8-25-2013

Maritime safety supervision and control of LNG vessels in China during the marine transportation process

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Dalian, China

Maritime Safety Supervision and Control of LNG Vessels in China during the Marine Transportation Process

By

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China

A research paper submitted to the World Maritime University in partial Fulfillment of the requirements for the award of the degree of

MASTER OF SCIENCE

(MARITIME SAFETY AND ENVIRONMENTAL MANAGEMENT)

2013

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.

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Date: July 18, 2013

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Acknowledgement

This dissertation was developed as part of my studies to apply for the master degree of Maritime Safety and Environmental Management at WMU and DMU. This dissertation would not have been completed successfully without the generous support of a number of people and organizations to which I would express sincere thanks and ultimate gratitude.

Firstly, I would like to give thanks to Dalian MSA, providing me such a long period of time to expand the horizons of maritime knowledge. I would also express my gratitude to staffs in this department, who supported me greatly when I studied in Dalian.

Secondly, I would like to give my sincere thanks to my research paper supervisor, Prof. Tian Baijun and his daughter. Prof. Tian Baijun and his daughter have provided me a lot of valuable and constructive advices in the writing process, such as the topics selection, data collection and modification of language. His serious scientific attitude, rigorous scholarship, improving work style, have deeply infected and inspired me.

Thirdly, I would like to give my sincere thanks to Professor Jan-Åke Jönsson and all other teachers attending this MSEM programme, whose professional presentations have not only improved my knowledge significantly but also benefited this research paper greatly.

Fourth, I would also deliver my sincere thanks to Ms. Wang Yanhua, who has devoted much of her time and energy to this programme, and always supported and taken care of the whole class.

Last but not least, the debts of thanks and appreciation are owed to my affectionate parents and my beloved boy friend, without whose love, encouragement and support, I would have not achieved any accomplishment including this paper.

Title of Research paper: **Maritime Safety Supervision and Control of LNG Vessels in China during the Marine Transportation Process**

Degree: **MSc**

Abstract

Energy is the most important material for economic and social development. With China's rapid economic development, the demand for energy is growing rapidly. Liquefied natural gas (LNG) is a clean and efficient energy, and its proportion in the energy structure is also increasing year by year. Most of our country's natural gas needs to be imported, part of which is transported by LNG vessels. LNG vessels have high risks, when accidents happen, vessels, channels and ports will be impacted hugely.

Considering the probabilities and consequences of accidents of LNG vessels simultaneously and citing the research results from the “Integrated Safety Assessment Report of Modern LNG Vessels ", this paper conducts a study on the risks of LNG vessels during the marine transportation process. The research results in this paper can be taken as an important way for the maritime sectors to understand risks of LNG vessels during the marine transportation process and they can also provide a reference for proposing LNG vessels navigation management measures. All of these have great significance in the safe navigation of LNG vessels.

In addition, according to the marine transportation risk analysis of LNG vessels, this paper summarizes some safety management measures of LNG vessels in modern foreign countries. Combined with the existing safety management systems, strategies and suggestions are also proposed to safety management of LNG vessels in order to further strengthen the safety management of LNG vessels during the marine transportation as well as the operation of discharge when LNG vessels reach a port.

KEYWORDS: LNG; LNG Vessels; Marine Transportation; Navigation Risks; Safety Management.

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List of Abbreviations

ALARP	As Low As Reasonably Practicable
ABS	American Bureau of Shipping
AMSA	Australian Maritime Safety Authority
BP	British Petroleum
BOG	Boil-off Gas
DNV	Det Norske Veritas
ESD	Emergency Shutdown
GIIGNL	Groupe Internationale des Importateurs due Gaz Naturel Liquefé
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
LNG	Liquefied Natural Gas
MAC	Maximum Allowable Concentration
PERC	Power Emergency Release Coupling
RPT	Rapid phase transition
SIGTTO	Society of International Gas Tanker &Terminal Operators Ltd
SFAIRP	As Far As Is Reasonably Practicable
USA	United States of America
UK	United Kingdom
ULCC	Ultra-large Crude Carrier
VTS	Vessel Traffic Service

Chapter Ⅰ Introduction

Liquefied Natural Gas, referred to as LNG, is a clean and efficient energy. With the development of economy, the demand for energy is growing. The introduction of liquefied natural gas and increasing the proportion of natural gas in energy consumption play a very important role in optimizing energy structure, protecting the ecological environment, solving the energy shortage and achieving sustainable economic and social development. In developed countries, the consumption of natural gas has reached 25% among the total energy consumption. In order to meet the requirement of growing demand for liquefied natural gas, in the southeastern coastal economically developed areas, our country has planned and developed a number of LNG terminals. According to some related statistics, Liaoning, Shandong, Guangdong, Fujian, Jiangsu, Zhejiang, Shanghai and other coastal areas currently are planning and constructing several LNG terminals to ensure the supply of natural gas in coastal and inland areas. With further growth of energy demand, the demand for LNG will be further expanded in our country.

Part of LNG is transported by LNG vessels. With the continuous development and progress of LNG vessels and LNG transportation technology, LNG vessels are growing rapidly and LNG transportation volume has also increased. Waterways have become an important means of transportation of LNG. But LNG vessels themselves are dangerous and unique. If an accident happened during the marine transportation process, flammable, combustible and other characteristics of liquefied natural gas can easily result in casualties and property losses. The characteristics of LNG bring greater pressure on navigation environment and safety in navigable waters of ports, meanwhile also coming up with new demands for the port management. In marine transportation, the sea route (or channel) is the supporting body of vessels for entering and leaving ports, and also is an important part of port transportation system. However, there is a certain particularity of LNG vessels due to the physical characteristics of LNG, so considerable risks exist in LNG vessels navigation. It is necessary to propose appropriate measures to reduce risks to ensure safety of LNG vessels by means of conducting research on risks during the marine transportation process of LNG vessels. Based on the risk analysis of LNG vessels during the marine transportation process, this paper helps provide scientific basis and references for decision making, enhancement and improvement of LNG vessels navigation safety management.

Chapter Ⅱ Composition, Physical and Chemical Properties and Hazardous Characteristics of LNG

2.1 Composition, physical and chemical properties of LNG

LNG is liquefied natural gas, liquid form of natural gas. The producing areas of natural gas are often far away from consumers. Natural gas is usually transported via vessels from the producing place to the final consumptions after liquefaction, and then gasified for consumers. Natural gas is not only clean, efficient and cheap to generate electricity in power plants, to cook and heat in homes and commercial establishments, to fuel our cars, but also raw materials of the oil industry for the production of fertilizers, plastics, fiber and many other kinds of products.

Natural gas has two sources. One is the natural gas processed from oil fields called associated gas; the other is obtained from a separate gas field, called non-associated gas. Most of the world's natural gas is non-associated gas, generally having high purity and high calorific value. Natural gas containing a small amount of heavier hydrocarbons is "dry gas", while that containing a lot of pentane is "wet gas."

Natural gas is gas mineral mixture of underground oil gas fields, generated by the interaction of plants and animals for billions of years, mainly composed of methane, accounting for 70% -95% volumes. The rest elements are ethane, propane and butane, as well as a small amount of impurities, such as nitrogen, carbon dioxide, hydrogen sulfide, etc (Xu, Chen, &Yu, 2006). LNG is liquefied from natural gas through compressing, cooling, and expansion and other processes. The composition of natural varies because of different producing areas. A typical composition of natural gas is shown in Table 1 (ABS, 2004).

Table 1- The Composition of Natural Gas from World's Major Producing Areas

Composition / Area	methane	ethane	propane	butane	pentane	nitrogen	carbon dioxide
Algeria	86.30	7.80	3.20	0.60	0.10	—	—
Libya	66.80	19.40	9.10	3.50	1.20	—	—
the North Sea	85.90	8.10	2.70	0.90	0.30	0.50	0.10
Iran	96.30	1.20	0.40	0.20	0.10	1.30	—
Abu Dhabi	82.07	15.86	1.89	0.13	—	0.05	—
Alaska	99.40	0.10	0.13	—	—	0.40	—
Indonesia	90.59	5.58	2.65	1.20	0.05	0.03	—
Brunei	88.00	5.10	4.80	1.80	0.20	0.10	—
Malaysia	94.54	3.25	1.50	0.61	—	0.10	—

Source: ABS. (2004). A presentation to china shipping group. LNG shipping seminar, Shanghai, China.

LNG is colorless, odorless, non-corrosive, non-toxic and cryogenic. It has high flash point, relatively low burning rate and non-corrosive properties. The specific gravity of LNG is between 0.442 and 0.474. Typical commercial LNG has the following properties (Fan, 1993):

Boiling point of LNG: atmospheric pressure -157 ℃ ~ -163 ℃; pure methane: -161.5 ℃;

LNG density: 0.47-0 .53; LNG calorific value: 25-34 Btu / cu.m. (1 Btu = 1.06 kj); calorific value of pure methane: 29 Btu / cu.m.;

Dry gas / dry air density: 0.58-0.67; methane / dry air concentration: 0.555;

Lower explosive limit (% accounted for the volume of air): 5.3; explosive limit (% accounted for the volume of air): 14.0; ignition point: 595 ℃;

Methane gas / liquid state volume ratio: 625:1.

LNG is odorless. But before it is sent to terminal users after gasification, smelly agent must be added so that users can identify and prevent the gas leakage from equipment. Natural gas is non-toxic. However, if in a confined, unventilated condition, because natural gas concentration is too high, it will cause suffocation due to lack of oxygen. LNG is non-corrosive and will not cause corrosion. Because LNG is lighter than water, if it accidentally leaks into water, it will float on water and will evaporate quickly and then vaporize.

2.2 Dangerous properties of LNG

The main component of LNG is Methane. According to different origins, natural gas also contains small amounts of ethane, propane, butane, and other natural gasoline. These substances are not only flammable and explosive materials and easily form explosive mixtures with air, but also apt to cause a fire or explosion.

LNG vapor is combustible only when concentration in the air is within a certain range, as shown in Figure 1. According to the mixed combustible gas volume percentage, the combustion explosion limit is 5.3% to 14%. When the LNG vapor is mixed with air, only the volume percentage of its volume from air ranges from 5.3% to 14%, once contacting with fire, burning occurs. Especially in the relatively confined space and poorly ventilated area, if natural gas leakage happens and contacts with combustion source, explosion will be caused and serious damages will be engendered.

When the concentration of LNG vapor in air exceeds the upper limit of combustion, such as in a fully enclosed space, because vapor concentration is too rich and due to lack of oxygen in the air, it will not burn. If LNG leaks in an open and well-ventilated place, because the density of LNG vapor is lower than air after gasification, it will quickly evaporate. So the concentration is very low in the air, in this case it is less than the lower flammability limit, and it will also not burn.

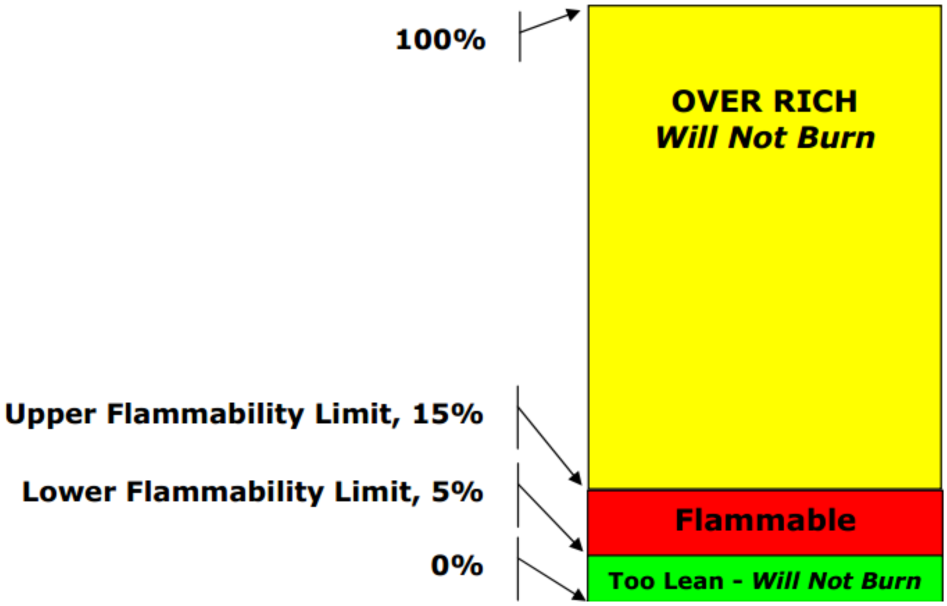


Figure 1 - Flammable Range for Methane (LNG)

Source: Michelle, M.F. (2006). LNG Safety and Security. http://www.beg.utexas.edu/energycon/lng.

As shown in Table 2, compared with other dangerous fuels, such as liquefied petroleum gas, whose upper and lower combustion limit is from 2.1% to 9.5, while gasoline is from 1.3% to 6%, because of needing more LNG to combust in a given area, LNG has relatively better security (Michelle, 2006).

Table 2 - Comparison of Properties of Liquid Fuels

Properties	LNG	Liquefied Petroleum Gas(LPG)	Gasoline	Fuel Oil
Toxic	No	No	Yes	Yes

carcinogenic	No	No	Yes	Yes
Flammable Vapor	Yes	Yes	Yes	Yes
Forms Vapor Clouds	Yes	Yes	Yes	No
Asphyxiant	Yes, but in a vapor cloud	Same as LNG	Yes	Yes
Extreme Cold Temperature	Yes	Yes, if refrigerated	No	No
Other Health Hazards	None	None	Eye irritant,narcosis,nausea, others	Same as gasoline
Flash Point(℉)	-306	-156	-50	140
Boiling Point(℉)	-256	-44	90	400
Flammability Range in Air, %	5-15	2.1-9.5	1.3-6	N/A
Stored Pressure	Atmospheric	Pressurized(Atmospheric if refrigerated)	Atmospheric	Atmospheric
Behavior if Spilled	Evaporates, Forming visible “clouds”. Portions of cloud	Evaporates, Forming vapor clouds which could be	Evaporates, forms flammable pool; environmental clean up required.	Same as gasoline

	could be flammable or explosive under certain conditions.	flammable or explosive under certain conditions.		

Source: Based on Lewis, William W., James P.Lewis and Patricia Outtrim,PTL,"LNG Facilities –The Real Risk,"American Institute of Chemical Engineers,New Orleans,April 2003,as modified by industry sources.

The following are eight aspects of hazardous properties of LNG:

1) Flammable and explosive

The main substances involved by LNG are all flammable. LNG has low flash point, small ignition energy. Once leakage happens and contacts with combustion source LNG is prone to result in fire and explosion accidents. Explosion conditions must be the concentration of mixed combustible materials with air within explosion limits and sufficient ignition energy. Ignition energy can be divided into: ① Direct Energy, including flames, electrical sparks and hot surfaces; ② Indirect Energy: including friction, impact, adiabatic compression, heat radiation, static electricity and so on. Once gas leaks via the device or pipelines, it is easy to spread in the air to form vapor clouds. Because of its lower explosive limit, a small amount of gas leak may form a combustible gas mixture with air. When the combustible gas mixture is burned, if diffusion space is limited, it will explode and pose a great threat on human life, vessels and equipments.

2) Cryogenic property

Taking methane, ethane, propane, butane for example, boiling points of them are

-161.5 ℃, -88.6 ℃, -42.1 ℃ and -0.5 ℃respectively. So they can exist only at a relatively low temperature and under a certain pressure in liquid form. In order to facilitate shipping, LNG is usually stored at low temperature and constant pressure. The working temperature is about -162 ℃ at this time, when the natural gas has been converted from gaseous into liquid condition and the volume has become one over six hundred of the same amount of gaseous LNG (Gluver, & Olsen,1998, May). LNG is cryogenic cargo. When it is in liquefied storage, the temperature is below the normal boiling point. Once it leaks and contacts the normal temperature and pressure, changes of the ambient temperature can cause rapid gasification of part of LNG. The heat required for the gasification is provided by the surrounding environment. Because latent heat of vaporization is more, a lot of heat is absorbed from the surrounding environment, resulting in partial hypothermia. Dangers caused by cryogenic LNG mainly refer to ship construction, equipment damage and harm to the human body due to low temperature resulting from accidental spills of LNG.

3) Volatility

The boiling point of LNG is about -162 ℃ and it is volatile. The storage equipments and pipelines of LNG also tend to absorb heat due to the extremely low temperature of LNG. As the temperature rises, vapor pressure of LNG increases rapidly. Therefore, storage tanks, evaporators and pipelines and other equipments should have sufficient intensity, and should have appropriate pressure relief measures to prevent LNG leakage due to bursting containers at elevated temperatures. If there are any small non-hermetic defects in the cargo system (cargo hold or cargo pipeline system), liquefied gas will leak and evaporate and become hidden dangers to sudden accidents.

4) Diffusivity

Once LNG vapors, expansion rate can be up to more than 600 times. With a high diffusion coefficient, the greater the rate of diffusion, the greater the risk of expansion and spread of fire caused by flammable gas. Once the large amount of LNG leaks and escapes in the air, it can quickly spread extensively, forming explosive mixture with air. And it can flow with wind, resulting in ignition of flammable gases. Finally explosion will happen and the combustion flame will spread, bringing great burning and thermal burning threats to the personnel. Meanwhile the equipment and surrounding environment are also impacted greatly (Chen&Cheng, 2007).

5) Easy to accumulate electrostatic charges

When LNG ejects from breakages of cargo holds, receiving station storage tanks and transport pipelines or its venting speed is too fast, electrostatic charges are easy to be produced, resulting in fire or explosion accidents.

6) Toxicity

LNG can also make human feel poisoning and suffocation. Natural gas and other hydrocarbon substances have some toxicity, and if there is leakage of cargo or careless operation, the operator will contact with LNG vapor. When workers are exposed to LNG vapor for a long term or large amount of LNG is leaked, both likely result in poisoning (Zhang&Wu, 2009). In addition, when the crews go into the cargo holds or cargo system equipment compartments to conduct maintenance operations, if before entering, degassing operations are not conducted to cargo holds or equipment compartments and toxic and harmful gases are not completely ruled out, these will result in oxygen partial pressure sharp decline in the local areas of compartments. The crew poisoning can also occur, and serious accidents like suffocation may occur as well (Serdar, Masaki & Masao). Judging whether LNG would cause harm to human health, a particularly important parameter is the maximum allowable concentration (MAC). For most people, this value is continuous contact for five days a week and for eight hours per day without producing dangerous mist or vapor concentration.

Table 3 shows MAC values of some related substances in the cooling mode published by China's “design and health standards for industrial enterprises” (TJ.36-79).

Table 3 - The MAC Table of Main Hazardous Substances

serial number	Name of hazardous substance	MAC（PPM）
1	methane	1000
2	ethane	1000
3	propane	1000
4	butane	600

Source: compiled by the author.

7) Thermal expansion and thermal spillover

LNG has a larger thermal expansion coefficient. Taking liquid methane for example, if the volume is 1at -40℃, when the temperature rises to 0℃, its volume has expanded to 1.094 with 9.4% increase in volume. When temperature rises to 40 ℃, its volume will expand to 1.236 and the volume has increased 23.6%. For a sealed container filled with liquefied gas, it can not bear the pressure generated by the thermal expansion of liquid. In addition, when new LNG is injected into cargo tanks, sometimes it is not well mixed with residual gas with different densities in tanks. That state will lead to cold and light gas being in the upper and hot and heavy gas being in the lower. The heat will pass from bottom to top in heat wave forms, resulting in the volume of upper gas expansion and substantial evaporation. This will make pressure within cargo tanks increase rapidly, eventually resulting in a large number of gas venting (R M Pitblado, J Baik, G J Hughes, C Ferro&S J Shaw, 2005, June). This phenomenon is known as “thermal spillover", also an important cause giving rise to gas accidents.

8) Pressure characteristics and hazards

① High pressure hazards

Due to the external heat transfer, the temperature of liquid cargo systems of LNG vessels will rise because systems are in closed state during the marine transportation process. The vapor pressure in cargo tanks will increase. Once the pressure is higher than the designed allowable value, it will cause damage to the system or form danger. Therefore, when you operate these equipments, such as opening the valve, blind plates and other equipment, you should observe and determine whether there is high pressure vapor or liquid within the system making use of instruments so as not to damage personnel and equipments.

②Superimposed pressure and tumbling

For LNG vessels or tanks in shore station during loading process, if the loaded liquid cargo has different temperature with cargo in tanks, the temperature difference will cause cargo tumbling in the mixing process of liquid with two different densities. Meanwhile there will be a large amount of released vapor accompanied by intense pressure rise phenomenon (Liang, 2006).

③ Negative pressure in cargo tanks

Under normal circumstances, whether it is carrying cargo or not, cargo tanks are low positive pressure in LNG vessels. In some special cases when negative pressure occurs in the cargo tanks, structure of cargo tanks may be destroyed in addition to inhaled air. We should particularly pay attention to membrane tanks with thin shielding materials, because smaller negative pressure or pressure difference can easily damage structure of the cargo tanks.

ChapterⅢ Definition, Classification and Characteristics of LNG Vessels

3.1 The definition and classification of LNG vessels

LNG vessels are specialized vessels for carrying LNG. The standard cargo capacity of such current vessels is from 12 to 15 ten thousand cubic meters. Some countries have been able to design LNG vessels which are 160,000, 200,000, and even 300,000 cubic meters large. However, due to constraints of port terminals and receiving stations, the capacity of cargo tanks for LNG vessels may be stable at the level of one hundred thousand cubic meters. For the design of this type of vessels, the main factors considered are the ability to adapt to dielectric materials with low temperature, and is handling volatile and flammable materials. The most notable feature of LNG vessels is the cargo containment system, which prevents the structure of the vessels from low temperature brittle fracture. Currently according to the different cargo containment systems, LNG vessels can mainly be divided into three kinds (Zhang, 1994).

1) MOSS LNG vessels (independent spherical tanks): This type of vessels is initiated by Norway and firstly launched in 1973 thereafter adopted by the United States, Germany, Japan and Finland. Most of Japan's sailing LNG vessels are of this type (as shown in Figure 2) (Zhang, 2007, March). Because tanks of this type of vessels are well-designed, so far they have had good safety records. These vessels have never stopped operating because of shortages or injuries of cargo tank systems. Moss spherical tanks have a good shape; therefore, thermal analysis and calculation are also facilitated. The calculation results show that in any state of the environment, cargo tanks are unlikely to be ruptured to cause disastrous

consequences. IGC code allows B type spherical cargo tanks not to use secondary shielding. But in general this type of structure usually adopts partial shielding, setting drip pans at the bottom of support system of cargo tank. When a small amount of liquid cargo leaks, they can be concentrated in drip pans, preventing damage to the ship structure (Li, 2003). The appearance of Moss type LNG vessels is shown in Figure 3.

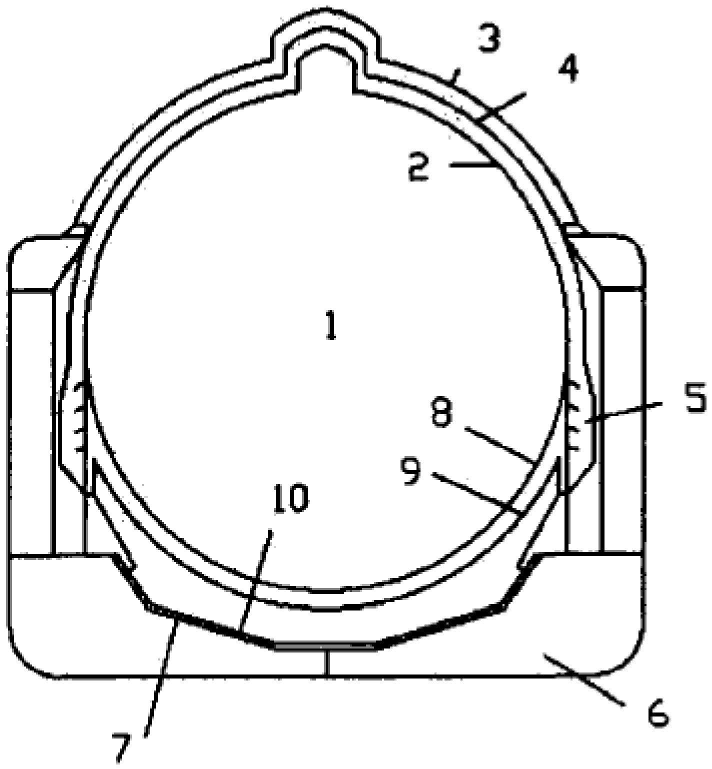


Figure 2 - MOSS Spherical Tank

1-tanks; 2-tank shell; 3-protective steel cage; 4-splash-proof shielding with insulating layer; 5-thermal barrier;6-ballast water tanks; 7-thermal barrier; 8-strengthened support units; 9-Protective cover; 10-drip pan.

Source: Zhang,D.Z. (2007,March). Selection and management for propulsion devices of LNG vessels. Dalian: Dalian Maritime University Press.

Figure 3- The Appearance of Moss Type LNG Vessels

Source: compiled by the author.

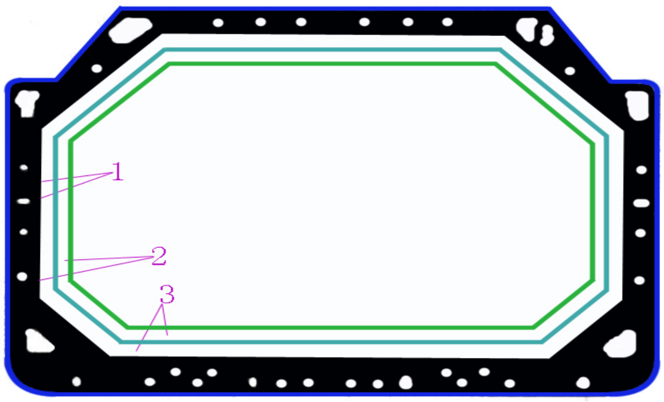
The advantages of MOSS vessels are: simple structure and easy stress analysis; solid aluminum alloy structure which will not be damaged as long as no direct impact; simple installation due to no internal stiffeners making LNG vessels individually built and shortening the construction cycle, easily checking the quality and having good safety property; less liquid surface shifting effect and no need to consider loading restrictions; less initial investment.

The disadvantages are: large size of this type of vessels, large opening deck, uncontinuous deck structure, many stress concentration points; high center of gravity of cargo; difficulty to manoeuvre particularly due to large windward area above the deck and not having ideal bridge sight despite the aftercastle of LNG vessels being largely higher than oil tankers.

2) Membrane type vessels (membrane type tanks)

Structurally, the membrane type cargo tanks containment system is composed of the main shielding, the main insulation layer, secondary shielding, secondary insulation layer and side tanks. The specific structure is shown in Figure 4. Currently membrane type tanks have mainly two types, namely Gaz Transport and HTechnigazH. The two types are similar. They all use steel sheet "membrane "as containment system due to its good flexibility. Using nickel steel including nickel and carbon, which account for 36% and 0.2% respectively, Gaz Transport membrane has very low coefficient of thermal expansion. This is a good solution to changes of materials affected by temperature (Liu, 2000).

The insulating layer of the two types of membrane systems are both filled with nitrogen. The insulating layer will be continuous monitored. Once methane is detected, it will be proved that leakage exists in the cargo membrane. In addition, the membrane type tanks require strict control of gas pressure in tanks, because it could likely cause membrane dropping from the insulating layer. Typical membrane type LNG carriers are shown in Figure 5.



1-full double hull structure; 2-cryogenic shielding layers (primary and secondary membrane); 3-cryogenic thermal-protective coating

Figure 4- Membrane Type Cargo Tanks Structure

Source: compiled by the author.

Figure 5- Typical Membrane Type LNG Carriers

Source: compiled by the author.

The main advantages of membrane type vessels are as follows: reduced structural weight of cargo tanks; shortened precooling time; wide viewing angle of bridge, thin ship form, small wind area, and higher propulsive efficiency (Zhang, Ye &He, 1994).

Disadvantages are: complex structure and higher management requirement; longer period of outfitting; thoroughly tested membrane of all tanks and adiabatic devices including fatigue test for cyclic load at low temperature (Cui, Li &Han ,2001).

3) SPB type vessels (prismatic type tanks)

Between tanks and inner wall of SPB type LNG carriers, there is left a large space. A bulkhead is set in the center of cargo tank to prevent fluid flow, which is independently developed technology of Japan's IHI. Because it is available for large LNG vessels of 200,000 cubic meters, this technology arouses great concern (Wang, 1998).

The material of prismatic type cargo tanks (as shown in Figure 6) is aluminum. Relative to the spherical tanks, the biggest advantage of prismatic type cargo tanks is the high utilization of space. An internal cross wall can prevent splashing liquid cargo to damage the bulkhead. The cooling rate of prismatic type cargo tanks is similar to that of spherical tanks, which is -6 ℃ /h. The requirements of internal strength of cargo tanks make this type of cargo tanks the most relatively heavy ones. Single tank weighs about 1,300 tons. Typical SPB type LNG carriers are shown in Figure 7.

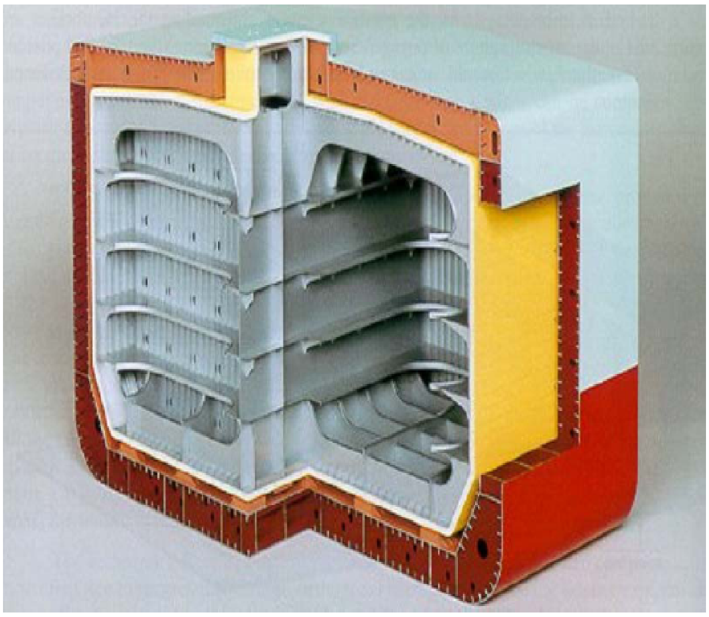


Figure 6- The Structures of Prismatic Type Tanks

Source: compiled by the author.

Figure 7- Typical SPB Type LNG Carriers

Source: compiled by the author.

3.2 Characteristics of LNG vessels

3.2.1 Structural features of LNG vessels

1) High safety requirements

At low temperature of -163 ℃, hull structure needs protection to resist low temperature.

LNG carriers must have double hull structure, with three to six independent cargo tanks and must apply cryogenic materials and high thermal insulation materials. In addition, the loading system must be absolutely sealed, with gas detection and alarm systems and barriers removing systems. Evaporation rate must also be strictly confined and controlled at less than 0.15% per day.

2) High requirements for the design and construction

Ship design, materials, crafts, construction technology and other aspects of LNG vessels have higher requirements than ordinary ships, so the ship's cost is far higher than normal vessels (Li, 2008).

3) Large dimension

Compared to other types of ships with the same dead weight capacity, large LNG vessels have large dimension.

4) Shallow draft and big windage resistance

The draught to molded depth ratio is less than 0.5 (the draught to molded depth ratio of normal ultra large scale vessels is greater than 0.75). So LNG vessels belong to large shallow draft vessels (Yuan, 2006). Compared to ULCCs or bulk carriers, LNG vessels have huge volume above water, so wind resistance is very significant.

5) Big dead zone

Because vessels are usually designed to stern-engined type, the height of freeboard is higher, leading to big dead zone in the bow of vessels (Gao, 2012, June).

6) Steam turbine as main engine (Li, 2006, September)

The working medium of steam turbine depends on the amount of steam generated by the boiler. The process of the boiler controlling steam production by adjusting the amount of fuel will waste a long time, so acceleration performance is poor. If the ship is slowed down too fast, too quickly discharging excess steam will also hazard the condenser.

Using steam turbine as the main propulsion system leads to ahead and astern manoeuvres needing a long time for reversing, about 120 to 180 seconds. So compared with the ship with the same deadweight ton and using diesel, the reversing stroke is long.

To prevent deformation and cracks happening on casing and rotor blade of steam turbine due to too large temperature changes, before starting, the steam turbine must be fully warmed up and warm-up time is at least four hours.

7) High Speed

The speed of ULCCs is generally 15 knots or so, while the speed of large LNG vessels is generally 20 knots or so.

8) Poor directional stability

LNG carriers have the general characteristics of ultra large ships. Due to shallow draft, high depth and big wind area, the directional stability of LNG carriers is worse than the ULCCs (Lu, 2006).

9) The unique cargo containment system

All LNG containment systems must have two functions: good insulating property to farthest control gas evaporation; isolating LNG and steel structure to prevent steel structure to be exposed to low temperature. Therefore, cargo tanks of LNG vessels are steel structure, cryogenic and internal insulation. Between the hull and the cargo tanks, there is very solid double hull structure.

3.2.2 The other features of LNG vessels

1) Special cargo operations

During the operation of LNG vessels, cargo tanks must be kept low temperature. In order to prevent fire hazards, loading and unloading of LNG are fully enclosed. Therefore, cargo operations of LNG have a certain particularity:

① Loading operations of LNG vessels

Loading time of a LNG vessel of 135,000 cubic meters is about 12 hours. The temperature of cargo tank when loading is started has great influence on the loading time. So often in the transport contract, provisions must be clear about the temperature of cargo tanks before loading. Typically, the temperature of the bottom of the cargo tank is about -162℃, the central temperature is about -130 ℃.

In the period of loading, LNG vapor and inert gas of cargo tanks are sent back ashore through the gas pipelines. When loading is started, the loading speed should be slow in order to control pressure in cargo tank. Prior to full loading, loading speed should also be slow to ensure safety. In the whole process of loading, the discharge rate of ballast water should be adjusted according to the loading speed in order to maintain the ship's draft unchanged (Zhao, 2005).

② Discharging operations of LNG vessels

For a full loading of 125,000m^3 LNG vessel, unloading takes about 12 hours. Pipelines and other equipments should also be refrigerated before unloading cargo. During the discharge, the gas of tanks on shore is sent back to LNG vessels.

For the voyage having ballast left, the LNG used for refrigeration of cargo tanks, in addition to meet the LNG evaporation during the voyage, under normal circumstances, before loading when the ship arrives at port, is still left in cargo tanks for a certain amount.

③ Utilization of BOG

The outside heat transferring into cargo holds are not able to completely be avoided due to temperature difference between inside and outside the cargo tank, so evaporation of LNG is inevitable in the cargo tank. Since LNG reliquefaction plant is very expensive, it is not installed on existing LNG ships. Currently the method to deal with gas evaporating out of cargo tank is to lead it into the engine room as the fuel of main boiler. When the ship lies at anchor, in addition to meet the need of facilities, the steam produced by combustion of boiler which is supplied by the BOG of LNG often has a surplus. The remaining vapor is generally sent to the condenser for condensation or other equipment.

2) Special technical management

① Higher maintenance and repair standards. General principles of maintenance and repair: periodic repairs to all components of the vessel during the entire service life; selection of qualified shipyards for long-term contracts; constantly collecting and analyzing repair data in order to improve ship operations. The higher maintenance and repair standards can make LNG vessels safely operated more than 40 years.

② Steam turbine as the ship's power. LNG vessel is the only ship type using the steam turbine, mainly due to the utilization of BOG. The crew generally requires passing the special training and examinations for steam turbine (Liu&Zhang, 2007).

③ More difficult ship maneuvering. Because the density of LNG is small (0.43 to 0.48), regardless of empty or full loading, draft of LNG vessel is shallow and freeboard is high. So the wind area and center of gravity are higher, leading to poor stability and more difficult ship maneuvering. For independent spherical vessels, the tall tanks can also affect the navigator's line of sight.

Chapter Ⅳ Development of Marine Transportation of LNG

4.1 Production and consumption of global natural gas

Production and consumption of global natural gas has grown steadily. Over the past 10 years, the average annual growth of production of global natural gas is 77.99 billion m^3 and the average growth rate is 10%. By 2011, the average consumption of global natural gas reached 3.2229 trillion m^3 (BP, 2012, June). As shown in Figure 8 (BP, 2012, June), the distribution of production and consumption of global natural gas is not balanced. Europe and Eurasia, North America and Asia-Pacific region are not only the world's major gas production regions, but also the three major consumption markets worldwide. In 2011, the production of natural gas in European was 1.0364 trillion m^3, accounting for 31.6% of the global total production of natural gas and being the first for each region. Meanwhile, the consumption is 1.1011 trillion m^3, accounting for 34.1% of the global total consumption of natural gas.

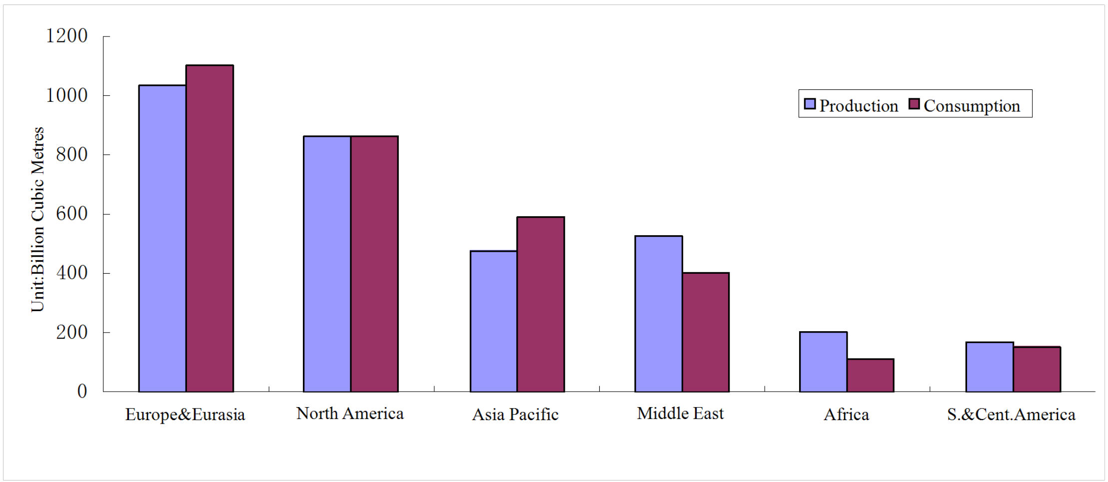


Figure 8 - The Distribution of Production and Consumption of Natural Gas in Each Region in 2011

Source: BP Statistical Review of World Energy June 2012.

http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481

Because the distribution of production and consumption of global natural gas is not balanced, production and consumption areas are often separated by vast oceans, so marine transportation is needed to be solved. The volume of liquefied natural gas is only 1/625 of original gas, so marine transportation can be achieved through the LNG vessels.

4.2 The development of foreign LNG marine transportation

In 1959, The Methane Pioneer which was remoulded from a general cargo ship initiated the world's first LNG marine transportation. Seven voyages of operating practices of this ship have contributed for the safe marine transportation of LNG (Huang, Ding & Sun, 2005, February).

Successful trial of the Methane Pioneer, a large number of natural gas found in Algeria and the demand for natural gas in the United Kingdom prompted the British to decide to import LNG from Algeria and to start the construction of LNG carriers. But the actual formation of a certain scale LNG marine transportation began in 1964. In 1969, two 71500 m^3 LNG carriers navigated between Alaska and Japan, as well as four 40000 m^3 LNG carriers sailing among Libya, Italy and Spain. In 1971 the LNG route from Boston to Algeria was opened. In 1972, there were seven 75000 m^3 LNG carriers operating between Japan and Brunei.

1964 to 1969 is the trial phase of LNG marine transportation. The LNG marine transportation went into a large-scale development phase in 70 years and LNG carriers constructed by every country are also larger. European countries such as

France, Spain, Italy, the Netherlands and Belgium, had also started to import LNG.

The total cargo capacity of the largest LNG ship built in 1964 is 27,000 m^3. In 1970, it reached 50,000 m^3. With the rapid development of construction technology of LNG vessels, the 131,000 m^3 of LNG ship was made in 1978 and the 136,000 m^3 LNG ship was built in 1987. At present, some advanced shipbuilding countries have successively designed more than 25 different ship types and conceived many transportation options. The 160,000 m^3, 200,000 $m^3$and 300,000 m^3 LNG ships have been designed. Due to restrictions of factors such as the depth of port, currently, the cabin capacity of the world's LNG vessels in operation are mainly stabilized at the level of about one hundred thousand cubic meters.

Japan was the first Asian country to import LNG. In 1969, Japan firstly imported LNG from Alaska of the USA. At present, Japan has been the world's largest importer of LNG. South Korea currently is the world's second largest LNG importer. It is thus clear that the world's largest LNG transport market is in the Far East.

The import and export trade of LNG have driven the rapid development of transportation of LNG vessels. As of February 29, 2012, global delivered LNG carriers were 361, with a total loading capacity of 52,908,000 m^3, of which loading capacity from125, 000 m^3 to 150,000 m^3 were 223, with a total loading capacity of 30,680,000 m^3, accounting for 58% of the total global loading capacity of LNG vessels. Numbers and loading capacity of global ships are shown in Table 4 (http://shipbuildinghistory.com/today/ highvalueships/lngactivefleet.htm).

Table 4 - Numbers and Loading Capacity of Global Ships

Loading capacity (ten thousand m^3)	Numbers (ships)	Total capacity (ten thousand m^3)	Accounting for Total capacity (%)
≥12.5	29	173.1	3.3
12.5-15	223	3068	58
15-21.5	80	1358.8	25.7
≤21.5	29	690.59	13

Source: http://shipbuildinghistory.com/today/ highvalueships/lngactivefleet.htm

4.3 Characteristics of LNG marine transportation

LNG marine transportation mainly has the following five characteristics (Qi, 2007):

1) Business structure varies owing to project

2) Relatively small investment risks

LNG transportation usually serves on long-term charter contracts and investment income is relatively fixed. The market has little effect on it. The biggest risk of transportation projects and the whole chain of LNG projects is the ability to pay the final users.

3) Safe, reliable and stable transportation

The vast majority of LNG ships service for the project. Once the ship can not continue to navigate when an accident occurs, it is difficult to find alternative vessels. Therefore, the safety management of LNG vessels is paid more attention in order to ensure the safe, reliable and stable transportation of LNG vessels.

4) Similar to the liner shipping

LNG transportation is similar to the liner shipping. According to annual, quarterly and monthly trading schemes decided in the LNG purchases and sales contracts, buyers and sellers develop transportation plans. Once the transportation plan is decided, it will not accept great change. Fixed ships sailing in a fixed route berth and leave the ports and berths as planned. Under normal circumstances, punctuality rate of LNG vessels is controlled within an hour.

5) Special shipbuilding and high investment costs

The transportation of LNG vessels is directed shipbuilding and special services. Each project has dedicated vessels. Because the small trade volume of world prompt cargo and short-term contracts, the shipowner must undertake high cost of capital and maintenance costs of LNG vessels due to insufficient income resulted from a small amount of spot LNG transportation. Expensive materials of cargo tanks, high-performance mechanical and electrical equipments, automation systems with high degree and the world's top ship construction standards and requirements result in larger costs of construction for LNG vessels than ordinary commercial vessels.

4.4 Development of LNG marine transportation in our country

In the early 1990s, China began to research using LNG. The total investment of LNG pilot project in Guangdong was up to 30 billion RMB. Since then, Fujian LNG project and Zhejiang LNG project started to implement. While other LNG projects such as Shanghai, Zhejiang, Jiangsu, Shandong, Liaoning, Hebei were also in active demonstration and planning. China Offshore Oil, China Petroleum and gas and China Petroleum & Chemical plan to build 10 LNG receiving centers over the next decade. China is expected to import liquefied natural gas up to 30,000,000 tons per year.

On April 3, 2008, Shanghai Hudong Zhonghua Shipyard built the world's largest membrane type LNG carrier, with loading capacity of 147,000 m^3. Then a second LNG vessel built by large LNG transportation project in Guangdong was delivered to shipowners on July 10, 2008 in Shanghai. Cargo tank of this ship was GTTNO.96E-2 membrane type. As of February 29, 2012, four LNG vessels had been delivered and six were under construction. In 2012, four orders were received (Chen, Xie, Ma &Jin).

Chapter Ⅴ Risk Analysis and Control of LNG Marine Transportation

5.1 Historical accident statistics and analysis of LNG vessels

5.1.1 Accident statistics of LNG vessels

According to the 2011 annual report of Society of International Gas Tanker &Terminal Operators Ltd (SIGTTO) (SIGTTO, 2011, December), by the end of 2011, the world has 89 LNG regasification terminals and 375 LNG ships in operation. By the end of 2012, the world has 93 LNG regasification terminals and 378 LNG ships in operation (GIIGNL, 2012). In the last 45 years, LNG vessels have achieved nearly 100,000 times loading and unloading operations in worldwide ports. Now more than 3,000 transportation tasks are completed per year by LNG vessels. According to the follow-up studies to accidents of LNG vessels by DNV, Lloyds, SIGTTO, OSC, Douglas Westwood and other organizations over the years, as of 2011, total accidents of LNG vessels with a more detailed record are 45 ones (Robin,2002), shown in Table 5. The probability of occurrence for accidents is 4.5×10^{-4}(time). Accidents in 1965, 1979, 1980, 1985 and 2006 reached three times, the highest were up to 5 times in 1974. According to the statistical data of the U.S. Colton company, LNG vessels put into operation in 1970 reached 9, 1980 reached 49, 1990 reached 81, 1998 reached more than 100, the year 2000 reached 120, the end of 2008 exceeded 300, and to March 6, 2010 had reached 337.

Table 5- Total Accidents of LNG Vessels as of 2011

Year	Accidents	Cut-off year	Ships in operation
1964	1		1
1965	3		
1966	1		
1968	1		
1969	1		
1970	1	1970	9
1971	1		
1974	5		
1977	1		
1978	1		
1979	3		
1980	3	1980	49
1983	1		
1984	1		
1985	3		
1989	1		
1990	1		71
1996	1		
1997	2		
1998	0		100
1999	1		
2000	0	2000	120
2001	1		
2002	2		

2005	2		
2006	3		
2007	1		
2008	1	2008	300
2010	1	2010	337

Source: Robin,P.(2002). LNG Accidents Review. DNV, 5-10.

Clearly, before 1998, the growth of LNG vessels was slow, four new vessels per year. Since then, with consumption of natural gas and growth of LNG trade, the explosive growth of LNG vessels began, with average nearly 20 per year. Compared to the growing LNG carriers, accidents of LNG vessels did not increase. To the contrary, the frequency of accidents is declining relatively to numbers of LNG carriers.

5.1.2 Distribution of accident consequences

The consequences of accidents of LNG vessels are hull structural damage, damage to cargo tanks, structural low-temperature cracking, damage to equipments, damage to unloading arm and no loss or unknown conditions. Details are shown in Table 6.

Table 6 - The Consequences of Accidents

consequences of accidents	numbers
damage to hull structure and cargo tanks	1
no loss or unknown conditions	5
structural low-temperature cracking	8
damage to hull structure and equipments	1
damage cargo tanks	10

damage to unloading arm and structural low-temperature cracking	1
damage to hull structure	12
damage to unloading arm	1
damage to hull equipments	6

Source: compiled by the author.

Structural damages to the hull caused by accidents like collision, stranding and others are 12 times, accounting for 26.7%. Then damages to the cargo tanks reached 10 times, accounting for 22.2%. The accident of hull structure and cargo tanks damaged concurrently is only 1 time. Structural low-temperature cracking due to leakage of LNG reached 8 times, accounting for 17.8%. The damage to unloading arm is only one time. The unloading arm and the structural low-temperature cracking appearing simultaneously is also 1 time. Damages to ship equipments reached 6 times. No loss or not recorded damages are five times (Zhang, 2011, August).

5.2 Hazard identification of LNG vessels

5.2.1 Hazard identification

1) Definition of hazard

According to the "Prevention of Major Industrial Accidents Convention" adopted by the 80th International Labour Conference and relevant standards in our country, hazard is defined as units, permanently or temporarily producing, processing, carrying, using or storing hazardous substances, and quantities of dangerous substances equal to or exceeding the threshold quantity (Wu, Gao &Wei, 2001).

2) Classification of hazards

According to the hazard classification theory, hazards can be divided into two categories:
The first category refers to the excess energy acting on human body or substances interfering with the energy exchange between human body and the outside world.

The second category refers to various unsafe factors that can lead to destroyed or failed energy or constraints or restrictions measures of dangerous substances. For LNG vessels, the second hazard is mainly reflected in the crew during the marine transportation of LNG vessels, terminal operating personnel in the process of discharging after ships arriving ports, failures of ship structures, equipments and systems, the environment and natural conditions of navigable waters in the process of ship sailing and corporate culture and management system of ship management companies.

3) Methods for hazard identification

Methods for hazard identification are generally divided into two categories: intuitive empirical method and system safety analysis (Wu&Zhang, 2008, September).
① intuitive empirical method: contrasted method, empirical method and analogy method;
② system safety analysis: applying systems safety engineering evaluation methods to conduct hazard identification.

5.2.2 Hazard identification of LNG vessels

In this thesis, Shenzhen Dapeng Bay is taken for example. According to the critical quantity defined in the GB18218-2000 "major hazard identification", cargo tanks and cargo pipelines of LNG vessels all belong to major hazard scope. The provisions of relevant major hazards should be executed on them and they should be strictly managed (Shenzhen Maritime Safety Administration, 2007, December).

According to the previous analysis of two hazards of LNG carriers, combined with characteristics of typical vessels in this thesis, based on the statistics and analysis of historical accidents, the 15 categories of scopes of hazard identification are defined. Table 7 shows the identified hazards of LNG vessels.

Table 7- Hazard Identification

The scope of hazard	1) Manufacturability leakage
Hazardous events (Hazard Identification）	①Leakage of ship cargo tanks; ②rupture leakage of liquid cargo pipelines, valves, flanges, etc.; ③leakage of compressor / cargo pump; ④leakage of junction of equipments and instruments; ⑤non-normal operation of cargo pump; ⑥ offshore abandoned cargo of LNG vessels; ⑦lack of standardization of cargo capacity of membrane type vessels and shielding rupture caused by shift of liquid in cargo tanks.
Risks of accidents	①Hull and structure damaged by brittle fracture; ②flammable vapor clouds moving to the downwind direction of the source of leakage; ③cold burns to personnel exposed to LNG.

Causes of accidents	① Collision; ② corrosion (internal / external); ③ erosion (impurities of flowing liquid, etc.); ④ mechanical action; ⑤ operational errors (over-voltage, etc.); ⑥ natural disasters (earthquakes, tsunamis).
Consequences of accidents	①Brittle fracture of hull structure and hull plate; ②flammable vapor clouds moving to the downwind direction of the source of leakage.

The scope of hazard	2) Collision
Hazardous events (Hazard Identification）	①Tugboat (such as supply vessels, standby vessels, etc.); ② round-trip transportation merchant vessels; ③ offshore oil storage vessels; ④ floating production systems at sea; ⑤ barges; ⑥ fishing vessels; ⑦ offshore warships / submarines.
Risks of accidents	Heavy collisions may result in damages to cargo tanks and leakage of LNG from cargo tanks.
Causes of accidents	①Ship manoeuvring errors; ②ship loss of motive power; ③ship routing errors; ④failure of ship dynamic positioning system; ⑤ inclement weather, etc.
	Results depending on the extent of damages of shielding systems for cargo; rapid evaporation of LNG from tanks; diffused vapor in the atmosphere; rapid evaporation will be caused when cargo leaks into cargo tanks and ballast tanks not designed for carrying LNG and the access speed of cargo will be reduced; any structural damage caused by "brittle fracture" are all due to exposure of non-cryogenic steel hulls and ship

Consequences of accidents	structures to the LNG; ship structural damage may resulting from "quick phase change"; combustible limits of vapor clouds generally in the range of visible concentrated clouds; diffusion rate depending on the wind and sea conditions; Flame front from the downwind burning ignition will burn back to the position of LNG leakage; secondary ignition of combustible materials caused by the flame front; Damages to the hull and thermal radiation to the second vessel; due to thermal radiation, secondary ignition will be caused to other vessels; in a closed space in the ship, when the ratio of gas and air develops in a appropriate scope, explosion will happen; explosive range of natural gas in the air is between 5% -15%; primary and secondary shielding will be separated from the inner shell of the ship due to the rapid formation of ice.

The scope of hazard	3) Stranding
Hazardous events (Hazard Identification）	①Ship runs aground in the hard rock at high speed; ②ship broadside being aground on hard rock due to ship drift or violent manipulation; ③ship runs aground due to ebb or large surge of the tide.
Risks of accidents	①Failure of ship inner shell cause water entering to the insulation space and increasing the heat transfer to the cargo; ② the LNG releasing from the main shielding.
Causes of accidents	①Ship manoeuvring errors; ②ship loss of motive power; ③ship routing errors; ④failure of ship dynamic positioning system; ⑤failure of ship mooring system; ⑥inclement

	weather, etc.
Consequences of accidents	Consequences of accidents should be divided into two cases: rupture of the inner shell, but there is no damage to the cargo shielding systems; rupture of main containment system for cargo.

The scope of hazard	4) Ship impact
Hazardous events (Hazard Identification）	① Sailing LNG vessels impact sinking, semi-submersible or floating objects; ②impact with ports, breakwaters or other port structures; ③impact with berthing ships.
Risks of accidents	Generally no damages to cargo system
Causes of accidents	①Obstruction in shipping channels; ② ship routing errors; ③ inclement weather, etc.
Consequences of accidents	Rupture of outer shell does not cause damage to the inner shell of the ship. Seawater going into ballast tanks, causing ship uneven prestowage, affects the normal sailing. Out of control of ship maneuvering, loss of normal ship floating condition, the ship off-course and so on may arise. Rupture of the inner shell causes no damage to the cargo shielding system: ① For spherical LNG vessels, seawater will seep into the support space and the insulating layer. This will result in an increase of the heat of the cargo system. Formed BOG will exceed the amount of the combustion of ship boiler. Extra vapor needs to be discharged into the atmosphere. ② For

	membrane type LNG vessels, the membrane cabins will be exposed to risks. Seawater will enter into the insulation spaces between the inner shell of cabin and secondary shielding. Rapid formed ice will separate the primary and secondary shielding with the inner shell. There is also the risk of membrane failure.

The scope of hazard	5) Fire of BOG
Hazardous events (Hazard Identification）	①Out of control of LNG evaporation system; ②out of control of monitoring system for cargo tanks; ③thermal radiation caused by other sources of ignition leading to high pressure in cargo tanks.
Risks of accidents	Damage to ship structures caused by thermal radiation; loss to the cargo monitoring function caused by thermal radiation; loss to navigation and propulsion systems caused by the secondary ignition sources in living accommodation, engine room, navigating and control center; uncontrolled venting system caused by the cargo tank pressure rise due to the loss of monitoring function.
Causes of accidents	LNG evaporation and failure of control system; other fire with no manufacturability.
Consequences of accidents	① If the small range of LNG flame is well protected by the water spray and the fuel supply is quickly cut off, effect is very little. ②the massive LNG fires with intense radiant heat would cause damage to the ship's structure and affect cargo

	monitoring system, which makes it difficult to isolate the original source of the leakage and affects the ship's ability to control the vapor pressure in cargo tanks, leading to uncontrolled ventilation, ignited discharged cargo vapor and additional disasters.③ If the water spray system is well protected, the flame in the cargo area shall not spread to living area or engine room. Main navigation and propulsion systems of ships will be well kept.

The scope of hazard	6) Leakage of LNG in the unloading process
Hazardous events (Hazard Identification）	Ship suddenly out of the parking position for various reasons during the unloading process and damages to unloading arm caused by failure of PERC system; leakage of valve for releasing residual of the unloading arm; seal leakage of unloading arm; unexpected move of pipelines in the precooling or unloading process; fracture of unloading arm due to too large cold stress; leakages caused by immediate response and effective function of ESD; leakage caused by immediate response, but failure of ESD or needs for manual shut of ESD; leakage caused by delayed reaction, but effective function of ESD; operators out of control or damages to liquid cargo pipelines; pipeline cleaning of unloading arm is not sufficient.
Risks of accidents	Damages to ship hull and structure caused by brittle fracture; flammable vapor clouds moving to the downwind direction of

	the source of leakage; cold burns to personnel exposed to LNG.
Causes of accidents	Unloading arm emergently separated from the ship unloading; corrosion (internal / external); erosion (impurities in flowing liquid, etc.); operational errors; mechanical action; natural disasters.
Consequences of accidents	Generally possible leakage scale: general leakage, typically 10% of the cross-sectional area of pipelines. Full-scale section of pipelines. Generally possible leakage time: immediate response and ESD effectively functioned, resulting in leakage for about 2 minutes. Immediate response but ESD failed or it needed manual shut, resulting in leakage for about five minutes. Delayed reaction, but ESD functioned effectively, resulting in leakage for about 10 minutes. Operators out of control or damages to liquid cargo pipelines result in leakage for about 20 minutes including closing the ESD valves normally for 1 to 2 minutes and the liquid leakage amount between the two valves of the PERC device.

The scope of hazard	**7**) Incontrollable ventilation of ship cargo tanks
Hazardous events (Hazard Identification）	Failure of safety valve; cargo heater is still in working condition after ship berthing; breakdown of ship boiler or processing capabilities of ship vapor not matching with ship steam generating capacity; delayed ESD reset.

Risks of accidents	Vapor pressure increased rapidly in cargo tanks; pressure in cargo tanks rises above the set pressure, usually 250mbarG; flammable vapor cloud will move downwind direction of the ventilation mast.
Causes of accidents	Under normal circumstances, LNG vapor should be sent to the boiler, but in some special cases, the cargo tank pressure may exceed the set pressure of the safety valve; the rapid increase of the cargo vapor due to large heat flowing through the insulating layer into the cargo tank will exceed capacity of the boiler. This situation will happen to ships when seawater goes into the insulation layer due to the ruptured inner and outer shell of the vessel; the saturation vapor pressure of the cargo close to the set pressure of safety valve and seriously rolling and pitching happen to the ship.
Consequences of accidents	①Uncontrollably discharged from venting mast of the cargo tank, the vapor initially is cold, heavier than air. Before becoming warm, vapor moves in the downwind direction and becomes lighter than air and continues to spread. ②the flammable range of vaporous cloud is generally within the range of visible vaporous cloud. Visible vaporous cloud forms due to condensation of water vapor in the air. If vaporous cloud contacts an ignition source, it will burn back to the source of leakage, which will result in the secondary combustion of combustible materials in the pathway of flame combustion. ③the risk area formed by uncontrolled leakage of vapor is generally less than that formed by the LNG primary

	source of leakage. Compared to LNG leakage, the risk of uncontrolled emission of LNG gas is much smaller. During alight breeze, the vapor will follow 100-150 meters with the wind, and then its temperature will rise and It will scatter and disappear.

The scope of hazard	8) Equipment failure
Hazardous events (Hazard Identification）	Cargo pump; liquid cargo pipeline valve; gas compressor and air compressor; electrical equipment; generators; steam turbine; fire pump; communications equipment; Speed control system or steering control system; ineffective cargo vapor backflow temperature regulator; ineffective cargo vapor backflow pressure regulator.
Risks of accidents	Affected normal ship loading and unloading operations; leakage of liquid cargo; uncontrolled cargo vapor pressure; lack of timely fire control; likely causing collision or stranding; cargo vapor with high temperature going into cargo tanks; leakage of ship cargo vapor pipelines, opening venting valve of cargo tanks.
Causes of accidents	Crew operational errors; obsolete and aging equipment; improper management measures.
Consequences of accidents	①The normal loading and unloading operations can not be completed. ②corresponding loss and damage caused by leakage of cargo. ③corresponding loss and damage caused by uncontrolled fire. ④liquid cargo leaks as a result of collision

	or stranding. ⑤thermal shock in cargo tanks results in damage to cargo containment system or higher temperature in structures at the top of cargo tanks.

The scope of hazard	9) Operational errors
Hazardous events (Hazard Identification）	Unclosed hull cathodic protection system before the ship reaching ports; ESD system is not properly and reliably connected before discharging; damages to the end face of ship unloading main flange caused by inappropriate operations to the ship unloading arm before unloading; starting unloading pump and unloading speed is not accordance with the correct operating procedures; inlet valve of shore tanks is suddenly closed; improper arrangement for ESD system checks; improperly unmooring when ship departures.
Risks of accidents	Potential difference between ship and shore; improperly working of ESD system; too fast starting speed of unloading; damaged liquid cargo pipelines and ship cargo pump; improper pipeline cleaning; damaged ship or port.
Causes of accidents	Sense of responsibility is not enough; unskilled professional work; management system is not strict; excessive fatigue.
Consequences of accidents	①Electric spark caused by improper ship / shore isolation may be due to ship / shore potential difference during the berthing period ②failure of the ESD system leads to ineffective cut-off of cargo pipelines in the emergency situations resulting in a large number of liquid cargo leaks. ③pressure and stress impact to unloading pipelines. ④intense pressure changes in

	cargo tanks. ⑤ LNG leaks.

The scope of hazard	10) Non-technology fire
Hazardous events (Hazard Identification）	Electrostatic ignition; electrical fire; fire in power area; helicopter fire; living area fire; kitchen fire; lightning stroke fire; other explosive fires.
Risks of accidents	Thermal radiation causes damage to ship structure; thermal radiation causes damage to the cargo containment; thermal radiation results in the loss of navigation and propulsion systems; loss of the cargo monitoring function results in rise of cargo tank pressure leading to uncontrolled venting system.
Causes of accidents	Crew operational errors; obsolete and aging equipment; improper management measures.
Consequences of accidents	① If the small range of LNG flame is well protected by the water spray and the fuel supply is quickly cut off, effect is very little. ②the massive LNG fires with intense radiant heat would cause damage to the ship's structure and affect cargo monitoring system, which makes it difficult to isolate the original source of the leakage and affects the ship's ability to control the vapor pressure in cargo tanks, leading to uncontrolled ventilation, ignited discharged cargo vapor and additional disasters.③ If rescue measures is appropriate, fire fighting is timely and the water spray system in cargo tanks is well protected, the flame shall not spread to cargo area.

The scope of hazard	11) Helicopter crashes
Hazardous events (Hazard Identification）	Helicopter crashed ships; helicopter crashed waters; helicopter crashed parking apron; leakage and fire when helicopter refueling.
Risks of accidents	Helicopter fire; thermal radiation to the surrounding environments; damage to the ship structure.
Causes of accidents	Helicopter breakdown; misoperation of helicopter pilots; inclement weather.
Consequences of accidents	① If the small range of LNG flame is well protected by the water spray and the fuel supply is quickly cut off, effect is very little. ②the massive LNG fires with intense radiant heat would cause damage to the ship's structure and affect cargo monitoring system, which makes it difficult to isolate the original source of the leakage and affects the ship's ability to control the vapor pressure in cargo tanks, leading to uncontrolled ventilation, ignited discharged cargo vapor and additional disasters.③ If rescue measures is appropriate, fire fighting is timely and the water spray system in cargo tanks is well protected, the flame shall not spread to cargo area.

The scope of hazard	12) Structural failure
Hazardous events (Hazard Identification）	Ships overload; marine corrosion; anchor damage; ship structural fatigue; earthquake; tsunami; inclement weather.
Risks of accidents	Damage to the ship's structure; ship out of control.

Causes of accidents	Ship losing buoyancy; ship losing stability; ship overloaded; ship improper stowage; ship structure long-term fatigue damage; collision; unexpected natural disasters.
Consequences of accidents	①General ship structural failure (corrosion, overload, etc.), if taken timely and effective measures to deal with them, will not cause serious consequences. ②structural failure of cargo tanks may cause leakage of liquid cargo. ③serious structural failure would endanger the normal ship navigation safety.

The scope of hazard	13)Occupational hazards
Hazardous events (Hazard Identification）	Fall; Fall into the sea; mechanical collision; burns; suffocation; poisoning; electric shock; frostbite; sudden accidents occur in the emergency drills.
Risks of accidents	Injuries to the personnel.
Causes of accidents	Operational errors of the personnel; inadequate training for the personnel; improper management measures; accidents and so on.
Consequences of accidents	①Casualties to crew or dock workers. ② affecting the normal operations of the vessel.

The scope of hazard	14) Natural environmental hazards
Hazardous events (Hazard Identification）	Inclement weather; earthquake; typhoons; tsunami; adverse tides or currents; low visibility.
Risks of accidents	Collision; stranding; ship impact; liquid cargo leaks in the dock unloading process; uncontrolled ventilation of cargo tanks; helicopter crashes; ship structural failure.

Causes of accidents	Weather forecast errors; inappropriate preparatory measures; improper emergency measures; accidents and so on.
Consequences of accidents	Structural failure; leakage of cargo; uncontrolled cargo vapor.

The scope of hazard	15) Others
Hazardous events (Hazard Identification)	Terrorist attacks; kidnapping.
Risks of accidents	Injuries to the personnel; structural damages to the ship; serious leakage accidents, secondary fire accidents and explosion accidents.
Causes of accidents	Political reasons; religions; others.
Consequences of accidents	①Intentional damages to LNG cargo tanks may be in the range of 2 to about 12 square meters. General scales of these damages are from 5 to 7 meters. ② Most cases of intentional damages will cause an ignition source and could cause large LNG fires. ③some intentional damages may cause the spread of vapor clouds, accompanied by ignition and fire. ④ignited LNG vapor in cargo tanks affects the structure of the ship or integrity of the LNG cargo tanks. However, in normal conditions, this case at the same time involves no more than 2 to 3 cargo tanks. ⑤for large leakage, the rapid phase transition (RPT) is possible. But the effect is generally confined near the source of leakage, not causing damages to the external

	structure. ⑥the potential harms of the source of leakage and other dangerous places should be in the very high risk level. ⑦ In general, the most meaningful impact of deliberately caused leaks to public safety and property damages is confined in about 500 meters. Even for the very large leakage, influence is not large outside the place 1,600 meters off the source point.

Source: Shenzhen Maritime Safety Administration. (2007, December). The report of safety management for LNG marine transportation. Unpublished lecture handout, Shenzhen, China.

ChapterⅥ Risk Assessment for LNG Vessels

6.1 The introduction to risk assessment method

According to the characteristics of LNG vessels and the current situation of LNG terminal in Shenzhen Dapeng Bay, combined with domestic and overseas evaluation methods, based on the hazard identification, safety / risk matrix for qualitative analysis and evaluation is used in this paper in order to understand the risk level of each unit. The 5 × 5 risk matrix is used for the assessment of the levels of risks, shown in Table 8 (Liu, Zhang &Liu, 2005).

Table 8- Safety / Risk Matrix

level	consequences		possibilities				
	casualties	damages	1	2	3	4	5
			rarely	infrequent	possible	occasional	frequent
1	negligible	negligible					
2	slight	slight					
3	primary	partial					
4	individual	regional					
5	multiple deaths	catastrophic					

Source: Liu,T.M.,Zhang,X.K.,&Liu,G.Z.(2005). Application guide for safety evaluation method. Beijing: Chemical Industry Press.

In this safety / risk matrix, probability of each risk event ranges from 1 (rarely) to 5 (frequent). Consequences include casualties, property damages, environmental impacts and the impact of the company's reputation and the impact range from 1 (minimal damage) to 5 (maximum damage). As shown in Table 9, risk matrix is divided into three different areas with different colors and each zone represents the different levels of risk acceptability and the necessary conditions for further evaluation.

Table 9 - The Risk Acceptability Represented by Risk Matrix Area

low	Acceptable risk area
middle	As low as reasonable practicable area
high	Unacceptable risk area

Source: http://en.wikipedia.org/wiki/ALARP

The assessment adopts the British safety principle called ALARP (http://en.wikipedia.org/wiki/ALARP). ALARP stands for "as low as reasonably practicable", and is a term often used in the milieu of safety-critical and safety-involved systems. The ALARP principle is that the residual risk shall be as low as reasonably practicable. It has particular connotations as a route to reduce risks SFAIRP (as far as is reasonably practicable) in UK Health and Safety Law. In practical applications, this principle requires to minimize the failure rate as far as possible. The principle divides risks into three categories:

1) Sufficiently small risks that can be ignored;

2) Large enough risks that can not be accepted;

3) Between the two above risks that must take effective feasible methods or measures below reasonable costs to reduce risks to an acceptable level.

6.2 Results of risk assessment for LNG vessels

Results of risk analysis for LNG marine transportation in this paper has cited the risk evaluation results in the “comprehensive safety assessment studies of modern LNG vessels ” (Wu, 2006, December), shown in Table 10.

Table 10- Evaluation Results from Safety / Risk Matrix

number	unit	Safety Accidents	probabilities	consequences	hazards
1	technological leaks	fracture leaks of LNG pipelines, valves, flanges and others	2	2	low
2		compressor /cargo pump leaks	2	2	low
3		Leakage in the junction of equipments and apparatus	2	2	low
4		non-normal operations of liquid cargo pumps	2	2	low
5		abandoned cargo by offshore LNG vessels	2	4	middle

6		due to not standardized cargo capacity of cargo tanks of membrane type LNG vessels, liquid cargo agitation in tanks caused ruptured shielding	2	3	low
7	ship collision	Tugboats (such as supply ships, standby vessels, etc.)	2	2	low
8		Round-trip transportation merchant vessels	2	4	middle
9		Offshore oil storage vessels	2	4	middle
10		Offshore floating production systems	2	3	low
11		Fishing boats	2	2	low
12		Barges / Yachts	2	2	low
13		Sea warships / submarines, etc.	1	3	low

14	Ship stranding	Ship aground on hard rocks at high speed	2	4	middle
15		ship drift or violent manipulation caused broadside of ship stranded on the hard rock	2	3	low
16		ebb tide stranding or the ship ran aground because of surges	2	3	low
17	Ship impact	Sailing LNG vessels hit sunken, semi-submersible or floating objects	2	2	low
18		with docks, breakwaters or other port structures	2	2	low
19		With berthing vessels	2	2	low

20	Leakage of LNG in the unloading process	For various reasons during the unloading process, the ship suddenly be out of the parking position and failure of PERC system resulted in damages to unloading arm	2	4	middle
21		sealing leaks of unloading arm	2	2	low
22		rupture of unloading arm due to too large cold stress	1	3	low
23		leakage caused by delayed reaction, but effectively contributing ESD	1	3	low

24		Operators out of control or damages to liquid cargo pipelines	2	3	low
25	non-technological fires	static electricity fires	2	3	low
26		lightning stroke fires	2	4	middle
27		Various naked flames	2	2	low
28		electric sparks	2	2	low
29		Mechanical sparks	2	2	low
30	others	terrorist attacks	1	5	middle
31		kidnapping	1	5	middle

Source: Wu,W.Q.(2006,December). Comprehensive safety assessment studies of modern LNG vessels. Unpublished master's thesis, Dalian, China.

According to the risk assessment results in the above safety / risk table, this matrix evaluation has analyzed a total of seven units and 31 possible safety incidents, and conducted qualitative analysis of probabilities and consequences. The risk results are 8 middle risks and 23 low risks. Thus, during the marine transportation, risks of LNG vessels are relatively not high. The key is more serious consequences of some accidents. But currently, from design to manufacturing, and to shipping managements, all steps of LNG vessels require high standards, strict and standardized managements, so probabilities of the emergence of various accidents are relatively low in history. Even so, the consequences of accidents are relatively serious. So in the daily operations and managements of the production, we must strengthen vigilance, pay high attention and conduct various activities strictly in accordance with regulatory requirements.

ChapterⅦ Risk Control Approaches

According to the previous risk analysis of LNG marine transportation, we have been fully aware of risk hazards of various aspects of LNG vessels during marine transportation. In order to achieve the established safety standards, ship design, construction, daily operation and maintenance, manning and so on should be in accordance with international conventions and industry standards. In addition, port authorities should also adopt special measures for LNG vessels entering and leaving ports. These measures include traffic monitoring, setting ship security zones, escorting tugs and restrictive operating conditions for different wind speeds and visibility, etc (MIKE& LOUIS, 2004).

Controlling LNG marine transportation risk has two ways. First, we could reduce the frequency of accidents through strengthening control of surrounding circumstances of the ship, setting control zones, reducing ship collision probability; Second, we could control the extent of accidents through controlling the gap diameter of the ship's cargo tank when an accident happens to reduce leakage amount, which can control and reduce the risk of LNG marine transportation. According to the previous risk analysis, this paper proposes the following three risk control methods to effectively guarantee the safety of LNG marine transportation (Hong, Jiang, Wei & Guo).

7.1 Improved ship design, special construction techniques and systematic function configuration

7.1.1 Ship design and construction

In accordance with the international gas convention (IGC rules), LNG vessels should adopt double hull and double bottom structure. The cargo tank locates inside the inner hull, from the cargo tank bulkhead to the outer hull at least 760mm. Compared to ordinary vessels, LNG vessel has a strong resistance to grounding and collision shocks. Theoretical analysis and previous accident records show that LNG vessel has a strong ability of resistance. The double hull structure can absorb a lot of impact energy before the inner hull and LNG cargo sealing system are damaged. Whether the cargo tank can be penetrated depends on the ship speed, the collision angle, position and shape of the bow of the collided vessel. Studies show that the drift speed from 3 to 5 knots can penetrate the side of the cargo tank. This speed has been far greater than the drifting speed of a non-powered LNG vessel and far greater than the maximum speed of the ship turning round in the harbor water areas (Wang, 2004, April).

Meanwhile, the structural design of double hull and double bottom for LNG vessels makes the cargo tank undamaged even if the ship runs aground. From the bottom of the cargo tank to the bottom of the ship, the distance is at least B / 5 or 2 meters. Experiments show that even the longitudinal high speed collision will not produce leakage for either spherical or membrane type LNG vessels occurring stranding.

For a floating membrane type LNG vessel with capacity of 138,000 m^3, cargo tank system can be broken down only being collided by ships (ship types, impact angles and speeds), shown in Table 11.

Table 11- Ship Types, Impact Angles and Speeds Leading to Breakdown of Cargo Tank Systems of LNG Vessels

Ship types	908	808	708	608	508	458
Small roro ships	8.4 knots	8.5 knots	8.9 knots	9.7 knots	10.9 knots	11.9 knots
Bulk cargo ships	3.8 knots	3.9 knots	4.1 knots	4.4 knots	5.0 knots	5.4 knots
Container vessels	4.7 knots	4.7 knots	5.0 knots	5.4 knots	6.1 knots	6.6 knots

Source: compiled by the author.

7.1.2 The adoption of special construction technologies

Currently, there are three types of cargo maintenance system for LNG transport vessels: membrane type cargo tanks, spherical cargo tanks and prismatic cargo tanks (Ian, 2002, March).

7.1.3 Equipped with fully functional overpressure protection systems, fire fighting systems, combustible gas detection and alarm systems

The safety valves ensure that all independent transmission systems of LNG pipelines do not overpressure. In hazardous gas areas, there exists very safe explosion-proof equipment. Practical experiences have shown that this explosion-proof equipment is very effective.

Locations where combustible gases may leak are equipped with high-sensitivity gas detection devices and the adiabatic locations in cargo tanks are also equipped with temperature, pressure monitoring systems, with these detection signals into bridges and the cargo control rooms. When the temperature, pressure, combustible gas contents are monitored to have deviated from the normal setting values, the alarm system will give alarm signals immediately. If the ship loading and unloading operations are in progress, the system will trigger emergency shutdown system (ESD) to cut off cargo delivery pipelines.

Fixed fire extinguishing systems of LNG vessels usually include dry powder extinguishing systems, water spraying fire extinguishing systems, and carbon dioxide fire extinguishing systems. Dry powder extinguishing systems and water spraying fire extinguishing systems are used for cargo spaces. Carbon dioxide fire extinguishing systems are used for the enclosed spaces such as the engine room. Relatively easily damaged areas, collecting tubes, tops of cargo tanks, cargo engine rooms, living areas, channels leading to the lifeboats are all protected by the water curtain systems.

7.2 The key of reducing risks is to ensure good navigable environments of harbor waters

When LNG vessels involve entering and leaving ports, berthing and unberthing operations and loading and unloading operations and other steps in port waters, those situations are far more complicated than maritime navigation. Therefore, ensuring good navigable environments of the harbour water areas and standardizing LNG vessels and sailing trends of other relevant ships can effectively reduce operational risks of LNG vessels in the harbour water areas. Management measures taken for LNG vessels navigating in ports / channels are as follows (Chen &Cheng, 2007).

7.2.1 Navigation statuses of ships in ports are strictly controlled; in particular, ships are not allowed to traverse the LNG shipping channels.

When LNG vessels enter ports, other vessels are prohibited to navigate in the same channels, giving some priority for LNG vessels entering ports. This is often used in secluded waters with small ship traffic flow. In the traffic-intensive waters, navigation status of ships around LNG vessels is strictly controlled. A moveable "safety zone" is delimited around LNG vessels. In this area, other vessels are prohibited entering.

7.2.2 Controlling sailing speeds of ships in the harbor areas

Establishment of an effective ship routes plan for arriving and departing ports will effectively manage and monitor the speed of ships sailing in the harbor areas, ship related personnel, ship maneuvering programs and the movements of other vessels in the harbor areas. The communication among the bridge of ship, shipowners, pilots, watch keepers and helmsmen should be well kept. Before ships arriving ports, effective checks should be implemented to ensure that the mandatory requirements for equipment, operations and certificates of seafarers have been executed. Before ships arriving at ports, the normal states of all the navigation equipment, propulsion equipment, steering devices and safety systems should be confirmed through ship/shore contacts. Any problems of the key equipment should be notified to the port authorities before ships entering ports.

For the safe speed, the densities, water depths, water currents and other factors of harbors are inconsistent, making it impossible to determine the specific safe speed for LNG vessels entering ports. Usually the normal design speed of LNG vessels is

20 knots or so and the maneuverability and wave-making resistance must be considered for the safe speed. That is, the ship must not only be ensured to be operated flexibly, but also to be ensured not to pose a threat to other ships around them through the ship's stern waves and transverse waves. The specific values of the safe speed can be provided by the ship in accordance with the actual situations and need a period of specific practices. Usually if the safe speed is too small, it may affect the operational performance of the ship. Tugs with appropriate quantities and horsepowers shall be arranged for guarding and towing.

7.2.3 Establishing and implementing operational requirements about prohibiting operations in inclement weather or prohibiting ship entering and leaving ports under low visibility

In fact, restricted conditions for operations under inclement weather or low visibility will be established in each port in the world. Relevant characteristics of wind areas and propulsion equipment of this type of ships should also be considered about restricted conditions for operations of LNG vessels. The operators should also recognize wind speed limits applicable for operations of unloading arms. When the wind speed is higher than the set maximum wind speed for limiting shifting berthing of ships in ports, port operations can be delayed until the speed decreases to the level allowing the transport of liquid cargo.

According to investigation and survey, Japan, the Middle East and some other countries usually limit entering and leaving ports of LNG vessels at night (Geng, Li &Li). In general, whether LNG operations at night are feasible depends mainly on port environments and navigation conditions, as well as the actual ship traffic flow at night.

7.2.4 Rigorous requirements for approach channels

Approach channel is a key factor involved in the safety of navigation and it has already been considered when LNG projects began to be planned. Its requirements are consistent with channel selections of other ships. LNG vessels may preferably be apart from other sailing ships with enough depth of water.

During the calculation of draught for ships entering ports, ship draught, height reduction of base below the stern caused by ship speed, height reduction below the ship's keel caused by jolt or shake of the ship, interactions between seabed and the bottom of the ship caused by navigation status are usually considered. There are no uniform standards to requirements for ship channel depth (Zou, Zhang &Gan, 2011).

Channel width is related with transverse wind, flow velocity and navigational speed. The width of the entire waterway should ensure sufficient navigable waters in all possible emergency operating conditions. The main factors that determine channel width are sailing characteristics of expected ships, maintaining directional stability and power and speed required by access to turning the corner of the channel under the most severe and allowed operating conditions. Curve width should be decided by the expected speed when the ship is passing this part.

7.2.5 Operational requirements for berthing and departing operations

Ship navigating in and out of the harbour should be characterized by the manoeuvres of large vessels. Except requirements of tug assistance as soon as possible, we must also pay attention to the following points for LNG vessels: ①early control of speed in the channel;② correcting effects of wind on the ship predictably and as soon as possible; ③controlling ship translational berthing speed less than 15 cm / sec, if necessary under 10 cm / sec; ④mooring ropes being all wire ropes in order to ensure the stability of the ship securing berths, if necessary, requirements for lashing and securing ashore ropes.

Quantities and horsepower for tugs in each LNG dock are not the same. Equipping with adequate port-working tugs to assist operations is an important measure to avoid collisions.

7.2.6 Strict compliance with standards of LNG terminal operations

In the design process of LNG terminals, based on the standards of various countries and international major oil companies, our country provides relevant regulations about allowed wind speed, wave height, visibility and flow velocity during the LNG vessels operating processes (Table 12) (Lv,2012,Iune).

Table12 - Standards for Domestic LNG Terminal Operations

number	operation phase	allowed wind speed （m/s）	allowed wave height		visibility	flow velocity	
			transverse waveH4%	following sea		transverse flow	direct flow
1	Navigating entering and leaving ports	≤20	≤2.0	≤4.0	≥1000	<1.5	≤2.5
2	Berthing operations	≤15	≤1.2	≤1.5	≥1000	<1.0	<2.0

3	loading and unloading operations	≤15	≤1.2	≤1.5		<1.0	<2.0
4	Mooring in the harbor	≤20	≤1.5	<2.0		≤1.0	<2.5
5	Unberthing operations	≤20	≤1.5	<2.0	≥1000	≤1.0	<2.5

Source: Lv,Y.X.(2012,Iune). Discussion on the characteristics and relevant technical requirements for berthing and departing operations of LNG vessels. Pearl River Water Transport.

7.3 The main way to reduce risks is to improve the port service quality and management level

7.3.1 Quality of operating personnels

The operation management program must include port service quality assurance procedures for ships and supporting vessels entering and leaving ports. All LNG vessels shall be provided with detailed loading procedures / cargo operating practices. Trained and experienced crew shall be provided according to the STCW95 convention. Therefore, all operations during the process of loading for LNG vessels have rules to follow.

7.3.2 Checks before ship's arrival

Checks before ship arrival should become a part of the entire program. Terminal managers (terminal docks) and port authorities may thus ensure that ships firstly arriving the ports are familiar with management procedures of significant risks and the crew recognize and are able to fulfill their responsibilities.

7.3.3 Route planning

No matter what type of ship, if managed well, sea routes from berth to berth will be designed. Design, planning marine transport routes can highlight some special hazards (such as shoals and obstructions) and some important control parameters (such as harbor speed, important maneuvering). Thus, through the program, deck officers can clearly understand what specific hazards are in the front, how to safely enter and leave ports and what should be done for each person to ensure that everything is under control.

The initiative program aims to provide continuous monitoring of the ship track, issue route deviation alerts as soon as possible and make rapid and effective response to the route deviation and dangers when ships are entering the harbor (such as collision risks). The expected speed should be indicated in each stage of the sailing process. If the ship's speed and the position in the channel do not match with the plan, the ship could not proceed.

7.3.4 Suspension program

Formal plan for entering and leaving ports should include the emergency plan for suspension of entering ports and protecting safety of the ship (such as mooring ship in a temporary anchorage or returning to the sea).

7.3.5 Managements for entering and leaving ports

The plan for entering and leaving ports is necessary, but the plan will have no effect if the ship's voyage is not monitored continuously according to the plan. All of risks in its adjacent areas and established route should be considered for the ship to ensure the ship's position and its course. The captain and pilot can obtain the information they want before maneuvering according to the plan. They can receive adequate warnings about the situation and development that may threaten the integrity of the navigation plan. If the pilot is on board, the management of the marine navigators will become especially important. The pilotage of pilots should be ensured effectively monitored.

7.3.6 Improving the operation level of pilots

For large ships, unless owning exemption certificates, or operations for entering and leaving ports in whichever ports in the world are required to have certified pilots to conduct pilotages. Professional standards and experiences of pilots vary greatly in different ports, but they are all familiar with characteristics of the ships they will pilot, which is the basic point (Hong&Guo, 2007, July).

Compared to common merchant ships, the operating performances of LNG vessels are very different, which is very important for pilots. Because almost all LNG vessels are relying on steam turbines for propulsion, while the bulk merchant ships in the world are driven by diesel engines. The response time of steam turbine propellers is longer than diesel engines used in other ships. Before LNG vessels entering ports, the captain must conduct a brief introduction to the ship's operating characteristics to pilots and discuss the route plans from the pilot station to the berth to ensure that plans are consistent with the actual navigation of the ship.

If LNG operations are not conducted previously in ports, then before conducting LNG operations, it is wise to provide the simulation trainings for pilots and possible masters of tugs. It is the best to appoint a professional team (pilotage and tugboat) for LNG operations, but even so, it is recommended that regular refresher trainings should be conducted to ensure that the professional team is capable of continuous competency.

7.3.7 Special defense program

In some environments of ports, some additional measures are required, most of which include direct interventions. Through direct interventions, the competent authority may control some or all aspects of LNG vessels when LNG vessels are passing through the port.

ChapterⅧ Marine Transportation Safety Management of LNG in Our Country

8.1 The overview of marine transportation safety management of LNG in foreign countries

This paper takes the safety management of LNG vessels in Australia as an example. In the maritime affairs, AMSA is quite different with maritime organization functions in China. Compared to mechanisms of our maritime sectors, Australian Maritime Administration does not have responsibilities including navigable management, emergency treatments for emergency accidents and search and rescue and treatments for pollution accidents. These responsibilities are undertaken by the port authorities and local government departments.

To reduce the operational risks of LNG vessels in ports, the port authorities in Australia have taken strict precautionary measures. These measures include entering and leaving ports of LNG vessels, berthing and departing operations, loading operations, pilotage and other aspects. These measures are provided by the BP, Shell and other world-famous oil companies and these companies are also as the managers to actively participate (Gladstone Ports Corporation, 2010, October).

8.2 Current marine transportation safety management of LNG in our country

For the management, the safety managements adopted for LNG marine transportation by the Shenzhen Maritime Safety Administration to some extent represent the current safety management model for marine transportation of LNG in our country. So, in this paper, the safety managements adopted for LNG marine transportation by the Shenzhen Maritime Safety Administration will be briefly introduced.

8.2.1 Safety managements adopted for LNG marine transportation by the Shenzhen Maritime Safety Administration

1) Safety managements for LNG terminal terminals

For the supervision and management of terminals and safety facilities, supervision and management measures should be implemented in strict accordance with various provisions in the "Port Law". According to the scopes of responsibilities, responsibilities should be divided and also cooperation and interaction are necessary. According to problems existing in the actual operations of terminals, the Maritime Safety Administration makes corrective recommendations to the related management departments of terminals in time. The design and construction of LNG terminals shall comply with relevant regulatory requirements. Adequate safety facilities for fire prevention, anti-explosion, leak-proof and preventing expansion and spread of accidents should be installed.

2) The reporting system before ship entering ports

According to the related provisions, LNG Vessels shall provide the expected time for arrival at ports 72 hours earlier (if the voyage is less than 72 hours, at the time leaving the above port) to the competent authority, confirm time for arrival at ports 24 hours earlier and report the time for arrival at reporting route two hours earlier. Based on the current reporting situation of ships, in order to effectively facilitate entering ports, ships often report their navigation and arrival dynamics to the

Shenzhen Maritime Safety Administration 72, 48, 24, 12 and 2 hours in advance. During the voyages of ships, ships shall submit written reports to the Shenzhen Maritime Safety Administration prior to entering ports when abnormal conditions possibly affecting ships entering and leaving ports, berthing or operations happen. Vessels shall report to the VTS center in Shenzhen according to the related provisions. LNG vessels should report when they plan to enter or leave Shenzhen ports in accordance with the relevant provisions of the carriage of dangerous goods.

3) The management for ships entering and leaving ports

LNG vessels should moor in the dedicated LNG anchorages. During the mooring period, safe watches and smooth communications should be kept. LNG vessels should maintain enough residual water depth and take the safe speed to navigate carefully when they are entering and leaving ports. When LNG vessels are entering and leaving ports, they should apply for convoy from Shenzhen Maritime Safety Administration and the competent authority could implement traffic control to the navigable waters according to the marine traffic conditions.

4) Monitoring to the berthing and departing and loading and unloading operations

The berthing and departing operations of LNG vessels should be conducted in the daytime with assistance of adequate tugs. Under normal circumstances, the bow should direct the departing channel during berthing period and emergency towropes should be available. When the ship moors at the pier, the state of stand by engine should be remained and monitoring measures should be required to be implemented. LNG vessels berthing and departing, loading and unloading operations, wind speed, wave height, flow velocity, visibility and other weather, sea conditions shall comply with the “terminal design procedures for LNG". LNG vessels should be prohibited to discharge BOG of LNG in ports. Supervisory personnel should be arranged to implement measures including the inspections before operations of dangerous goods and on-site inspections and so on. If defects are detected, ships and docks must be required to rectify and reform timely. On-site supervisory personnel should check written agreements between ship and shore including cargo operations, emergency matters between ship and shore and so on, as well as various safety measures of ships and terminals before the operations of LNG vessels. On-site supervisory personnel should also check whether the firefighting equipment in the terminal is in readily available condition, whether the water pressures of fire fighting water, water curtain and spray system are maintained in the rated pressure, whether the fixed combustible gas detection devices and pyrotechnic detection device are in good working conditions. During the loading and unloading period, the maintenance operations affecting the ship power and manoeuvring shall not be carried out and operations and maintenance such as thermotechnical operations affecting the safe operations of cargo also shall not be conducted.

5) Some special management during the supervision

During the unloading period, when ship encounters special circumstances, such as abnormalities of ship cargo tanks or ashore liquid cargo tanks, thunder and lightning weathers, wind speed, wave height, flow rate and other weather or sea conditions, etc. beyond requirements in the “terminal design procedures for LNG", fire alarms that may affect operational safety and other situations endangering safety occurring around the terminal, ship and shore should immediately stop operations, and at the same time notify the other party and take appropriate safety measures. Supervisors should supervise whether ship and shore promptly stop operations and take appropriate safety measures.

8.2.2 Emergency measures for LNG accidents developed by the Shenzhen Maritime Safety Administration

According to the related provisions, terminal companies should develop contingency plans, report contingency plans, emergency equipments and devices to the competent authorities for the records and organize staff to conduct trainings and drills in accordance with the emergency plans. Vessels shall organize regular crew drills in accordance with the ship's emergency plans. Vessels and terminal companies shall carry out collaborative drills in accordance with the requirements in the corresponding contingency plans. When accidents or abnormal conditions of the cargo system happen, ships should take effective measures in accordance with contingency plans, immediately report to the competent authorities and accept the investigation and handling of competent authorities. In addition to the above requirements, the Shenzhen Maritime Safety Administration also has developed accidents emergency measures for collision, stranding, uncontrolled discharge, the LNG leaks from ship's cargo pipelines, cargo catching fire, the ship catching fire berthing in the LNG terminals, fire in the terminal, personnel falling into water from the ship or the terminal and other LNG accidents.

ChapterⅨ Recommendations for Safety Management of LNG Marine Transportation

Once major accidents of LNG vessels happen in the port, damages are not only caused to the crew, but also to the surrounding environments. According to the records of Japan and the US, frequencies of major accidents in the harbor area of LNG vessels are as shown in Table 13.

Table 13 - Frequencies of Major Accidents

Name of port	frequencies of major accidents
Kobe, Yokohama and other major ports	10^{-3}～10^{-4}
Various ports in New York, Providence and Savannah	3×10^{-3}
Los Angeles and Chesapeake Bay(Boston)	10^{-4}

Source: compiled by the author.

From the table we know that frequencies of accidents of LNG vessels in ports of Bosotn were significantly reduced for a few levels compared to other ports. This is because that the port took effective measures such as entering ports under good visibility, equipping with pilot boats, controlling channels and so on. In order to avoid the occurrences of major accidents of LNG carriers, in addition to improving the ship's navigational equipments and improving qualities of the crew, the well-developed navigation rules are important. Thus, navigation rules and other regulations must be developed for ports transporting LNG vessels.

Based on the particularities of marine transportation of LNG and the experiences of supervisions, the following ten measures for strengthening safety management of marine transportation of LNG are proposed.

1) Complete laws and regulations constructed for port safety managements

According to the requirements of laws and regulations developed by the competent departments for transportations, combined with the actual situations of LNG receiving terminals, port management departments should establish and complete regulations for safety management of LNG marine transportation and develop relevant technical manuals to accomplish having laws to abide by and standardize managements. If norms need to be changed due to emerging LNG vessels, such as port emergency plans, the competent departments should modify the norms as soon as possible for safety management of LNG marine transportation having laws to abide by.

2) Strengthen safety assessment checks and supervisions for the LNG terminals

According to the “terminal design procedures for LNG", the relevant information should be submitted to the maritime sector after the final acceptance of the terminal project. After examination and verifying conducted by the maritime sector, berthing and loading and unloading operations of LNG vessels can be carried out.

3) Increase the supervision to safety knowledge trainings for LNG terminal operators

The specific operation is divided into four stages including before operation, operation preparation, conducting operation and after operation. Safety knowledge trainings for LNG terminal operators should be integrated into the four stages. Meanwhile a better mechanism is needed to monitor the terminal management and operational organizations to implement.

4) Competent departments should establish interaction and coordination mechanisms with the related terminal organizations

Specialized personnel of the terminal management departments have been trained and can conduct a 24-hour tour of inspections in the operating terminals. After further trainings, they can provide 24-hour on-site monitoring information of all cases about LNG operations to the competent maritime sectors. Advantages of implementing on-site inspections of the maritime sectors and so on can provide the final security check safeguard in order to further verify the safe operation of the ship. If the conditions allow, this collaboration mechanism can be further expanded to coordinate with the relevant LNG transportation companies.

5) Accelerate the cultivation of professionals in maritime administrations and strengthen personnel trainings

The levels of site supervisors could be improved through increasing the introduction of professional and technical personnel and trainings for business key members and sending relevant personnel to learn onboard, inspect related equipments with the surveyors and understand the relevant knowledge in the LNG shipyards and other means. Experts and scholars carrying out researches on LNG vessels can be invited to train safety supervision and management personnel. Maritime supervision and management departments should make supervision and management of LNG documented and systematized.

6) Strengthen the effective management of navigation environment

Maritime sectors should timely carry out detailed analysis for navigation environments and conditions of waters near berthing terminals of LNG vessels and risk analysis for channels to establish the appropriate contingency plans. In bad weather conditions, communication of information is needed to be strengthened, patrol force should also be increased to guide the ship safe mooring and watching over and exchange of dynamic information should be in time. Standardizing ship sailing behaviors in the dedicated channels for LNG vessels is to improve navigation environment and to enhance the safety and reliability of navigations of LNG vessels. Using ship reporting systems, the maritime administration will label and track to implement full traffic organizations for LNG vessels in waters controlled by the ship traffic management center. Giving full play to roles of maritime management resources on traffic organization and management is to effectively improve the ability to monitor the waters, thereby ensuring and improving the ship sailing order in navigable waters of LNG vessels.

7) Strengthening the scientific managements of pilots for LNG vessels

Maritime sectors can take advantage of rights given by the laws and regulations to strengthen the scientific managements to pilots and require pilot stations to develop scientific and reliable pilotage manipulation programs in advance aiming at different types of vessels and develop relevant risk analysis and contingency plans to ensure pilot safety.

8) Establish the appropriate contingency plans

Port management departments should develop contingency plans, report contingency plans, emergency equipments and devices to the competent authorities for the records and organize staff to conduct trainings and drills in accordance with the emergency plans. Vessels shall organize regular crew drills in accordance with the ship's emergency plans. Vessels and terminal companies shall carry out collaborative drills. When accidents or abnormal conditions of the cargo system happen, ships shall immediately report to the competent authorities. When accidents happen during the operations, the terminal shall take effective measures and immediately report to the competent authorities. LNG terminal shall establish the LNG terminal contingency plans including all aspects of the emergency actions taken in emergency situations.

9) Establish a thorough source control system for LNG shipping companies

Competent authorities shall vigorously promote the LNG shipping companies to strive to become self-discipline, self-motivation, self-improvement and continuous improvement security self-controlled enterprises. They shall also strengthen the inspections for LNG vessels, exams and certifications for the crew, supervision and management and process control for LNG transportation company approvals and its safety management system audit to strengthen the safety management of LNG vessels from the source.

10) Improve quality of the crew for LNG vessels

In order to strengthen safety management of LNG marine transportation, our country shall have our own LNG fleets. In addition to the LNG shipbuilding technologies, the crews with high-quality are also critical for LNG vessels.

Chapter Ⅹ Conclusions

This thesis has identified hazards for LNG vessels and evaluated risks. Through the risk identification study, a total of seven dangerous elements are defined focusing on 31 possible security incidents. Eight moderate hazards and 23 low risk sources are identified. Moderate risk sources include abandoned cargo at sea of LNG vessels, ship collisions of LNG vessels with large ships, LNG vessels stranding with high speed, failure of the PERC system during the unloading process, fires caused by lightning strokes during the unloading process, terrorist attacks and kidnappings and so on. Three ways for risk control are proposed: improved ship design, particular construction techniques and systematic function configuration to maximize the reduction of risks due to ship design, construction, and its structure; ensuring good navigable environment of harbor waters is the key to reduce risks; the improvement of the port service quality and management level is the main way to reduce risks. Ten recommendations for strengthening safety management of LNG marine transportation in our country have also been given in this thesis.

According to the statistics, over the next 10 to 15 years will be China's largest development period of LNG transportation market (Guo, 2011, May). Especially successively constructed LNG terminals in the coastal areas and operations of China LNG shipping companies will bring us a lot of safety management issues to be resolved.

Only through transportation competent departments in our country, after full investigation, considering the current situation of safety management of LNG marine transportation, introducing national laws and regulations to promote the development of LNG marine transportation in our country, ensuring the security of national energy, continuing to support, strengthen and standardize LNG marine transportation, and strengthening safety management, an active role can be played in comprehensively building a moderately prosperous society and achieving sustainable developments.

References

ABS. (2004). *A presentation to china shipping group*. LNG shipping seminar, Shanghai, China.

BP Statistical Review of World Energy June 2012. http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481

Chen,G.H.,&Cheng,S.B.(2007). Consequence Simulation on LNG Leakage Accidents and its Quantitative Risk Assessment. *Natural Gas Industry*, 6, 133-135.

Chen,S.P.,Xie,F.S.,Ma,Z.P.,&Jin,S.F. *Shipping status and development trend of LNG vessels*. Lanzhou University of Technology, Lanzhou.

Chen,G.H.,&Cheng,S.B.(2007). Consequence Simulation on LNG Leakage Accidents and its Quantitative Risk Assessment. *Natural Gas Industry*, 6, 133-135.

Cui,Y.S.,Li,P.Y.,Han,H.D. (2001). Researches for structural types of tanks for LNG vessels. Collected papers from the Seventh National Marine Technology Symposium.

Gao,W.L.(2012,June). Risk researches on navigation dynamic of LNG vessels in the Dapeng Bay. Wuhan University of Technology.

Fan, S.Q. (1993). LNG vessels.Dalian: Dalian Maritime University Press.

Gluver, H., & Olsen, D. (1998, May). Current practice in risk analysis of ship collisions to bridges. *Proc. of the International Symposium on Advances in Ship Collision Analysis*, 10-13, 85-96.

GIIGNL. (2012). The LNG industry.

Guo,W.Z.(2011,May). The Study on the economical channel width for very large LNG carrier. Wuhan :Wuhan University of Technology.

Gladstone Ports Corporation. (2010, October).LNG Vessel Operating Parameters in Port of Gladstone.Port Notice.

Geng,J.Z.,Li,X.D.,&Li,Y.B. The feasibility study for implementation of entering and leaving LNG terminals at night in our country. http://www.paper.edu.cn.

Hong,H.Y.,&Guo,X.B.(2007,July). The thinking of effective supervision of Liquefied natural gas (LNG) vessels. *China Water transportation.*

http://en.wikipedia.org/wiki/ALARP

Hong,H.Y.,Jiang,Y.G.,Wei,W.J.,&Guo,X.B. *Risk analysis and control for marine transportation of LNG vessels*. Shenzhen Maritime Safety Administration.

Huang,H.T.,Ding,R.,&Sun,K.(2005,February). Current situations and outlooks for world LNG shipping market. *World Shipping, 28* (1).

Ian,H. (2002,March). Future Development options for LNG marine transportation. AIChE 2002 Spring National Meeting, New Orleans.

Liang, J.G. (2006). Analysis for LNG safe marine transportation. *Shipping Management, 28*(9), 27-29.

Li,G.(2008). Prevention and treatment of common LNG accidents.China: China Petrochemical Press.

LNG Carriers in Service or Under Construction. http://shipbuildinghistory.com/today/ highvalueships/lngactivefleet.htm.

Li,P.Y. (2003). Marine technology of liquefied gas.Dalian: Dalian Maritime University Press.

Liu,H.(2000).The current status of development of world LNG vessels.*Technical and economic information of shipping industry*.

Liu,T.M.,Zhang,X.K.,&Liu,G.Z.(2005). Application guide for safety evaluation method. Beijing: Chemical Industry Press.

Liu,Y.L.,&Zhang,D.Z.(2007). Analysis and discussion for LNG propulsion system. *Ship&Boat*, 1, 34-42.

Lv,Y.X.(2012,Iune). Discussion on the characteristics and relevant technical requirements for berthing and departing operations of LNG vessels. *Pearl River*

Water Transport.

Li,J.(2006, September). Researches of world LNG vessels. *Journal of Shengli College China University of Petroleum, 20*(3).

Lu,Z.C.(2006). Ship maneuvering.Dalian: Daliann Maritime University Press.

MIKE, H., & LOUIS, G. (2004). Guidance on risk analysis and safety implication of a large liquefied natural gas (LNG) spill over water. Albuquerque, New Mexico: Sandia National Laboratories.

Michelle, M.F. (2006). *LNG Safety and Security.* http://www.beg.utexas.edu/energycon/lng.

Qi,C.Z.(2007). Transportation characteristics and development of LNG vessels. *Marine technology*, 1, 41-43.

R M Pitblado, J Baik, G J Hughes, C Ferro&S J Shaw. (2005, June). Consequences of liquefied natural gas marine incidents.*Process Safety Progress*, *24* (2), 108-114.

Robin,P.(2002). LNG Accidents Review. DNV, 5-10.

Shenzhen Maritime Safety Administration. (2007, December). *The report of safety management for LNG marine transportation.* Unpublished lecture handout,Shenzhen,China.

SIGTTO. (2011, December). Annual Report, UK.

Serdar, K., Masaki, F., &Masao, F. Analysing of maritime accidents by approaching method for minimizing human error. *Naval Research Logistics*.

Wang,Y.D.(1998).The introduction to recently built four vessels by Kawasaki Heavy Industries .*Technical and economic information of shipping industry*,4,8-11.

Wu,W.Q.(2006,December). *Comprehensive safety assessment studies of modern LNG vessels*. Unpublished master's thesis,Dalian,China.

Wu,Z.Z.,Gao,J.D.,&Wei,J.D.(2001). Risk assessment method and its application.China: Metallurgical Industry Press.

Wu,W.Q.,&Zhang,B.(2008,September). Risk assessment for leakage of liquid cargo of LNG vessels.*Navigation of China, 31*(3).

Wang,J.H. (2004,April). Chinese Liquefied Natural Gas (LNG) construction situation analysis. *Jiang Su Ship,21*(4).

Xu, X.X., Chen, W.P., &Yu, J.H. (2006). Types and characteristics of LNG transportation. *Oil & Gas Storage and Transportation.*

Yuan,H.L. (2006).Development of ship type of a 147000 m^3 membrane LNG tanker.*Ship &Boat,* 6,10.

Zhang,W.H. (2011, August). Historical accident researches for LNG vessels.*Ship&Boat, 22*(4).

Zhang,B.,&Wu,W.Q.(2009). Analysis and researches for consequences of major accidents of LNG vessels. *Navigation of China*, *32*(1), 77-81.

Zhang,Z.X. (1994). Ship type structure, equipment and safe transportation of LNG. Beijing: China Communication Press.

Zhang,D.Z. (2007,March). Selection and management for propulsion devices of LNG vessels. Dalian: Dalian Maritime University Press.

Zhang,Z,X.,Ye,C.H.,&He,C.Z.(1994).Ship type structure, equipment and safe transportation of LNG vessels.Beijing: China Communication Press.

Zhao,Z.L.(2005). Safety assessment for ship-shore link-up and navigation process in ports of LNG vessels. Shanghai: Shanghai Maritime University.

Zou,H.B., Zhang,B.G., &Gan,L.X.(2011). The adaptability of LNG vessels entering and leaving the Shenzhen Western public channels. *Marine Technology,* 5.