, surrounded by the double hull carrier's structure. Membranes tanks are non-self-supporting tanks consisting of thin layers (membranes) supported through insulation by adjacent hull structure. The membranes are designed to compensate thermal effects without significant stresses. In order to control the effects on ship structure from a potential leakage of cryogenic liquids, the Code requires that a secondary barrier is to be provided (Deybach, 2003).

The double membrane design consists of one (or two) thin layer of stainless steel or alloy steel of high nickel content, with thicknesses ranging between 0.7 and 1.2 mm. It is capable to contain a hydrostatic load 25.000 m³ of LNG, but uses the vessel structural support (Pitblado et al. 2004). The two membranes are separated by a thin layer of perlite, plywood and insulating polyurethane foam. The tanks are kept at a very low positive pressure and the boil-off gas is collected supplying fuel for the vessels propulsion. There is no bottom connection whatsoever in order to avoid leaks or failures.

The barriers between the outside environment and LNG cargo are: double hull, the inner hull structure, the outer membrane, the isolation plywood box and inner membrane. The ships are usually equipped with load stabilization systems to prevent the movement effects (sloshing) of the liquid cargo due to the ship's (solid) motion during storms, harsh weather or sea force. The gap between the load and the water is at least 2 m, and often 3 to 4 m. A large cofferdam separates each tank with the respective membranes, reducing the potential of an undesirable event occurred in a tank affects the adjacent tank. An example of this type of tank is introduced in Figure 7 (c) and Figures 11 (GT no. 96 system), 12 (GTT Mark III system) and 13 (CS1 system).

The cargo containment system consists of insulated cargo tanks encased within the inner hull and located in-line from bow to stern. The void spaces between the inner and outer hull are used for ballast and also to protect the cargo tanks in case of grounding or collision. Membranes functions as a huge containment inside the hull fabricated of a thin metal layer that works as a primary barrier. This layer receives another layer of insulation followed by a thin layer of metal (primary barrier), insulation, secondary membrane barrier, and further insulation in a 'sandwich' construction. The membrane is designed in such a way that thermal and other expansion or contraction is compensated for without undue stressing of the membrane.

10.2.1. Type-A independent tanks

10.2.1.1. The GTT No. 96 Membrane System

The cargo tanks are separated from other compartments, and from each other, by transverse cofferdams which are dry compartments. The description that follows is of a GazTransport No. 96 double membrane system design. Although the principal design features will be similar in other systems, e.g. Technigaz, there will be differences in membrane construction and insulation structure.

Pursuant to the Fig. 11, according to GTT[19], the No. 96 membrane system consists fundamentally of a cryogenic liner directly supported by the ship's inner hull. The liner consists of two identical metallic membranes and two independent insulation layers. The primary and secondary insulation layers are fabricated of Invar (36% nickel-steel alloy[20] - high nickel content with low thermal contraction coefficient)) with 0.7 mm thick. The primary membrane has the function to contain the LNG cargo, and the secondary (identical to the primary) has the function to guarantee 100 % of redundancy in case of eventual failure or leakage.

The main function of the membranes is to prevent leakages, while the insulation supports and transmits the loads. Additionally, they minimize the heat transfer between the cargo and the inner hull. The secondary membrane, comprised between the two insulation layers, not only provides a safety barrier between the two layers, but also reduces convection currents within the insulation. The primary and secondary insulation voids are kept under an inert nitrogen atmosphere with pressure control. This nitrogen buffer cannot in any case exceed the cargo tank pressure. This is to prevent the membranes from collapsing inwards.

Therefore, the insulation design is supposed to guarantee[21]:

- The heat inflow be limited to such an extent that the vaporization (BOR) being is about 0.15%/day based on sea surface temperature of 32°C and air temperature 45°C;
- The inner hull steel does not attain a temperature below its minimum design value, even in the case of failure of the primary barrier;
- Any deflections resulting from applied strains and stresses are acceptable by the primary barrier.

Another important function of the thermal insulation is to act as a barrier to prevent any contact between ballast water and the primary barrier, in the event of leakage through the inner hull.

These two identical layers of membrane/insulation, is such that given a leak in the primary barrier, the cargo will be contained by the secondary barrier. The secondary barrier is designed to contain any possible leakage of cargo for a period of 15 days (according to the IGC Chapter, item 1V 4.7.4). This system ensures that all the hydrostatic loads of the cargo are transmitted through the membranes and insulation to the inner hull plating of the ship.

[19] Available: http://www.gtt.fr/en/technologies-services/our-technologies/no96 Access: 28 Dec 2015.
[20] Alloy composition: 35-36.5% w/w Ni, < 004% C, < 0.25% Si, < 0.2-0.4% Mn. < 0.oo15 % S, < 0.008% P, remaining % Fe.
[21] Available: http://www.liquefiedgascarrier.com/LNG-vessel-construction.html.Acces 28 Dec. 2015

In the GazTransport No. 96 design, the inner hull, that is, the outer shell of each tank, is lined internally with the patent tank containment and insulation system, consisting of:

- A thin flexible membrane ('primary'), which is in contact with the cargo. This is made from Invar[22] and has a typical thickness of 0.7mm;
- A layer of primary insulation made of plywood boxes filled with typical thickness of 230 mm;
- A second flexible called 'secondary', similar to the first, made also of Invar with typical thickness of 0.7mm;
- A second layer of boxes, also filled with Perlite[23], and in contact with the inner hull, called the 'secondary insulation', typically of 300 mm thickness;
- These two thermal insulation layers consist of load bearing system fabricated of plywood standard boxes of 1 m x 1.2 m, filled with expanded perlite.

The primary layer is held by means of the primary couplers, which are fixed to the secondary coupler assembly. The secondary layer is fixed by means of the secondary couplings anchored to the inner hull. The No. 96 design principles can be visualized in Fig. 25 and the tank geometry is depicted in Figs. 26 (a) and (b).

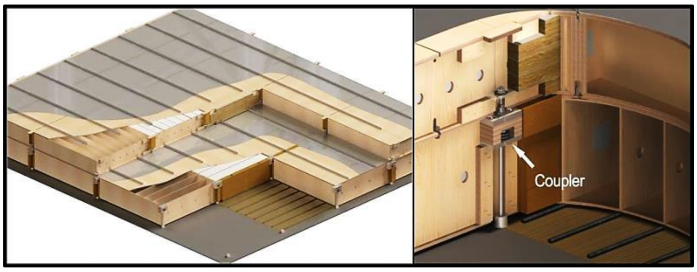


Figure 25 – The No. 96 principle.
Available: http://www.gtt.fr/en/technologies-services/our-technologies/no96 Access: 29 Dec 2015

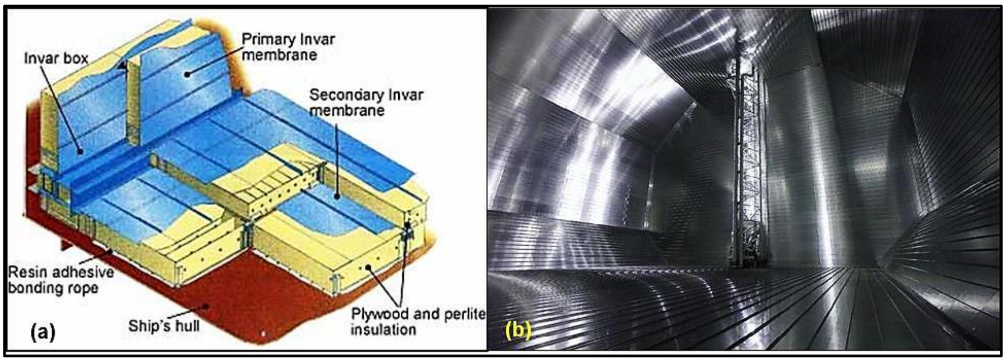


Figure 26 – (a) Arrangement of both membranes, (b) The cargo tank after fabrication.
Available: (a) www.twi-global.com (b) (Moktahab et al., 2014). Access: 2 Jan 2016

The boil-off issue is addressed by GTT to meet the requirements for lower rates as a first step, replacing the perlite in the boxes by glass-wool, included in a newer version, the **No. 96-GW**. GTT otherwise considers that 'evolution' is not a structural change, since the bearing plywood structure is kept identical to the No. 96 system, guaranteeing a BOR of 0.125% of the volume carried per day. With another design for even better thermal efficiency, GTT proposed the **No. 96-L03** design, where GTT sustains that it is possible to obtain a BOR of 0.105 %.

The No. 96 an the further improvements allegedly claimed by GTT for the two versions of this design systems, **No. 96 GW** and **No. 96-L03**, can be watched in the video movies available in http://www.gtt.fr/en/technologies-services/our-technologies/no96.

10.2.1.2. GTT Mk III

Following Fig. 12, in accordance with to GTT[24] and CCNR/OCIMF (2010), this design consists of a cryogenic liner directly supported by the internal ship's hull. The liner is made of a primary metallic membrane of corrugated (or *waffles*) stainless steel 304 L, with 1.2 mm thick to allow for expansion and contraction, located on top of a

[22] Invar also known generically as FeNi36 (64FeNi in the US), is a Ni-Fe alloy, notable for its uniquely low coefficient of thermal expansion. *Invar* comes from *invariable*, referring to its relative lack of expansion or contraction with temperature changes.
[23] Perlite is an amorphous volcanic glass that has relatively high water content, typically formed by the hydration of obsidian.
[24] Available in: http://www.gtt.fr/en/technologies-services/our-technologies/mark-iii. Access: 24 Dec. 2015

prefabricated insulation panel, including a complete secondary membrane. The primary membrane contains the LNG cargo and is directly supported by and fixed to the insulation system. Standard size of the corrugated sheets is 3m x 1m.

CCNR/OCIMF (2010) point out that in the original Mark I design, the insulation that supports the primary membrane consisted of laminated balsa wood panels held between two plywood layers, and the face plywood formed the secondary barrier. The balsa wood panels were interconnected with specially designed joints comprising PVC foam wedges and plywood scabs and were supported on the inner hull of the tanker by wooden grounds.

In this new version, presented in Fig. 27 (a) and (b), this membrane is folded to create corrugations.

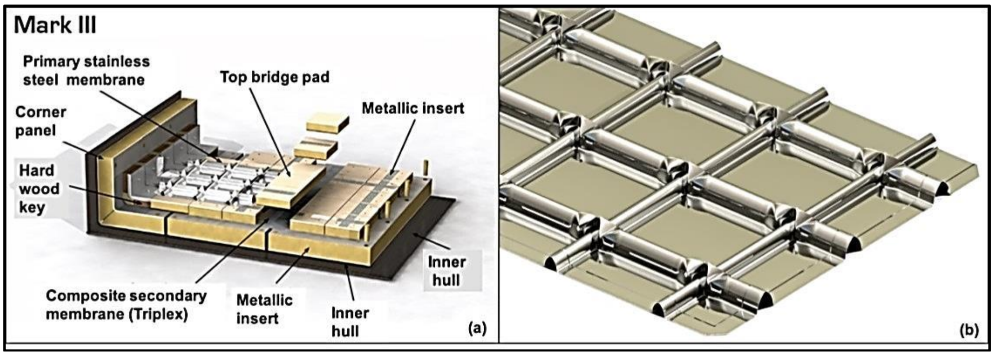


Figure 27 - (a) The Mark III original design (b) Mark III stainless steel corrugated membrane.
Available: http://www.gtt.fr/en/technologies-services/our-technologies/mark-iii Access: 28 Dec 2015

The membrane of the tank of a LNG methane carrier can be watched in the video movie available in https://www.youtube.com/watch?v=zGNFKGq5vhI

The knot is the intersection of the corrugations (small and large corrugations). The secondary membrane is made of Triplex, a composite laminated material, i.e., a thin sheet of aluminum between two layers of glass cloth and resin. It is positioned inside the prefabricated insulation panels between the two insulation layers. In Fig. 28 (a) and (b) is depicted a carrier with the Mark III cargo tank assembled its hull.

Figure 28 - (a) LNG carrier with a Mark III cargo tank in the hull (b) Internal view of the Mark III cargo tank.
Available: (a) www.lngworldnews.com Access in: 28 Dec 2015; (b) (Moktahab et al., 2014) and http://www.gtt.fr/product/mark-iii-system/ Access: 17 Aug 2015.

Two evolutions are also addressed by GTT in the same fashion as above: (i) for a lower BOR solution with the **Mark III Flex** design, and (ii) with increases for strength, with the **Mark III Flex HD** design.

The two versions of this design, Mark III and Mark III Flex, can be watched in the video movies available in http://www.gtt.fr/en/technologies-services/our-technologies/mark-iii.

10.2.1.3. Double membrane tanks with technology of TechniGaz & GazTransport CS1 System

This design was previously introduced in Fig. 13.

CS1 design is a new LNG cargo containment system designed by GazTransport and Technigaz, based on two existing technologies, respectively, Mark III and No. 96. It adopts the benefits of the reinforced PUF and two membranes with 0.7 mm thick (first) fabricated with Invar and the second made of a composite aluminum-glass fiber called ‘triplex’ (Chapot, 2002).

The Gaz Transport membrane containment system, GT No. 96, consists of a structure made of plywood filled with perlite in order to keep tightness and insulation. Its design is composed of two Invar membranes: one for the primary barrier, and the other for the secondary barrier. They are linked to the double hull thanks to an Invar tube. The insulation is 530mm thick and is constructed with perlite. The boxes are connected to the double hull by the means of couplers.

On the other hand, the Technigaz design, TG Mark III, consists of two layers of reinforced PUF separated by 'triplex' in order to set an insulation device. Technigaz technique adopts a stainless steel primary membrane and a triplex secondary membrane. The triplex is a composite material made of aluminum-glass fiber. The insulation is of 270 mm height with reinforced PUF panels. These panels are linked together with top bridge pads and bonded to the double hull.

GazTransport and Technigaz are merged in one company, whose latest containment system, the Combined System Number One, CS1, incorporates features from the existing GT No. 96 as well as of the TG Mark III systems (Moktahab et al., 2014; Chapot, 2002). CS1 design uses a primary Invar membrane linked to the double hull tanks to Invar tubes and a secondary Triplex membrane. The insulation space has 285 mm height and it is filled with reinforced PUF panels bonded to the double hull. CS1 uses reinforced polyurethane foam insulation and two membranes, the first one 0.7 mm thick made of Invar, the second made of a composite aluminum-glass fiber called triplex. Double membrane tanks with technology of TechniGaz & GazTransport CS1 System, have been presented in Fig. 13.

10.2.2. 'Type-B' independent tanks

In 2004 the American company Ocean LNG, Inc., Houston, Tex., obtained from the classification society American Bureau of Shipping (ABS) Approval in Principle (AIP) certificate for a new type of cylindrical dished ended tank with capacity of 180,000 m^3. The cargo tank measures 36 m in diameter with 40 m of cylindrical height, with capacity of 36,000 m^3 of LNG each. The tank design was created by Brevik Technology, a VARD affiliate company, with the intention of lowering the cost of construction for LNG and LPG carriers while providing a solution for the small-scale transport of gas[25].

As part of its AIP process, ABS evaluated the overall tank and vessel design to include containment system and structural strength feasibility, tank support system, amidships section scantlings, stability analysis, hull form and speed calculations, hydrodynamic analysis and overall feasibility of the Ocean LNG carrier design[26].

Compared to the spherical tanks arrangement, the Ocean LNG's system, according to the company, can increase the load capacity within the same hull by 25%, only by maximizing the empty spaces in the hull. This configuration would provide, as informed by the company, full access to the isolation and structure inspections.

One aspect considered in ocean movements is the cargo tank's ability to support dynamic loads from sloshing, when the tank is half full. Membrane system, for example, is sensitive to such loads. Tanks of this vessel would be designed according to the IMO's Type B for independent tanks, based on the concept of 'leak before failure'. The cargo tanks are designed to minimize the filling limitations due to sloshing effects. These effects lead to problems on the cargo tanks structure and on the turret of the LNG dispatch pumps. The tanks are arranged vertically within the hull in a similar way of Moss' system. In the vertical position, the upper dished head penetrates partially in the carrier's main deck. The vertical support system is the key point of the new tank design and the viability of the system, as informed by Ocean LNG. In this design, the cargo tanks are supported vertically at the double bottom and horizontally at the main deck level by means of support blocks with load bearing insulating support devices. The vertical support system consists of two sectional ring supports and the horizontal support system consists of a collar ring that maintains constant support to the tank, both in warm and cryogenic conditions.

This system uses insulation material of high density, load-bearing consisting of vacuum-impregnated wood veneer with synthetic phenolic resin, The outfitting of the tanks is similar to the Moss' spherical tanks with the same type of insulation, i.e., expanded polyurethane or polystyrene, with external aluminum sheeting acting as the second barrier, as specified the IGC Code. Some characteristics of the insulation material are: (i) to be stable and waterproof, (ii) to have a high level of compressive strength, and low thermal conductivity[27]. Figure 29 shows the schematic drawing of the independent tank type B of the Ocean LNG, Inc.

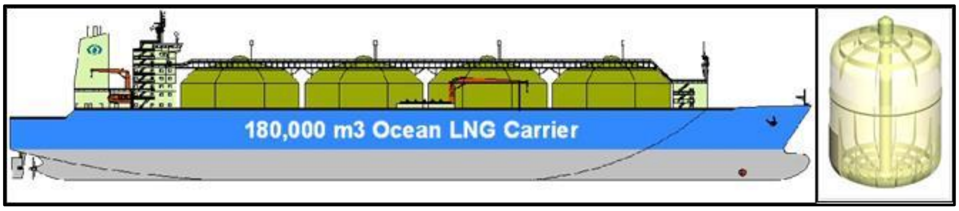


Figure 29 – Profile view of the Ocean LNG's carrier and the **'**Type-B' independent tank. Source: Esteves (2010).

[25] Available: http://ww2.eagle.org/en/news/press-room/2015/abs-approval-to-brevik-independent-tank-containment-system.html. Access: 2 Jan 2016
[26] Available: http://www.marinelog.com/DOCS/NEWSMMIV/MMIVNov30b.html. Assess: 3 Jan 2016.
[27] Available: http://fairplay.ihs.com/ship-construction/article/4194766/the-shape-of-things-to-come#sthash.Gr21QKtt.dpufier Access: 3 Jan 2016

10.3. Materials used in the cargo tank construction of gas carriers

According to the main codes (IGC Code, 1993, 1975; SIGTTO, 2010, and others), the definition of materials is governed by the cargoes' minimal operation temperature. It is followed by the compatibility with the cargo that will be transported, and the temperature range which it is considered to vary between -180°C and -55°C. Materials shall comply with the temperature toughness required by certain services.

Most of the cargo tanks are built with stainless steel, which is the construction material that retains its flexibility and robustness over the temperature range considered. Nevertheless, problems may occur if the material used is subjected to a very fast a local cooling down, as could be the case of a LNG droplet falling over a very warm plate of cargo tank wall. A high and fast heat transfer rate is supposed to take place from the plate to the cryogenic liquid, and at a specific point of the plate the temperature will decrease rapidly provoking a large thermal stress area between that point and the surrounding area. Cracking may occur due to this sudden thermal stress.

That is crucial for the most of metals and its alloys (excluding aluminum) since they can be subject to brittle below some cryogenic temperatures. The IGC Code specifies the limits for low temperatures for different types of steel down to -55°C, as well as reference should be given to classification society rules.

One important aspect related to carriers' construction is the leak detection of the cargo being transported. The Codes recommend a basic concept to be considered in the design of cargo tanks, is that it should 'leak before failure'.

It is supposed that the primary protection barrier will fail progressively, and not in catastrophic or sudden way. To fulfill this premise, gas detection systems shall be able to capture any small LNG leakage that may occur within the insulation still at early stages. The best place to fit the detection system is at mid waist (membrane or prismatic tanks) or at the equatorial ring (if spherical tanks) areas at the drip pan. The pan shall be installed directly underneath each cargo tank, in order to accommodate temperature sensors sensible to the presence of LNG that will be drained gravitationally to the drain piping. The whole system is supposed to be designed to support cryogenic temperatures.

10.4. Tanks thermal Insulation

Considering the variety of external environment temperatures that LNGCs experiment during their transcontinental voyages added to loading/unloading operations during docking in terminals, thermal insulation must be provided to refrigerated cargo tanks due to the main reasons:

- Protection of the vessel structure around the cargo tanks from the effects of low temperature;
- Minimize heat flow into cargo tanks to reducing boil-off.

To perform the abovementioned functions, Insulation materials must fulfill some requirements:

- Possess low thermal conductivity;
- Have ability to support loads;
- Withstand mechanical damage;
- To be light weighted;
- To be unaffected by liquid or vapor cargoes temperatures and physical/chemical properties.

The ingress of water or water vapor into the cargo tank not only results in loss of insulation efficiency but it may cause progressive freezing and condensation, implying in subsequent and extensive damage of the insulation layers. Additionally, thermal insulation plays an important function to provide a 'vapor sealing', keeping the humidity as low as possible within void and hold spaces. Therefore, a protection method is necessary to be provided such as, foil skin that could act a vapor barrier to surround the system.

Depending on the design of the CCS, thermal insulation may be applied over various types of surfaces. 'Type-A' receives the insulation applied either directly over the cargo tank or to the inner hull, but the most common situation is direct application over the cargo tank. 'Types B or C' receive the insulation applied directly to outer surfaces of the cargo tanks. Most of the insulation is flammable products, so care should be taken in its application to avoid fires.

11. Comparison of Kværner Moss Type B, Tecnigaz GTT and IHI SPB Type B designs

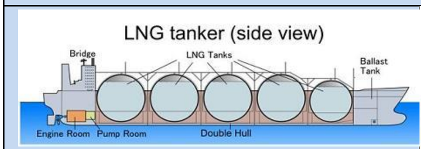
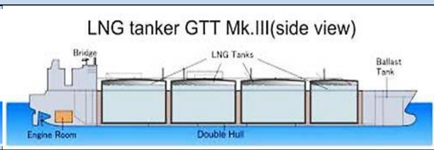
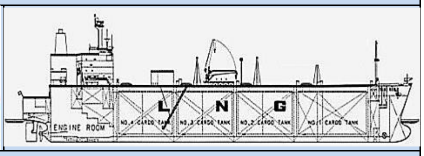
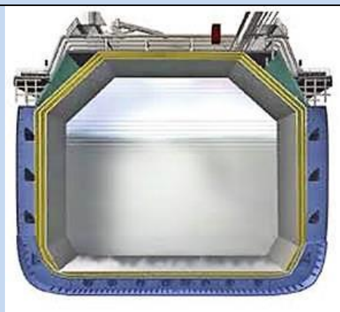
As basic criteria, the three designs were compared qualitatively considering carriers with the same capacity and size. For the purpose of the present report, the comparison takes into consideration operational, constructive and safety aspects only, with no quantitative simulations or forecasts about structural integrity, materials of construction, design or any other performance parameters. The objective is to present a general and preliminary appraisal about the three technologies, based on the information available in the open literature

Table 5 reflects the observations, conclusions and personal internalizations obtained by the authors during the reading of all surveyed references. The goal was to gather information, organize all the data captured from each of the technologies, and tabulate them on a structured and comparative basis. Around fifty attributes were considered as plausible of being compared, since they were present with common sense in each one of the technologies. Thus, the work ends with a summary and a conclusion of all material presented.

The most critical concern of the LNG carriage organizations face today is how to meet and manage the new safety, environmental and economic challenges. The three technologies here considered are designed to provide extra physical barrier between the cargo and the external environment, when compared to the double hull oil tankers. Because of its shape, the sphere is separated from the external environment, for the most part, besides being endowed with additional structural barriers.

The risks of accidents with either technology are considered equivalent (Sandia, 2008). Similarly, as the membrane and self-supported prismatic tanks technologies utilizes its internal volume more efficiently there are no large voids, but otherwise it has less relief areas. Table 5 presents some of the key design characteristics that differentiate the three technologies.

Table 5 - Comparison among construction technologies for the carriers' cargo tanks
Based on: IHI (2016)[28], Golar (2016)[29], Moon et al. (2015), ABS (2014), Bureau Veritas (2014), Moktahab et al. (2014), Lucjan (2013), ISSC (2012), ABS (2009), SANDIA (2008), Tusiani & Shearer (2007)[30], Gilmore et al. (2007), Zalar et al. (2006), Otta (1997).

Constructive, operational and commercial characteristics of the cargo tanks		
Spherical Type B: Kvæner Moss	**Membranes Type A: GTT No. 96 & TGZ Mark III**	**Prismatic Type B: IHI-SPB**
Profile		
		
Containment Section		
		
Key design characteristics (Pros and Cons)		
(1) Accessibility: difficult to main deck and containment system and for inspections and maintenance	Difficult	Good
(2) Aspects with positive appraisal: The void spaces between inner and outer hulls are used for water ballast, providing protection to the cargo tanks in case of grounding or collision; there is no secondary barrier as a function of its spherical design, providing high degree of safety against fractures or failures; it utilizes the concept "leak before failure", presuming that the first safety barrier fails progressively, and not catastrophically or suddenly; gas detection captures even small LNG leakages within the insulation, in the	Suitable in general terms for smaller gross tonnages; it maximizes the use of 'hold volumes' to accommodate the cargoes; practically unrestricted navigation visibility (low protuberance on the topside deck); lower wheelhouse and air drafts for cargoes control	Eliminates virtually sloshing loads, making it possible to be used partially filled; it is advantageous to carry sudden "cargoes of opportunities", adopts relatively flat surfaces in its construction, facilitating uses in FLNGs; can have tailored construction to fit specific hulls; it permits automatized construction work

[28] Available: www.ihi.co.jp/offshore/whatisspb_e.htam. Access: 8 Jan 2016
[29] Available: http://www.golarlng.com/index.php?name=seksjon/Stock_Exchange_Releases/Press_Releases.html&pressrelease=1418882.html. Access: 13 Jan 206
[30]Avaialable: https://www.google.com.br/search?q=lng+carriers&es_sm=93&biw=1600&bih=799&tbm=isch&tbo=u&source=univ&sa=X&ved=0CD0QsARqFQoTCI7MyKCYjskCFco3Pgod2XkG8w Access: 13 Nov 2015.

event of a crack that may occur in the tank material; a drip pan is provided below the cargo tank with temperature sensors to capture the LNG presence		
(3) Analysis of cargo tanks structures: easiest reliability: potentially high, due to structural analysis	Structure is difficult to analyze and difficult to assure fatigue failures, potentially could require higher repair time over the project life	Structure can be inspected and risk of fatigue failures minimized, tanks can be 100% constructed and inspected before the vessel is installed
(4) Assembly: can be in parallel to the hull construction	After the hull construction	Parallel to the hull construction
(5) Ballast tanks: Easy to repair	Difficult to repair (due to membranes)	Easy to repair
(6) Boil-off rate: Advances in Insulation materials is capable to reduce BOR from 0.15%/day to 0.1%/day or even lower	Addition of boxes in secondary spaces and replacements of perlite by glass wool (insulation materials) allegedly may reduce the BOR in GTT No. 96, using the same foam with thickness increased in Mark III Flex produced analogous results	Advances in Insulation materials is capable to reduce BOR from 0.15%/day to 0.1%/day or even lower
(7) Canal charges/gross tonnage: Higher/around 40% higher than membrane tanks	Lower, smaller gross tonnage	Lower, smaller gross tonnage
(8) Cargo containment system: Generally not susceptible to the sloshing phenomena; limited in increase of the sphere diameter, so larger LNG capacity can be gained only by the extension of the vessels' length, what is undesirable from the stability and global strength aspect. Moreover, they have low hull volume efficiency, high windage area (which limits the passage under the bridges at some terminals) and restricted deck area for the installation of regasification equipment.	More susceptible to the sloshing phenomena, low building and investment cost with compact CCS design (maximized cargo capacity, low depth and windage area)	Generally not susceptible to the sloshing phenomena, it proposes the advanced technical achievement of sloshing-resistant design with the low flush deck, however being yet too expensive solution for the wide practical use
(9) Cargo operation - Emergency discharge of the cargo: necessary when all cargo pumps in a cargo tank fail; capable of pressure discharge; in case of pressure discharge at sea, the operation should perform under still water condition; the operation must be controlled at low pressure, and it is strongly recommended to monitor the rate of pressure increase in the cargo tank, (iv) ballast adjustment must be also performed to keep the ship balanced during emergency discharge	It should be equipped with emergency spare cargo pump; before and during jettisoning LNG into the sea requires extreme consideration; caution is also required; this tank has an emergency cargo pump for discharging LNG when both cargo pumps fail; each tank has a column where an electric emergency cargo pump is lowered and a column with a nitrogen purge connection is to be used as an emergency cargo pump; in principle, one emergency cargo pump is installed on the ship to cover all cargo tanks	Pump pit is located at the bottom of CCS at the depth of 300 mm, assuring complete discharge of cargo liquid when required, since the main pump can drain the liquid when the level reaches -150 mm. The liquid filling line does not end at the bottom but, otherwise, it extends to both tank's bow and stern sides. This makes purge operations very effective. Additionally, horizontal girders are used for inspection works. In dry docks, the inspection is completed in a half day.
(10) Cargo operation – LNG jettisoning to the sea: Necessary in case of a containment or insulation system failure in one or more cargo tanks; carried out with single main cargo tank discharging LNG through a portable nozzle. Moss tanks are weak against outer pressure and differential pressure control is essential to them	It should be equipped with emergency spare cargo pump; before and during jettisoning LNG into the sea requires extreme consideration; caution is also required, since it requires differential pressure control between hold spaces and the tanks needing pressure control. The hold space is used as inspection space facilitating inspections and maintenance.	It does not need differential pressure control between hold space and tank. The hold spaces can be used as inspection venues to facilitate inspection and maintenances
(11) Cargo operation – Cargo loading, offloading and delivery: pressure drops occurs and this geometry has similar approach to those of LNG cargo pumps and related pipes	Pressure drops occurs in related lines; loading and unloading times are different, since available NPSH varies providing that cargo level varies with operating time	This configuration allows to LNG be carried with the vessel partially loaded even amidships, with faster loading/unloading when docked even to FLNG, FPSO, FSRU, etc..

		The stiff tank plates are not likely to increase internal and external pressure in the vapor space, being unnecessary to control the differential pressure. This space can be accessed and used otherwise for maintenance and inspection. Provides more cargo delivery with less heel (pump pit) and smaller pit for the suction of the dispatch pump; smaller BOGs (boil-off gases) and no spray or vapors formation during the ballast voyage; does not require vacuum or nitrogen purge tests in the vapor space
(12) Cargo tank warm-up and cool down times: as required	As required	Long, due to high thermal mass of tank and insulation
(13) Carrier dimensions when compared to others with the same capacity: larger	Smaller than spherical tanks	Smaller than spherical tanks
(14) Cool-down time: 16 hours, satisfying the temperature requirement of the equator sensor at -110°C; during the cool-down the maximum suction volume observed was about 12,000 m³/hr @ 1.5 hour	Cool-down time: about 10 hours with a cargo atmosphere of -140°C	(i) less influence from bad weather, (ii) shorter dry-docking time (2 weeks per five years)
(15) Deck structure: it is not part of the cargo tank structure	Deck structure provides support to the cargo tank	Deck structure independent from the cargo tank
(16) Divisibility: not divisible	Hard to subdivide	Easy to subdivide transversal and longitudinally
(17) Fuel consumption: higher, due the volume utilization; it is necessary more fuel to carry the same volume of the others designs	Lower than Kvæner Moss	Lower consumption (less horsepower consumption with compact hull form); more cargo deliverability per transported volume thanks to less heel of the pump well; less BOG due to the nominal lower vaporization within the cargo tanks; no spray in ballast voyage
(18) Hull structure: independent	Reacts to the hull structure	Independent from the hull structure
(19) Hull strength and fatigue issues: Large spherical Moss carriers might suffer when submitted to excessive hull's torsional response by virtue to wide openings in the strength deck and non-continuous tank dished-ends. Critical structural details such as side longitudinal beams, inner hull hopper knuckles, tank skirt foundations, inner hull side connection to the foundation and tank dished ends connections to the main deck must be analyzed considering fatigue aspects	More susceptible to the vertical bending moment. The increase of transverse web frame spacing and relative stiffness between bottom transverse and longitudinal girders have an important effect on the fatigue life of inner hull hopper knuckles and foot of the cofferdam. Other critical structural details from the fatigue point of view are cofferdam stringers, cofferdam girders in the double bottom and liquid cover dome	One of the characteristics of the SPB prismatic tanks is its free shape, since it is constructed with stiffened plates. This allows constructing the ship's hull considering the best hull performance given a design condition (draft, beam, etc.) and designing cargo tanks to follow the hull contour afterwards, leading to a compact LNGC with reliable hull shape. So the natural frequency of the liquid movement inside tank is different from that of ship's motion, eliminating chances of resonance between the liquid cargo and ship movements. Because of the nature of stiffened plate structure, the tank has the same strength to support inner and outer pressures.
(20) Integration with the FLNG topside: yes	Yes	Easy integration with the FLNG's topside[31]
(21) Liability to puncture or damage: almost none	More liable caused by cargo surge and maintenance entries	Almost none
(22) Main deck: dished ends[32]. Worst configuration, affecting among other aspects, the visibility	Bevelled. Average configuration, with some free space areas; better visibility than the Moss design	Completely plain from starboard to port side and from bow to stern without truncation of prisms, spherical

[31] Main deck of the FLNG vessel; the place where the petroleum of the formation is primarily processed.
[32] Carrier main deck.

		caps or dished-ends. One important characteristic of this design is the deck that is completely flat from side to side, with no obstacles on the deck when compared with membrane and extruded sphere on the deck of Moss LNGCs. This contributes to less wind resistance thus with less power consumption, easy maintenance and easy navigability and maneuverability.
(23) Maneuverability with high wind area: less	Good	Easy navigation
(24) Membrane capability to withstand sloshing impulse loads: Independent CCSs Type B generally are not sensitive to sloshing, however, Moss tanks are limited to the sphere diameter to increase its capacity, being necessary to extend the ship's length with undesired issues, countless to low hull volume efficiency	Low construction costs due to the CSS's compactness (low windage area with maximized cargo capacity) being, in principle, more suitable for carriers of large capacities. When compared to SPB tanks, attention should be paid to partial filling if large capacities are considered. New membrane CCSs are being developed in major Korean shipyards	If compared to Moss tanks, SPB cargo tanks proposes a sloshing resistant design with its low flush topside deck, but this solution must be evaluated economically for carriers with capacities above 180,000 m^3
(25) Navigation visibility: poor, more affected by 'metocean' conditions poor	Unrestricted due to flat continuous deck	Unrestricted due to flat continuous deck
(26) Navigation in Artic/ice routes: Challenges: Cold temperature difficult for personnel, equipment, structures; Ice sheet covering the sea; Icebergs; Polar Night; Extreme environment with severe storms; Distance to supporting basis; Environment extremely sensitive to emissions and pollution. Possible for the post-'Sayaendo' design	Need 'winterization', i.e., to be prepared for safe operation in extreme cold weather conditions by adapting the design and operation procedures to the requirements imposed by the intended service. Mean daily temperatures below 0°C are expected to be encountered by the ship during the voyage or in port. Carrier must be classified for this service	Need 'winterization', i.e., to be prepared for safe operation in extreme cold weather conditions by adapting the design and operation procedures to the requirements imposed by the intended service. Mean daily temperatures below 0°C are expected to be encountered by the ship during the voyage or in port. Carrier must be classified for this service
(27) Operation: in every weather condition; Uptime of 99% during the summer months; key environmental considerations: no excessive heat dumping – MSO compressor installed to export BOG, ΔT max = 9°C from seawater inlet to seawater discharge; no overboard bilge etc. (pump to holding tank for barge transfer)	Operates in extreme conditions (polar weather	In every weather condition; Does not require differential pressure control; no temperature profile control, no cargo level restriction, no heating coil operation
(28) Operational history: excellent	Excellent	Few LNGCs in operation
(29) Partial filling: no restrictions, with no limitations	Limitation above and below certain cargo tank volumes, due to sloshing problems	No limitation
(30) Potential slosh damage: almost none	High	Almost none
(31) Pressure control devices: susceptible to the control of outer and differential pressures	Susceptible to the control of outer and differential pressures	It does not use pressure control devices between hold spaces and tank shell
(32) Pressurization for emergency discharge: yes, in case of cargo tank failure	Yes, in case of cargo tank failure	It does not need differential pressure control between hold space and tank, while membrane and moss are weak against outer pressure and differential pressure control is essential to them. Moreover, the hold space is used as inspection space facilitating inspection and maintenance.
(33) Proven technology: strong; most proven of all second generation CCS	Good, overcoming Moss tanks	Good, but with small quantities of LNGCs launched to sea
(34) Propulsion system (diesel engines, gas and steam turbines, boil-off re-liquefaction, dual-fuel electric systems): higher consumption, due to	Average consumption	Low consumption

the poor hull volume utilization		
(35) Quantity of LNGCs constructed: hundreds	Hundreds	2, as 2007 end
(36) Reliability of the containment system: Tank system is the easiest to analyze structurally. Therefore it can be constructed more reliable	Structure cannot easily be analyzed and therefore it is difficult to assure absence of fatigue failures. This could potentially lead to costly off-hire and repair time over the project life	Most ship with years of operating without primary barrier failure. Structure can be analyzed and risk of fatigue failures can be minimized. Cargo tanks can constructed and 100% inspected prior to installation in the carrier
(37) Rollover, load stratification and BOR: In principle it was unlike to occur. It was supposed the cargo tank's spherical shape added to the carrier's motion during the voyage would strengthen the convection current ensuring thorough mixing of the tank inventory. But a serious rollover occurred in 2008 with a Moss carrier of 125,000 m³, and when compared to the La Spezia incident, demonstrated that LNG carriers can do experiment stratification and rollover if 'heavy' LNG is loaded under a heel of lighter density (SIGTTO 2012). The cargo tank is designed to be thermally insulated in order to restrict the boil-off rate not to exceed 0.15% of the gross cargo volume per day @ 32℃ of seawater temperature and 45℃ ambient air temperature. To accomplish this issue, a trade-off must be defined between BOR and insulation thickness. Reducing the BOR implies in an increase of insulation cost, and vice versa. The BOR is presented as a function of insulation thickness with a generally accepted boil-off gas rate of 0.15%/day. Insulation and cargo handling system should be designed based on the specified BOR. Reducing cargo BOR may be a matter of increasing the insulation thickness, without substantial changes to tank design. As insulation is placed on the outer wall of the tank, there is enough space in the voids around the spheres to boost the thickness of the insulation. BOG rates can be reduced to less than 0.08%/day increasing the tank's insulation	According with GTT and Technigaz, the membranes are designed to compensate thermal and other expansion or contraction without undue membrane stress. In order to meet requirements for lower boil-off, the Mark Flex III design envisages the increase of the insulation thickness up to 400mm without changing the R-PUF density (130 kg /m³) or changing the thickness of the primary insulation space. As a result, with the standard foam density and a global thickness equal to 400mm, a guaranteed BOR of 0,085% of tank volume/day can now be proposed, using efficient R-PUF. The same approach is used in No. 96 design to meet the requirements for lower boil-off, as a first step, the perlite in the boxes has been replaced by glass-wool. GTT informs that, for instance, the No. 96 GW design adopts the bearing plywood structure kept identical to No. 96 system, guaranteeing that the BOR is between 0,125% and 0,13% of the tank volume/day. Addition of boxes in secondary spaces and replacements of perlite by glass wool (insulation materials) allegedly may reduce the BOR in GTT No. 96, using the same foam with thickness increased in Mark III Flex produced analogous results	According to IHI, the prismatic tank is divided into four compartments by bulkheads LNG leak proof. It also avoids, in principle, the occurrence of load stratification that may take place due to the sudden mix of LNG with different densities, compositions and heat capacities in the bottom of the ship's tanks (rollover). If this occurs with two layers of LNG the sudden mix may result in the release of large amounts of vapor.
(38) Safety design in case of grounding/collision or other emergency: safest system in event of grounding or collision; tank structure independent of the hull and cargo tanks. These tanks ca be pressurized for an emergency discharge in case of cargo pump failure	Damage to hull of vessel may be more easily transmitted to tank structure than with freestanding tanks. Membranes systems are also more liable to damage or puncture due to causes such as surging of cargo in tank for inspection or entry of cargo tank for repair, maintenance or inspection	Compared with membrane system presents less likelihood of the hull damage being transmitted to cargo tanks. More efficient use of the cubic space
(39) Sloshing: It is a powerful response of the liquid within the cargo tank when it is submitted to external random and forced movements. These	Generally affected. Common operations take place with the cargo tank fully laden at 95% of tank height or with minimum cargo contents of less than 5% of tank	Allegedly, the tank is subdivided by a centerline liquid tight bulkhead and a swash bulkhead into 4 spaces. As a consequence, according to shipyard,

movements are highly non-linear and affected by several parameters. Considerable attention should be paid to this motion energy when its frequency domain, assume values close to the cargo tank's natural period. Resonant liquid flow cannot be generalized, since it appears in different circumstances depending on tank geometry, tank filling height, predominant direction of excitation and magnitude of ship movement. Moss tanks generally are less affected than the membrane type.	height during the return ballast voyage, in order to minimize the sloshing effects. Some improvements in the tank design made possible to extend the upper filling limit to 80% or even 70% of the filling height for conventional carriers. However, due to the new market profiles, demanding even more partial cargo tank's filling due to the small-spot trading, the development of extra-large membrane carriers, computational tools to predict these effects were developed. It is important to consider different types and nature of sloshing and its dynamic effects on large liquid free surfaces, specially during transoceanic carriers' voyages in different seas with different 'metocean' conditions	natural frequency of the liquid inside tank is far from that of carrier's motion, eliminating resonances of the liquid cargo and ship two motions. Consequently, no sloshing problem is expected and any level of the cryogenic loading in tank is always possible. This enables partial loaded voyage, quick dispatch from the berth in emergency, and this supposedly makes SPB best suited to FPSO, FSRU etc. in which tanks are always half loaded.
(40) Tank service life: About 4 times more membrane tanks	Four times less than the spherical tank	Equivalent to the spherical cargo tank
(41) Tank structure: independent of hull	Higher	Independent of hull
(42) Turret of the LNGC pumps: rigidly bolted[33]	Supported	Rigidly bolted
(43) Utilization of the hull volume for the cargo capacity: lower	Relatively higher utilization of the hull volume for the cargo capacity. For the same cargo capacity, the ship dimensions of the membrane tanks are somewhat smaller than those of the spherical tanks. In addition, the membrane LNG carrier is capable of loading more than 8% LNG cargo in identical principal ship dimensions.	Relatively higher utilization of the hull volume for the cargo capacity. For the same cargo capacity, the ship dimensions of the membrane carriers are somewhat smaller than those of the spherical ships
(44) Utilization of the available cargo voids and hold spaces: provides the worst utilization	Average utilization	Since Type-B prismatic tanks are independent of the carrier's structure, they maximize the available cargo voids. The hold spaces are used for inspection and maintenance
(45) Vapor generation during cargo transfer: Limited. Moss design allows increased pressure pumping. Increased pressure undercools the LNG reducing substantially BOG. Additionally some condensation, resulting in no surplus of vapor in transfer lines	Vapor is generated according the membrane design friction	Some vapor is generated
(46) Visibility (blind zones) of LNG carrier at ballast condition: lower visibility; CCSs have influence on the transport capacity and on the visibility. Lower visibility with almost the same principal ship dimensions, except cargo capacities (Moss = 185,000 m³ and Membrane =204,000 m³)	As the main deck is beveled, the visibility is average with some free space areas	Completely plain from starboard to port side and from bow to stern without truncation of prisms, spherical caps or dished-ends provides the best visibility
(47) Void space between LNGC and cargo tanks: yes; less efficient	Almost none, with maximum usage for cargo	More efficient use of volume voids
(48) Water ballast: Yes	Yes	Yes
(49) Welding work: automatic in 95%	Intensive during construction, increasing the probabilities of defects	Almost all welding is automatic (85%)
(50) Wheelhouse and cargo control room air drafts: none	Low	Low

[33] Platform structure to fix the stud bolts of the dispatch pumps.

12. Findings, perceptions and challenges for the new trends that are coming to LNG carriers' business

From the material prospected in the open literature and here dully referenced, it can be resumed:

1. The CCSs used currently for LNG carriers are focused mainly on spherical (Moss), membrane (GTT No. 96 and Mk III) and some few cases of prismatic design SPB. Spherical and membrane have different advantages and disadvantages;
2. Some terminals, ports or canals authorities charge the internal volume of the carrier due to void spaces around the tanks, reason why contributed to the fleet of membrane ships be higher than the spherical ones;
3. The advent of FLNGs plays similar role of FPSOs in the past decade, to monetize the offshore exploitation allocated to gas fields or associated gas with oil production, as well as stranded gas reservoir, and consequently will require specific and new regulations that must consider specific design and operation;
4. Offshore gas production in large scale (e.g., Campos Basin, North Sea, Asia-Pacific), fatally will require FLNGs to produce, liquefy and storage LNG abroad in open oceanic waters, in lieu to transport it to shore, demanding another design conception for LNG carriers afterwards, adequate for offshore loading/offloading;
5. These offshore scenarios bring new operation profiles exposing the carriers harsh environmental and 'metocean' conditions, bringing new impacts on safety and in the manner to construct and classify the new and the revamped carriers to face these new challenges;
6. Large FLNGs under construction (e.g. Prelude) are expected to bring new design conceptions requiring, for example, longitudinal bulkheads that may consider the sloshing loads in cargo tanks with intermediate filling degree and the need to strength deck structures to accommodate onboard liquefaction plants. These may suggest changes that may bring to the current carrier fleet;
7. LNGC propulsion systems traditionally have used steam turbines, since they allow easy disposal of cargo boil-off. However, they are not very thermally efficient. In the recent years to use both dual-fuel diesel electric propulsion systems and slow speed diesel systems with onboard gas re-liquefaction. With the new gas availability, new types for the usage of the LNG are expected to occur, such as the use of the LNG as fuel for carrier propulsion and other types of ships. Nevertheless, this new massive consumption, consequently, will bring profound and stricter changes in environmental and emission requirements in order the LNG can be used as a new 'clean' alternative as fuel. Whatever may be the system, some key parameters should be considered to name a few, efficiency, gas prices, forced boil-off, maneuverability, saving of spaces, BOG utilization;
8. The rise of consumption markets associated with the low unit transportation costs requirements, stimulate the trend to use even more small-spot trading on a solid safety basis for offshore cargo transfer. Inevitably, the use as much as possible of flexible operation with partial fillings turned out to be a real demand. These issues pose challenges for the industry of LNG carriage;
9. To cope with today's reality, a new-generation of extra-large membrane LNG ships has surged with cargo capacities about 200,000-250,000 m³, pushing the design of these ships to higher levels of safety and structural requirements;
10. If the average capacities of the current carriers (about 180,000 m³) are going to be overcome, terminals' restrictions (draft and depth) may pose the need to increase the width and length of the current carriers, increasing the levels of stress in the unit structures;
11. The CCSs for LNGCs are regulated since 1970's and well established through IGC Code and Classifying Societies. Notwithstanding, the recent trends observed in offshore production and terminals operational regimes point even more that carriers need to be designed and suitable for any filling height within the cargo tank;
12. Aspects such as follows shall be considered to define the most suitable carrier size, (i) reliability and dry-docking time for repairs, important to define quantities and the fleet's ships sizes, (ii) flexibility for short-term deliveries, routes and delivery scenarios, (iii) terminals' accessibility restrictions, i.e., displacement, discharge time campaigns;
13. For such sizes, the sloshing feasibility assessments are deserving even more particular attention due to the different types/nature of sloshing liquid free surfaces involved, providing the differences of transoceanic sea behaviors in each quadrant of the globe, and the new needs for partial filling within the cargo tanks;
14. Sloshing takes place mainly due to resonant movements of the free liquid surface within the cargo tank with a frequency that is close to the lowest natural frequency between the tank and the liquid carried. Consequently, care should be given in the design to avoid this resonance, selecting the optimum filling level, as well as operate the ship in a such manner to avoid this resonance;
15. The trend observed recently for carriers with even higher capacities emphasizes the importance to the violent sloshing and high impact pressures by virtue of carriers movements. These impacts brings real concerns for membrane tanks but not so critical for spherical tanks however for all the designs pump turrets may experiment

large loadings. Therefore, the prediction and control of these loads and the structures responses are of utmost importance for the CCSs and its reliability;

16. The design of large LNGCs the hydro-elastic interaction between external wave loads and carrier's structure may develop impacts such as springing and whipping, which the evaluation of its hydro-elastic of linear and non-linear responses should be addressed;
17. The failure modes coupled with hazards posed over main structural components of the ship should be addressed in a management system focused on inspection and monitoring. As part of the asset's integrity management are to be identified, assessing probabilities of failures and the respective consequences in order to evaluate the risks. Risk mitigating measures must be allocated to the most critical items optimizing inspections, maintenance and monitoring the global integrity of the asset;
18. New progresses are being observed in the CCSs markets, however it is necessary to investigate if they are complying what is established in the IGC Code. It sounds that new regulations might be implemented in order to capture and handle these innovations;
19. Besides the existing CCSs membrane types, i.e., No 96, Mark III and CS1 with proven technologies, since 2014 new types of membrane systems are being implemented: (i) Samsung SCA-W/S (by Samsung H.I.), (ii) KOGAS KC-1 (by Kogas), (iii) Hyunday Membrane System (by Hyunday H.I.), and (iv) the New multipurpose IMO Type B system developed by NASSCO in association with Braemar Engineering, the WAVEspec FPS (NASSCO)[34]
20. New spherical Type B Moss thanks also with updated concepts are already a reality (e.g. "Sayaendo" with 'strech' type innovations). And the same is being observed with the existing membrane technologies, for Mark III Flex (Low BOR, sloshing reinforced), No. 96 BOR (Glass wool, No. 96 L03 and No. 96 L03+) and Mark V;
21. Developing of new routes in the Northern Sea Route (NSR), jumping from 1.3 Mtonnes in 2012 to about 40 Mtonnes in 2021. Russian gas and Artic navigation could be opened commercially around 2018,and new demands are expected to occur with calculation of ice loads, design considerations to operate in the Artic, carriers' winterization, ships of Polar Class with customized CCSs for membrane or Type B tanks as well (Moss or SPB). These vessels are supposed to be customized to operate with moderate ice bow for open sea and light, moderate and heavy ice conditions I seasonal navigation in the Artic, demanding for specific Ice Class and Notations;
22. The evolution of shipping profile considering new international rules and technological advances, in fields such as emissions of NO_x, SO_x, propulsion efficiencies, carriers sizes, use of the BOG as fuel to drive the carrier, even lower BORs;
23. New demands posed for operational regimes with improved flexibility in filling/offloading levels between shuttle ships moored ship-to-ship to FSRUs/FPSOs/FLNGs considering harsh 'metocean', requiring retrofits of the CCSs to allow vessel-to-vessel operations, emergency disconnection during the cargo transfer.

13. Disclaimer

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