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Study on safety escort of LNG carriers in port water area

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STUDY ON SAFETY ESCORT OF LNG CARRIERS IN PORT WATER AREA

By

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DECLARATION

I certify that all the material in this research paper that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this research paper reflect my own personal views, and are not necessarily endorsed by the University

(Signature): Wang Lei

(Date): 29th June 2017

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ABSTRACT

Title of Research paper: **Study on Safety Escort of LNG Carriers in Port Water Area**

Degree: **MSc**

In this research paper, the properties of LNG and the specialties of LNG carrier are firstly introduced. Then, the data of 170 LNG carrier accidents collected from 1964 to 2017 are analyzed, and the conclusion of most accidents happened in port is drawn.

Simultaneously, the Formal Safety Assessment (FSA) is carried out to analyze the navigational risks of LNG carriers and to prove the conclusion. Furthermore, it is concluded that the risk of collision between LNG carriers and merchant ships is a medium risk and should be controlled. It is decided to reduce the probability of collision by establishing a Moving Safety Zone around LNG carriers, and to mitigate the severity of consequences of the accident by setting the Leakage Hazard Zone, and to protect the two zones by means of tugs or boast escort.

Through the studies on the theory of Ship Domain and the empirical coefficient, the mathematical model of Moving Safety Zone is introduced, by which the scope of Moving Safety Zone can be quantitatively calculated and obtained. On the other hand, the pool fire experimental results of Sandia National Labs are used to classify 3 categories of Leaking Hazard Zones of LNG carrier. Finally, the general standards, requirements, plans and supports for tugs or boats escort are recommended to enhance the practicality of this paper.

KEY WORDS: LNG carrier, port water area, safety escort, accident data analysis, Formal Safety Assessment, Moving Safety Zone, Leaking Hazard Zone.

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LIST OF ABBREVIATIONS

AIS	Automatic Identification System
BLEVE	Boiling Liquid Expanding Vapor Expansion
CEE	Center for Energy Economics
Col/Cnt	Collision or Contact
CCS	Cargo Containment System
DOE	United States Department of Energy
DWT	Dead Weight Tonnage
EM	Equipment failure
ECDIS	Electronic Chart Display and Information System
FSA	Formal Safety Assessment
FSRU	Floating Storage and Regasification Unit
FE	Fire or Explosion
GRT	Gross Tonnage
GIIGNL	International Group of Liquefied Natural Gas Importers
Grd	Grounding
HW	Heavy Weather
ISM	International Safety Management
IMO	International Maritime Organization
IGU	International Gas Union
IGC	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

IMDG	International Maritime Dangerous Goods Code
L/U	Loading and Unloading
LHZ	Leaking Hazard Zone
MSZ	Moving Safety Zone
OCIMF	Oil Companies International Marine Forum
RPT	Rapid Phase Transition
RADAR	Radio Detection and Ranging
RPG	Rocket Propelled Grenade
SIGTTO	Society of International Gas Tanker and Terminal Operators
SIRE	Ship Inspection Report
VTS	Vessel Traffic Service

CHAPTER 1

INTRODUCTION

1.1 Background

LNG, as an efficient and clean energy, has drawn great attentions of most countries around the world. The LNG shipping industry also flourished with the energy demand, environmental protection requirements, technological upgrading and regional inequalities of resource distribution. From the first LNG commercial shipments in 1964 (CH • IV international [CH • IV], 2014, p.3), to the end of 2016, the number of LNG fleets has increased to 478 carriers, and the total transport volume has reached 69,300,000 m^3, covering the world's major energy consuming countries and regions (The International Group of Liquefied Natural Gas Importers [GIIGNL], 2017, p.12). However, as a way of energy transport, the hazards and potential risks of LNG carriers facing are more serious than other ships. Although there has not been a record of a total loss of ship or a death of crewmember in the course of LNG shipping history (CH • IV, 2014, p.3), the accidents caused by the inadvertent storage and transport of LNG on land are harrowing. In 1944, a LNG tank damage occurred in the United States Cleveland and the LNG vapor ignited and exploded, killing 128 people and 225 injured (CH • IV, 2014, p.6). In 1973, an explosion happened in the process of LNG tank maintenance in Staten Island, the

United States, which resulted in 40 lives instantly disappear (CH • IV, 2014, p.9). These painful accidents have always reminded us, to this energy beast, we must always maintain awe. In the chain of LNG mining, refining, transportation, storage and use, even a tiny negligence is not allowed. Especially for the LNG shipment, the crew and carriers face with a more critical environment, the safety requirements and standards should be more rigorous.

1.2 Objective

The author of this paper is a 10 years experienced port VTS officer, who has an insightful understanding to the traffic safety and risk management of LNG carrier. In order to perfect his own work and provide referable experiences, the author extensively studied all aspects of the LNG shipping industry chain, and found that the current studies on LNG carriers safety mainly focus on the LNG carrier construction, LNG cargo storage, port loading and unloading operations and safety management, etc., yet the navigational safety of LNG carriers during in port were considered less. As a result, the author finally chose the topic "Study on Safety Escort of LNG Carriers in Port Water Area" as the research direction. For the high-risk cargo transportation, although there is a good safety record before, the risks of LNG shipment would not disappear before unloading from ships. Any negligence may lead to a chain reaction and eventually lead to disaster. Especially in the port water area, the navigable waters are limited, the hydrological and meteorological conditions are complicated, the densely populated areas are nearby, and the ecological environment is fragile. In addition, in recent years, the number and volume of LNG carriers have increased significantly; the navigational safety of LNG carriers in port has become a very sensitive and cannot be ignored problem. At present, effective and reasonable ship escort should be one of the best external safety measures to protect LNG carriers in port.

1.3 The current studies

Internationally, people has accumulated a great deal of experience in the safety management of LNG carrier, LNG terminal management, cargo handling operations and personnel training, and technologies and norms are becoming more integrated. And many authoritative industry organizations such as the Oil Companies International Marine Forum (OCIMF) and some of the ship classification societies have published a number of LNG carrier transport-related technical standards and operational guidelines.

The International Group of Liquefied Natural Gas Importers (GIIGNL) had studied the frequency of accidents and the amount of cargo leakage that occurred in the LNG industry during the period 1965-2007. The results showed that the indicators have been reduced to a lower point after 2000; the main causes of the accident were improper operation and improper equipment maintenance; the most of accidents happened in the process of LNG loading and unloading; Earthquakes, typhoons and other force majeure have little effect on the accidents occurrence. (Anthony & Deborah & Pierre, 2013, p. 17)

Erik Vanem et al. Collected 182 LNG carrier accidents from 1964 to 2006, divided them into eight types of risk models, quantified the risks by using event tree method, and found that the risks were mainly concentrated in collision, grounding, fire or explosion and loading or unloading accidents, in which the collision is the highest risk value. The study concluded that the risks of LNG carrier transport are within acceptable scope. (Vanema, Antaob, Østvikc, & Comas, 2008, p. 134)

The United States CH • IV international and the Center for Energy Economics (CEE) of the University of Texas publish LNG Industrial Safety Accident Statistics at regular intervals. The statistics on LNG carrier accidents indicate that LNG carriers had maintained a good safety record, no large-scale leakage occurred. (Center for Energy Economics [CEE], 2012, p.5)

In the report of "FSA, Liquefied Natural Gas (LNG) Carriers - Details of the Formal Safety Assessment" (MSC 83 / INF.3) submitted by the Danish Government to IMO in 2007, the 158 LNG carriers accidents occurred during transport were collected. Through Formal Safety Assessment (FSA), the main risks are identified, analyzed and controlled, and the control options are evaluated and the recommendations are put forward. Not only provided the risk control options for LNG carrier transportation, but also provided a scientific risk assessment method. (International Maritime Organization [IMO], 2007, p.3)

The Moving Safety Zone in this paper is defined as that in the process of LNG carrier navigating in port, in order to ensure the safe navigation, a certain area of waters is set around it, which is a controlled area, other ships are prohibited from entering. The scope of the area shall be related to the ship's maneuvering abilities, the cargo hazards and the port navigational environment; the Leaking Hazard Zone is defined as a dangerous area established after the occurrence of LNG carrier's accident, if other unrelated ships and persons enter the area, they would suffer threats to their own safety. The scope of the area is related to the severity of the accident, the hazard extent of cargo and natural environment, etc.

In the article "Liquefied Natural Gas (LNG) Infrastructure Security: Background and Issues for Congress", Paul W. Parfomak referred to the safety zone and guard zone around the LNG facility which was set up by the United States Coast Guard in response to terrorist threats. And the scopes of these areas were described; meanwhile the necessary security measures were required to protect them. (Paul, 2003, p. 13)

In 2009, Professor Jamin Koo et al. used the event tree method to study the safety issues of LNG receiving stations. Through the risk analysis software PHAST, they simulated the accidental leakage of LNG, and obtain the dimensions of safety zone and explosive hazard zone. (Koo, Kim, So, & Yoon, 2009, p.330)

In 2012, Doctor Michelle Michot Foss released the article of "LNG safety and security". In this research report, some of the properties of LNG were summarized, and proposed to establish a safety zone to protect LNG carriers, including the safety measures, as well as the factors which would influence the establishment of a safety zone. (CEE, 2012, p.39)

From 2008 to 2011, Sandia National Lab (the United States), according to the request from The National Energy Board, carried out a series of experiments and computational simulations for LNG carrier leakage, including containment system damage and leaking analysis, tank hole size analysis after collision, large scale LNG fire test, LNG hull steel plate low temperature damage analysis and LNG carrier joint damage analysis, the results provide a comprehensive LNG leakage accident related data. It is concluded that the hazard area of the LNG carrier can be determined according to the heat flux within a certain period and area. (United States Department of Energy [DOE], 2012, p.22)

In 2013, Henryk Sniegocki gave a comprehensive application of SIGTTO's recommendations on LNG carriers' channel, underkeel clearance, air draught, turning waters, VTS, traffic separation scheme, moving safety zone and ship speed limits. Finally, he recommended that people should follow the SIGTTO requirements and recommendations and also should take into account the local situation. (Henryk, 2013, p. 420)

According to the "Design Code of General Layout for Sea Ports" (JTS165-2013) issued by the Ministry of Transport of China in 2013, it requires traffic control and boats escort when LNG carrier navigating in port water area. In addition to the escort, other ships should keep at least 1 nm from the navigating LNG carriers. In practice, to ensure the navigational safety of LNG carrier, most of ports have established their own escort regime and moving safety zones. (Design Code of General Layout for Sea Ports 2013)

1.4 Methodology and data resources

The study methods used in this paper include:

(1) Using general statistical analysis and cross analysis to analyze the accident data;

(2) Using the Formal Safety Assessment (FSA) method recommended by IMO to analyze the navigational risks of LNG carrier in port;

(3) Using the theory of ship domain in the field of Marine Traffic Engineering to calculate and determine the scope of Moving Safety Zone.

The data in this paper are mainly derived from:

(1) International Maritime Organization（IMO）;

http://www.imo.org/

(2) The International Group of Liquefied Natural Gas Importers（GIIGNL）;

http://www.giignl.org/

(3) The Society of International Gas Tanker and Terminal Operators (SIGTTO);

http://www.sigtto.org/

(4) CH·IV International;

http://www.ch-iv.com/

(5) Center for Energy Economics (CEE);

http://www.beg.utexas.edu/energyecon/

(6) United States Department of Energy (DOE);

https://energy.gov/

(7) BP Amoco;

https://www.bp.com/

(8) International Gas Union (IGU);

http://www.igu.org/

(9) Oil Companies International Marine Forum (OCIMF).

https://www.ocimf.org/

1.5 Structure of paper

In this research paper, the properties of LNG carriers and cargos are firstly introduced in chapter 2. Then, the data of 170 LNG carrier accidents collected from 1964 to 2017 are analyzed, and the conclusion of most accidents happened in port is drawn in chapter 3. Subsequently, in the chapter 4 the Formal Safety Assessment (FSA) is carried out to prove the conclusion and to analyze the navigational risks of LNG carriers. Furthermore, it is concluded that the risk of collision between LNG carriers and merchant ships is a medium risk and should be controlled. In chapter 5, it is decided to reduce the probability of collision by establishing the Moving Safety Zone, and to mitigate the severity of consequence of the accident by setting the Leakage Hazard Zone, and to protect the two zones by means of tugs or boats escort. Simultaneously, through the studies on the theory of Ship Domain and the empirical coefficient, the mathematical model of Moving Safety Zone is introduced, by which the scope of Moving Safety Zone can be quantitatively calculated and obtained. On the other hand, the pool fire experimental results of Sandia National Labs are used to classify 3 categories of Leaking Hazard Zones of LNG carrier. Finally, the general standards, requirements, plans and supports for tugs or boats escort are recommended to enhance the practicality of this paper.

CHAPTER 2

LNG and LNG carrier

2.1 Properties of LNG

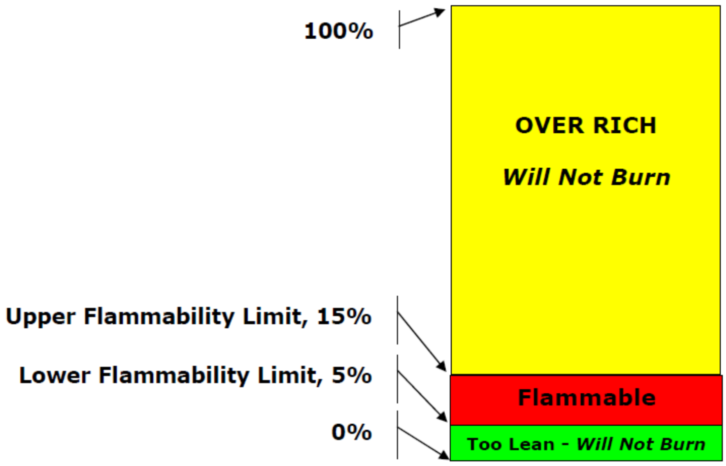
2.1.1 Physicochemical properties

Methane is the main component of Natural gas. It is classified as Class 2.1 dangerous goods in "International Maritime Dangerous Goods Code" (IMDG Code), which is with the properties of colorless, odorless, non-toxic, flammable, incorrosive, soluble in oil, but insoluble in water, softening rubber, etc. Under a standard atmospheric pressure, the gaseous density is 0.7174kg/m^3; the relative density of 0.5548 (relative to the air density), lighter than air; it can be liquefied either by compressing or by cooling; the boiling point is -161.5℃.

Liquefied Natural Gas (LNG) is obtained by cooling the natural gas under an atmospheric pressure to -162℃, so that to facilitate storage and transportation. 1m^3 LNG gasification can be about 600m^3 of natural gas (Nakazawa, 2016, p.60). The liquid density of LNG is about 45% of the water density; it will float on the surface if leaking into water.

2.1.2 Leaking hazards

(1) Pool fires. If LNG spills occur near an ignition source, a mix of the evaporating gas and air will burn above the LNG pool. Such pool fires are intense and burn far more rapidly and hotly than e.g. oil and gasoline fires. Furthermore, they cannot easily be extinguished and all the LNG must normally be consumed before they go out (IMO, 2007, P.8). Methane flammable range is between 5% and 15% (CEE, 2012, p.14), as shown in Figure 2.1. For methane vapors derived from LNG, with a fuel-air mixture of about 10 percent methane in air and atmospheric pressure, the



autoignition temperature is above 1000 ℉ (540 ℃) (CEE, 2012, p.15).

Figure 2.1 - Flammable Range for Methane (LNG)

Source: CEE. (2012). *LNG safety and security*. Retrieved June 2, 2017 from the World Wide Web: http://www.beg.utexas.edu/energyecon/LNG_Safety_and_Security_Update_2012.pdf

(2) Cryogenic temperatures. LNG is produced by cooling down the natural gas to -162 ℃. If it is released, direct contact with the cryogenic liquid will freeze the point of contact and damage tissues of humans, animals and aquatic fauna. Embrittlement leading to structural failure and equipment damage may also occur when materials not designed for such low temperatures come into contact with LNG. (IMO, 2007,

p.8)

(3) Asphyxiation. Because the volume of LNG is only 1/600 of the volume of natural gas at atmospheric pressure, a non-ignited LNG vapor could displace breathable air (IMO, 2007, p.8), causing the oxygen content in the air to drop rapidly. If the oxygen content in the air is less than 15%, the human behavior will be affected. If the oxygen content is reduced to below 6%, the person in this air will die.

(4) Rapid Phase Transition. LNG leakage occurs and contacts with water, because the density of LNG is smaller than the water's, it will float on the surface of water. If a large number of LNG leak to the water, it may vaporize too quickly causing a rapid phase transition (RPT) (CEE, 2012, p.19). Such a rapid phase transition might have the potential to shatter windows and glass nearby but is only assumed to constitute a minor hazard to nearby people and structures (IMO, 2007, p.8).

(5) Explosion. LNG is obtained by low temperature treatment at atmospheric pressure, so the damage to the cargo hold cannot cause an explosion. However, if the LNG inside the containment system is affected by an external fire source, the pressure in the tank will increase rapidly, eventually causing the explosion. This is called the Boiling Liquid Expanding Vapor Expansion (BLEVE). According to record, LNG carrier has not suffered such incidents, but liquefied petroleum gas storage tank had such an accident. (Alderman, 2005, p. 147)

2.2 Specialties of LNG carrier

2.2.1 General specialties

(1) High construction cost. LNG carriers transport LNG with -162 ℃ low temperature, such ship is a high-tech, high challenge and high value product, single carrier cost about 200 million US dollars.

(2) Strict construction requirements. LNG carrier is a 2G type ship. A type 2G ship is

a gas carrier intended to transport the products that require significant prototypes to preclude their escape. (International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk [IGC], 2014, p. 17)

(3) Gigantism. In recent years, due to the strong competition of LNG world trade, the loading capacity of single LNG carrier is continuously increased. At present the largest Q-Max type LNG carrier loading capacity has reached 260,000m^3.

(4) High freeboard. Due to the special structure of LNG cargo hold, the freeboard of carrier is higher than ordinary ships, so the impact of wind and current will be more obvious than others. At the same time, due to the small density of goods, the center of gravity of LNG carrier would also be higher after loading.

2.2.2 Structural features

Depending on the different cargo containment system, LNG carriers engaged in ocean-going transport are dominated by two types of design, spherical type and membrane type. Both spherical and membrane carriers are double-hulled, equipped with 4-6 cargo tanks and no longitudinal bulkheads.

(1) Spherical type LNG carrier (Moss type): the patent of spherical tank belongs to Norway Moss Maritime Corporation (http://www.mossww.com), which launched in 1973 for the first time. The cargo tank is made of aluminum alloy, and the shape is a sphere. The wind effect is strong to the carrier due to the high freeboard and tank shape. It is difficult to maneuver with low ship's speed, and the blind area in front of ship is large.

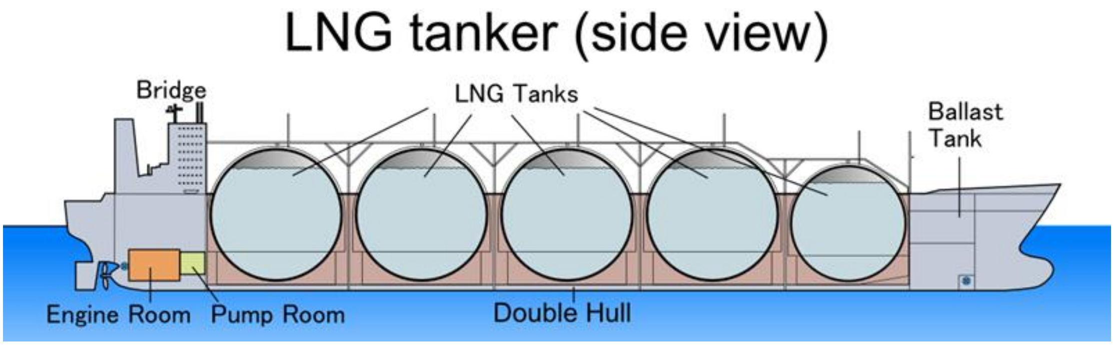


Figure 2.2: Side view of spherical type LNG carrier

Source: Retrieved June 2, 2017 from the World Wide Web: http://www.wikiwand.com/fr/Méthanier

(2) Membrane type LNG carrier: the patented technology is developed by the French company Gaztransportz & Technigaz (GTT) (http://www.gtt.fr). The main models are Mark III and No.96. The loading capacity of cargo tank is large, and the wind effect is small on deck, the view from bridge is better than Moss type. But the height of LNG in tank is limited due to sloshing effect (CEE, 2012, p.19).

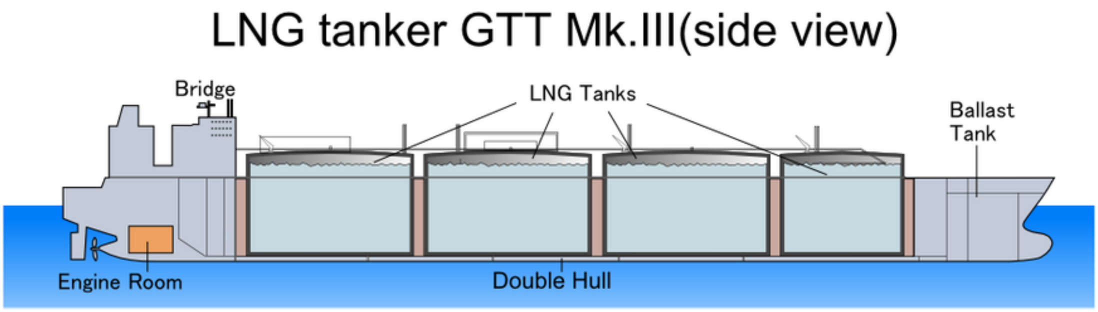


Figure 2.3: Side view of membrane type LNG carrier

Source: Retrieved June 2, 2017 from the World Wide Web: http://www.wikiwand.com/fr/Méthanier

2.2.3 Maneuvering characteristics

(1) Large blind area, significant impact from wind and current. Due to the structural features of LNG cargo tank, LNG carrier has a larger blind area, keeping lookout is

more difficult. On the other hand, LNG carrier has higher freeboard and wider body. When encountered with strong wind or current, the impact will be more obvious than ordinary ships.

(2) Big inertia force due to the gigantism of ship. One of the common characteristics of large ships is the large inertia force, coupled with the structural characteristics of LNG carriers, which led to the ship's longer stopping distance.

(3) Bad rudder efficiency. Compared with ordinary ships, LNG carrier has relatively poor rudder efficiency. Especially in the case of full loaded, LNG carrier's huge inertia will affect the ship’s steering; prolong the reaction time of course altering. As a result, the officers or captain of LNG carrier are required to take measures earlier; when at the low speed, they are required to take a large steering angle to overcome.

(4) Poor heading stability. LNG carriers, especially large LNG carriers, are relatively poor in heading stability. Some of LNG carriers are equipped with bow thruster, but the power is often not enough.

In summary, the LNG carrier's maneuverability is relatively poor, and considering the high risk of LNG cargo, it needs larger water area for buffering. So the safety zone is set in some ports, and patrol boats and tugs escort are very necessary.

2.2.4 LNG fleets

At the end of 2016, the total LNG tanker fleet consisted of 478 vessels at the end of 2016. It included 24 FSRUs (Floating Storage and Regasification Unit) and 30 vessels of less than 50,000 cubic meters. Total shipping capacity at the end of 2016 stood at 69.3 million cubic meters. Total operational capacity (vessels that are known to be in service) amounted to 64.7 million cubic meters (GIIGNL, 2017, p.12). 10 new orders were placed, including one FSRU and 3 bunkering vessels. Comparing with 33 new orders placed in 2015. This is the lowest number of new orders since 2010. At the end of 2016, the order book comprised of 137 carriers, 121 of which were above 50,000 cubic meters. 64 vessels were scheduled for delivery in 2017(GIIGNL, 2017, P12).

For the ship's type, at the end of 2016, there were 337 membrane type LNG carriers, 115 moss types and only 26 other types. In the case of loading capacity, 349 LNG carriers (73%) were within the loading capacity of 90,000-170,000 m^3, 90 ships were Q-Flex and Q-Max (19%) models. In terms of age, the average age of current fleet is about 11 years and nearly 60% of ships are below 10 years and nearly 80% of ships are less than 15 years old. The following figure 2.4 gives more details.

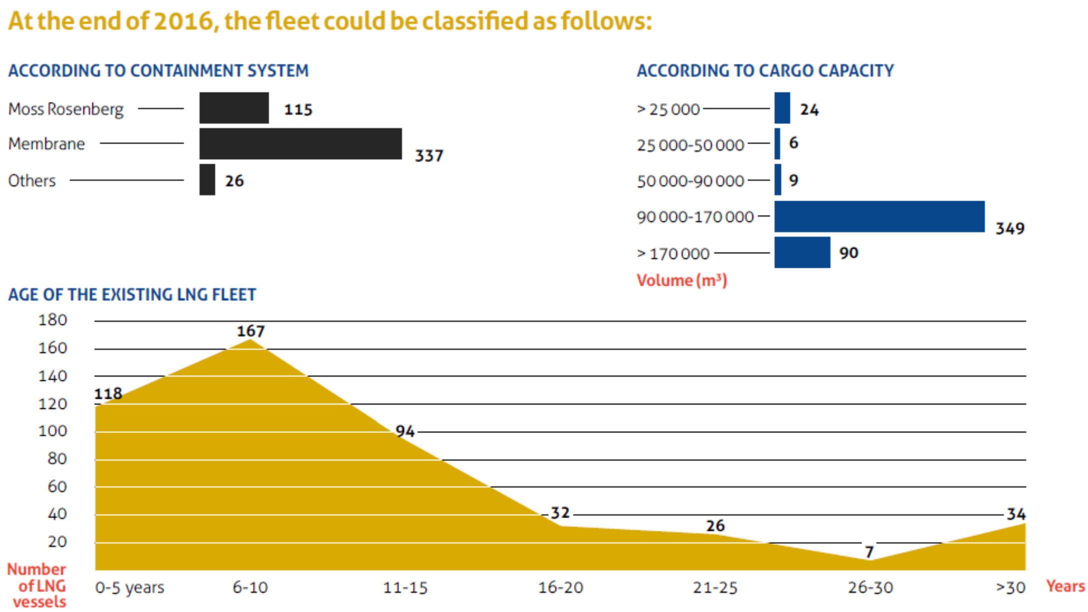


Figure 2.4: LNG fleets at the end of 2016

Source: GIIGNL. (2017). *annual report 2017*. Retrieved June 2, 2017 from the World Wide Web: http://giignl.org/sites/default/files/PUBLIC_AREA/Publications/giignl_2017_report_0.pdf

At present, the world's largest LNG shipwners include Qatar Gas, Petronas, Teekay Corporation and Mitsui OSK Lines (MOL). Among them, up to the early of 2017, the fleet of Qatar Gas consists of 63 wholly- and jointly-owned LNG, and has a combined carrying capacity of over 8.5 million cubic meters or 15% of the world capacity (http://www.nakilat.com.qa/Page/Vessel). Teekay Shipping. Up to May 2017, its LNG fleet includes 32 wholly-owned carriers and other 18 newbuildings are on order, and has a combined carrying capacity of over 5.5 million cubic meters or 9% of the world capacity (http://teekay.com/fleet/).

2.3 Chapter summary

In this chapter, the hazards of LNG transportation are introduced from the aspects of LNG cargo and carrier respectively, the structural features of LNG carrier are explained and the present LNG fleets in the world are introduced. Meanwhile, the maneuvering abilities of LNG carrier are summarized to pave the way for the accident analysis.

CHAPTER 3

Data analysis

3.1 Scope of data collection

The LNG carrier accident data collected in this paper is mainly composed of two parts:

(1) Most of the accident data is derived from a document "FSA − Liquefied Natural Gas (LNG) Carriers − Details of the Formal Safety Assessment" (MSC 83/INF.3) issued by IMO. The report was submitted by the Government of Denmark in 2007 to conduct a risk assessment of LNG carriers in accordance with today's highly respected Formal Safety Assessment (FSA). In the report, Erik Vanem and Rolf Skjong et al. collected a total of 182 incidents and accidents related to LNG carriers with more than 62,000 GRTs from 1964 to 2005 (including 2005), in which 24 accidents were caused in the process of ship's construction, dock maintenance, pirate attacks, towing, trial flights, so they were removed. The remaining 158 incidents and accidents were taken as standard samples and were analyzed in detail in the report. (IMO, 2007, p.5)

(2) After 2005, the LNG carrier market had experienced several delivery peaks. The number of fleets had grown from just exceeding 200 (2006) to 478 (2017). Due to the influence of market supply and demand and ship's gigantism, many advanced technologies have been applied to the construction of new LNG carriers, which are

far-reaching for the safety of LNG carriers in the future. In order to reflect the rapid growth of the number of LNG carriers in the past 10 years and consider the safety improvement brought by advanced technology as far as possible, this paper collected 13 cases of LNG carrier incidents and accidents (see appendix) from the beginning of 2006 to the early of 2017. One of them is removed because of pirate attack. The remaining 12 accidents, combined with the 158 incidents collected from the IMO report, total 170 LNG carrier accidents are analyzed in this paper.

3.2 Overview of statistical indicators

The following 3 statistical indicators are selected to analysis the accident data of LNG carriers:

(1) **Accident time**. Refers to the year when the accident occurred, which can better reflect the time distribution of the accidents. Every five years is a time period in this paper;

(2) **Ship status** when accident occurred. A complete LNG carrier voyage cycle includes: loading at LNG export terminal, followed by long distance sailing to LNG receiving terminal, after unloading at the receiving terminal, back to the export terminal. The main operations of the LNG carrier during the whole period can be divided into Loading/Unloading, Maneuvering in port, Mooring/Anchoring, En route and others (incomplete records). (Chen, 2015, p.21)

(3) **Accident types**. In this paper, the types of LNG carrier accidents are divided into 7 categories (in IMO MSC 83/INF.3 report, the types of accident were classified into 8 categories. In this paper, combine the collision with contact as 1 category), which are: cargo leaking while loading and unloading (**L/U**), collision or contact (**Col/Cnt**), grounding (**Grd**), fire or explosion (**FE**), ship equipment failure (**EM**), heavy weather (**HW**) and cargo containment system damage (**CCS**).

3.3 Summary of overall accidents

A total of 170 LNG carrier accidents from 1964 to 2017 are collected in this paper. Figure 3.1 shows the time distribution of accidents as per 5-year interval (only 4 years from 2014 to 2007). The number of historical accidents experienced a rapidly increase from the early of 1970s. After 10 years, around the year of 1980, it reached the peak and then declined suddenly. Until the beginning of 1990s, it recovered to the level of the early of 1970s, which was around 10 accidents every 5-year. Finally, it stabilized below 10 accidents in each period.

Since the LNG carrier was officially put into operation in 1964, the number of LNG carrier accidents increased from less than 10 accidents per 5 years to 70 accidents around the early of 1980s. Then the number surged to the historical peak (70 accidents from 1979 to 1983), accounting for 41.2% of the total number, and soon dropped in the beginning of 1980s. However, the overall number of accidents in 1980s was still higher than other periods. In the 1990s, the trend of LNG carrier accidents tended to be stable, approximate 10 accidents in each 5 years. After entering the 20th century, in every 5 years the number of accidents further dropped to the single digits. In the total 170 accidents, there were 28 accidents of LNG cargo leakage; all the accidents did not result in death of crewmember. If separating the location of the 170 accidents into in port and en route, there were 113 cases happened in port, 42 occurred en route, and other 15 accidents cannot be inferred through the records. It is clear that the number of accidents occurred in port is significantly larger than that en route.

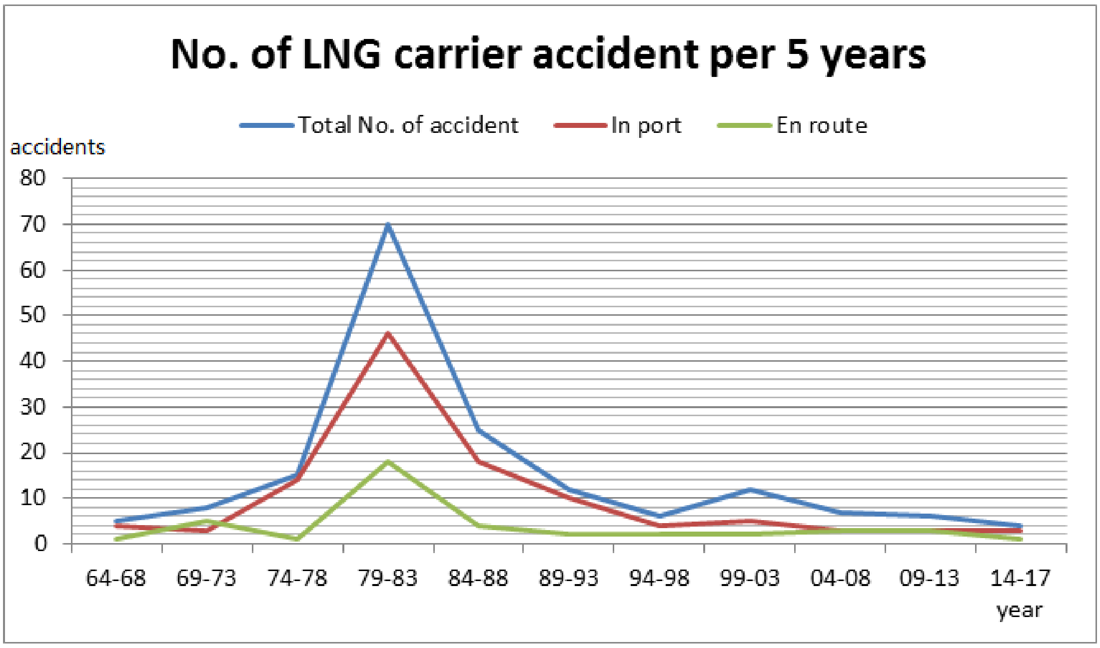


Figure 3.1: Number of LNG carrier accidents per 5 years, 1964-2017

Some experts had expressed doubts about the surge in accidents from the late 1970s to the early 1980s, and they had also analyzed the phenomenon in the assessment report submitted to the IMO by the Danish government, believing that “Possibly, the relatively high number of casual occur from 1976 to 1985 may be due to underreporting of accidents by periods and do not necessarily mean that the actual number of which was very much higher in this period (E.g. information about merely four incidents occurring during the years 1991-1995 seems very low). (IMO, 2007, p.21)

3.4 Statistical analysis

3.4.1 Accident time

The period of 1974-1988 had experienced the highest frequency of LNG carrier accidents, 110 accidents, accounting for 54% of the total number, and an average of

37 accidents every 5 years, much more than other periods with the average level of 7.5 accidents every 5 years. The main reasons for causing this situation may be found in the aspects of technology, management and personnel qualification.

(1) The design and construction technology for LNG carrier at early day was in an experimental and initial stage. There are Conch type, Esso type and Worms type LNG carriers (collectively referred to as "other types") before the occurrence of Membrane type and Moss type. France's Gaz Transport No.82 membrane type LNG carrier first appeared in 1969, France's Technigaz's Mark I type membrane type LNG carrier was first introduced in 1972, and Norway's Moss Maritime's first moss type LNG carrier was built in 1973. Compared with other types, they are more advanced in technology and safer for crew.

(2) At the beginning of 1980s, although the fleets of LNG carriers were continuously increasing, the conventions or norms for LNG carrier design and construction, LNG cargo handling and personnel training had been delayed. The design and construction of the original LNG carrier was in accordance with the requirements issued by classification societies. And when it became aware of the need for a globally harmonized rule, IMO established "the International Code for the Construction and Equipment of Liquefied Gases in Bulk (IGC)", which adopt as the mandatory amendments to the SOLAS Convention and entered into force at 1 July 1986. This convention significantly promoted the safety management level of LNG carriers.

(3) The above two points are more from the view of "ship". For controlling the "human factors" in LNG carrier accidents, except the requirements of IMO Convention, some standards and guidelines issued by committees and organizations are also contributing. The Society of International Gas Tanker and Terminal Operators (SIGTTO) was established in 1979 with an initial 13memberships (http://www.sigtto.org). It was established to harmonize the safe operating standards between carriers and terminals. The members of the organization shared technical

experiences or work with other related organizations to develop technical specifications and operational guidelines to improve the operational safety of LNG carriers, terminals and personnel. Today, the members of SIGTTO control 97% of LNG carriers and terminals around the world. More than 50 books, guidelines and recommendations have been published, covering all aspects of LNG shipping industry. Similarly, Oil Companies International Marine Forum (OCIMF) (https://www.ocimf.org/) was established in 1970, similar to the nature of SIGTTO, the members are major oil companies. In addition to the publication of the standards and guidelines, OCIMF also presented the Ship Inspection Report (SIRE) in 1993 to inspect the OCIMF members' ships in accordance with the SIRE procedure. The inspection is not only closely related to the management of the tanker, but also related to ship management and crew quality. SIGTTO and OCIMF's industry standards are usually subject to the IMO Convention.

It can be seen that the most frequent occurrence of LNG carrier accidents was in the period of 1974-1988, which was just the time before IMO and those organizations launching the convention and guidelines. The number of LNG carrier accidents has been significantly reduced after the promulgation of the above rules and regulations.

3.4.2 Ship status

In this paper, when accidents occurred the status of LNG carriers are divided into 5 categories, which includes **Loading/Unloading**, **Maneuvering in port**, **Mooring/Anchoring**, **En route** and **others** (incomplete records). Through the analysis to the selected 170 accident samples (as shown in Table 3.1), It is known that the number of the accidents occurred during cargo handling operations is the largest (56 cases), accounting for 32.9% of the total, followed by 43 accidents occurred during the ship Maneuvering in port, and 14 accidents occurred when ships were anchoring or mooring. The above status normally happened in port, totally accounting for 66.5% of the all accidents.

Table 3.1- The overall distribution of LNG carriers' status when accident occurred

Operation	Occurrence No.	Percentage	Cumulative Percent
Loading/Unloading	56	32.9%	32.9%
Manoeuvring in port	43	25.3%	58.2%
Mooring/Anchoring	14	8.3%	66.5%
En route	42	24.7%	91.2%
Others	15	8.8%	100%
Total	**170**	**100%**	

Source: Primary data are derived from the IMO report "*FSA – Liquefied Natural Gas (LNG) Carriers – Details of the Formal Safety Assessment*" (MSC 83/INF.3) (2007) and the appendix of this paper

Table 3.2 shows the distribution of ship's status when accident occurred over every 5 years. The accidents occurred during loading and unloading operations still rank the first, with an average of 5.1 accidents every 5 years. The accidents occurred during maneuvering in port changed significantly over the periods, with 79.1% occurred before 1989. The accidents occurred during anchoring and mooring were few and scattered. The number of accidents occurred during sailing en route and the number of the accidents occurred during maneuvering in port were almost the same, with 3.8 accidents per 5 years. Sum up the accidents occurred in ports, we could obtain an average of 10.3 accidents per 5 years, which are almost 3 times of the average number of accidents occurred outside of ports. Based on the above analysis, we may conclude that the accidents involving LNG carriers often occurred in port.

Table 3.2- The every 5-year distribution of LNG carriers' status when accident occurred

Time (year)	Loading/ Unloading	Manoeuvring In port	Mooring/ Anchoring	En route	Others	Total
1964-1968	3	0	0	1	1	**5**
1969-1973	4	1	0	2	1	**8**
1974-1978	6	3	3	2	1	**15**
1979-1983	20	22	2	19	7	**70**
1984-1988	9	8	2	4	2	**25**
1989-1993	5	2	2	2	1	**12**
1994-1998	2	2	0	2	0	**6**
1999-2003	2	3	2	3	2	**12**
2004-2008	2	2	0	3	0	**7**
2009-2013	3	0	0	3	0	**6**
2014-2017	0	0	3	1	0	**4**
Total	**56**	**43**	**14**	**42**	**15**	***170***

Source: Primary data are derived from the IMO report "*FSA – Liquefied Natural Gas (LNG) Carriers – Details of the Formal Safety Assessment*" (MSC 83/INF.3) (2007) and the appendix of this paper

3.4.3 Accident types

In this paper, the types of LNG carrier accidents are divided into 7 categories, which include cargo leaking while loading and unloading (**L/U**), collision or contact (**Col/Cnt**), grounding (**Grd**), fire or explosion (**FE**), ship equipment failure (**EM**), heavy weather (**HW**) and cargo containment system damage (**CCS**). The percentage and cumulative percent of the 7 types of accidents are shown in Table 3.3. The ship equipment failure (**EM**) (60 cases) was the most frequent accidents, accounting for 35.3% of the total number of the accidents, followed by the collision or contact (**Col/Cnt**) accidents and cargo containment system damage (**CCS**) accidents, which also reached as many as 30 cases and 27cases respectively. The accidents of cargo leakage while loading and unloading (**L/U**) were also very frequent accidents, which were 24 cases. The frequency of fire or explosion (**FE**), grounding (**Grd**) and heavy weather (**HW**) were less than others, each only no more than 10 cases. Judging from the frequency of accidents, the most frequent two types of accidents were the ship equipment failure (**EM**) and collision or contact (**Col/Cnt**).

Table 3.3- The distribution of the types of LNG carriers' accidents

Type	Occurrence No. (accidents)	Percentage (%)	Cumulative percent (%)
EM	60	35.3%	35.3%
Col/Cnt	30	17.6%	52.9%
CCS	27	15.9%	68.8%
L/U	24	14.1%	82.9%
FE	10	5.9%	88.8%
Grd	10	5.9%	94.7%
HW	9	5.3%	100%
Total	**170**	**100%**	

Source: Primary data are derived from the IMO report "*FSA – Liquefied Natural Gas (LNG) Carriers*

– *Details of the Formal Safety Assessment"* (MSC 83/INF.3) (2007) and the appendix of this paper

3.4.4 Cross analysis

Subsequently, a cross-analysis of the distribution of accident types and ship status are shown in Table 3.4:

Table 3.4 - The cross analysis between accident types and ship status

Type	Loading/ Unloading	Manoeuvring In port	Mooring/ Anchoring	En route	Others	Total
EM	19/26%	12/27.9%	4/28.6%	22/52.3%	3/20%	**60**
Col/Cnt	2/4%	**18/41.9%**	3/21.4%	7/16.7%	0	**30**
CCS	4/8%	3/7.0%	4/28.6%	9/21.4%	7/46.7%	**27**
L/U	24/48%	0	0	0	0	**24**
FE	7/14%	2/4.7%	0	0	1/6.7%	**10**
Grd	0	5/11.6%	2/14.3%	3/7.1%	0	**10**
HW	0	3/7.0%	1/7.1%	1/2.4%	4/26.7%	**9**
Total	**56**	**43**	**14**	**42**	**15**	***170***

Source: Primary data are derived from the IMO report "*FSA – Liquefied Natural Gas (LNG) Carriers – Details of the Formal Safety Assessment"* (MSC 83/INF.3) (2007) and the appendix of this paper

As can be seen from Table 3.4, the most of categories of accident types occurred in the process of LNG carrier maneuvering in port (6 kinds of accident types had appeared), in which the most common type of accidents was collision or contact (**Col/Cnt**), accounting for 41.9%, followed by equipment failure (**EM**) accounting for 27.9%. The proportion of grounding (**Grd**) accidents also reached 11.6%. Through the cross analysis, it can be seen that due to the port limit, including narrow navigable waters and high density traffic, the mainly external threat to the safety of LNG carriers in port is collision risk.

3.5 Chapter summary

In this chapter, the author mainly analyzed the historical accident data of LNG carriers. Through the overview of accident trends and the analysis for the three statistical indicators (the accident time, ship status and accident types), the following conclusions are drawn: the number of LNG carrier accidents reached a peak around 1980s, and then with the improvement of relevant technology and promulgation of mandatory conventions, the trend of accidents has been effectively curbed; In all 170 incidents, the most of accidents occurred in ports, accounting for 66.5%. The collision is a major risk threatening the safety of LNG carriers while maneuvering in port.

CHAPTER 4

Risk assessment

4.1 Risk factors

The influential factors to the safety of LNG carrier while maneuvering in port include but not limited to human factors, ship factors and navigational environment.

4.1.1 Human factors

Human factors mainly include the crew's misoperation, carelessness and negligence etc., which could cause ship's accident. It is widely believed that about 80% of marine accidents are caused by human factors. Therefore, it is very important to study the human factors and analyze the risks of personnel behavior in shipping and take corresponding preventive measures. In order to ensure the safety of LNG carriers while maneuvering in port and to reduce the impact of human factors, all crewmembers served on board a LNG carrier should hold the qualification certificates issued in accordance with STCW convention. In addition, the crew should also have the necessary safety knowledge and operational skills for LNG, hold the appropriate certificate of competency or special training certificate.

4.1.2 Ship factors

Ship factors include both the ship itself and the ship management. Ship's quality and its seaworthiness are the prerequisite for safe navigation. Of course, the factors of ship itself include but not limited that whether the fire-fighting equipment, life-saving appliances, navigation equipment and other mechanical and electrical equipment are in good order.

4.1.3 Navigational environment

(1) Navigable waters. It refers to the safe place or space for ship's movement, composed of port waters and waterways. The port waters include harbor basin, mooring area, anchorage, U-turn area, etc. The waterway is a lane with a certain depth, width, clearance height and bending radius which can be safely used for navigating.

(2) Natural environment. It refers to the weather, hydrology, terrain condition, etc. Meteorological conditions include visibility, wind, water depth, current, tides, waves, freezing, etc.; terrain conditions include the width and bend of the waterway, uneven bottom, shoal reefs, etc.

(3) Traffic conditions. It refers to the layout of the port and waterways, navigation aids and facilities, traffic flow and density, VTS management, etc.

4.2 Identification of hazards

The purpose of hazard identification is to identify a list of hazards and associated scenarios prioritized by risk level specific to the problem under review. This purpose is achieved by the use of standard techniques to identify hazards which can contribute to accidents, and by screening these hazards using a combination of available data and judgment (IMO, 2015, p.8). It is the first step of Formal Safety Assessment (FSA). The methods of hazard identification include identification of possible hazards and ranking them:

(1) **Identification of possible hazards**: The approach used for hazard identification generally comprises a combination of both creative and analytical techniques, the aim being to identify all relevant hazards. And a coarse analysis of possible causes and initiating events and outcome of each accident scenario should be carried out. (IMO, 2015, p.8)

(2) **Ranking**: The identified hazards and their associated scenarios relevant to the problem under consideration should be ranked to prioritize them and to discard scenarios judged to be of minor significance. (IMO, 2015, p.8)

According to the results of LNG carrier accident statistics analysis in chapter 3 of this paper, and refer to other researches regarding the safety of LNG shipment, the hazards of LNG carrier navigating in port mainly include 3 categories and rank them as follow:

(1) LNG carriers collide with other ships (**LNG carrier collision**);

(2) LNG carriers contact with pier or other mooring ships (**LNG carrier contact**);

(3) Navigational accident related to severe natural environment (**Severe natural environment**).

4.3 Risk analysis

After identifying the potential risks for LNG carrier navigating in ports, the risk value of each risk items should be quantitatively analyzed by use of accident and failure data and other sources of information as appropriate to the level of analysis. The risk analysis refers to the process of quantifying the probability of accident occurrence and the severity of accident consequence, which could be obtained by analyzing the historical accident data and estimating the loss of life and property. The procedure includes: analyzing the likelihood of occurrence of a risk event (**probability**); estimating the severity of hazard of the possible risk event (**consequence**); calculating the risk value of the possible risk event.

The risk analysis is estimated for all uncertainties and risk factors in the process of LNG carrier navigating in port. A comprehensive and systematic analysis of the probability of each risk and the severity of the consequence should be carried out. The main task of risk analysis is to rank the risk scenario. In the follow-up risk assessment, we need only to analyze the high risk and medium risk events in detail, ignore the low risk events, grasp the key points, and reduce the risk value. Therefore, the objects of the risk analysis for LNG carrier navigating in port are to analyze the individual risks, rather than the societal risks.

4.3.1 The methods of risk analysis

The methods of risk analysis include **risk probability estimation** method and **risk consequence estimation** method. The risk probability estimation is mostly based on statistical analysis and inference method. Statistical analysis refers to the historical statistical data or a large number of tests to estimate the probability, which is an objective estimate; inference method is that when the data is incomplete, experts based on experience, knowledge or similar events to infer the probability, which is a personal subjective judgment. Risk consequence estimation methods include probabilistic tree analysis, Monte Carlo simulation, etc. Mainly through the use of modern computer technology, the use of probability theory and mathematical statistics principles for probability analysis, indicating the severity of the risk.

The risk is determined by the consequences and the probability. The **risk matrix** is an effective risk management tool which can achieve quantitative risk analysis by estimating the consequences and the probability. The basic idea of the risk matrix is to establish a standardized matrix for the reference of ranking risk. Through proper quantifying and ranking the consequence and probability of risks, people can establish a standard matrix for the reference of an identified risk, and determine the rank of the risk. By ranking the risk, people can concentrated on the high and medium risk and ignore the low one.

In this paper, the risk probability (**P**) is divided into 4 ranks, from 1 (Extremely remote) to 4 (Frequent), as listed in Table 4.1.

Table 4.1- The frequency index of risk occurrence

Classes	**Risk probability (P)**	**probability Index (per ship-year)**	**Definition**
1	Extremely remote	10^{-5}	Likely to occur once in the lifetime (20 years) of a world fleet of 5,000 ships.
2	Remote	10^{-3}	Likely to occur once per year in a fleet of 1,000 ships.
3	Reasonably probable	0.1	Likely to occur once per year in a fleet of 10 ships.
4	Frequent	10	Likely to occur once per month on one ship

Source: Refers to the appendix 4 "*Initial Ranking of Accident Scenarios*" in IMO document "*Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO Rule-making Process*" (MSC-MEPC.2/Circ.12/Rev.1) (2015).

The severity of consequences (**C**) is also divided into 4 ranks, from 1 (Minor) to 4 (Catastrophic), see Table 4.2. Among them, the severity of consequence is related to property losses, personnel injuries and other factors. Because LNG leakage has little impact on the environment, environmental damage factors are not considered.

Table 4.2- The severity index of consequence

severity of consequences (C)		**1**	**2**	**3**	**4**
		Minor	Significant	Severe	Catastrophic
People	Crew	Single or minor injuries	Multiple or severe injuries	Single fatality or multiple severe injuries	Multiple fatalities
	Others	No injury	Single or minor injuries	Multiple or severe injuries	Fatalities or multiple severe injuries
Property		Local equipment damage	Non-severe ship damage	Severe damage	Total loss
Severity Index (Equivalent fatalities)		0.01	0.1	1	10

Source: Refers to the appendix 4 "*Initial Ranking of Accident Scenarios*" in IMO document "*Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO Rule-making Process*" (MSC-MEPC.2/Circ.12/Rev.1) (2015).

To facilitate the ranking and validation of ranking, it is generally recommended to define consequence and probability indices on a logarithmic scale. A risk index may therefore be established by adding the probability/frequency and consequence indices (IMO, 2015, p.39).

In general: Risk (R') = Probability (P') * Consequence (C')

So: Log (R') = log (P') + log (C')

P '- actual probability, the corresponding probability rank is P, and P = log (P');

C'- actual consequence, the corresponding consequence rank is C, and C = log (C');

R'- actual risk, the corresponding risk rank is R, and R = log (R').

So it is possible to quantify the risk value using the following formula: R = P + C.

(IMO, 2015, p.39)

The risk matrix for LNG carriers navigating in port is shown in Table 4.3 and the risk ranks are shown in Table 4.4.

Table 4.3- Risk matrix

Occurrence Possibility (P)		Consequence Severity (C)			
		1	2	3	4
		Minor	Significant	Severe	Catastrophic
1	Extremely remote	2	3	4	5
2	Remote	3	4	5	6
3	Reasonably probable	4	5	6	7
4	Frequent	5	6	7	8

Source: Refers to the appendix 4 "*Initial Ranking of Accident Scenarios*" in IMO document "*Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO Rule-making Process*" (MSC-MEPC.2/Circ.12/Rev.1) (2015).

Table 4.4- Risk rank

Risk Value	Rank
≤ 4	Low Risk
5、6	Medium Risk
≥ 7	High Risk

Source: Refers to the appendix 4 "*Initial Ranking of Accident Scenarios*" in IMO document "*Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO Rule-making Process*" (MSC-MEPC.2/Circ.12/Rev.1) (2015).

4.3.2 Risk estimation

According to the risk matrix, the rank of the risks identified in section 4.2 could be estimated as shown in Table 4.5.

Table 4.5- Risk estimation of LNG carrier navigating in port

Hazards	Accidents & Incidents	P	C	R
LNGC collision	LNGC collides with tug	2	1	3
	LNGC collides with barge	2	2	4
	LNGC collides with fishing boat	3	1	4
	LNGC collides with commercial ship	2	3	5
LNGC contact	LNGC contacts with obstruction	2	1	3
	LNGC contacts with wharf or other port constructions	1	2	3
	LNGC contacts with mooring ship	2	2	4
Severe natural environment	Severe weather	1	3	4
	Typhoon	1	3	4
	Earthquake	1	3	4
	Adverse tide or current	2	2	4
	Poor visibility	3	1	4

In general, due to the uncertainties of small draft boats maneuvering in port, the probability of collision involving LNG carriers and them (e.g. fishing boats) would be reasonably probable, but to consider the little damage to large LNG carriers, the consequence is minor, so the risks is low. By contrast, although the probability of collision involving LNG carriers and other big merchant ships navigating in port is remote, the consequence would be severe, so the risk is medium. To consider the risks result from the severe natural environment like typhoon, the consequence would normally significant or severe. However, because the minor probability of occurrence of natural catastrophes and the weather is predictable, so the risk is low. In conclusion, the risk of collision involving LNG carriers and other merchant ships is medium risk, which should be controlled.

4.4 Risk control options

For the medium risk, there are some effective measures and options to deal with. Through the proper service and management of port VTS, it can be controlled. And the mandatory pilotage is also a good choice. In this paper, the safety escort of LNG carrier in port would be discussed in the following chapter.

4.5 Chapter summary

In this chapter, the risk analysis for LNG carrier navigating in port is carried out by the mean of FSA. Firstly, the influential factors to the safety navigation of LNG carriers are introduced from three aspects: human, ship and environment. Secondly, according to the conclusion of chapter 3 the hazards to LNG carriers are identified. And then the risks of causing these hazards are quantificationally analyzed by using risk matrix. It is concluded that the risk of collision involving LNG carriers and other merchant ships in port is a medium risk and should be controlled. Finally, one of the risk control options, safety escort, is mentioned to prepare for next chapter.

CHAPTER 5

Safety escort

According to the statistical analysis of LNG carrier accident in Chapter 3, it is known that the frequency of collision accident is the highest (accounting for 41.9%) while LNG carriers navigating in port. By the risk analysis in Chapter 4, it is concluded that the risk of collision involving LNG carriers and other merchant ships in port is a medium risk, which should be controlled. The risk estimation method described in Section 4.3.1 shows that the risk of an accident is determined by the probability and the consequence of the accident. Therefore, to reduce the risk, people have to minimize the probability of collision and the severity of consequence.

A port authority could reduce the probability and the consequence of collision through establishing a traffic separation scheme to separate opposite traffic flows, and through establishing a port VTS to harmonize the traffic situation and to enhance the emergency response. The ship could reduce the probability and consequence of collision through using AIS, ECDIS and other advanced navigational equipment to assist collision avoidance, and through carrying out emergency drill to promote the safety awareness of crewmember. Of course, the implementation of safety escort for LNG carriers in port is also a good way to reduce the probability and the consequence of collision. In order to well organize the escort, two kinds of zones would be discussed in this chapter, one is the Moving Safety Zone, and another is the

Leaking Hazard Zone.

5.1 Moving Safety Zone

5.1.1 Definition

The Safety Zone of LNG carrier has always been an important concept in navigational safety management and research. In the process of LNG carrier entering and leaving the port, in order to protect its navigation safety, a certain range of waters is usually set around the LNG carriers. And some escort tugs are arranged at the boundary of the water area, to warn other ships in vicinity, and to avoid the entry of them, who would pose a threat to the normal navigation of LNG carriers. This area is commonly referred to as the Safety Zone of LNG carriers. Considering that the location and range of the zone would change with the movement of the LNG carrier, the zone is also known as the Moving Safety Zone, as shown in Figure 5.1. The establishment of Moving Safety Zone can effectively improve the navigation safety of LNG carriers and reduce the probability of collision accident.

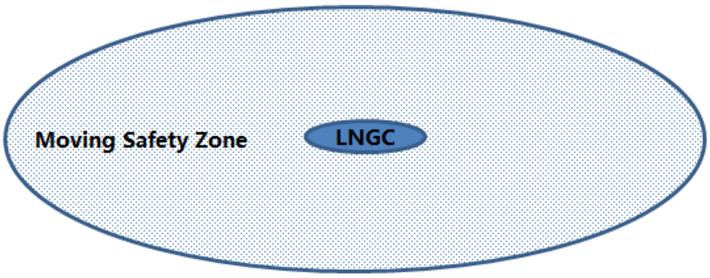


Figure 5.1: Sketch map of moving safety zone

5.1.2 Reference

Up to now, there is no uniform standard for establishing a Moving Safety Zone, and lack of relevant research. Different countries and ports have various requirements, as shown in Table 5.1.

Table 5.1: Scopes of safety zone around LNG carrier

Country	port	To ship's bow	To ship's aft	To ship's sides	To mooring ship
The United States	Cook Inlet	1000 yard	1000 yard	1000 yard	1000 yard
	Boston	1000 yard	1000 yard	1000 yard	
Greece	Freetport	2 nm	1 nm	1000 yard	1000 yard
Norway	Snohvit	1.5 nm	1.5 nm	1.5 nm	200 m
China	Shanghai	2.5*L	2.5*L	1*L	150 m
	Shenzhen	1000 m	1000 m	500 m	500 m
	Taiwan	1 nm	1 nm	150 m	100 m

Note： 1 yard = 0.9144 m; 1nm = 1852m

Source: Various collections

5.1.3 Ship Domain

In 1963, Fujii, a pioneer of Japan Marine Traffic Engineering, developed the concept of Ship Domain in the study of the traffic capacity of a waterway, and released an article entitled "Traffic Capacity" in the British Journal of Navigation in 1971. In the article he defined the ship domain as the area around a ship where the most of other ships would avoid entering into (Fujii & Tanaka, 1971, p.545). Afterward, the British scholar Goodwin defined it as: an effective water area around a ship, where is necessary for the ship to maintain the navigational safety (Goodwin, 1975, p.330). Since then, British scholars Davis, Lewison, Goldwel, Abdel-Gali, Dutch scholar Van-der Tak and other scholars commenced to research and establish different type of mathematical model for ship domain and posed different views (Davis, Dove & Stockel, 1980, p.219). The theory of ship domain was developed gradually.

It can be seen that the definition of Ship Domain is basically the same as that of

Moving Safety Zone and the function is exactly the same. Therefore, we can quantify the scope of Moving Safety Zone by studying the domain of LNG carrier.

5.1.4 Mathematical model

Fujii conducted a series of marine traffic surveys in coastal waters of Japan and analyzed the two-dimensional frequency distribution of the relative position of the ships. The model of Ship Domain in coastal waters was obtained. It was an ellipse around the ship, as shown in Figure 5.2 (Wu & Zhu, 2004, p. 120). The long axis was about as long as 8 times of ship's length (L) and the short axis was about 3.2 times of the length of the ship. When the ship navigated in port or narrow strait, the ellipse would shrink to 6L as the long axis and 1.6L as the short axis.

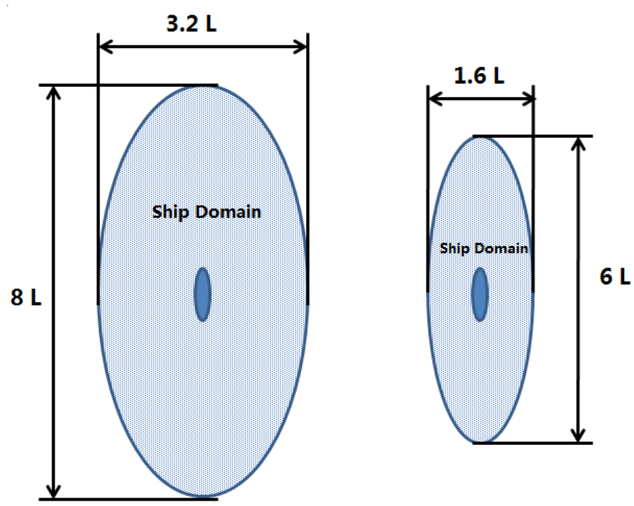


Figure 5.2: Sketch map of Fujii model for Ship Domain

Source: Wu, Z. L., & Zhu, J. (2004). *Marine Traffic Engineering*. Dalian: Dalian Maritime University Press.

The scope of Ship Domain is affected by three factors, which are human factor (captain, officers, etc.), ship factor (speed, maneuverability, etc.) and external conditions (traffic density, hydrometeorological conditions, etc.). It is difficult to obtain by mathematic calculation. However, through the long-term observation method, people can draw a position distribution map around the observed ship, and obtain a blank area around her, where can be seen as the Ship Domain of the ship. It is indeed a more practical approach. In this paper, **the model of Fujii Ship Domain is adopted to set the Moving Safety Zone around a LNG carrier.**

Most of Scholars' researches on the field of Ship Domain were concentrated in the 1960s and 1970s. At that time the ship size and speed, traffic density, navigational equipment, communications equipment, safety management, etc. were quite different from present. The implementation of ISM greatly improved the level of ship safety management, effectively reducing the impact of human factors. Most of port waters are covered by VTS, which has already reduced the risk of collision significantly. On the other hand, in recent years, the ship's gigantism, high-speed trend is more obvious, the cost of ship and the sensitivity of port waters are also continuously increased. All of these factors will influence the scope of Ship Domain. Therefore, the scope of Ship Domain would be quite different from Fujii model. **So the observed dimensions of Fujii model would be not adopted in this paper**. It is intended to obtain the scope of Ship Domain by calculating and setting empirical parameters.

5.1.5 Quantitative calculation

The Ship Domain of a LNG carrier in port water area is set to be elliptical, and the long axis (Y-axis) of the ellipse is the ship's course (over ground). Taking into account the research results of Fujii, Goodwin and other scholars, and for the convenience of calculation, the LNG carrier is placed in the center of ellipse, as shown in Figure 5.3.

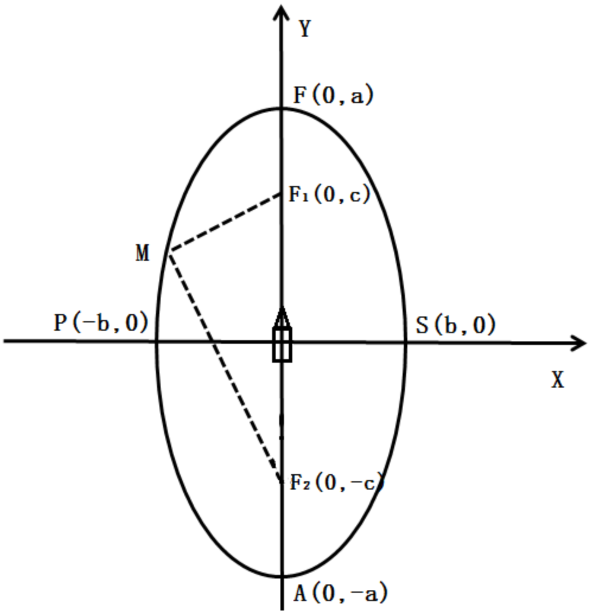


Figure 5.3: Sketch map of ellipse model Ship Domains

Assume that: **M**（x, y）is an arbitrary point on the ellipse; **A** (0，-a); **F** (0，a); **S** (b，0); **P** (-b，0), so｜M F_1｜+｜M F_2｜=2**a**. The standard equation of the ellipse (focuses on Y-axis) is $\frac{y^2}{a^2}+\frac{x^2}{b^2}=1$ (a> b > 0), the coordinates of focuses is F_1 (0, c), F_2 (0, -c), and $c^2=a^2-b^2$.

Assume that: the length overall of the LNG carrier is L (m), therefore the length of the long semi-axis of the ellipse: **a**=C*L (m); the length of short semi-axis: **b**=K*L (m). Thereinto: "C" is a long axis coefficient of Ship Domain, and; "K" is a short axis coefficient of Ship Domain.

The value of **a** and **b** is related to the ship's **speed**, **draft**, **load capacity** and local **visibility**, **area**, **weather**. The variation coefficients are assumed to be: speed coefficient (f_S), draft coefficient (f_D), load capacity coefficient (f_L), visibility coefficient (f_V)、area coefficient (f_A)、weather coefficient (f_W). So:

$a=C*f_S*f_D*f_L*f_V*f_A*f_W*L$ (m);

$b=K*f_S*f_D*f_L*f_V*f_A*f_W*L$ (m).

The values of all coefficients are obtained by observation, statistical analysis, experiment and judgment of experts. The following Table 5.2 is introduced by the experts from Qingdao port, it is only for reference.

Table 5.2- Scopes of coefficient value in Qingdao port

Coefficients	Scope	Value	Note
C	/	2-4	Experimental data, according to port condition. In general, a port, with good navigational infrastructures, should choose a relatively small value.
K	/	1-3	Experimental data, according to port condition. In general, a port, with good navigational infrastructures, should choose a relatively small value.
f_S	Speed（kn）<5	0.5	experimental data
	5≤ Speed（kn）<6	0.6	
	6≤ Speed（kn）<7	0.7	
	7≤ Speed（kn）<8	0.8	
	8≤ Speed（kn）<9	0.9	
	9≤ Speed（kn）<10	1	
	10≤ Speed（kn）<11	1.1	
	11≤ Speed（kn）<12	1.2	
	12≤ Speed（kn）<13	1.3	
	13≤ Speed（kn）<14	1.4	
	14≤ Speed（kn）<15	1.5	
	15≤ Speed（kn）<16	1.6	
	16≤ Speed（kn）<17	1.7	
	17≤ Speed（kn）<18	1.8	
	18≤ Speed（kn）<19	1.9	
	19≤ Speed（kn）<20	2.0	
	20≤ Speed（kn）	2.1	

f_D	Draft (m) <10	1	experimental data
	10≤ Draft (m) <12.5	1.1	
	12.5≤ Draft (m) <15	1.2	
	15≤ Draft (m) <17.5	1.3	
	17.5≤ Draft (m) <20	1.4	
	20≤ Draft (m)	1.5	
f_L	Load capacity (m^3) < 200,000	1	Q-Flex & Q-Max LNG carriers should be 2.
	Load capacity (m^3) ≥ 200,000	1.5	
f_V	1.5< Visibility (nm)	1	experimental data
	1.2< Visibility (nm) ≤1.5	1.1	
	0.9< Visibility (nm) ≤1.2	1.2	
	0.6< Visibility (nm) ≤0.9	1.3	
	0.3< Visibility (nm) ≤0.6	1.4	
	0< Visibility (nm) ≤0.3	1.5	
f_A	Near berth	0.5	For other areas, select according to the water area of navigational availability.
	Vicinity of turning point	0.8	
	Channel	1	
f_W	General weather	1	Severe weather is defined as: Wind speed ≥ 14 m/s (Moderate gale and above), or wave heigh ≥ 2m, whichever is greater.
	Severe weather	2	

To determine the scope of Ship Domain (Moving Safety Zone) of a LNG carrier, firstly, the values of all coefficients should be chose according to the actual condition of local port, and then to obtain the length of **a** and **b** through the calculations. Secondly, the area of the ellipse can be obtained by the formula " $S = \pi ab$". Finally, the coordinates of focus points $\mathbf{F_1}$, $\mathbf{F_2}$ and the arbitrary point **M** could be obtained, and the boundary of Ship Domain is determined.

5.1.6 Example verification

Taking the port of Qingdao as an example, as the top 10 ports in the world, there are around 120 merchant ships navigating in the water area every day, including LNG carriers. assuming that a full loaded Q-Max type LNG carrier with a loading capacity of 260,000 m^3 is navigating in the port, the ship length overall is 300m, the breadth is 50m, the draft of the ship is 15m, fairway speed 12kn and slowdown to 6kn before berthing, visibility is good, normal weather conditions. The scopes of its ship domain in the fairway and arriving berth are calculated by the formulas in 5.1.5 and shown in Table 5.3.

Table 5.3: Dimensions of ship domain for Q-Max LNG carrier in Qingdao port

Position	a (m)	b (m)	area (km^2)
In channel	1521	761	3.6
Arriving berth	819	410	1.1

As can be seen in table 5.3, the distance from the ship's head to the forward boundary of Moving Safety Zone is " $a - L/2 = 1371\text{m} \approx 0.74\text{nm}$", the same as the aft; the distance from each ship's side to the abeam boundary of Moving Safety Zone is "$b - B/2 = 736\text{m} \approx 0.4\text{nm}$". This scope is similar to the requirements in Shenzhen port and Taiwan port as shown in table 5.1. Therefore the calculation method is practicable.

5.2 Leaking Hazard Zone

5.2.1 Definition

The Leaking Hazard Zone is the area where may be threatened by LNG pool fire if LNG leakage occurred from a LNG carrier. When the LNG carrier accident is in the unknown stage, or has clearly identified LNG leakage, in order to protect the safety of life and property around the LNG carrier, the Leaking Hazard Zone should be established around the LNG carrier to isolate the ship in distress and other ships and personnel.

5.2.2 Scope

According to the report of Sandia National Labs issued in 2004 "Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water", the Leaking Hazard Zone of a LNG carrier may be determined by the heat flux in the unit area (Hightower, 2004, p.74). The hazard area is divided into 3 zones according to the heat flux and damage (see Table 5.4).

Table 5.4: The classification of hazard zones by LNG fire heat flux

Hazard zones	Heat flux (kw/m^2)	Damage
Zone 1	≥ 37.5	Thermal radiation could pose a severe public safety and property hazard
Zone 2	37.5--5	Thermal radiation transitions to less severe hazard levels to public safety and property
Zone 3	≤ 5	Thermal radiation poses lesser risks to public safety and property

Source: Hightower, M., et al. (2004). *Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural (LNG) Spill Over Water (Sandia National Laboratories)*. Retrieved June 7, 2017 from the World Wide Web: http://prod.sandia.gov/techlib/access-control.cgi/2004/046258.pdf

The scope of the 3 types of hazard zones is related to the quantity of LNG leakage. According to the Sandia National Labs research, in normal circumstances, for **accidental LNG spills**, the damage hole of the cargo containment system would be in the range of 0.5-1.5m^2, the range of **Zone 1** is about 250m around the ship; **Zone 2** is in the range of 250-750m around the ship and **Zone 3** is around the ship more than 750m. For a large number of **intentional LNG spills** (e.g. terrorist attack), the damage hole of the cargo containment system would be in the range of 5-7m^2, and **Zone 1** is about 500m around the ship; **Zone 2** is in the range of about 500-1600m, **Zone 3** is around the ship more than 1600m. (Hightower, 2004, p.74)

5.3 Escort operation

In order to ensure the safety of LNG carriers, the escort tugs shall, during the course of the inbound and outbound navigation of LNG carrier, be arranged at the boundary of the Moving Safety Zone to warn the other ships.

(1) Escort tugs should maintain a good navigation order in the fairway and control the traffic flow in vicinity of the LNG carrier to ensure the clear of fairway;

(2) Escort tugs should label the boundary of the Moving Safety Zone of the LNG carrier in her RADAR or ECDIS, other ships are prohibited from entering into;

(3) In the vicinity of the island and the high density traffic area, the escort tugs should evacuate the ships near the area in advance to ensure the clear of fairway for the navigational safety of the LNG carrier;

(4) When the maneuverability of LNG carrier is restricted in port, the escort tugs should assist her to maneuver;

(5) In the process of escort, the escort tugs should take emergency response to deal with any emergency.

5.4 Communication mechanism

To ensure the safety of LNG carriers and smooth the escort operations, the various organizations involved in escorting should establish a good communication mechanism to ensure real-time, barrier-free communication.

(1) The port VTS center shall choose a radio dedicated channel which could communicate with the escort agency and boats, LNG terminal, LNG carrier and her pilot.

(2) Before the LNG carrier enters or leaves the port, the LNG carrier should report to the port VTS center and confirms the navigation plan. The escort agency shall organize the escort fleet and personnel to reach the starting point 30 minutes before

the LNG carrier’s arriving to clear the fairway.

(3) If the other ships do not follow the orders issued by escort tugs, the escort tugs should call VTS center for assistance.

(4) The navigational warning regarding escort operation should be broadcasted to other ships a few hours before, which would leave enough time for them to prepare for the situation.

5.5 Escort tugs and personnel

5.5.1 Power of escort tugs

During the escort process, the LNG carrier's engine failure should be taken into account. The escort tugs should have the ability to provide sufficient support to ensure the effective control of the LNG carrier when it is out of control.

According to the requirements in Chinese “Design Code of General Layout for Sea Ports 2013”, the necessary power of tugs to assist the ship maneuvering is calculated by the following formula.

$$\mathrm{BHP} = \mathrm{KQ}$$

Thereinto: BHP is the abbreviation of Break Horse Power (KW); K is a coefficient, when ship’s DWT>50000t，K=0.08; Q is DWT (t).

For example：a Q-Flex type LNG carrier (217,000m^3), DWT is 121945.8t: BHP=0.08×121945.8=9755.7（kW）≈13267.7 horse power; a Q-Max type LNG carrier (266,000m^3), DWT is 163922t: BHP=0.08×163922=13113.8（kW）≈17834.7 horse power. The calculation is based on the condition of no wind and current, if in the condition of strong wind and current, the power or the number of tugs should be increased accordingly.

5.5.2 Standards of escort tugs

(1) Speed. The speed of escort tugs should not be less than the speed of LNG carriers (rang from 8-12kn), therefore, the maximum speed of escort tugs should not be less than 12kn;
(2) Navigational equipment: the Moving Safety Zone and the Leaking Hazard Zone should be labeled on the radar or ECDIS of escort tugs, so the navigational equipment has to be functional;
(3) Fire-fighting. In case of LNG leakage emergency, one of the escort tugs should have the ability to fight the fire; and all the tugs should equip the funnel with fire dampers.

5.5.3 Personnel

Escort command personnel should be qualified and familiar with the escorting waters environment, familiar with the "International Regulations for the Preventing Collisions at Sea 1972", familiar with the properties of LNG and the specialties of LNG carrier, while he or she should have the good communication and coordination capabilities, good English. Meanwhile he or she should have the ability to identify the risks and hazards in the process of escorting and can take appropriate measures to control them.

5.6 Escort plan

The escort vessel shall be capable of marking the Moving Safety Zone and the Leaking Hazard Zone of the LNG carrier. The boundaries of the two zones are set in accordance with the standards of 5.1.5 and 5.2.2 of this chapter respectively. According to the scope of Moving Safety Zone and the requirements of the escort tugs power, this paper proposes two escort plan (Fig. 5.4) from different sea conditions. The plan A is prepared for a better sea condition and the plan B is prepared for a harsh sea conditions.

(1) Plan A: 3 escort tugs needed, one is for the guide, and the other two are for the maneuver. One of which is a fire-fighting tug. In the process of escorting, the tugs should be positioned at the boundary of the Moving Safety Zone. With the gradual reduction of LNG carrier speed, the range of Moving Safety Zone should be reduced accordingly.

(2) Plan B: 4 escort tugs needed for harsh sea condition in case of emergency. Others are the same with Plan A.

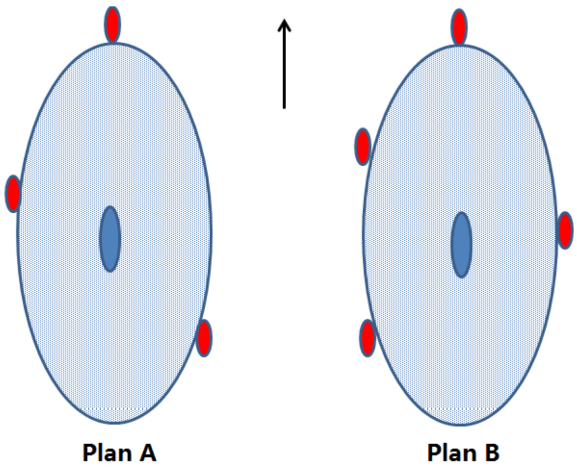


Figure 5.4: Sketch map of escort tugs or boats positioning

5.7 Escort supports

(1) The local rules or regulations should be established by port authority or maritime administration to normalize the escort operation.

(2) The escort agency shall have the qualification of escort, its qualification and ability should be recognized by port authority or maritime administration.

(3) An integrated emergency response plan should be established by all agencies involving in escort operation. And port authority or maritime administration should

designate a person to maintain and improve it. The content of the emergency response plan should at least include the disposal procedure of LNG leakage and pool fire, the emergency evacuation plan, the responsibility of each agency, etc.

(4) An LNG related experts group should be established and maintained to ensure to receive proper and correct expertise in the event of emergency.

5.8 Chapter summary

In this chapter, to minimize the probability and consequence of the collision accidents involving LNG carrier and other merchant ship in port, the author mainly studies the establishment of LNG carrier Moving Safety Zone and Leaking Hazard Zone. The model of Fujii Ship Domain is adopted as the mathematical model of Moving Safety Zone, and a method for calculating the scope is proposed. And then take the Qingdao port as an example to verify the reliability of the calculation model. Meanwhile, use the LNG pool fire test results of the United States Sandia National Labs to set up LNG carrier Leaking Hazard Zone. And some requirements, standards and supports for escort operation, communication mechanism, escort tugs and personnel and two escort plans are also discussed.

CHAPTER 6

Conclusion and prospect

In this research paper, the properties of LNG and the specialties of LNG carrier are firstly introduced. Then, the data of 170 LNG carrier accidents collected from 1964 to 2017 are analyzed, and the conclusion of most accidents happened in port is drawn. Simultaneously, the Formal Safety Assessment (FSA) is carried out to analyze the navigational risks of LNG carriers and to prove the conclusion. Furthermore, it is concluded that the risk of collision between LNG carriers and merchant ships is a medium risk and should be controlled. It is decided to reduce the probability of collision by establishing a Moving Safety Zone around LNG carriers, and to mitigate the severity of consequences of the accident by setting the Leakage Hazard Zone, and to protect the two zones by means of tugs or boast escort. Through the studies on the theory of Ship Domain and the empirical coefficient, the mathematical model of Moving Safety Zone is introduced, by which the scope of Moving Safety Zone can be quantitatively calculated and obtained. On the other hand, the pool fire experimental results of Sandia National Labs are used to classify 3 categories of Leaking Hazard Zones of LNG carrier. Finally, the general standards, requirements, plans and supports for tugs or boats escort are recommended to enhance the practicality of this paper.

All in all, the conclusions of this research paper are as follows:

(1) The LNG carriers face with the most of safety risks while navigating in port and through the Formal Safety Assessment the risk of collision with other merchant ship is determined as a medium risk which should be controlled.

(2) Propose the methods to control the collision risk. One of them is to isolate the LNG carrier from other ships through establishing a Moving Safety Zone, which can reduce the probability of the accident. And another one is to setting a Leaking Hazard Zone to reduce the severity of consequence of the accident. The two zones should be protected and maintained by escort tugs or boats.

(3) Put forward a mathematical model of Moving Safety Zone according to the theory of Ship Domain, and calculate the scope by setting empirical coefficients; using the LNG pool fire test results of the United States Sandia National Labs to set up 3 categories Leaking Hazard Zone.

(4) Recommend two escort plans according to the sea condition, and discuss the standards of escort operation, communication mechanism, escort supports, escort tugs and personnel.

With the continuous adjustment of the global energy structure, the share of Liquefied Natural Gas is increasing; the global LNG shipping industry will maintain a strong momentum in the next few decades. The study on the safety of LNG carrier transportation, including safety escort, would draw more attentions. The development of ship technology will be moving towards a more intelligent and more economical direction, there is no exception to LNG carriers, and more likely in the leading position. Imagine that when an unmanned, LNG-powered LNG carrier navigates in the port water area, how to ensure her safety and the safety of port. On the other hand, the study on the Moving Safety Zone needs to be further discussed, and this kind of study may be a functional technology in the field of unmanned ship.

Set the ship's Moving Safety Zone as if equip the ship with a safety cover, excluding the human factors, the intelligent computers will protect this cover by accurate calculation and auto-command the ship, almost all ship accidents can be avoided.. Finally, regarding the serious situation of global anti-terrorism, ship’s navigational safety can no longer be treated with the traditional way; many extreme situations need to be taken into account. In 2016, a Teekay's LNG carrier "Galicia Spirit" was attacked by armed terrorists using Rocket Propelled Grenade (RPG). Fortunately, the ship was not seriously damaged, but it also sounded the alarm for us. Whether the future LNG carrier escort need to join the anti-terrorism considerations, which is a question worthy of our thought.

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APPENDIX

Historic LNG carrier accidents with and without spillage of cargo （2006-2017）

The following table contains a list of known past incidents involving LNG carriers. Both minor incidents and serious accidents are included, but incidents involving small LNG carriers, i.e. less than 6,000 GRT are left out. The source of information for the various incidents is given in the rightmost column. The shaded rows correspond to incidents that are considered out of scope. The incidents are categorized according to the following crude accident categories:

- Collision: Col
- Grounding: Grd
- Contact: Cnt
- Fire or explosion: FE
- Equipment or machinery: EM
- Heavy Weather: HW
- Loading/Unloading: L/U
- Cargo containment system: CCS

#	Year	Ship name (Year built)	Type of Cargo containment *- Membrane* *- Spherical* *- Other*	Activity	Injuries /fatalities	LNG spill	Incident category	Incident description	Source
								barrier.	
1.	200	Golar	Spherical	Unloading	No	No	L/U	On 14 March 2006, LNG carrier Golar Freeze was	IMO

	6	Freeze (b. 1977)						alongside and discharging her cargo at Savannah USA. An inbound tanker passed astern in speed excess of 14 knots. The close proximity caused the discharging vessel to vibrate. Cargo operation stopped. The accident resulted in both gangways being destroyed but there was no other damage and no injuries. https://gisis.imo.org/Public/MCI/Browse.aspx?Form=Annex1&Action=View&IncidentID=5741&AnnexID=6495	
2.	2007	Ibra LNG (b. 2006)	Membrane	Transportation	1 electrician died	No	EM	On 3rd February 2007, the LNG tanker "IBRA LNG" was on her way to Qalat LNG Terminal. It was founded that the electrician was traoed in the elevator shaft. Rescue operation carried out, but unfortunately he finally lost his life. https://gisis.imo.org/Public/MCI/Browse.aspx?Form=Annex1&Action=View&IncidentID=6363&AnnexID=8154	IMO
3.	2009	Matthew (b. 1979)	Membrane	Transportation	No	No	Grd	On December 15, 2009, the liquid natural gas carrier Matthew grounded on coral reef habitat off the south coast of Puerto Rico near Guayanilla. The vessel was eventually freed from the reef with the assistance of local tug boats. https://darrp.noaa.gov/ship-groundings/lng-carrier-matthew	NOAA
4.	2010	Bluesky (b. 2006)	Membrane	Unloading	No	No	EM	Bluesky, the TMT-controlled carrier was damaged at GDF Suez’s Montoir de Bretagne terminal in France when a valve was by-passed and liquid passed into the gas take-off line during discharge operations. The damage sustained extended to part of the ship’s manifold and its feed lines without damage to the shore-side systems. No LNG release was reported.	CH-IV

								http://www.ch-iv.com/assets/documents/Safety%20History%20of%20International%20LNG%20Operations.pdf?/pdfs/Safety%20History%20of%20International%20LNG%20Operations.pdf	
5.	2010	LNG Edo (b. 1980)	Spherical	loading	No	No	L/U	During loading operations at the Bonny LNG terminal in Nigeria, LNG Edo took a significant list. The cause of the list was found to be abnormal ballast water distribution in the ship's tanks. The distribution in the ballast tanks was returned to normal and loading was completed. There were no injuries and any pollution or damage. http://www.ch-iv.com/assets/documents/Safety%20History%20of%20International%20LNG%20Operations.pdf?/pdfs/Safety%20History%20of%20International%20LNG%20Operations.pdf	CH IV
6.	2011	Excelerate (b. 2006)	Membrane	Unloading	No	Yes	EM	On 1 March 2011, at port of Milford haven, leakage of LNG during a discharging operation due to a defective thermo-well, resulting in a crack to the main deck. https://gisis.imo.org/Public/MCI/Browse.aspx?Form=Annex1&Action=View&IncidentID=8304&AnnexID=11475	IMO
7.	2011	LNG River Orashi (b. 2004)	Membrane	Transportation	1 officer died	No	EM	On the 13th September 2011, the LNG Carrier "LNG River Orashi" was on its way through the South Atlantic to Korea. When the Chief Officer, Cargo Engineer and Bosun inspected the ballast tanks as part of routine planned maintenance. The Chief Officer descended to the bottom of the tank. https://gisis.imo.org/Public/MCI/Browse.aspx?Form=Annex1&Action=View&IncidentID=8520&AnnexID=14738	IMO
8.	2013	Al Gharrafa (b. 2008)	Membrane	Transportation	No	No	Col	While transiting the Singapore Strait en route to Japan, the Qatari-chartered *Al Gharaffa* collided with the Greek Controlled, 10,114-teu *Hanjin Italy*. The LNG Carrier suffered severe bow damage, however there were no injuries, no damage to the containment system, and no LNG was released. http://www.ch-iv.com/assets/documents/Safety%20History%20of%20International%20LNG%20Operations.pdf?/pdfs/Safety%20History%20of%20International%20LNG%20Operations.pdf	CH IV

9.	2014	Navigator Scorpio (b. 2009)	Membrane	Transportation	No	No	Grd	At 1521 on 3 January 2014 the Liberia registered liquefied gas carrier, Navigator Scorpio, ran aground on Haisborough Sand in the North Sea. The vessel was undamaged by the grounding and there were no injuries or pollution; 2.5 hours later, it refloated on the rising tide. https://assets.publishing.service.gov.uk/media/547c6f1740f0b60241000000d/NavigatorScorpio.pdf	MAIB
10.	2015	Zarga (b. 2009)	Membrane	Tied up at jetty	1 officer injured	No	EM	On 2 March 2015, a deck officer on board the LNG carrier, *Zarga*, suffered severe head injuries when he was struck by a mooring rope that had parted while repositioning the vessel at the South Hook LNG terminal, Milford Haven. http://www.safety4sea.com/wp-content/uploads/2016/02/UK-MAIB-Safety-Bulletin-01-16-Zara-mooring-accident-2016_01.pdf	MAIB
11.	2016	Lijmiliya (b. 2009)	Membrane	Tied up at jetty	No	No	Col	The UK's Port of Milford Haven confirmed that in the early hours of Sunday morning July 10th, an incident occurred when its pilot vessel St Davids made hard contact with LNG carrier Lijmiliya during a routine transfer of pilot operation. http://www.safety4sea.com/pilot-vessel-hits-lng-carrier-at-uk-port/	Port of Milford Haven
12.	2016	Galicia Spirit (b. 2004)	Membrane	Transportation	No	No	/	The Teekay LNG carrier Galicia Spirit was attacked by RPG fire on 8 nautical miles off Perim Island, Yemen. Heavy armed men in a skiff approached the vessel from the Yemen coast and fired an rocket propelled grenade (RPG) over the large gas carrier. Fortunately, the vessel was not seriously damaged and the fire did not caused explosion. Also there were no injured people on board.	Reuters/ Safety4sea

								http://uk.reuters.com/article/uk-yemen-shipping-attack-idUKKCN12Q1UD	
13.	2017	Al Khattiya (b. 2009)	Membrane	Anchored at anchorage	No	No	Col	On 23 February 2017, while the 315m-long Al Khattiya was at anchor at Fujairah in the United Arab Emirates. It was hit by Suezmax crude carrier Jag Laadki, There have been no injuries or reports of pollution. Two of Al Khattiya's ballast tanks were breached with a loss of some ballast water. http://www.lngworldnews.com/oil-tanker-hits-q-flex-lng-carrier-al-khattiya-off-fujairah/	LNG World News