공학석사 학위논문

LNG 추진선과 LNG 운반선의 안전 규정에 대한 연구

A study on safety regulations of LNG carriers and LNG fuelld ships

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본 논문을 하승만의 공학석사 학위논문으로 인준함.

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초록

최근 IMO의 환경 규제가 강화됨에 따라, 기존 선박 연료를 대체하는 친환경 연료인 LNG를 사용하는 선박이 대폭 증가하는 추세에 있다. 또한, LNG 산업의 공급과 수요가 모두 확대됨에 따라 이를 운송하는 LNG선의 발주 및 운항이 증가하고 있다. 한편 IMO에서는 '가스 또는 저인화점 연료를 사용하는 선박의 안전에 대한 국제기준(IGF Code :International Code of Safety for Ships using Gases or other Low-flashpoint Fuels)' 을 마련했을 뿐만 아니라, '액화가스산적운반선의 안전에 대한 국제 기준(IGC Code : International Code for the Construction and Equipment of Ships carrying Liquefied Gases in Bulk)' 을 전면 재개정하였다. 이러한 규정들은 건조 중인 선박에 실제 적용 단계에 있으며, 조선소, 선급 및 선주 등 이해관계자들은 해당 규정의 적합성에 대한 의구심을 종종 제기해왔다.

본 연구에서는 LNG 추진선과 LNG 운반선의 안전성 강화와 해당 규정의

신뢰성을 향상을 위하여 다음 두 가지 연구를 수행하였다. 첫 번째 연구에서는 IGC Code 및 IGF Code의 안전 규정을 비교 분석(Gap analysis)하였다. 그 결과 IGF Code와 IGC Code의 주요 차이점을 식별하였으며, 특히 LNG 추진선과 LNG 운반선에 동일한 기기 시스템이 설치된 기관실의 규정과 관련해서 IGF Code 및 IGC Code 규정 간에 일치시켜야 하는 부분이 있음을 확인할 수 있었다. 두 번째 연구는 IGC Code의 개정된 화물탱크의 충전한도 요건의 적합성 평가에 관한 연구를 수행하였다. 개정 전 IGC Code 적용 대비 항차당 0.5%의 화물을 적게 선적해야 하는 규정으로서 산업계에게 엄청난 영향을 미치는 새로운 규정이다. 격리된 증기 포켓(isolated vapour pocket)과 관련된 충전한도 요건의 적합성을 확인하기 위하여, 위험도 분석, 경제성 분석 및 환경영향 분석을 실시하였다. 그 결과 안전 규정 강화 시 안전성 확보는 물론이고 실용적이고 환경적인 측면을 고려해야 함을 알 수 있었다. 이러한 연구는 특정 규정의 적합성을 검토하기 위한 절차의 좋은 예로 볼 수 있다.

두 연구의 결과를 바탕으로 향후 후속 연구를 통해 IGC Code 및 IGF Code의 개정 가능성을 확인할 수 있었다. 향 후 LNG 운반선 및 LNG 추진선의 안전 규정 개발 시 안전성 강화는 물론이고 해당 규정의 신뢰성을 향상에 기여할 것으로 판단된다.

KEY WORDS: IGC Code, IGF Code, LNG 운반선, LNG 추진선, 증기포켓(Vapour pocket), 충전한도(Filling limit)

Chapter 1 Introduction

1.1 Background

Liquefied natural gas (LNG) is a convenient form for maritime transport to markets where bulk pipelines are not technically or economically feasible (Aronson and Westermeyer 1982; Mankabady 1979). Specially-designed cryogenic marine vessels, known as LNG carriers, have been used for its transportation. Since January 1959 when the first LNG carrier, Methane Pioneer,(5,034 DWT) has emerged, the worldwide LNG fleet has reached 478 vessels at the end of 2017(IGU 2018).

On the other hand, with the increasing trend of cleaner shipping, the environmental benefits of using LNG as a new source of marine fuel have been proven significant, compared to existing marine diesel fuels (BP 2018; Ryuichi et al. 2018). LNG fuelled ships other than gas carriers have been in service since 2000 and have consistently contributed to reducing ocean emissions such as CO2, SOx ,NOx and particulates (Jeong et al. 2017; Øyvind and Erikstad 2017; Rahim et al. 2016). The number of LNG fuelled ships has increased dramatically over the past few years, totalling 121 vessels in operation and 126 ships on orders as of the April of 2018 (DNVGL 2018).

LNG is a convenient form of natural gas that can reduce its volume to 1/600 times. For liquefaction, the temperature of the medium is normally maintained at around -163° C at atmospheric pressure in a specially-insulated cryogenic tank (Saleem et al. 2018). In the event of a leak, the liquid would rapidly evaporate when exposed to normal atmospheric conditions. This rapid phase transition can pose a direct danger to humans. In particular, cryogenic temperatures cause burns to nearby people, and massive vaporization suffocates to anyone in a confined space. Leaky media can also cause severe damage to the ship structure, such as structural embrittlement, when it touches a ship hull.

On the other hand, people can obscure the fact that LNG is a more dangerous substance that can be fired or exploded if given the opportunity to ignite. The type of fire and explosion may depend on the surrounding conditions on whether open or confined. Although the probability of a fire or explosion is lower than the direct risks, the consequences of such an accident are tremendously high. Given the risk that can be expressed as a combination of the probability and the consequence, the safety issues associated with the transport or use of LNG for marine purposes must be understood and handled properly.

Due to these characteristics of LNG, regulations on LNG fuelled ships and gas carriers have been crucial role to cover the risk originated by LNG. As various regulations have been developed recently, we need to not only ensure a greater degree of commonality amongst the diverse regulations we have today, but also verify as to whether applied regulations have been properly developed.

1.2 Aim and objectives

The overall aim of this thesis is to contribute to enhancing the safety of the LNG carriers and LNG fuelled ships by addressing the current regulations and complementing regulatory and practical gaps. More specifically the objectives are as follows:

- To examine and make a survey of the relevant current regulations.
- To enhance understanding of the safety of LNG in the marine field as well as to make a critical review of the current regulatory framework.
- To investigate the regulatory gaps and to guide proper solutions.
- To suggest future research work for enhancing the safety of LNG ships.

1.3 Literature review

Not surprisingly, in an effort to enhance the safety of LNG handling, International Maritime Organization (IMO) has developed two international codes: International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), in 1986 and subsequent amendments in 1994 and 2014 and International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code), which came into force on 01 January 2017.

A conceptual diagram for a brief overview of the formulation process in IMO for both Codes is described in Figure 1.

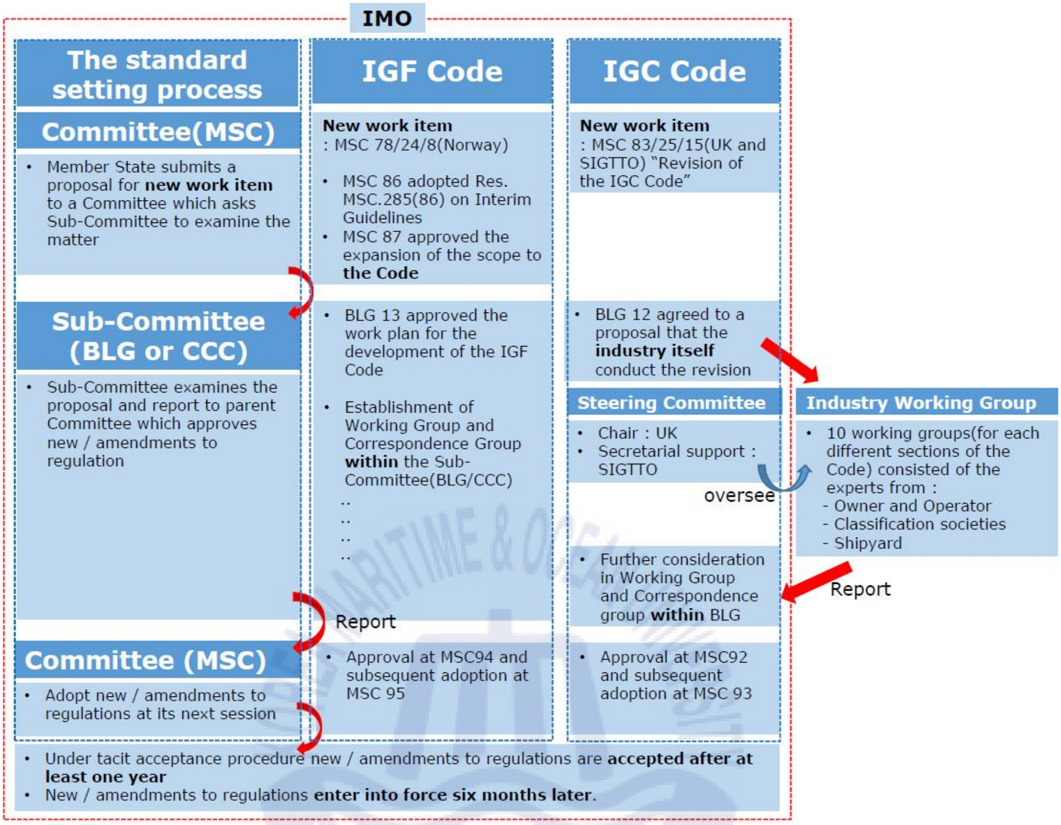


Figure 1 A brief overview of the formulation process in IMO for both Codes

1.3.1 IGC Code

The IGC Code, firstly adopted in 1983, has been uniformly applied to LNG carriers engaged in international voyages. It provides the international standards for the safe transport of liquefied gases and other specified substances listed in chapter 19 of the IGC Code through maritime transport routes to minimize risks to ships, crew and the environment. Over the three decades, there have been a remarkable technical advancements in LNG systems, in particular LNG re-liquefaction and regasification equipment, ship-to-ship LNG transport, LNG propulsion systems and a wider range of gas transporter sizes.

Despite a series of revision on the IGC Code during several decades, it turned out that the advanced technologies were unstable to the prescriptive nature of this old-fashioned Code. As a result, the overhaul of the old Code was accomplished, thereby the new IGC Code, as amended by resolutions MSC.370(93), was adopted in 2014 that addresses a number of important amendments to the LNG cargo containment system. Figure 2 summarizes the brief history of the IGC Code.

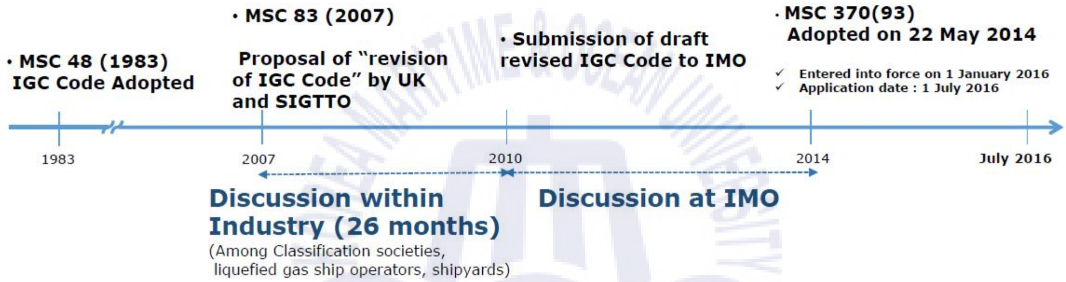


Figure 2 Timeline of IGC Code

1.3.2 IGF Code

Until the 21st century, there was no safety regulation for LNG fuelled ships other than LNG carriers. Due to the remarkable growth of ships using LNG fuels backed by stringent environmental regulations, it became an urgent matter to develop a unified international Code. In this context, IMO's Maritime Safety Committee (MSC) began developing new regulations in 2004 to ensure the safety of LNG fuel vessels. As a result, IMO Res.MSC.286 (85) (IMO 2009) - Interim Guidelines on Safety for Natural Gas-fuelled Engine Installations in Ship was adopted in 2009. For the next phase of work, the IGF Code has entered into force on the 1st of January 2017. This Code particularly deals with mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems for using low-flash point fuels which can be applied for LNG fuelled ships to minimize the risk to the ship, its crew and the environment, taking into account the nature of the fuel concerned (IMO 2015c). As of 2017, the IGF Code is to be applied to approximately 200 LNG fuelled ships in various ship types such as passenger ships, tankers and bulk carriers, container ships, dry cargo vessels, service and supply vessels, car/passenger ferries, PSVs, and Ro-Ro vessels (Corkhill 2017). The timeline of IGF Code is summarized in Figure 3.

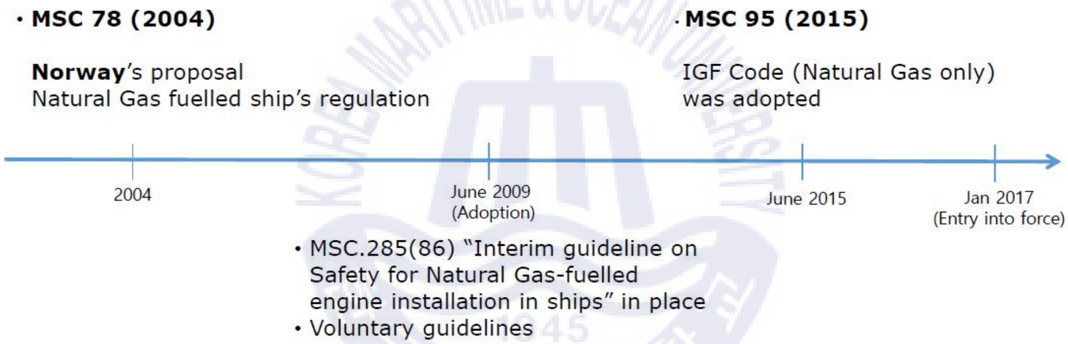


Figure 3 Timeline of IGF Code

1.3.3 Harmonization between IGC code and IGF Code

While developing the two Codes, there have been several issues. In the meeting of IMO Sub-Committee on Bulk Liquids and Gases (BLG), at its fifteenth session, it was addressed that the draft of two codes, particularly, the safety requirements of engine rooms, should be harmonised recognising that the IGF Code has broader implications for using LNG as fuel rather than cargo. For regulatory harmonisation, the IMO Sub-Committee on BLG had to establish a joint correspondence group (IMO 2011e; IMO 2012a). In the development of the IGF Code, it has been stated that the Code should be aligned with the draft revised IGC Code as much as possible because many parts of LNG fuelled ships are very analogous to the counterparts of LNG carriers (IMO 2011a, 2011b, 2011e; IMO 2012a). However, since the two Codes were developed at similar times, the unification works failed to be made properly. Moreover, different working groups in IMO were so dedicated to each Code that the safety requirements of the two Codes were deemed to diverge. Under this circumstance, the correspondence group had to concede that it was difficult to seek alignment in the condition that one of them was almost finalised, whereas the other was still under development (IMO 2011d; IMO 2012a). At MSC 92, it has been agreed that the new IGC Code should not set a precedent for the IGF Code while their relationship would be discussed once the two codes are finalised (IMO 2013b). Given that, at MSC 95, the IGF Code was adopted (IMO 2015c).

It is worth noting that any ship using low-flash point fuel is required to comply with either the IGC or the IGF Codes but they can't both applied to the same ship. i.e. Gas carriers will be exempted from the application of the IGF Code.

As can be seen from the Figure 4, except for the engine room, LNG fuelled ships and LNG carriers have different functions, layout and design features and risks to some extent, which is why it is necessarily to have separate regulations. Nonetheless, the regulatory differences still can confuse stakeholders since they have considerable similarities but also areas of inconsistencies, particularly engine room systems. The potential for future inconsistency, misinterpretation and misunderstanding of regulations in a fast expanding sector of the industry would inevitably lead to an increase in incidents which would threaten both ship and human lives in addition to legal allegations. Therefore, the necessity of actions to be taken in order to avoid such outcomes is paramount.

In this respect, we need further investigation to compare and contribute to harmonizing these Codes by identifying the regulatory gaps between the IGC Code and the IGF Code.

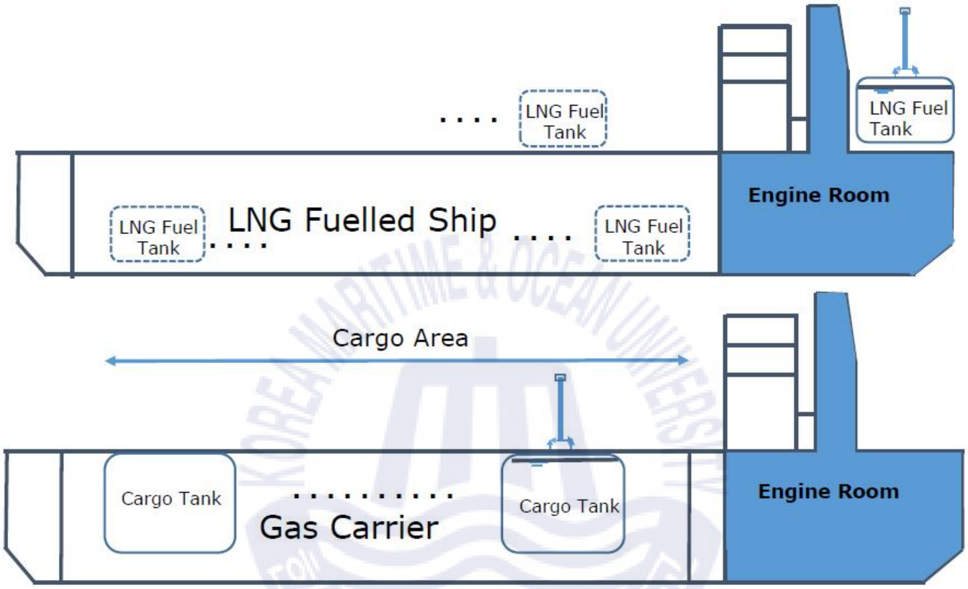


Figure 4 Brief arrangements of LNG fuelled ship and LNG carrier

1.3.4 Revised requirement on filling limit in LNG Carrier

Along with the increasing number of LNG carriers, the IGC Code was initially developed between the late 1970s and early 1980s to provide an international standard for the safe carriage by sea of liquefied gases, reflecting the best practice at the time.

Much of the new IGC code has been reflected in best practice applied to the latest LNG carriers in the marine industry. One of the major changes was for criteria on permitting filling limits greater than 98 %, which included the requirement that no isolated vapour pocket can appear and remain out of pressure control in the event of excessive list or trim condition specified in 8.2.17 of IGC Code.

The original IGC Code restricted the LNG cargo in membrane type tanks to not be filled higher than 98 % if it cannot meet some specific safety requirements stated in chapter 8 and 15 of the Code; the new IGC Code has similar regulations relating to filling the cargo. On the other hand, in terms of ‘some specific safety requirements’, regulatory differences are observed between the original and new IGC Codes; more stringent conditions due to isolated vapour pocket have been applied to the new IGC Code than the original one.

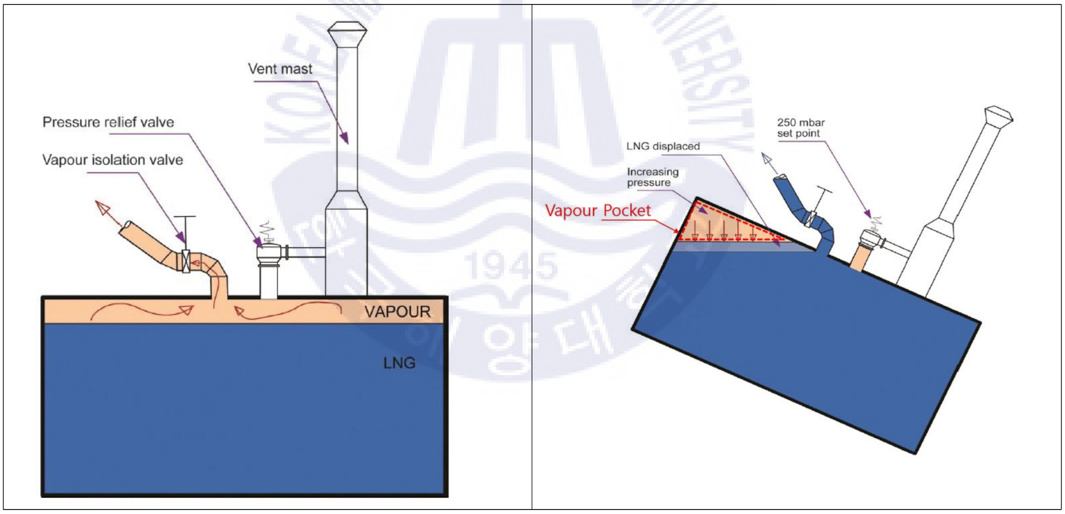


Figure 5 Cargo tank under normal conditions (Left) and cargo tank under abnormal conditions (Right) (SIGTTO 2016)

As shown in Figure 5, under certain static list and/or trim conditions, there may be the potential of forming the trapped gas, which is known ‘vapour pocket’, in cargo tanks with no means of normal escape through the tank safety valves and the gas dome exhaust. The trapped vapour is more likely to lead the cargo liquid to overflow into the vapour header, or if not managed correctly, into the tank pressure relief valve (PRV) exhausts.

This new requirement has the significant influence on ship’s design and operation for membrane cargo tanks. As a result, without the design modification, most of the membrane type tanks covered by the new IGC Code were limited to filling 98 % of the LNG cargo while previous membrane cargo tanks could commonly have the filling limit to 98.5 %.

Such an enhancement of the new IGC Code was originally borrowed from IACS Recommendation 109 developed in 2009. However, most classification of Societies had not considered adopting the recommendation with regard to the vapour pocket included in Rec. 109 into their own rules until entering into forth of the resolutions MSC.370(93). Nonetheless, the main text in the recommendation was incorporated into new IGC Code. This means that such a requirement was not best practice which had been applied before the timing of the amendments.

In the meantime, SIGTTO has published the information paper of “Awareness of Isolated Vapour Pockets in Membrane Type LNG Cargo Tanks(2016)” to raise industry awareness of the potential for isolated vapour pockets to form on membrane type LNG carriers. It provided the information to operators regarding the action to be taken in the highly unlikely scenario of a large angle of heel forming vapour pockets within a membrane tank. According to the information paper, interestingly it is noted that over fifty year operations including 85,000 voyages and 170,000 port calls, no accidents related to the vapour pocket in the cargo tanks were reported. Given this, the circumstances where an isolated vapour pocket might form are deemed as extremely unlikely. In this context, it is required to further investigate the adequacy or inadequacy of one of current debating issues - the enhanced safety level of the LNG filling limit.

Chapter 2 Methodologies

2.1 Research method applied in gap analysis between the IGC Code and the IGF Code.

As the approach to conducting gap analysis, first of all, the two Codes were examined chapter by chapter as shown in Table 1. Then, in order to draw a comprehensive understanding of the history and the technical background of the two Codes, this study reviewed most of the IMO documentations and working group reports associated with the development of these Codes. The know-how gained through the implementation of Korean Register projects and feedback received from stakeholders, particularly the shipowners and shipyards were used for this analysis. As a process of the gap analysis, the safety requirements of the IGC Code were applied to a 180K LNG carrier and a 7.5K small LNG bunkering vessel, and those of the IGF Code were applied to an LNG fuelled 50K DWT bulk carrier and a 325K LNG fuelled ore carrier.

Table 1 Chapters matching for the IGC and IGF Codes

IGC Code		IGF Code	
Ch.1	General	Ch.2 and 4	2. General
			4. General requirement
Ch.2	Ship survival capability and location of cargo tanks	Ch.5	5.3 Regulation – General i.e. tank location
Ch.3	Ship arrangements	Ch.5	5. Ship design and arrangement
Ch.4	Cargo containment	Ch.6	6. Fuel containment system
Ch.5	Process pressure vessels	Ch.5,7	5.7 Reg. for location and

	and liquids, vapour and pressure piping systems	and 8	protection of fuel piping 7.3 Reg. for general pipe design 8 Bunkering
Ch.6	Materials of construction and quality control	Ch.7	7.4 Regulation for materials
Ch.7	Cargo pressure/ Temperature control	Ch.6	6.9 Reg. for maintaining of fuel storage condition
Ch.8	Vent systems for cargo containment	Ch.6	6.7 Reg. for pressure relief system
Ch.9	Cargo containment system atmosphere control	Ch.6	6.10~12 Reg. on atmospheric/ environmental control within the fuel containment system/ fuel storage hold space 6.13 Reg. on inerting 6.14 Reg. on inert gas production and storage on board
Ch. 10	Electrical installations	Ch.12 and 14	12 Explosion 14 Electrical installations
Ch. 11	Fire protection and extinction	Ch. 11	11 Fire safety

2.2 Approach applied in the study on the adequacy of the revised regulation of filling limit in LNG cargo tank

We should ensure that additions and modifications to the regulatory framework are based on relevant statistics, research and analysis. In this context, a more in-depth analysis is necessary so that we can really understand the underlying trends and the proper level of safety regulations. This study has developed a framework to compare holistic costs or benefits of two incompatible regulations on LNG filling limit in order to assess not only the safety aspect, but also economic and environmental impacts in the life cycle points of view. It can be expressed a modified multi-criteria decision making process that is appropriate to answer questions about whether we need to keep the filling limit at 98.5 % or reduce it to 98 % from the economic, environmental and risk perspectives.

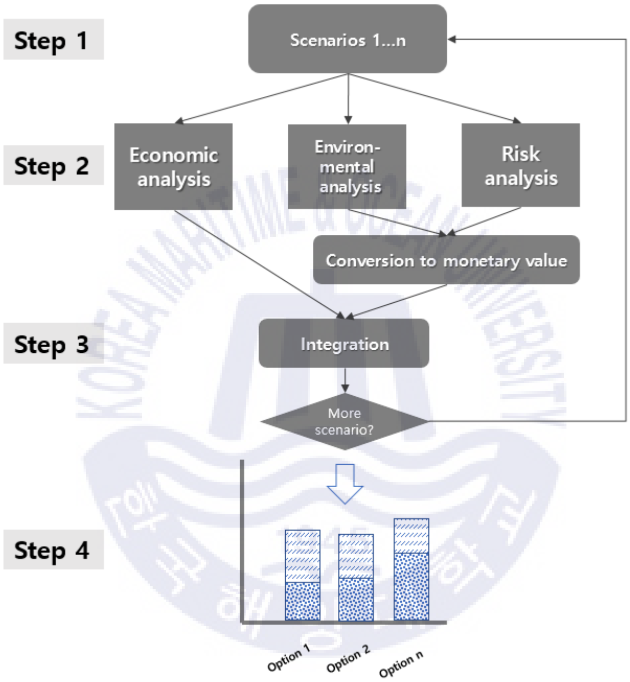


Figure 6 Outline of the proposed multi-criteria decision making process

The proposed framework consists of four steps as outlined below:

- Step 1: Scenario identification

All credible scenarios, whose performances are subject to the comparison, are identified in this step. This includes key parameters and inputs that are closely related to the cost, environmental, and risk impacts of the selected scenarios. There are no limitations on the number and scope of scenarios, but this research has clear definitions for two scenarios where the base scenario is the 98% filling limit and the alternate scenario is 98.5%.

- Step 2: Analyses

At this step, we will examine the performance of selected scenarios with economic, environmental, and risk perspectives. This step was designed to measure and assess the operating performance of LNG carriers in accordance with the defined scenarios.

Cost parameters associated with the filling limits are used for the economic analysis. They can be expressed in Eq.1(Jeong et al. 2018).

$$ECI=C_{FC}+C_{L}+C_{SC} \quad \text{Eq. 1}$$

Where,

ECI	Economic cost impact
C_{FC}	Cost of fuel consumption
C_{L}	Cost of labour
C_{SC}	Cost of ship chartering

Environmental analysis takes into account the following types and amounts of emissions that occur during ship operation: CO_2, NOx, HC, SOx and PM (particular matter). The emission levels were then converted into monetary values(Jeong et al. 2018).

$$EI_{i,j}=C_{CO2_{i,j}}\times Q_{CO2_{i,j}}+C_{NOx_{i,j}}\times Q_{NOx_{i,j}}+C_{SOx_{i,j}}\times Q_{SOx_{i,j}}+C_{PM_{i,j}}\times Q_{PM_{i,j}} \quad \text{Eq. 2}$$

Where,

EI	Environmental impact
C_{CO2}	Cost of CO_2
C_{NOx}	Cost of NO_x
C_{SOx}	Cost of SO_x
C_{PM}	Cost of PM
Q_{CO2}	Quantity of CO_2

Q_{NOx} Quantity of NO_x
Q_{SOx} Quantity of SO_x
Q_{PM} Quantity of PM

Risks can be expressed as a combination of the frequency of occurrence of an unwanted event and the severity of the incident, so the risk impact may be:

$$RI_{i,j} = (F_{LR_{i,j}} \times F_{IG_{i,j}}) \times C_{LR_{i,j}}$$ Eq. 3 (Jeong et al. 2018)

$$C_{LR_{i,j}} = C_{F_{i,j}} \times N_{F_{i,j}}$$ Eq. 4 (Jeong et al. 2018)

Where,

RI Risk impact
F_{LR} Frequency of LNG release
C_{LR} Consequence of LNG release
C_F Cost of fatalities
N_F Number of fatalities

- Step 3: Integration of analyses results

The total lifetime cost is expressed as an integration of three effects that represent the overall performance of the LNG carrier in the two scenarios.

$$TC_{i,j} = ECI_{i,j} + EI_{i,j} + RI_{i,j}$$ Eq. 5 (Jeong et al. 2018)

Where,

TC_i Total cost at scenario, i
ECI_i Economic cost impact at scenario, i
EI_i Environmental impact at scenario, i
RI_i Risk impact at scenario, i

- Step 4: Evaluation of the best scenario

From the results of the analyses, the best scenario can be identified as the last step. It can bring about the further discussion on the holistic cost and benefit across the scenarios.

Chapter 3 Study 1: Regulatory gaps between LNG carriers and LNG fuelled ships

3.1 Gap analysis between IGF Code and IGC Code

In this chapter, a gap analysis identifying the differences or discrepancies of the safety requirements for LNG carriers and LNG fuelled ships in accordance with the IGC and the IGF Codes is provided. There are differences between both Codes which are not necessary considered as discrepancies since some of these differences are justified due to the change of the functions, sizes, application environment, and risks.

3.1.1 Risk assessment

According to the IGC Code 1.1.10, while not specifically required to LNG carriers, risk assessment is commonly applied to the floating storage regasification units (FSRUs) and ships operating for the purpose of receiving, processing, liquefaction and storage of gas. It is also stipulated in IGF Code 4.2 and applied to the particular areas of LNG fuelled ships: sizing of drip trays; design of airlocks; liquefied gas containment system; determination of additional relevant accidental load scenarios; design and arrangements for bunkering station; alternative calculations for ventilation capacity for tank connection space; provision of gas detectors; and limit state design (IMO 2015b, 2015d).

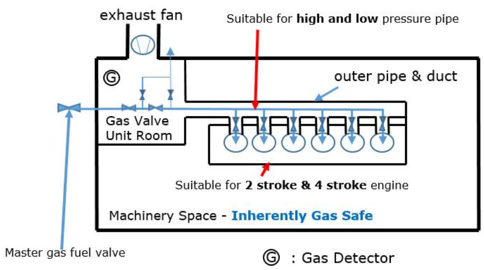
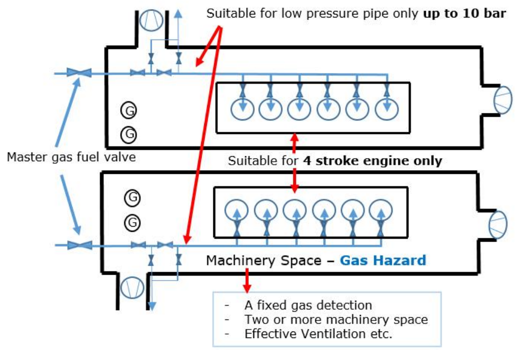
3.1.2 Machinery space concept

The machinery space in which gas engines are installed and operated is particularly prone to accidents of fire and explosion. According to the IGF Code 5.4, LNG fuelled ships are supposed to meet one of the two machinery concepts: either 'gas safe machinery space' or 'ESD protected machinery space' (IMO 2015c).

In the concept of the gas safe machinery space, any single fault is not allowed to cause the gas release into the machinery space. Therefore, preventive measures such as double-walled piping systems must be applied to capture the leaked gas.

Unlike the gas safe machinery space, gas leakage can be released into the machinery space under the concept of the ESD protected machinery space in the event of such an accident. Instead, the entire machinery space affected by the initial release must be isolated without losing propulsion power. To meet this requirement, two identical machinery spaces need to be segregated, meaning that any common boundary is not allowed (IMO 2015c). The conceptual designs for both spaces are described in Table 2.

Table 2 Conceptual designs for the machinery spaces

<table>
<tr><th>Gas safe machinery space</th><th>ESD protected machinery space</th></tr>
<tr><td>
</td><td>
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Meanwhile, a regulatory disparity was identified: while both machinery spaces are applicable to LNG fuelled ships based on the IGF Code, the IGC Code only accepts the concept of the gas safe machinery space for LNG carriers.

The gas safe machinery space is so designed to ensure the absolute prevention from initiating gas leak. On the other hand, the ESD protected machinery space is focused on the post-treatment of the initial gas leak. Given the fact, it may be credible to think that the gas safe machinery space is inherently safer and more reliable than the ESD protected machinery space. Consequently, the IMO Sub-Committee on BLG agreed that the use of the ESD machinery space concept would not be suitable for the gases heavier than air or having low-flash points (IMO 2011c). Nonetheless, given that the gas engines used for both types of vessels are identical, there still leaves ambiguity as to why ESD-protected engine spaces are acceptable for LNG fuelled ships and why they are not for LNG carriers.

Also, the IGF Code 9.7 limits the pressure of the gas fuel supply system for gas engines in the ESD protected machinery space to 10 bar. This provision technically restricts the use of all two-stroke gas engines that have pretty much higher fuel gas pressures than the threshold (Fernandez et al. 2017).

3.1.3 Fuel containment system (LNG storage tank)

There are four main types of LNG fuel tanks used on board at present: one is a membrane type (integrated into hull structure), and the others are independent types A, B and C respectively. Although LNG cargo storage tanks and fuel containment systems are identical, regulatory discrepancies have been found in various parts of the safety requirements.

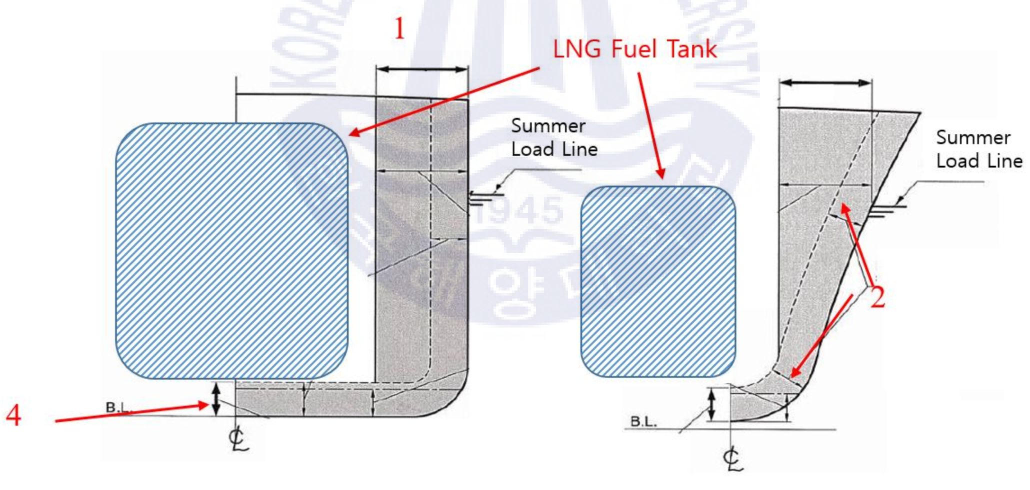
3.1.3.1 Tank location

Both Codes provide specific guidelines on LNG tank location to secure the LNG tank from external damages such as collision and grounding by keeping the minimum distance of the LNG tank from the ship side and bottom hull. The safety distance is determined in accordance with the hazardous levels of the liquid stored in the tank expressed as Type 1G, 2G and 3G; Type 1G is regarded the most hazardous cargoes whereas 3G is the least hazardous ones (IMO 2014c).

The IGC Code categorizes the LNG cargo into Type 2G, thereby the safety requirements for the Type 2G tank is applicable to LNG carriers. On the other hand, the IGF Code groups the LNG as fuel into the Type 1G, therefore the LNG fuelled tank are subject to the Type 1G requirements (IMO 2013b). Table 3 summarizes the guidelines on establishing the safety distance stated in the IGC and IGF Codes; it is entirely credible to point out that the safety requirements for IGF Code are more strictly regulated than the IGC Code (IMO 2011c).

Table 3 Requirements of tank location in a deterministic approach

No.	Tank location	Requirements
IGC Code (Ch.2.4)		
Distance from side shell (Type 2G)		0.8~2 m
IGF Code (Reg. 5.3.3)		
1	Transverse distance from ship side	Ship breadth/5 m or 11.5 m, whichever is less at summer load water line
2	Distance from side shell	0.8~2 m
3	Longitudinal location	abaft the collision bulkhead
4	Vertical distance from bottom shell	Ship breadth/15 m or 2.0 m, whichever is less



As an alternative, the probabilistic approach to the distance of the LNG tank can be more flexibly deployed without reducing the safety aspect. In this context, the IGF Code 5.3.4 alone introduced the probabilistic approach to determine the safety distance using the concept of the damage stability analysis in accordance with SOLAS II-1 (IMO 2013a; IMO 2014a, 2014b). About this, transverse distance from ship side can be considered using Eq. 6

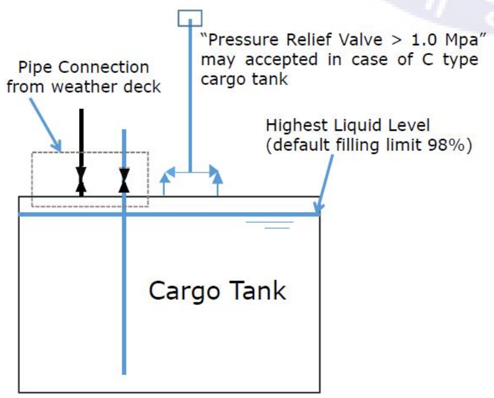
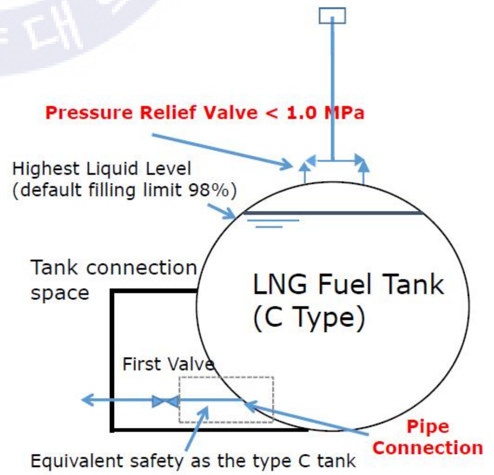
f_{CN}=fl · ft · fv   Eq. 6

Where, f_{CN} is the parameters to be included in a simplified assessment of probability for hitting the tank in a collision (f_{CN} shall be less than 0.02 for passenger ships and 0.04 for cargo ships); fl is the longitudinal factor; ft is the inboard penetration factor; and fv is vertical factor.

Given that whether it is a form of cargo or fuel, the storage of the LNG in a vessel is technically same and there may be no or inconsequential difference in the potential risk associated with mechanical and external damages, the regulatory disparity is contrary to what our common knowledge tell us; that is the equal level of safety requirements should be affixed in both Codes.

3.1.3.2 An arrangement of tank pipe connection

Table 4 Requirements for tank pipe connection

<table>
<tr><th>IGC Code</th><th>IGF Code</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

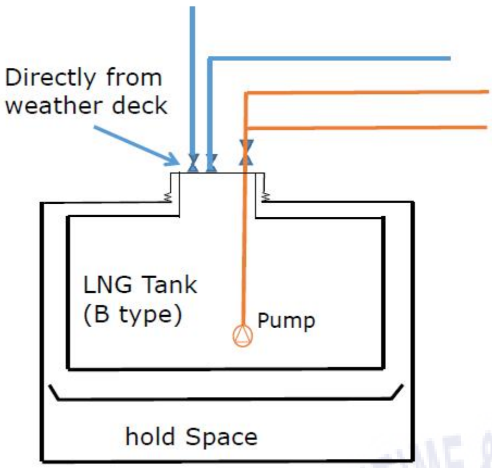
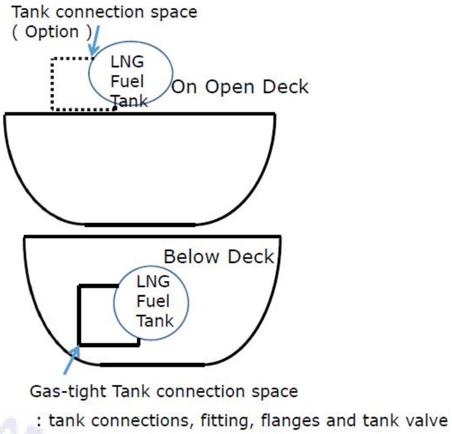
The key differences are described as below:

- The IGF Code 6.3.1 requires that the maximum allowable relief valve setting (MARVS) be 1.0 MPa or less regardless of tank type. In the IGC Code 4.23, the setting pressure for type C tank can be set 1.0MPa or higher.

- Pipes mounted on the head of the LNG cargo tank are to be fitted above the highest LNG level in the tanks (IGC Code 5.5.2.1); if using type C fuel tank having the tank connection space, the pipes can be connected below the highest liquid level following the IGF Code 6.3.5.

The concept of the tank connection space described in the IGF Code is compared to the equivalence of the IGC Code in Table 5. According to the IGF Code 6.3.4, if the tank connection space is not on the open deck, all connection systems - piping, fittings, flanges, tank valves, etc. - are to be exclusively arranged within the tank connection space or what is so-called 'Cold Box' which are to be designed to contain the LNG leakage if any. Meanwhile, in the LNG carriers, all piping systems connected to the cargo tank is to be directed from the weather decks(IGC Code 5.2.2.1.3)(IMO 2015c).

Table 5 Concept of tank pipe connection

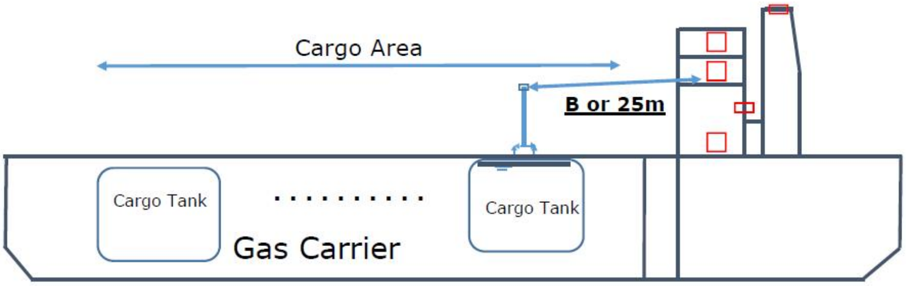
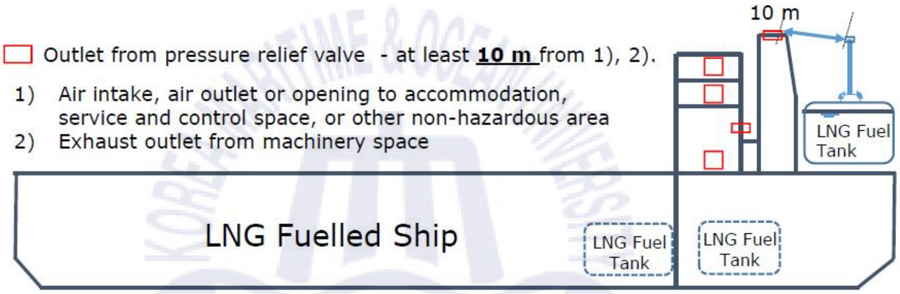
IGC Code	IGF Code
	

The differences of safety requirement for tank pipe connection between the IGF and IGC Codes may not lead to significant controversy in ship design, construction and operation. However, this information and justification are believed to help stakeholders to gain a better understanding during applications of the two Codes.

3.1.3.3 Arrangement of pressure relief system

In order to prevent the unwanted gas release out of the pressure relief valve (PRV) from escalating incidents, each Code provides the safety requirements for arranging the PRVs in different ways which are described in Table 6.

Table 6 An arrangement of pressure relief system

	Arrangement
IGC Code	
IGF Code	

The key differences are described as below:

- IGC Code 8.2.11.1 demands that the outlet from the cargo pressure relief valve (PRV) be arranged at least 10m distance from the nearest – air intake, air outlet or opening to accommodation spaces, service spaces and control stations, or other non-hazardous areas – or equal to ship breadth or 25 m, whichever is less.

- IGF Code Part A-1, 6.7.2.8 requires the outlet from the pressure relief valves should be place at minimum 10 m distance from the non-hazardous areas, such as service and control spaces, air intake and outlet or opening to accommodation and exhaust outlet from machinery installations.

Although both Codes require the safety distances from the non-hazardous areas, the level of such distances is divergent based on whether they are fuel tanks or cargo tanks (IMO 2014c; IMO 2015c). This regulatory discrepancy needs to be justified in a clearer way through systematic studies on investigating the adequacy and inadequacy of both Codes.

For an example of the IGF Code, the safety distance of 10 m may be not applicable to small ships; 10 m distance may be not significant for large ships, while it may be for small ships. Therefore, it was of a view that the degree of safety requirements of the IGF Code should be coupled with a risk-based approach rather than the size of the ship.

3.1.3.4 Control of tank pressure and temperature

To control of tank pressure, temperature and boil off gas(BOG) in both Codes, one of the following methods should be applied with design range: re-liquefaction and thermal oxidation(combustion) of the vapour, liquefied gas fuel cooling or pressure accumulation (IMO 2014c; IMO 2015c). Table 7 indicates the relative applicability of the four methods with the sample of Type C LNG fuel tank and membrane cargo tank which are most widely applied tanks to data. The term “applicability“ is used to measure how the proposed method is compatible with actual operating characteristics.

Table 7. Applicability of control system for tank pressure and temperature.

	Methods	Equipment	IGF Code (C Type Fuel Tank)	IGC Code (Membrane Tank)
1	Re-liquefaction of vapour	Re-liquefaction System	√	√√
2	Thermal oxidation of vapour	Internal Combustion Engines, Boilers, Gas Turbines	√√	√√
		Gas Combustion Unit	√	√√
3	Pressure accumulation	Pressure Relief Valve, Insulation	√√	√
4	Liquefied gas fuel cooling	Cooling Coil	n/a	n/a

√ : applicability low , √√ : applicability high

It is viewed that the difference in the relief valve setting values of the tank led to the different applicability in terms of the methods of re-liquefaction of vapour and pressure accumulation.

According to the IGF Code 6.9.1.1, the pressure and temperature of the LNG fuel tanks should be controlled and maintenance for a period of minimum 15 days after the initial activation of these safety systems. Such requirements are not stated in the IGC Code for LNG cargo tanks (IMO 2016c).

3.1.4 Safety systems

In this part, the gap analysis identifying the difference or discrepancies of the safety requirement related to fire safety, ventilation system, piping design, etc. between is provided.

3.1.4.1 Piping design

Since LNG is a cryogenic media, the piping system for transferring this liquid is carefully designed. Both Codes commonly require the piping systems with the design temperature lower than minus 110° C or colder to be subject to the stress analysis (IGF Code 7.3.4.5, IGC Code 5.11.5) (IMO 2014c; IMO 2015c).

However, the IGF Code additionally requires that the piping systems with the maximum working pressure of 1.0 MPa or higher, regardless of the design temperature, are subject to such analysis (IMO 2015c). This means that the fuel supply piping systems for two-stroke gas engines applied to LNG fuelled ships are subject to the stress analysis while the same systems are not subject to the analysis when mounted on LNG carriers. The risk of the gas leak from high-pressure pipes is critical, potentially leading to an increase in accidents associated with the safety of ships and crew and the marine environment. Given this, it was of our view that the stress analysis for the high-pressure piping system is to be carried out regardless of the ship types. Therefore, the update of the IGC Code is necessary.

Some other differences in the arrangement of LNG piping systems between the two Codes are described in Table 8 (IMO 2014c; IMO 2015c).

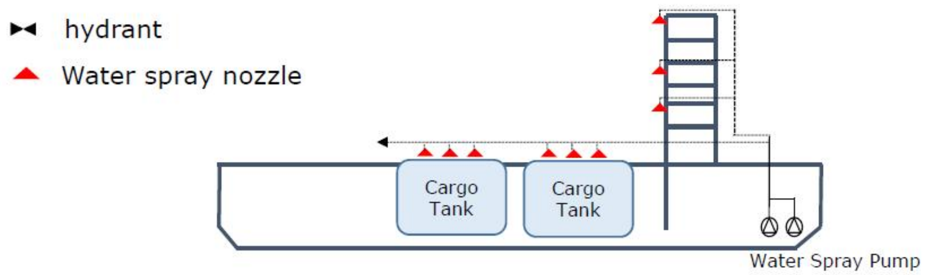
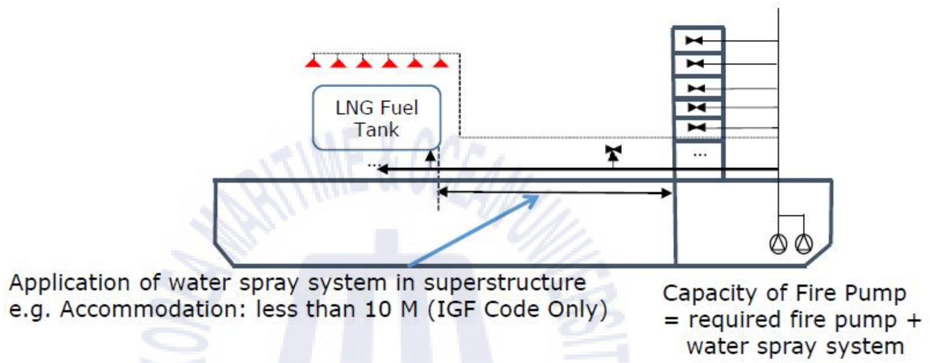
Table 8 Safety requirements for LNG piping systems

Items	IGC Code	IGF Code
Double Wall Piping system in gas safe machinery spaces	- Ventilated air (30 air changes/hour) - Inert gas (e.g. nitrogen) (IGC Code 16.4.3)	- Ventilated air (30 air changes/hour) - Inert gas (e.g. nitrogen) - Other solution providing an equivalent safety level, e.g. Vacuum - especially for LNG (IGF Code 9.6.1)
Duct or outer pipe containing high-pressure gas piping system	NIL	Pipes with design temperature lower than -55° C (IGF Code 7.4.14)
Duct or Outer pipe around LNG fuel piping system	NIL	Pipes with design temperature lower than -165° C (IGF Code 7.4.1.5)

3.1.4.2 Water spray system

In terms of the regulations on the water spray system as a fixed fire-fighting system, the summary of the gap analysis is illustrated in Table 9. The major difference lies in the scope of the areas to be protected.

Table 9 Safety requirements for LNG piping systems

<table>
<tr><th></th><th>Arrangement</th></tr>
<tr><td>IGC Code</td><td>
</td></tr>
<tr><td>IGF Code</td><td>
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</table>

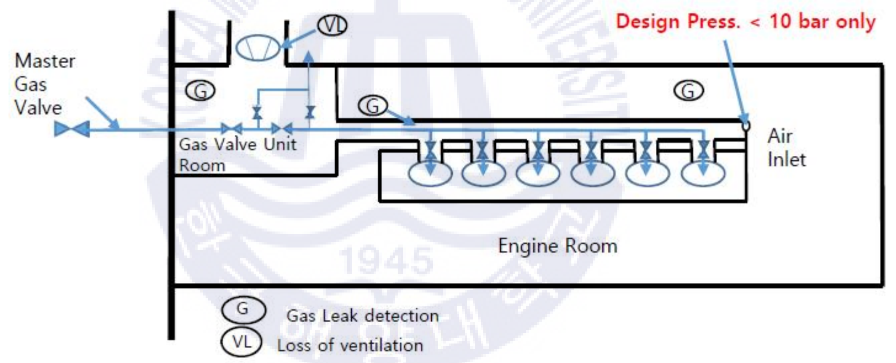
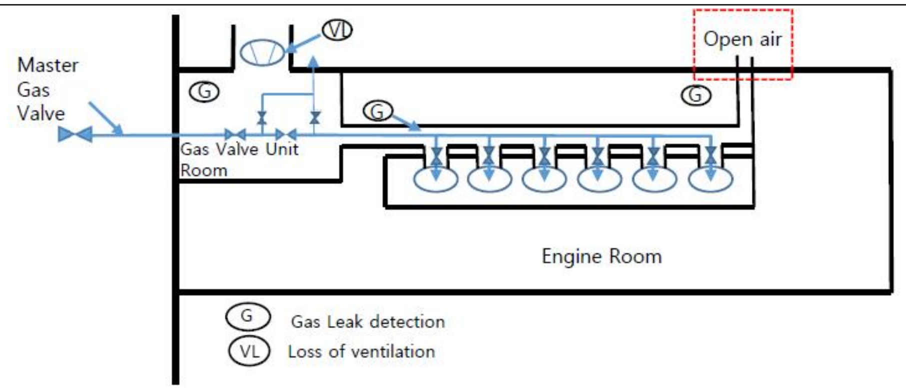
The IGC Code stipulates that exposed boundaries facing the cargo area, such as deckhouses and bulkheads of superstructures, should be covered by the water spray system. Besides, various other areas to be protected by the system are defined in the IGC Code 11.3.1 (IMO 2014c).

The coverage of the water spray system is relatively narrow for the LNG fuelled ships, compared to that for LNG carriers due to the extent of the hazards and the tank size limitation. Meanwhile, taking into account that the LNG fuel tank can be arranged in many different ways, the ship structures in the vicinity of the fuel tank may be exposed to the fire risk; the effect of fire near the LNG fuel tank can be minimized by segregating the LNG fuel tank on open decks from the boundaries of various hazardous and non-hazardous area such as superstructures, compressor rooms, pump-rooms, cargo control rooms, bunkering control stations, bunkering stations and deck houses. In this philosophy, the IGF Code 11.5.2 stipulates that the water spray system is installed for all fuel tanks placed less than 10 m away from such boundaries (IMO 2015c).

3.1.4.3 Duct and double wall pipes in machinery space

Regulatory imbalances can also be found in the safety requirements for the application of the duct and double wall pipes shown in Table 10.

Table 10 Safety requirements for fuel gas piping systems (duct and double wall pipes) in machinery space

	Arrangement
IGC Code	
IGF Code	

The gas safe machinery space concept in the IGC Code requires all gas piping in the machinery space to be enclosed in a gas-tight double barrier without openings to the machinery space. However, ventilation inlets in connection with the double pipe in the machinery space may be permissible for the low-pressure gas piping systems on the condition that gas detection system is installed in the surrounding engine room space (IMO 2011d).

According to the IGC Code 16.4.4.2, ventilation inlets and outlets to the double pipe should be led to cargo area in case of gas fuel with the operating pressure of 1 MPa or greater (IMO 2014c). This means that the adverse effects of fuel gas pressure are taken into account in the IGC Code so as to minimise the potential risk of fire and explosion by placing the ventilation inlets and outlets in the cargo area.

On the other hand, the IGF Code 13.8.3 has a somewhat different view on the coverage of this safety system. The unified interpretation of the IGF Code with regard to ventilation inlet for double wall piping or duct is that the ventilation inlet for the double wall piping or duct should be located in a non-hazardous area having the open air and away from ignition sources (IMO 2016d). This implies that air inlets for the annular space and the gas valve unit room should be located in an open space for both low pressure and high-pressure gas fuel.

This interpretation (IMO 2016a) is based on:

- The machinery space contains multiple ignition sources. Consequently, even in gas safe machinery spaces, permitting ventilation inlets to draw air from the machinery space may not be the best of options;
- Inlets to ventilation systems for the hazardous area zone 1 cannot be located in the machinery space;
- The actual ventilation rate is not defined by the requirement for 30 air

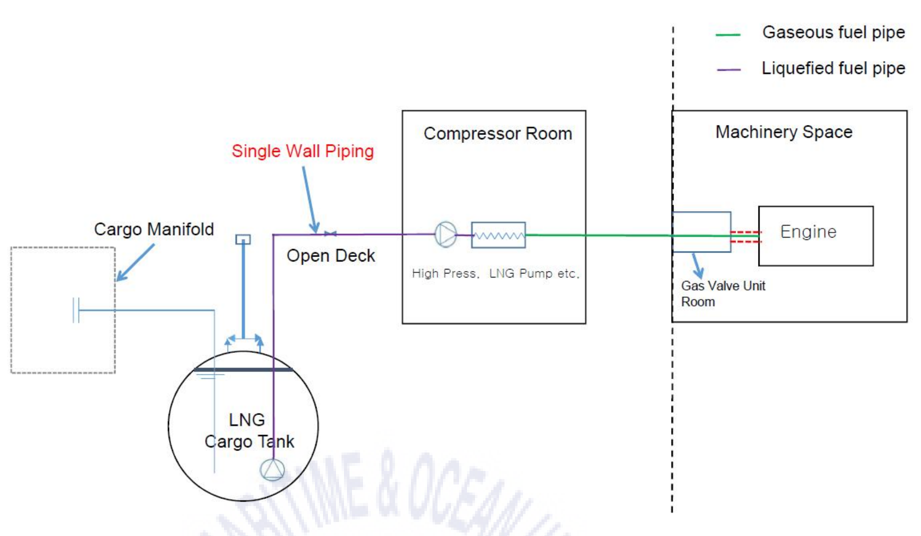
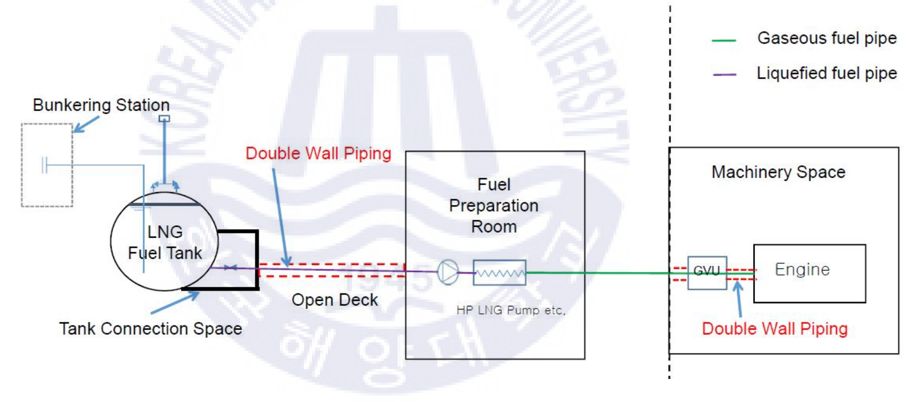
changes per hour in the annular space between the inner and outer pipe(IGF Code 9.6.1.2). Consequently, an assumption that the ventilation rate will be larger than the leakage rate to prevent gas in the machinery space cannot be made.

On the other hand, IMO Sub-Committee on Carriage of Cargoes and Containers (CCC) was of the view that the interpretation text for IGF Code is not necessarily compatible with the IGC Code. Therefore, the LNG fuelled ships are subject to some different arrangements for ventilation inlets of the double wall piping and the duct (IMO 2016b). However, it was our thought that this regulatory disparity would leave the potential for future inconsistency, misinterpretation and misunderstanding in a fast expanding sector of the industry.

3.1.4.4 Duct and double wall pipes outside machinery space

For LNG carriers, the secondary enclosure of the on-deck liquid fuel gas pipe between the fuel gas pump in cargo tank and the high pressure pump in compressor room is not required, whereas this safety measures should be applied to the equivalent pipe in case of LNG fuelled ships to comply with the amended IGF Code 9.5.6(IMO 2017a, 2017b). Table 11 illustrates such a difference between the two Codes.

Table 11. Safety requirements for piping systems outside machinery space.

<table>
<tr><th></th><th>Arrangement</th></tr>
<tr><td>IGC Code</td><td>
</td></tr>
<tr><td>IGF Code</td><td>
</td></tr>
</table>

3.1.4.5 Ventilation

While both Codes refer to IEC 60092-02:1999 regarding the requirements of ventilation, the IGF Code alone requires the mechanical ventilation system to be fitted to the tank connection space, ESD protected machinery space(IGF Code 13.4.1)(IMO 2014c; IMO 2015c). The safety requirements pertinent to mechanical ventilation systems provided in the IGF Code are represented in Table 12.

Table 12 Safety requirements for ventilation system

Items	IGC Code	IGF Code
Fuel Preparation Room or Compressor Room	Minimum 30 time air changes per hour (IGC Code 12.1.3)	Minimum 30 time air changes per hour (IGF Code 13.6)
Tank connection space	N/A	Minimum 30 time air changes per hour (IGF Code 13.4)
ESD protected machinery space	N/A	Minimum 30 time air changes per hour (IGF Code 13.5.2)
Ducts and double pipes	Minimum 30 air changes per hour(except when supplying the inert gas to double pipes) (IGC Code 16.4.3.2)	- The reduction to 10 air changes per hour is permitted if automatic filling of the duct with nitrogen is arranged upon detection of gas(IGF Code 9.6.1.2), or - 30 air change per hour or less is accepted if ensuring a flow velocity of minimum 3m/s (IGF Code 13.8.4)

The level of the redundancy for ventilation fan in fuel preparation room is equivalent to the compressor room in LNG carriers. The IGF Code 9.6.1.2 and 13.8.4 also provides specific parts with some flexibility concerning ventilation capacity for duct and double wall pipe. The capacity of the ventilation can be 30 time air changes per or less hour if ensuring a flow velocity of minimum 3 m/s(IGF Code 13.8.4). Furthermore, the reduction to 10 time air changes per hour is permitted if automatic filling of the duct with nitrogen is arranged upon detection of gas(IGC Code 9.6.1.2) (IMO 2015c).

Given the uniform condition between LNG fuelled ships and LNG carriers, the fact - that the mitigation requirements for the ventilation capacity of the double walled pipe specified in the IGF Code are inconsistent with the requirements of the IGC Code - appears to lead to a future debate on ventilation requirement.

3.1.5 Cargo manifold / bunkering station

The installation of the vapour return line is considered optional for LNG fuelled ships, whereas it is mandatory to the vessels subject to the IGC Code as described in Table 13.

Table 13 Requirement for vapour return line

Items	IGC Code	IGF Code
Vapour return	Vapour return line is to be provided(IGC Code 5.6.3)	- Vapour return line is optional - Dry disconnect type with additional safety dry breakaway coupling/self-sealing for quick release (IGF Code 8.4)
Emergency shut-down	ESD-1 or ESD-2	ESD-2 only
Fire fighting system	Dry powder monitor(s) (IGC Code 11.4.3)	- Permanent dry chemical powder fire-extinguishing system (IGF Code 11.6.1) - Portable dry powder fire extinguisher with at least 5 kg capacity (IGF Code 11.6.2)

For LNG carriers, the cargo manifold is located in the cargo area above the weather deck in accordance with the IGC Code and close to the mid-ship as practicable (SIGTTO 2011). On the other hand, for LNG fuelled ships, the location of bunkering station can be arranged to various locations depending on ship characteristics such as fuel tank location, ship type, nature of cargo etc.

In an emergency situation, cargo manifold for LNG carriers is controlled by one of the ESD-1 and ESD-2 defined in the SIGTTO Guideline (SIGTTO 2009). However, the bunkering system is required to be controlled by only ESD-2 systems such as safety dry breakaway coupling/self-sealing for quick release. Here are some details for ESD-1 and -2;

- ESD-1: Emergency shutdown stage 1 - shuts down the cargo transfer operation in a quick controlled manner by closing the shutdown valves and stopping the transfer pumps and other relevant equipment in ship and shore systems.
- ESD-2: Emergency shutdown stage 2 - shuts down the transfer operation (ESD-1) and uncouples the loading arms after the closure of both the ERS isolation valves.

The IGC Code simply requires the provision of dry powder monitor(s) to protect any load/unload connection area, whereas the IGF Code 11.6 requires the provision of permanently installed dry chemical powder fire-extinguishing system as well as a portable dry powder fire extinguisher with at least 5 kg capacity (IMO 2014c; IMO 2015c).

For LNG-fuelled ships, LNG bunkering is an inevitable process. The most established method of LNG bunkering is the transfer of LNG from the LNG terminal to the receiving vessel in a manner similar to the loading and unloading of LNG cargo into the cargo tank.

However, due to the lack of terminal infrastructure, several alternatives have emerged, such as the use of LNG tank trucks, LNG feeders or portable LNG tanks which may be pertinent to higher potential hazards than the conventional terminal bunkering.

Although IMO and regional organizations have developed a series of safety requirements, particularly the presence of watch keeper, the installation of ESD system and firefighting systems, the failure of these systems cannot be ignored. The current rules and regulations concerning the design, construction and operation of LNG bunkering system lack specific quantified guidelines.

ISO/TS 18683 (ISO 2015) recommends establishing a safety exclusion zone around the LNG bunkering areas access to which is to be restricted to all non-essential personnel during bunkering in order to minimize the probability of ignition, thereby the threat to human lives if an accident. Such a safety exclusion zone includes the supply point and the onboard bunkering station (Jeong et al. 2017).

Given the fact that the IGC Code for LNG carriers, or related standards, does not specify the need of the safety zone for LNG cargo transfer, the safety requirements on the LNG bunkering may be considered stringent.

3.1.6 Miscellaneous systems

In this part, the gap analysis identifying the differences or discrepancies of the control, monitoring and safety system between two(2) Codes is provided.

3.1.6.1 Temperature indicator

LNG bunkering may encounter the potential risk of rapid fuel tank pressurization by the mixing of different temperature/properties of fuels which may be produced/supplied from different areas. In this context, the temperature indicator in LNG fuel tank is a key equipment to prevent the risk of a rapid rise of pressure caused by mixing fuels with different temperature before a bunkering operation. Besides, it is also used to prevent stratification phenomenon during the fuel agitation operation when some different temperature layers are confirmed after bunkering (IMO 2015a).

Therefore, the number of temperature indicators to be installed in LNG fuel tank is more than that of LNG cargo tank (IMO 2015b, 2015c). According to IGF Code 15.4.11, Type C tank supplied with a vacuum insulation system and pressure build-up fuel discharge unit are excluded because the fuel in this tank may not age by not ejecting of the boil off gas(BOG) during the voyage and bunkering. Whereas, the application of this requirement of temperature indicator in the IGC Code is the same for all tank type including the Type C.

3.1.6.2 Gas detection

The IGF Code requires a gas dispersal analysis or physical smoke test to decide the best arrangements for gas detectors, but the IGC Code does not specify such a requirement (IMO 2014c; IMO 2015c). The setting value for gas detection is also stricter at 20% lower explosion limit (LEL) in the IGF Code than 30% LEL in the IGC Code. The IGC Code 13.6.19 requires two portable gas detection equipment or more while the IGF Code 15.8.6 does not specify a mandatory number.

3.2 Result and discussion

This study carried out a gap analysis identifying the differences or discrepancies of the safety requirements for LNG carriers and LNG fuelled ships in accordance with the IGC and the IGF Codes. As a result, the following parts, in particular, in IGC Code and IGF Code were identified as main gaps of the safety requirement for the engine room system.

Table 14 Gaps of the safety requirement for the engine room system

Items	IGC Code	IGF Code
Concept of machinery space (chapter 3.1.2)	Gas safe machinery space only	Gas safe machinery space or ESD protected machinery space
Stress analysis on piping system depending on pressure (chapter 3.1.4.1)	No specific requirement	The piping with working pressure of 1.0 MPa or higher
Requirements for duct and double wall pipe in case of gas fuel with the operating pressure of 1.0 MPa or greater (chapter 3.1.4.3)	The openings for ventilation inlets and outlets of the double pipe to engine room are accepted.	Ventilation inlets and outlets of the double pipe should be led to open air, e.g. outside of engine room
Requirements for ventilation of duct and double wall pipe(chapter 3.1.4.5)	30 air change per hour	30 air change per hour or less is accepted if ensuring a flow velocity of minimum 3m/s

Despite the increasing popularity of LNG carriers and LNG fuelled ships, the current international Codes seem to need some improvement in terms of achieving uniform safety requirements. There is some disharmony across the provisions which has never received thorough investigations.

Typically, the design of LNG fuelled ships is analogous to conventional LNG carriers in many aspects, such as the arrangement of LNG storage tanks and the loading/unloading systems and their operating procedures. It was viewed that the regulatory inconsistencies across the two Codes may cause the different application of safety requirements to the exactly-same systems, leading to significant differences in the design of LNG carriers and LNG fuelled ships. In particular, LNG carrier with gas engines is also regarded as the same type as the LNG fuelled ship. However, such a LNG carrier is only subject to the IGC Code, but not the IGF Code. Given this, regulatory discrepancies between the two Codes may aggravate ambiguity. It is, therefore, necessary to promote transparency in the disciplined regulations.

In this context, a particular emphasis of this study was placed on overviewing the regulatory gaps between the IGC and the IGF Codes in an effort to contribute to unified implementation for discordant provisions in these Codes. Hence, this study suggests that the IMO should take a proactive action to narrow the gaps between the two Codes by proposing revisions or unified interpretations for the discords discussed in the previous chapters; it may either need to revise the IGC Code according to the IGF Code or vice versa in order to harmonize both Codes based on proper maritime architecture and engineering principles and practices.

The main base of the IGF Code for ships using LNG as a marine fuel is the experience and knowledge of similar systems of LNG carriers. Therefore, they particularly need to be reviewed and revamped based on proper systematic risk assessment of the LNG fuelled ships.

In recent years, IMO regulations have become increasingly diverse and complicated; thereby stakeholders encounter difficulties in designing and adapting them to ships and even costly. For instance, shipyards, who have extensive experience in designing LNG carriers, are confused about applying some different safety regulations to the same system (e.g., the engine room system) when constructing LNG fuelled ships. This gap is also the same for the Flag State and Classification Society which approves ships. In this context, this study is believed to be a useful guide in enhancing a general understanding of the similarities and inconsistencies between the two Codes. It may help stakeholders to identify further actions to be taken, while to prevent ship designers from becoming confused by regulatory differences.

Chapter 4 Study 2: Investigation on the adequacy of the revised regulation of filling limit in LNG cargo tank

4.1 Case Study

The selected case ship was a 174K LNG carrier engaged in the international service between Incheon, South Korea and Sabine Pass, USA. Figure 7 shows the basic information of the case ship.

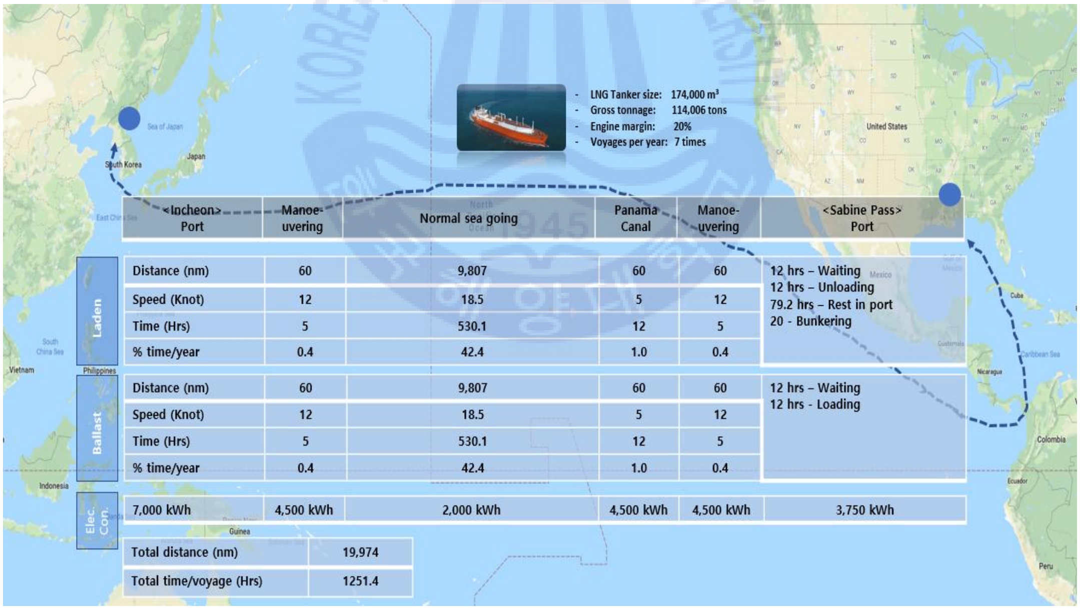


Figure 7 Case ship information

4.1.1 Step 1: scenario identification

As earlier discussed, this study considered two credible scenarios in cargo carriage; Base scenario was 98 % LNG filling to each cargo tank, whereas alternative scenario was 98.5% LNG loading. Table 15 shows the quantity of LNG cargo transported to destination during the ship lifetime.

Table 15 Lifetime quantity of cargo transported

Cargo tank	NO.1	NO.2	NO.3	NO.4
Capacity (m3,100%)	24,668	50,238	50,238	49,097
Filling limit (98.5%)	24,297.98	49,484.43	49,484.43	48,115.06
Filling limit (98%)	24174.64	49233.24	49233.24	48115.06
Life time cargo transported (m^3)	Base	29,364,372.9		
	Alternative	29,215,315.17		
	Difference	149,057.73		

It is assumed that the amount of boil off gas used as fuel was not reflected and considered in the lifetime quantity of cargo transported.

4.1.2 Step 2: Analyses

4.1.2.1 Economic analysis

Economic analysis was focused on estimating the monetary value converted from the difference in the cargo transported between the two scenarios; that was 149,057.73 m^3. In this context, this study assumed that the alternative scenario would require one more voyage for transporting the remainder. Hence, the operation costs for the additional voyage were taken into account for the alternative scenario. The following parameters were used for the calculation.

- Daily fuel consumption: 82.8 t/day
- Fuel price: $473.5/t in Hong Kong (Ship&Bunker 2018)
- Labor cost: $4,000/month/crew (by curtesy of a Korean LNG shipping

company)

- Cost of ship chartering: $85,000/day (Corkhill 2018)

Therefore, total cost for one voyage was estimated at about $ 17.1 M.

4.1.2.2 Environmental analysis

Table 16 shows emission quantities from LNG engine operation and their potential costs. From the ship operational profile, the following parameters were considered for the analysis.

- Operation load : NCR (nominal continues rating) 10,845 kW
- Engine running hour: 1,024 h/voyage

Table 16 Engine emission levels and potential costs (unit: g/kWh) (emission data in gas only mode was referenced from the emission test file 2018 by curtesy of MAN Diesel, Maibach et al. 2008)

	Emission types						
	CO_2	O_2	CO	NO_x	HC	SO_x	PM (mg/m^3)
Qty (g/kWh)	577	1,359	0.64	11.58	0.19	10.96	0.54
Cost ($/ton)	24	-	-	3,900	-	6,600	60,700

Total cost of environmental impact was estimated at about $ 10.6 M.

4.1.2.3 Risk analysis

4.1.2.3.1 Risk models related to vapour pocket in LNG cargo tanks

The starting point for this study was the assumption that the LNGC cargo tanks had been filled to 98.5%(at loading temperature) at an LNG terminal and then scenarios that could resulted in isolated vapour pockets was explored and then the risk associated with these scenarios was assessed.

It should be understood that the excessive static list or trim condition specified in 8.2.17 of IGC Code where isolated pockets may form could stem from the events of a grounding, collision or contact. The relevant data of these accident scenarios was based on MSC 83/INF.3 "FSA-Liquefied Natural Gas(LNG) Carriers Details of the Formal Safety Assessment".

The main assumptions of the scenario are as follows:

- Striking(active or passive in terms of collision): For striking ships, the probability receiving critical damage is assumed to be negligible. It is considered that LNG carrier is struck in 50% of the collision accident.
- Loading conditions (laden voyage or ballast voyage): Vapour pocket could occur in loaded conditions.
- Damage in cargo area or not: In terms of the possibility of vapour pocket, the list condition is more critical than trim condition due to tank shape. In light of this, the damage in the cargo area was considered.
- Critical damage (Cargo tank damage) : A critical damage in this study means the case of any damage in the cargo areas that extends through the double hull and also penetrates the cargo tanks in loaded conditions. The LNG leak from cargo tank has significantly high risk than the leak from the vent mast due to vapour pocket.
- Vapour pocket occurrence: This study considered only the case of the damage of double hull damage(not cargo tanks) in considering the vapour pocket scenario.

Taking account of the above, the modeling of the scenario on vapour pocket in LNG cargo tanks was developed as shown in Figure 8(Left):

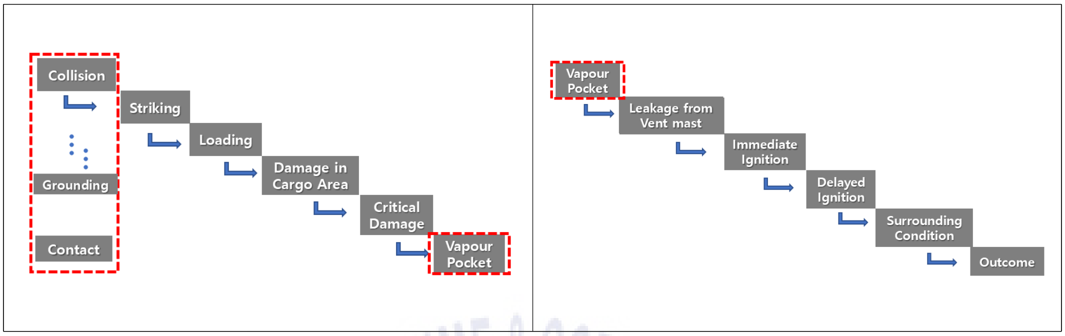


Figure 8 Risk model for vapour pocket

As aforementioned above, no isolated vapour pocket should be created within the cargo tank under the trim and list specified in 8.2.17 of the IGC Code when a filling limit greater than the limit of 98% is permitted. In light of this, the assumption is that a possibility for the base scenario (98 %) on the occurrence of the isolated vapour pocket in the event of the excessive list or trim condition was considered zero in this study, while 100% for alternate scenario (98.5%).

Following the occurrence of vapour pocket in the cargo tank, the assumptions for scenario of the consequence were considered as shown in Figure 8(Right):

- Leakage(overflow) from vent mast : The event that may lead to this overflow cannot be precisely calculated as it depends on a number of factors. The overflow of cargo liquid into the vapour header earlier before the overflow from vent mast. Nonetheless, a conservative assumption that "if isolated vapour pocket is created, and then overflow from vent mast always arise" was used.

- Immediate ignition in the vent mast & Delayed ignition : the probability of ignition which is commonly determined by the phase and release rate was estimated; and a DNV model for immediate ignition as presented in Table 17 and OGP models for delayed ignition described in Table 18 were used in this study.

Table 17 Probability of immediate ignition (DNV 2012)

Release rate (kg/s)		Immediate ignition probability
Gas	Liquid	
Less than 1	Less than 1.2	0.0001
1-10	1.2-25	0.001
Over 10	Over 25	0.01

Table 18 Probability of delayed ignition (Pesce, Paci et al. 2012, Jeong et al. 2017, OGP 2010)

Release rate(kg/s)	Ignition condition		
	Gas (open deck)	Gas (congested)	Liquid
0.1	0.001	0.001	0.001
0.2	0.0011	0.0023	0.0014
0.5	0.0011	0.0066	0.0022
1	0.0012	0.015	0.003
2	0.0022	0.0174	0.0042
5	0.005	0.0213	0.0066
10	0.0091	0.0247	0.0092
20	0.0168	0.0287	0.0129
50	0.025	0.035	0.02
100	0.025	0.04	0.028
200	0.025	0.04	0.028
500	0.025	0.04	0.028
1000	0.025	0.04	0.028

- Surrounding condition (opened or congested condition): The condition of the leakage from vent mast was considered "opened condition"
- Outcomes (flash fire, jet fire/pool fire, VCE(explosion), no fire(Cryogenic Damage*)): The events for flash fire and jet fire/ pool fire were only considered.

  *Cryogenic damage was not considered at this study

Table 19 shows the historical records of accidents associated with LNG carriers. Given that, there has no accidental record leading to LNG release from any cargo tank, such accidents are not directly contributed to what we were concerned. However, in this analysis, we have taken a conservative stance where assuming all accidental frequencies for vapour pocket may lead to the release of LNG. In addition, the release of LNG was assumed to claim the total loss of life.

Table 19 Accident frequency estimates (IMO 2007, Vanem, Antao et al. 2008).

Accident category	Accidents	Frequency(per ship year)
Collision	19	6.7×10^{-3}
Grounding	8	2.8×10^{-3}
Contact	8	2.8×10^{-3}
Total	35	1.23×10^{-2}

4.1.2.3.2 Event Trees

Based on the information summarized above, the event trees on the scenarios related to vapour pocket due to the collision, grounding and contact were developed as shown in Figure 9, Figure 10 and Figure 11. The first five levels (from the left) were based on the "FSA – LNG Carriers" indicated in

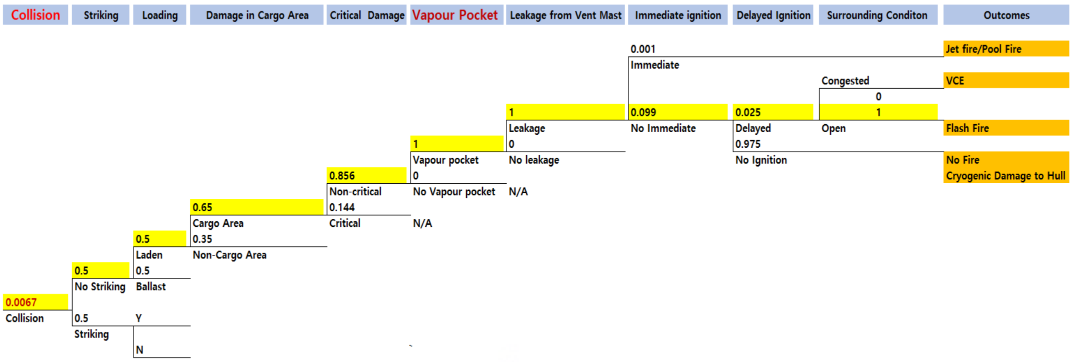


Figure 9 Event tree for collision – vapour pocket

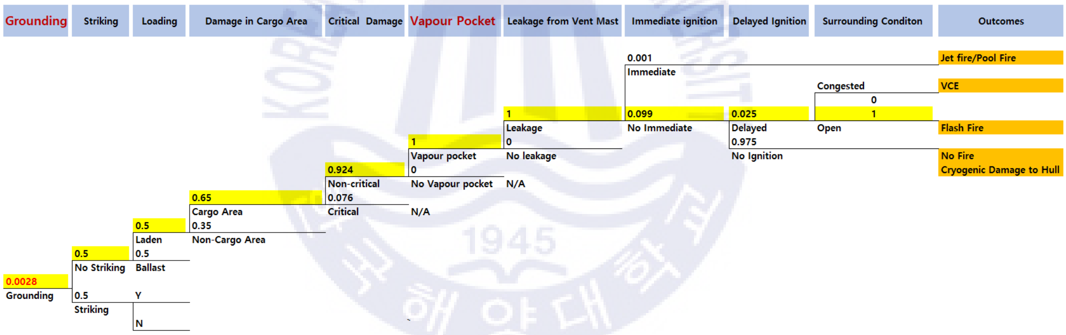


Figure 10 Event tree for grounding – vapour pocket

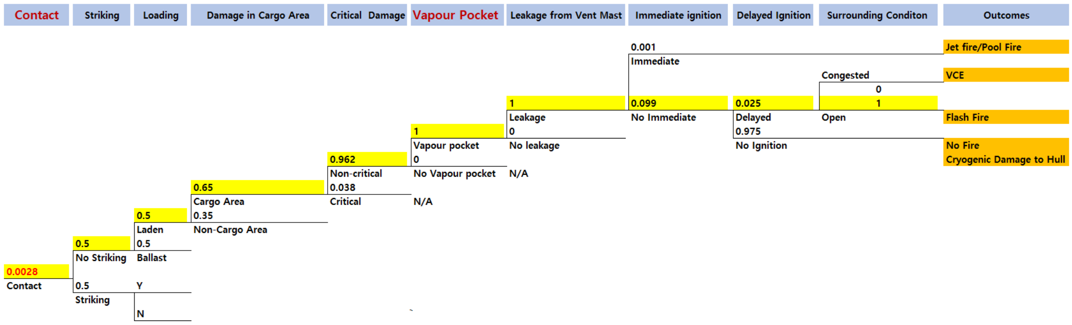


Figure 11 Event tree for contact – vapour pocket

For the process of risk analysis and conversion to costs, the following parameters are used.

- Cost of fatality: $ 3,000,000 / person (IMO 2007)
- Number of fatalities at sea : 30 persons (crews)
- Vessel voyage: sea going – 84.8 % and other than sea going – 15.2 %

Total cost of risk was about $4.4 M.

4.1.3 Step 3: Integration

This step integrates the results of the analyses carried out in the previous step. Given the all impacts were converted into the monetary values, the stakes of the results represent the total costs for each scenario. The results are shown in Figure 12, revealing that the alternative scenario requires about $ 23.5 M more than the base scenario.

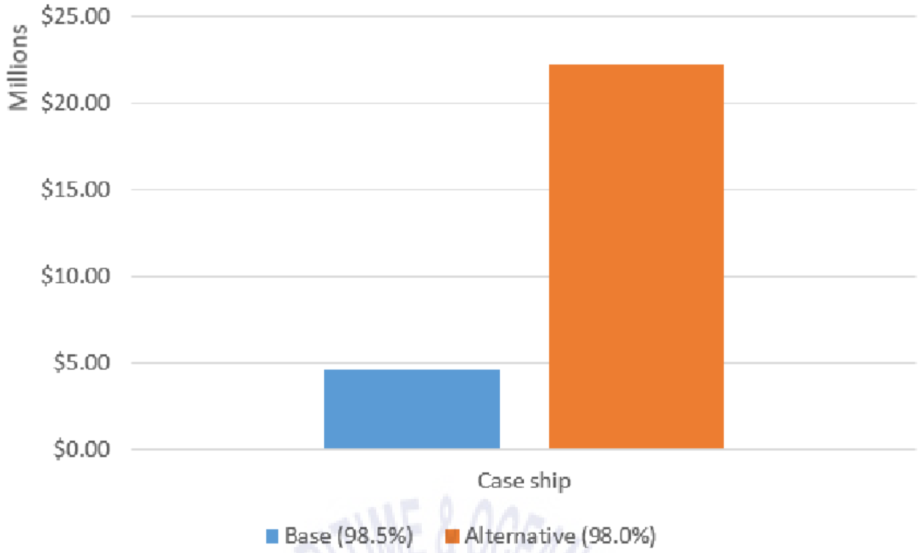


Figure 12 Total costs for base and alternative scenarios

4.1.4 Step 4 : Evaluation of the best scenario

Given the total cost of the alternative case is higher than that of the base case, it can be said that the base scenario is more desirable than the alternative one. Moving back to the original question, it can be concluded that the filling limit of LNG cargo can be kept 98.5 % rather than reduced to 98.0 %. It may be considered that this statement verifies the inadequacy of the new IGC Code requirements on the filling limit.

Given different characteristics across LNG carriers and their voyage profiles, it can be argued that the analysis results obtained from a single case ship may be dangerous to accept for the general observation. In this context, we have extended this study to some other LNG carrier to achieve a general trend or discrepancy. The information of the selected vessels are as shown in Table 20.

Table 20 Information of case vessels

Vessel	DWT [ton]	Engine type	Speed [kts]	Tank capacity [m^3]	Engine [kW]	One voyage [days]
A	75,463	Steam turbine	20.3	138,366	28,610	30
B	71,041	Steam turbine	19.3	138,366	20,596	17
C	75,079	Steam turbine	20.3	138,214	21,334	16
D	75,159	Steam turbine	20.3	138,333	28,603	30

Given the selected vessels are run by steam turbine systems, emission levels from the exhaust gases are calculated based on Table 21.

Table 21 Steam turbine emission levels (unit: kg/tonnes) (Entec 2002)

	Emission types						
	CO_2	O_2	CO	NO_x	HC	SO_x	PM (mg/m^3)
Qty(g/kWh)	3,200	-	0.43	6.98	-	60	2.5

Figure 13 shows the results of sensitivity analysis where the same trends were observed across the cases. That states the base scenario is absolutely optimistic than the alternative scenario.

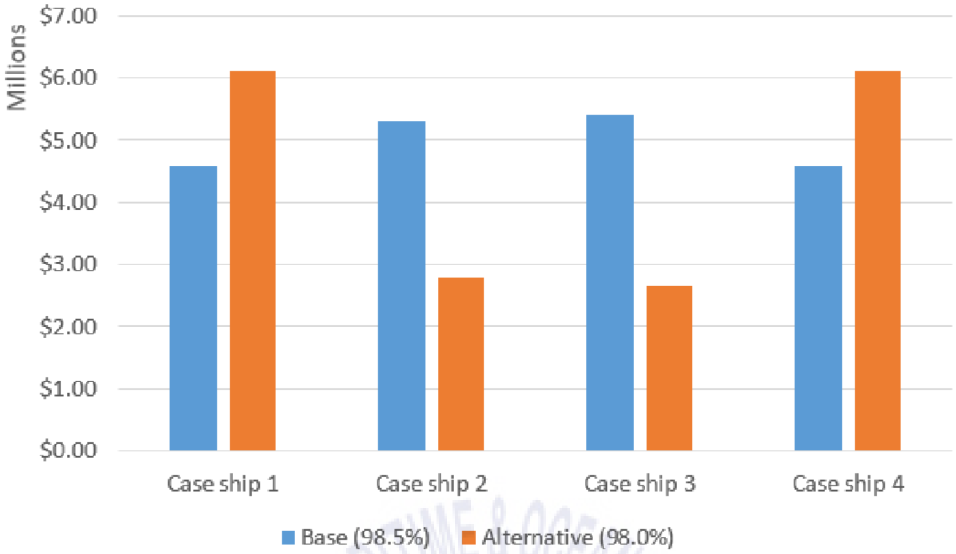


Figure 13 Total costs for base and alternative scenarios for various ships

The sensitivity analysis brought an interesting result. For case ships 2 and 3, it turned out the total costs associated with Base scenario are higher than these with alternative scenario.

The common characteristics of those vessels were that they were engaged in relatively short route; one voyage was more or less 16 days only. However, other vessels, which had more than 30 days for a single voyage, revealed that the total costs of alternative scenario is higher than the base one. From this, we can confirm that the time duration spent for each voyage is the key parameter to determine whether the base case is optimistic or not.

4.2 Discussion

This study investigated a regulatory discrepancy regarding the LNG filling limit of the cargo tank between the original and the new IGC Code. According to the new IGC Code, without design modification, the LNG carriers with keels laid, or at a similar point of construction, on or after 1 July 2016 are subject to 98% of the LNG filling limit, while the existing LNG carriers built before the milestone can continue to ship 98.5% of the LNG filling limit with LNG cargo.

The findings are believed to provide stakeholder insight into the demonstration of the inadequacy of the new regulation. This paper concluded that the LNG filling limit should be returned to 98.5 % as presenting the holistic benefits of such a scenario.

Hence, it revealed that the overregulation to be considered could bring severe commercial, economic and administrative burdens upon national administrations and the industry. Therefore, it can be believed that the appropriate level of regulation is crucial to avoid adverse effects on the sustainable development of shipping and trade.

On the other hand, we may need a more in-depth analysis of statistics and data so that we can really understand the underlying trends and causal factors of casualty transport. Wherever possible, we, therefore, can ensure that additions and modifications to the regulatory framework to be based on relevant statistics, research and analysis

Chapter 5 Conclusion

This paper provides a valuable insight towards developing new regulations on LNG carriers and LNG fuelled ships as well as investigating and evaluating the adequacy of current regulations. Research findings can be summarised as below:

- Through the gap analysis, it was found that the LNG-fuelled-ships are generally subject to a higher level of safety requirements by the IGF Code, compared to the equivalences for LNG carriers by the IGC Code. It seems to have originated from the gap between the brevity of LNG fuelled ships and LNG carriers with the perfect safety records. However, it was also thought that some regulations in these Codes lacked clear technical justification, whereas some others appeared to be too severely applied, disregarding the successful safety record of LNG carriers over the several decades.
- Given the different risk natures between delivering LNG as cargo and using LNG as fuel, the two Codes may not be able to be fully identical; if a clear technical justification is provided, different regulations may be acceptable. However, it should be noted that the equal level of safety requirements must be applied at least where the same systems and arrangements are applied. The disparity in the safety requirements for the engine room systems can be a good example.
- The study suggests that the IMO should consider these findings, taking into account both experience and technical developments when the IMO

periodically review these Codes and consider to amend the regulation in the Codes. In particular, the following parts in IGC Code and IGF Code were proposed to go through a rigorous revision for bridging the gaps of the safety requirement for the engine room system: concept of machinery space (chapter 3.1.2), the stress analysis on piping system (chapter 3.1.4.1) and the safety requirements for duct and double wall pipe (chapter 3.1.4.3) and ventilation (chapter 3.1.4.5) discussed in this study.

- Given that regulatory compliance should be practical and cost-effective, based on appropriate environmental, technical and socio-economic considerations, this study on the revised regulation of filling limit in LNG cargo tank is regarded a good example of providing procedures for examining the adequacy of certain regulations. This not only takes into account the work done to reduce administrative burdens, but also paves the way for better regulation, avoiding unnecessary requirements and addressing useless and unnecessary requirements.

- Finally, it is important to note that the use of the proposed multi-criteria decision making process expected to contribute to strengthening the future regulatory process toward probabilistic and realistic evidence-based path rather than deterministic path.

References

Arnsdorf I. 2013 Dec 4. Shell, GE to build nation’ s first LNG fueling stations for cargo ships. Bloomberg News. [accessed 2018 May 5].

https://fuelfix.com/blog/2013/12/04/shell-ge-to-build-nations-first-lng-fueling-stations-for-cargo-ships/

Aronson JD, Westermeyer W. 1982. Us public and private regulation of LNG transport. Mar Policy. 6(1):11-26.

BP, 2018 Jul 18. Fleet first: new gas ships set sail with latest tech. BP Magazine. [accessed 2018 Nov 15].

https://www.bp.com/en/global/corporate/bp-magazine/innovations/new-lng-liquefied-natural-gas-ships-support-bp-strategy.html

Corkhill M. 2017 Apr 24. The world’s LNG-fuelled ships on order. LNG World Shipping.

Corkhill, M. 2018 Aug. 31. LNG world Shipping - Healthy freight rates and 2018 LNG shipping predictions. from https://www.lngworldshipping.com/news/view,healthy-freight-rates-and-2018-lng-shipping-predictions_50323.htm [accessed 2018 Aug 31].

DNV, 2012. Failure Frequency Guidance: Process Equipment Leak Frequency Data for Use in QRA. Oslo Norway.

DNVGL. 2018. LNG regulatory update “Best fuel of the future “, conference & study tour

Entec. 2002. Quantification of ship emissions

IGU. 2018. 2018 World LNG Report. World Gas Conference Edition.

IMO. 2007. MSC 83/INF.3 FSA – Liquefied Natural Gas (LNG) Carriers Details of the Formal Safety Assessment London, London: International Maritime Organizaion.

IMO. 2009. MSC 285(86). Interim guidelines on safety for natural gas-fuelled engine installations in ships. London: International Maritime Organizaion.

IMO. 2010. Comments on the report of the Correspondence Group on the Development of the Draft International Code On Safety For Gas-Fuelled Ships (IGF Code). BLG 15/6/1(France).

IMO. 2011a. Development of Provisions For Gas-Fuelled Ships. Report of the working group (Part 1). BLG 15/WP.5.

IMO. 2011b. Development of Revised IGC Code. Report of the correspondence group. BLG 16/7.

IMO. 2011c. Proposals for modifications to the draft IGF Code. BLG 16/6/2(Japan).

IMO. 2011d. Proposal for modifications to the draft revised IGC Code. BLG 16/7/2(Norway).

IMO. 2011e. Report to the Maritime Safety Committee and the Marine Environment Protection Committee. BLG 15/19

IMO. 2012a. Report to the Maritime Safety Committee and the Marine Environment Protection Committee. BLG 16/16

IMO. 2013a. Development of risk-based distance criteria for gas fuel tanks for inclusion in the draft IGF Code, SDC 1/24(Norway)

IMO. 2013b. Harmonizing distance criteria for gas fuel tanks and assumed penetration depth providing appropriate collision protection and damage stability, SDC 1/24/4(CESA)

IMO. 2013b. Report of the Maritime Safety Committee on its Ninety – Second Session,. MSC 92/26.

IMO. 2014a. Report of the Maritime Safety Committee, SDC 1/26

IMO. 2014b. Report of the Maritime Safety Committee on its Ninety – Fouth Session,. MSC 94/21.

IMO. 2014c. International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk(IGC Code), Resolusion MSC.370(93) adopted on 22 May 2014

IMO. 2015a, Measures for bunkering safety operation, MSC 95/3/14(Japan)

IMO. 2015b. Report of the Working Group, Adoption of IGF Code. MSC95/WP.7

IMO. 2015c. International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels(IGF Code) , Resolution MSC.391(95)

IMO. 2015d. Editorial clarifications needed in order to ensure homogeneous application of risk assessment in conjunction with part A-1 of the draft IGF Code, MSC95/3/15 (China, Germany, Japan, Republic of Korea, Spain and CESA)

IMO. 2016a. Draft unified interpretations on the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code). CCC 3/10/1(IACS).

IMO. 2016b. Report of the Working Group, Amendments to The IGF Code and Development Of Guidelines For Low-Flashpoint Fuels. CCC 3/WP.3.

IMO. 2016c. Report to the Maritime Safety Committee and the Marine Environment Protection Committee. CCC 3/15.

IMO. 2016d. Unified Interpretations of the IGF Code. MSC.1/Circ.1558

IMO. 2017a. Proposed amendments to the IGF Code. CCC 4/3/1(IACS)

IMO. 2017b. Report to the Maritime Safety Committee and the Marine Environment Protection Committee. CCC 4/12.

ISO. 2015. Guidelines for systems and installations for supply of LNG as fuel to ships. Geneva, Switzerland.

Fernandez IA, Gomez MR, Gomez JR, Insua AB. 2017. Review of propulsion systems on LNG carriers. Renew Sust Energ Rev. 67:1395-1411.

Saleem A, Farooq S, Karimi IA, Banerjee R. 2018. A CFD simulation study of boiling mechanism and BOG generation in a full-scale LNG storage tank. Comput Chem Eng. 115:112-120.

Jeong B, Lee BS, Zhou P, Ha S. 2017. Evaluation of safety exclusion zone for LNG bunkering station on LNG-fuelled ships. J Mar Eng Technol. 16(3):121-144.

Jeong, B., Oguz, E., Wang, H., & Zhou, P. 2018. Multi-criteria decision-making for marine propulsion: Hybrid, diesel electric and diesel mechanical systems from cost-environment-risk perspectives. Applied energy, 230, 1065-1081.

Maibach, M., Schreyer, C., Sutter, D., Van Essen, H. P., Boon, B. H., Smokers, R., & Bak, M. 2008. Handbook on estimation of external costs in the transport sector. Ce Delft.

Mankabady S. 1979. Financing LNG carriers. Mar Policy. 3(3):225-231.

Nwaoha T, Yang Z, Wang J, Bonsall S. 2013. A fuzzy genetic algorithm approach for analysing maintenance cost of high risk liquefied natural gas carrier systems under uncertainty. J Mar Eng Technol. 12(2):57-73.

OGP, 2010. Risk Assessment Data Directory. Ignition probabilities, London, UK.

Øyvind P, Erikstad SO. 2017. A two-stage optimization approach for sulphur emission regulation compliance. Marit Policy Manag. 44(1):94-111.

Pesce, M., et al. 2012. Modelling ignition probabilities within the framework of quantitative risk assessments. Chemical Engineering Transactions 26: 25-31.

Rahim MM, Islam MT, Kuruppu S. 2016. Regulating global shipping corporations' accountability for reducing greenhouse gas emissions in the seas. Mar Policy. 69:159-170.

Ryuichi S, Usami T, Furuichi M, Teranishi H, Kato H. 2018. How do the new shipping routes affect Asian liquefied natural gas markets and economy? Case of the Northern Sea Route and Panama Canal expansion. Marit Policy Manag. 45(4):543-566.

Ship&Bunker 2018. World Bunker Prices. from https://shipandbunker.com/prices #MGO [accessed 9 May 2018].

SIGTTO. 2009. ESD Arrangements & Linked Ship/ Shorre Systems For Liquiefied Gas Carriers.

SIGTTO. 2011. Recommendations for Manifolds for Refrigerated Liquefied Gas Carrier.

Vanem, E., et al. 2008. Analysing the risk of LNG carrier operations. Reliability Engineering & System Safety 93(9): 1328-1344.