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Risk analysis of fire/explosion to the LNG fuelled passenger ferries

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Risk Analysis of Fire/ Explosion to the LNG Fuelled Passenger Ferries

By

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MASTER OF SCIENCE

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DECLARATION

I hereby certify that all the materials 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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ABSTRACT

Title of the research paper: **Risk Analysis of Fire/ Explosion to the LNG Fuelled Passenger Ferries**

Degree: **MSc**

The research paper is a study of fire/explosion risk on the LNG fuelled passenger ferries. The principal of FSA methods in the IMO guideline is followed and techniques of Preliminary Hazard Analysis (PHA), Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) are used in the study.

The development of LNG fuelled passenger ferries around the world is introduced briefly at first, their specific design, arrangement and related safety requirements are discussed, the major LNG related hazards are also represented in the paper. In Step 1 of hazard identification, the potential hazards of fire/explosion on LNG passenger ferries are identified and ranked according to the different operation phases of the ship by the PHA. In Step 2 of risk analysis, a quantitative assessment to the high risks of fire/explosion and related scenarios are conducted by setting up risk models, some assumptions and results from other related reports and study are used in the calculations.

Based on the analysis to the high risk areas of fire/explosion on the LNG fuelled passenger ferries, potential measurements to reduce the risks are recommended, and some suggestions for the safety administration are put forward.

KEYWORDS: Risk, Analysis, Fire/ Explosion, LNG fuel, Passenger ferry

TABLE OF CONTENTS

DECLARATION ii
ACKNOWLEDGEMENTS iii
ABSTRACT iv
TABLE OF CONTENTS v
LIST OF TABLES vii
LIST OF FIGURES viii
LIST OF ABBREVIATIONS ix

Chapter Ⅰ Introduction 1
1.1 Background 1
1.2 Objectives and scope 1
1.3 Methodology 2

Chapter Ⅱ Brief Introduction to the LNG Fuelled Passenger Ferries 4
2.1 LNG fuelled passenger ships around the world 4
2.2 Ship design and arrangements 6
2.2.1 LNG fuel tanks 6
2.2.2 Engine room safety concepts 7
2.2.3 Bunkering 9
2.2.4 Hazardous areas 11
2.3 Areas of safety concern 11
2.3.1 LNG specific hazards 11
2.3.2 Special concerns to the LNG fuelled ships 13
2.4 Safety rules and regulations 13
2.4.1 Maritime regulations for all passenger ships 14
2.4.2 Regulations specific to the LNG fuelled passenger ships 14

Chapter Ⅲ Identification of Fire/ Explosion Hazards to the LNG Fuelled Passenger Ferries 16
3.1 Objective and scope 16
3.2 Methods and techniques 16
3.3 The background of LNG safety incidents 18
3.4 The generic model of LNG fuelled passenger ferries 20
3.5 Identification of fire/ explosion Hazards 21
3.6 Ranking of the hazards 25

3.7 Summary 27

Chapter Ⅳ Risk Analysis to the High Ranking Hazards and Associated Scenarios 29
4.1 Scope of study 29
4.2 Method and techniques 29
4.3 Risk model 29
4.4 Consequence assessment 31
4.4.1 Fire/ explosion in accommodation 32
4.4.2 Fire/explosion on vehicle deck 33
4.4.3 Fire/explosion in machinery spaces with no LNG leakage and ignition.. 34
4.4.4 Fire/explosion due to damage of containment caused by collision 35
4.4.5 Fire/explosion due to damage of containment caused by grounding 38
4.4.6 Fire/explosion due to damage of containment caused by contact 40
4.4.7 Fire/explosion due to bunkering failure 42
4.5 Risk summation 42
4.6 Summary 43

Chapter Ⅴ Recommendations 44
5.1 Identified high risk areas and recommended measures 44
5.2 Suggestions for the safety administration 45

Chapter Ⅵ Conclusions 47

Reference 48

LIST OF TABLES

Table 1- LNG fuelled ships in operation worldwide……………………………. 5

Table 2- Confirmed orderbook of LNG newbuilds……………………………… 5

Table 3-Major marine LNG incidents……………………………………………19

Table 4-Potential hazards related to the fire/ explosion of LNG fuelled passenger ferries……………………………………………………………..24

Table 5-Definition of frequency index………………………………………….... 26

Table 6-Definition of consequence index……………………………………...26

Table 7-Risk index (RI)………………………………………………………… 26

Table 8-Fire Subcategories rankings by the risk matrix…………………………. 27

Table 9-Possibility and frequency of different scenarios caused by collision…… 37

Table 10-Possibility and frequency of different scenarios caused by grounding... 40

Table 11-Possibility and frequency of different scenarios caused by contact…… 41

Table 12-Summary of risk calculations of fire/explosion………………………...43

LIST OF FIGURES

Figure 1-A generic risk management process…………………………………… ...3

Figure 2-The LNG tank sizes for some selected ships already built or under construction…………………………………………………… 6

Figure 3-The gas tank location of the LNG fuelled ships…………………………. 7

Figure 4-Double piping in the inherently gas safe engine room………………….. 8

Figure 5-ESD Protected Engine Rooms…………………………………………… 9

Figure 6-The bunkering system of gas fuelled ships……………………………… 11

Figure 7-Framework of Preliminary Hazard Analysis (PHA)……………………... 18

Figure 8-The Risk contribution tree of fire/explosion of the LNG fuelled passenger ferry…………………………………………………………..30

Figure 9-Overall risk model of fire/explosion on LNG fuelled passenger ferries.… 31

Figure 10-The Event Tree of fire/explosion at accommodation…………………... 32

Figure 11-The Event Tree of fire/explosion on vehicle deck……………………... 33

Figure 12-The Event Tree of fire/explosion in machinery spaces…………………34

Figure 13-The Event Tree of fire/explosion caused by collision…………………...37

Figure 14-The Event Tree of fire/explosion caused by grounding……………….... 39

Figure 15-The Event Tree of fire/explosion caused by contact……………………41

LIST OF ABBREVIATIONS

CCS	China classification Society
CNG	Compressed Natural Gas
DNV	Det Norske Veritas
ESD	Emergency shutdown
ETA	Event Tree Analysis
FMEA	Failure Mode and Effects Analysis
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
HAZID	Identification of Hazards
HAZOP	Hazard and Operability Studies
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MSC	Maritime Safety Committee
PHA	Preliminary Hazard Analysis
PLL	Potential Loss of Life
RCT	Risk Contribution Tree
RPT	Rapid phase transition
STS	Ship to Ship
TPS	Intermediate tank to ship
TTS	Truck to ship
WIAT	What If Analysis Technique

Chapter Ⅰ Introduction

1.1 Background

LNG is a kind of clean energy and an alternative fuel to the fuel oil applied on board. It is an efficient way to eliminate the emission of SOx and particular matters of ships, and could cut down the emission of NOx and CO_2 by about 80% and 20% respectively compared to the high sulphur residual fuels (BV, 2001).

LNG firstly has served as a marine fuel since 1964 on the LNG carriers by using the boil-off gas, and was utilized in the boiler or duel fuel engines (Herdzik, 2011, p.169). Under the background of stricter international regulations and regional legislations on the ship emission control as well as high oil price, a rapid development of LNG as a fuel source on the other type of vessels can be seen in the past decade, especially on the passenger ferries and cargo ships engaged in coastal or short sea transportation. On the other hand, because of the special characteristics of LNG, it brings many concerns and doubts on the safety issues as a new type of fuel on the ships during the application. Many risks such as cryogenic damage, fire/ explosion should be assessed in the operation and safety management.

1.2 Objectives and scope

This paper is intended to investigate the causes of fire/explosion risks during the operation of LNG fuelled passenger ferries and identify their consequences to the crew and passengers on board to the possible extend, to recommend mitigation measures in the safety management.
The LNG fuelled passenger ferries with dual fuel engines or gas engines which are regulated by the IMO "Interim guidelines on safety for natural gas-fuelled engine installations in ships" are in the scope of study. The fire/explosions caused by terrorisms or during the repair and maintenance in the shipyards are out of the scope.

1.3 Methodology

The methodology introduced in Step1 and Step2 of formal safety assessment of IMO guideline was followed. Scenarios and risk models of fire/explosions were set up based on the LNG special hazards, ship design and arrangements as well as different operation phases of the ship. Because of the limited historical statistics and data of LNG fuelled ferries as a new type of ships, literature reviews and other risk assessment reports and studies on the LNG carriers and passenger ships are referred and utilized in HAZID session and quantification of the frequency and fatalities to the possible extend.

According to the IMO guideline on the formal safety assessment (FSA) (IMO, 2007, p.5), the following steps should be followed and the risk management process is shown in Figure 1:

1. Identification of hazards;
2. Risk analysis;
3. Risk control options;
4. Cost benefit assessment;
5. Recommendations for decision-making.

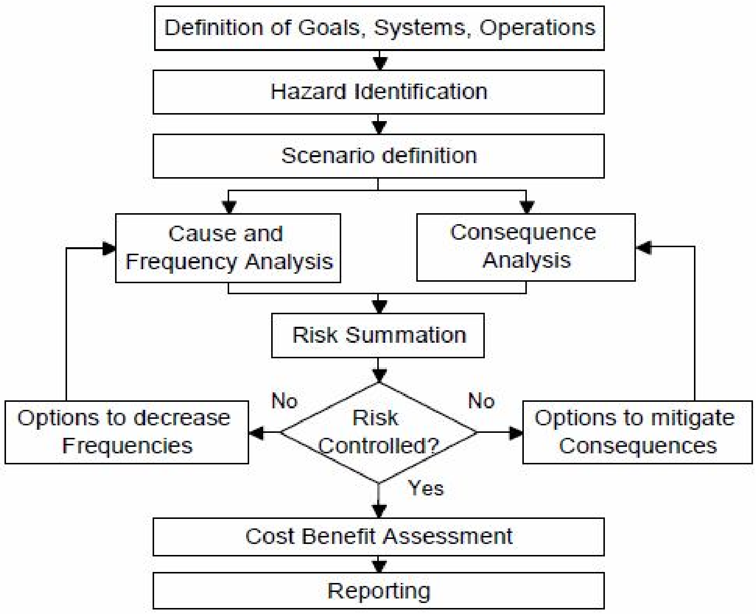

Figure 1 A generic risk management process (Source: MSC Circ. 1023)

Chapter Ⅱ Brief Introduction to the LNG Fuelled Passenger Ferries

2.1 LNG fuelled passenger ships around the world

The car ferry "Glutra" finished in 2000 was the first LNG fuelled passenger ferry in the world. Since then, a number of LNG passenger ships of similar type were built, most of them are in Norway. Up to June of 2012, there were 30 LNG fuelled ships in operation and 32 confirmed LNG new builds of the world, as shown in Table 1 and Table 2 (DNV, 2013). Most of the LNG fuelled passenger ships are engaged in short sea or coastal transportation.

The world's largest LNG fuelled passenger vessel "Viking Grace" was delivered in January of 2013, which was constructed for the Viking Line to operate in Finland, Sweden and along the Baltic countries. It has a capability for about 2800 passengers, 200 crew, 1300 lane meters for trucks and 500 lane meters for cars (Washington, 2011).

High speed LNG catamaran had been under construction in Australia and planned to go into service in 2012 between Buenos Aires and Montevideo. It will be dual fuel, capable of operating on LNG or diesel, and will have capacity for 153 vehicles, 1,000 passengers, and have speeds up to 50 knots (Washington, 2011).

However, many more countries seem eager to use LNG (and CNG) as alternative ships fuel. A demonstration project has been started for operation of LNG fuelled riverboats at the Yangtze River in 2010 under the cooperation of China MSA, CCS, ship owners and LNG supplying company. According to the estimation of IMO, there would be 800-1000 LNG fuelled ships up to 2015 around the world (Pan & Liu, 2012).

Table 1 LNG fuelled ships in operation worldwide

(Up to June of 2012, source: DNV)

Year	Type of vessel	Owner	Class	Year	Type of vessel	Owner	Class
2000	Car/passenger ferry	Fjord1	DNV	2010	Patrol vessel	REM	DNV
2003	PSV	Simon Møkster	DNV	2010	Car/passenger ferry	Fjord1	DNV
2003	PSV	Eidesvik	DNV	2010	Patrol vessel	REM	DNV
2006	Car/passenger ferry	Fjord1	DNV	2010	Car/passenger ferry	Fjord1	DNV
2007	Car/passenger ferry	Fjord1	DNV	2010	Car/passenger ferry	Fjord1	DNV
2007	Car/passenger ferry	Fjord1	DNV	2010	Car/passenger ferry	Fosen Namsos Sjø	DNV
2007	Car/passenger ferry	Fjord1	DNV	2011	PSV	DOF	DNV
2007	Car/passenger ferry	Fjord1	DNV	2011	Chemical tanker	Tarbit Shipping	GL
2008	PSV	Eidesvik Shipping	DNV	2011	Car/passenger ferry	Fjord1	DNV
2009	PSV	Eidesvik Shipping	DNV	2011	PSV	Solstad Rederi	DNV
2009	Car/passenger ferry	Tide	DNV	2012	Car/passenger ferry	Fjord1	DNV
2009	Car/passenger ferry	Tide	DNV	2012	PSV	Eidesvik	DNV
2009	Car/passenger ferry	Tide	DNV	2012	PSV	Olympic Shipping	DNV
2009	Patrol vessel	REM	DNV	2012	PSV	Island Offshore	DNV
2009	Car/passenger ferry	Fjord1	DNV	2012	General Cargo	Nordnorsk Shipping	DNV

Table 2 Confirmed orderbook of LNG newbuilds

(Up to June of 2012, source: DNV)

Year	Type of vessel	Owner	Class	Year	Type of vessel	Owner	Class
2012	PSV	Eidesvik Shipping	DNV	2013	Ro-Ro	Norlines	DNV
2012	Ro-Ro	Sea-Cargo	DNV	2013	Ro-Ro	Norlines	DNV
2012	Ro-Ro	Sea-Cargo	DNV	2013	RoPax	Viking Line	LR
2012	High speed RoPax	Buquebus	DNV	2013	Tug	Buksér& Berging	DNV
2012	PSV	Island Offshore	DNV	2013	PSV	Harvey Gulf Int. Marine	ABS
2012	PSV	REM	DNV	2013	PSV	Harvey Gulf Int. Marine	ABS
2012	Car/passenger ferry	Torghatten Nord	DNV	2013	Patrol vessel	Finish Border Guard	GL
2012	Car/passenger ferry	Torghatten Nord	DNV	2013	Car/passenge ferry	Society of Quebec ferries	
2012	Car/passenger ferry	Torghatten Nord	DNV	2013	Tug	CNOOC	
2012	Car/passenger ferry	Torghatten Nord	DNV	2013	Tug	CNOOC	
2012	Harbor vessel	Incheon Port Authority		2014	Car/passenger ferry	Society of Quebec ferries	
2013	RoPax	Fjordline	DNV	2014	Car/passenger ferry	Society of Quebec ferries	
2013	RoPax	Fjordline	DNV	2014	Tug	Buksér & Berging	DNV
2013	General	Cargo Eidsvaag	DNV	2014	PSV	Harvey Gulf Int. Marine	ABS

2013	Car/passenger ferry	Norled		2014	PSV	Harvey Gulf Int. Marine	ABS
2013	Car/passenger ferry	Norled		2014	PSV	Remøy Shipping	

2.2 Ship design and arrangements

Because of the use of LNG as fuel on board, the ship design and arrangements of LNG fuelled ferries should comply with the specific requirements of IMO regulations and Class Society rules to the gas-fuelled ships, and also should satisfy the general requirements to the all passenger ships. The specific ship design and arrangements of LNG fuelled ferries mainly include:

2.2.1 LNG fuel tanks

The energy density of liquefied natural gas (LNG) increases by 600 times compared to its gas state at the normal pressure and room temperature, but it is only about half the energy density of oil. So the space for the LNG is larger than for fuel oil on board. In the existing LNG fuelled ships, the LNG is stored in cylindrical, double-wall, vacuum insulated stainless steel tanks, the tank pressure usually is less than 5 bar and the typical size is less than 200m^3 (Danish EPA, 2010, pp. 23-25).

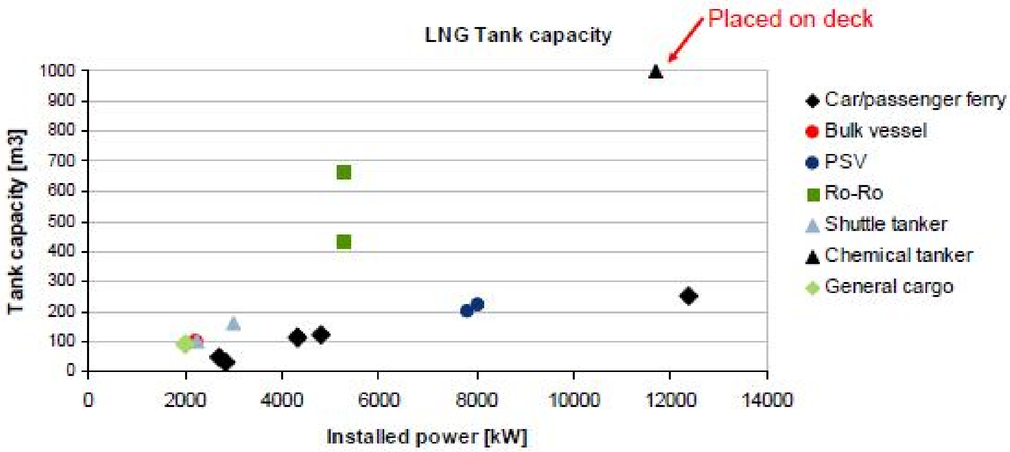

Figure 2 The LNG tank sizes for some selected ships already built or under construction (Source: Danish EPA)

According to the requirements of IMO "Interim guidelines on safety for natural gas-fuelled engine installations in ships", LNG fuel tanks should be an independent tank designed in accordance with Chapter 4 of the IGC Code, and the height of outlet from the pressure relief valves as well as the safety distance from air intake, air outlet, opening and furnace installation are required. LNG fuel tanks could be located on open deck or in enclosed space if fulfill certain requirements. For passenger ships, the LNG fuel tanks should be located at least B/5 from the ship's side when on open deck; LNG fuel tanks with a maximum acceptable working pressure of 10 bar may be located in enclosed space, and gas storage tanks should be located as close as possible to the ship centerline: minimum B/5 from the ship side, minimum, the lesser of B/15 and 2 m from the bottom plating, and not less than 760 mm from the shell plating(IMO, 2009, p.19), just as showed in Figure 3 .

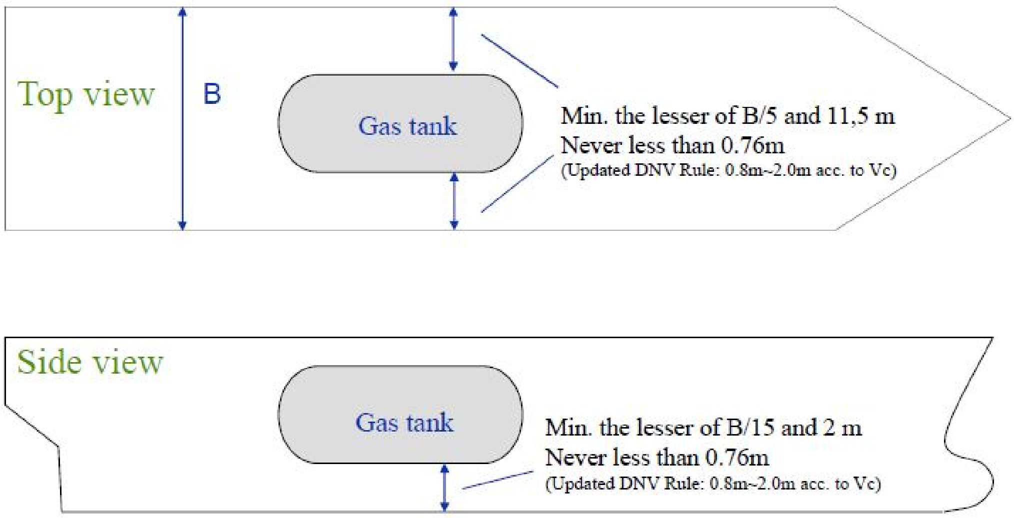

Figure 3 The gas tank location of the LNG fuelled ships (Source: DNV)

2.2.2 Engine room safety concepts

According to the IMO interim guidelines on the gas fuelled ships, two alternative system configurations may be accepted: Gas safe machinery space and ESD-protected machinery space.

In the Inherently Gas Safe Engine Rooms, the space is considered gas safe under all conditions, normal as well as abnormal conditions (IMO, 2009, p.15). All gas supply piping within machinery space is double pipe/ duct which is pressurized and filled with inert gas or ventilated and fitted with gas detection. The room around is an ordinary machinery space without special requirements. The concept is mandatory for high pressure piping (>10 bar), but can also be used with low pressure installations.

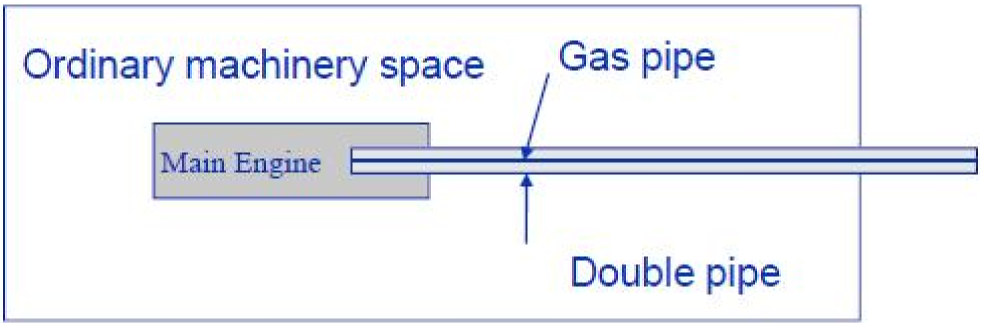

Figure 4 Double piping in the inherently gas safe engine room (Source: DNV)

ESD protected machinery space is arranged that is considered non hazardous under normal conditions, but under certain abnormal conditions may have the potential to become gas hazardous. In the event of abnormal conditions involving gas hazards, emergency shutdown (ESD) of non-safe equipment (ignition sources) and machinery shall be automatically executed while equipment or machinery in use or active during these conditions shall be of explosion protected design (IMO, 2009, p.16).

In the ESD Protected Engine Rooms, Gas detection system with at least 3 detectors in ER should be arranged, and two detectors read 20% LEL (lower explosion limit), when the detectors are activated the fuel supply automatically shuts down and all non explosion protected equipment is to be electrically disconnected. The pressure in gas supply lines within machinery spaces should be less than 10 bar and two or more engine rooms should be independent of each other. The Ventilation should be 30 air changes / hour and there are limitations of the equipments which can be located in the engine rooms (Deng, 2012).

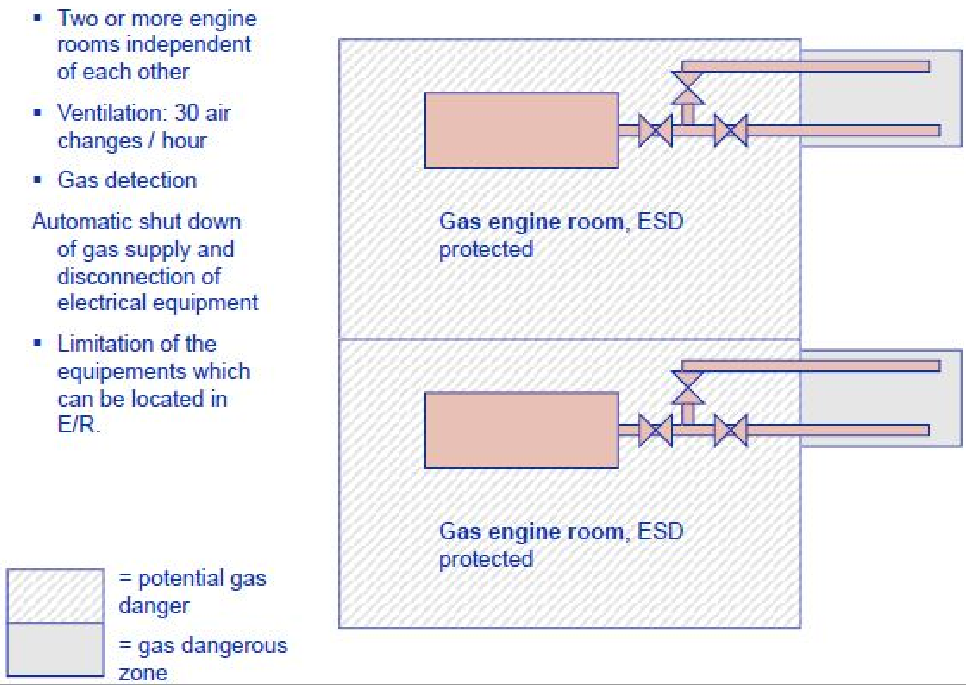

Figure 5 ESD Protected Engine Rooms (Source: DNV)

There are also requirements on the propulsion redundancy that at least 40% of the propulsion power plus normal electrical power should be maintained if the gas supply is shut down to any machinery space due to a gas leakage.

2.2.3 Bunkering

IMO Interim guidelines on safety for natural gas-fuelled engine installations in ships provides requirements of the fuel bunkering system and distributing system to the gas fuelled ships (see Figure 6), there are also other related rules and regulations such as the CCS and DNV class rules and rules developed by the Norwegian Maritime Directorate for the issue. However, less experience and documentations are on the port and bunker operations for LNG, standards don't cover this issue completely. DNV has proposed to develop standard for LNG bunkering equipment and procedures to ISO TC67/WG10, many companies and individuals have expressed indicated interest for participation (Rysst, 2011). Under the condition of miss of standards, risk assessment should be followed in the safety management.

There are mainly three bunkering solutions to do LNG bunkering: Truck to ship (TTS), Intermediate tank to ship (TPS) and Ship to Ship (STS), each method has its own characteristics and applicability.

Truck to ship (TTS) bunkering method is the most common method today, but the volume of bunkering is limited each time. About 25 tonnes of LNG could be carried by the LNG tank truck depending on its capacity and the national transport regulations as well as the infrastructure of the road. If the volume of the LNG fuelled ships is large (>50 tonnes), other bunker methods would be better. On the other hand, there is a significant impact of the possibilities to parallel operation when the bunker operation was carried out on the quay side of the vessel, cargo and passenger handling might be conducted.

Another common bunkering method is Intermediate tank to ship (TPS). LNG fuel is bunkered by pipeline directly from an intermediate LNG tank ashore. The size of LNG tank could vary from a few tones to several thousands of tones depending on the demand of LNG fuelled vessels and condition of location. But the flexibility is limited as the bunkering position is fixed.

Ship to Ship (STS) bunkering is the feasible option on the flexibility and capacity compared other two bunkering methods, which could be used to bunker most kind of ship types, but the initial investment and operational cost would be reasonable high. (Algell & Bakosch, 2012, p.77)

For the LNG fuelled car and passenger ferry “Glutra” of Norwegian, it has two LNG tanks onboard and 32 m^3 each. Refueling is conducted every 4-5 days and takes 1-2 hours for a truckload of 40 m^3 of LNG. The bunkering operation is carried out when the ferry is at berth for night and no passengers on board. For the other LNG fuelled passenger ferries in Norwegian such as Tidekongen, Tidedronningen and Tideprinsessen operating from Oslo, their LNG tank onboard are 29 m^3 and they are refueled about once a week by a dedicated truck with a typically capacity of 50 m^3 (Danish EPA, 2010, p.26).

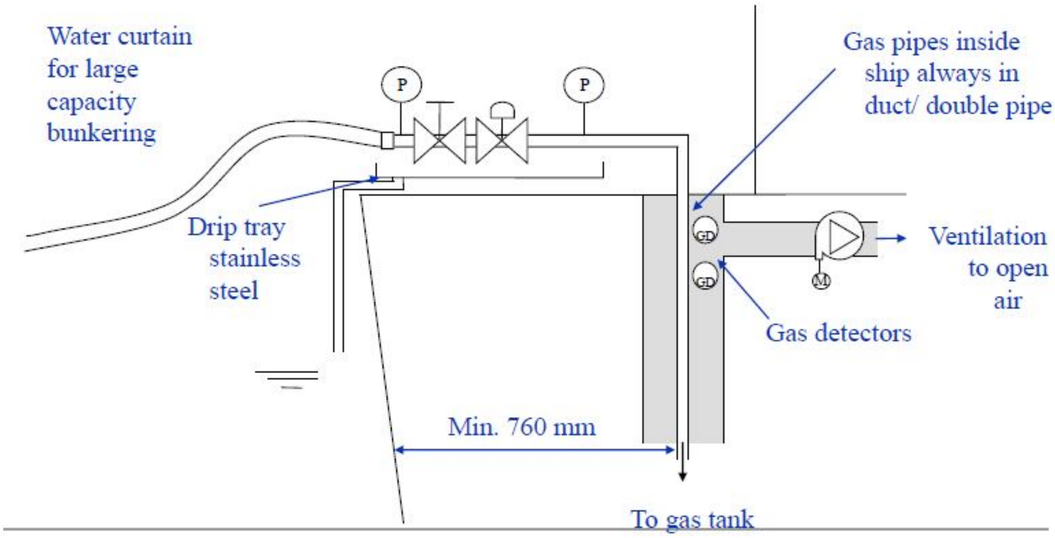

Figure 6 The bunkering system of gas fuelled ships (source: DNV)

2.2.4 Hazardous areas

Hazardous area zones are defined in the IMO "Inter guidelines on safety for natural gas-fuelled engine installations in ships", the areas with risk of explosive gas atmosphere are analyzed and classified. Hazardous areas are divided into Zone 0, Zone 1 and Zone 2. Electrical equipments located in the hazards zones should be certified as explosion safe in that zone (Deng, 2012).

2.3 Areas of safety concern

2.3.1 LNG specific hazards

Liquefied natural gas (LNG) is at about temperature of -163 °C, and it is a clear, non-corrosive, non-toxic, cryogenic liquid at normal atmospheric pressure, the boiling point is -161.5 °C at normal conditions and the flash point is -187.8 °C , the specific gravity of liquid is 0.45 and 0.6 of gas (Herdzik, 2011, p.170).

The flammability range for vaporized LNG in air is 5% (LFL) to 15% (UFL) and its auto-ignition temperature is above 540 °C (Foss, 2012, pp.14-18). The types of potential LNG hazards of most concern by the operators and stakeholders include:

Explosion. An explosion may happen when LNG reaches its flammability mixed with air and ignited or uncontrollably released from a pressurized state. If there is a structural failure such as puncture of the container, there would be an uncontrolled release. However, LNG usually is stored at an extremely low temperature (-163 °C), so no high pressure is required to maintain its liquid state.

Vapor Clouds. When the LNG is warmed up, it turns from liquid to gas. Initially the gas is colder and heavier than the surrounding air and a vapor cloud would be formed above the released liquid. After the gas is warmed up, it would mix with the surrounding air and disperse into the atmosphere. The vapor clouds may be ignited and cause fire/explosion if it concentrates within its flammability range and encounter an ignition source.

Pool fire. If the leakage of LNG mixed with the air is ignited by the ignition source nearby, there would be a pool fire above the LNG pool. The pool fire would be more rapid and intense than the oil fire. It could not be extinguished easily before the LNG is consumed up or the source of LNG leakage is cut off. The thermal radiation of a pool fire may cause injury to the people and damage to the property within certain distance depending on the scale of the pool fire (IMO, 2007, p.8).

Cryogenic damage. LNG is stored at extremely low temperature (about -163℃), so it would cause metal embrittlement, cracking or structural failure if the containment systems fail to work. It also would cause frost burns to the personnel if protective equipments are not wear during the operation or encounter accidental leakages of the LNG.

Rapid phase transition (RPT). If large amount of LNG is leaked on water, it would vapor very quickly and cause a rapid phase transition (RPT). During the process, heat is transferred from water to the LNG at a temperature difference of about 175℃ (depending on the temperature of the water) and cause physical or cold explosion. It ranges from small pops to blasts large enough to potentially damage lightweight structures (Foss, 2012, p.19).

Sloshing. If the LNG tank on ship is partially filled, a violent motion of the fluid would be caused and lead to an increased high pressure of LNG on the tank walls, especially in the bad weather and rough sea.

Boiling liquid expanding explosions. An explosion might be caused if the LNG tank ruptures because that the temperature in the LNG tank is above the boiling point of the LNG and the pressure relief system of the tank is out of function.

2.3.2 Special concerns to the LNG fuelled ships

Due to the specific chemical and physical properties of LNG, special consideration should be taken into account in the design, construction, installation, commissioning and operation of LNG fuelled ships compared to the conventional oil fuelled ships. Risk assessments to the LNG specific hazards need to be carried out, and the following important aspects should be considered:

1. Risks originating from fuel storage and gas supply system
2. Risks related to the bunkering operations
3. Risks related to external forces to the fuel storage facility
4. Risks associated to collision/ contact involving LNG fuelled vessels

The main consequences related to health and safety risks at LNG fuelled propulsion systems are fire and explosion (Danish EPA, 2010, p.110).

2.4 Safety rules and regulations

2.4.1 Maritime regulations for all passenger ships

IMO has developed and adopted a series of regulations on the safety of passenger ships, and most of the regulations are the consequences of lessons and experiences drawn from the major passenger ship accidents which resulted in a large number of life loss of the crews and passengers. (IMO, 2008, p5)

The international convention for the safety of life at sea (SOLAS) is the most important regulation for the safety of passenger ships, which contains the basic construction and management requirement and covers the major areas related to the safety of passenger ships: subdivision and stability; fire safety; life-saving appliances; machinery and electrical installation; safety management, etc. There are also a number of mandatory codes under the SOLAS convention for the safety of ships, such as the ISM code, FSS code and ISPS code which have more detailed requirements for the safety and security of passenger ships.

Other safety and environmental issues such as load limit of the ship are contained in the International convention on Load Lines (LOADLINE) (IMO, 2005) , the issues of steering, lights and signals are contained in the International Convention for the prevention of Collisions at Sea (COLREG) (IMO, 2003), the issues related to the training of crews on board are contained in international Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW Convention) (IMO, 2011) and issues of ship pollutions are contained in the International Convention for the Prevention of Pollution from Ships (MARPOL) (IMO, 2002). They are applicable to passenger ships as well as other types of ships.

2.4.2 Regulations specific to the LNG fuelled passenger ships

The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code) provides a serious of requirements to the safety related to the ship design, construction, equipments and operations of ships carrying liquefied gases for bulk (IMO, 1993). However, it is not applicable to the LNG fuelled ships other than LNG carriers, but it allows the natural gas which flashpoint is below 60℃ applied on board as a fuel. Some of the classification societies have developed requirements for the use of natural gas as fuel on ships based on this code (Danish EPA, 2010, p.59). A number of regulations of the IMO "Interim guidelines on safety for natural gas-fuelled engine installations in ships" also refer to the IGC code on some specific requirements such as the Material requirements, Arrangement of entrances and other openings, LNG fuel storage tanks and etc.

The "Interim guidelines on safety for natural gas-fuelled engine installations in ships" was developed by the IMO to provide an international standard for natural gas-fuelled ships other than vessels covered by the IGC Code (IMO, 2009). The requirements to the LNG fuelled passenger ships in the guideline are stricter than other types of natural gas-fuelled ships. Its goal is to ensure the arrangement and installation of gas-fuelled machinery for propulsion and auxiliary purposes have an equivalent level of integrity in terms of safety, reliability and dependability compared to the conventional oil fueled types. On the other hand, the International Code of Safety for Gas-fuelled Ships (IGF Code) is in the process of developing by the concerned committee of IMO.

There are also class society rules and national regulations for the LNG fuelled ships, such as the DNV and CCS publish the guidelines for the design, installation and survey of gas-fuelled propulsion systems. In Norway, the introduction of LNG fuelled ships has lead to an adaptation of the regulations set by the Norwegian Maritime Directorate (NMD) in 2000 (Danish EPA, 2010, p.58). However, there are a number of areas related to the safety of LNG fuelled ships haven't been covered, such as the operation of bunkering, the specific standards on the training and certification of seafarers work on the LNG fuelled ships.

Chapter Ⅲ Identification of Fire/ Explosion Hazards to the LNG Fuelled Passenger Ferries

3.1 Objective and scope

The objective of this chapter is to identify the hazards related to the fire/explosions and related scenarios on the LNG fuelled ferries during the operation, to provide a list of prioritized hazards and their associated scenarios in the next step of risk analysis.

The HAZID focuses on the hazards of fire/explosions during the operation of LNG fuelled ferries. The hazards of fire/explosions when ship is at yard for repairs/docking are out of scope. The fire/explosions caused by the terrorism attack also are not included in the scope.

The HAZID session focuses on the LNG fuelled passenger ferries with dual fuel engine or gas engine, and the following operational phases are taken into account in this session:

1. Loading
2. Departing quay
3. Under way
4. Arriving at port, mooring and preparing for unloading
5. Unloading
6. Bunkering

3.2 Methods and techniques

“Hazard” is defined as a potential to threaten human life, health, property or the environment. Both of creative and analytical techniques are used for the identification of hazards (IMO, 2007). These techniques generally include (Pan, 2004, p.17):

1. Brainstorming;
2. Fault Tree Analysis (FTA);
3. Event Tree Analysis (ETA);
4. Hazard and Operability Studies (HAZOP);
5. Failure Mode and Effects Analysis (FMEA);
6. What if Analysis Technique;
7. Preliminary Hazard Analysis (PHA).

In this study, because the LNG fuelled passenger ferry is a new type of vessel and the historical data is limited, so the method of brainstorm and Preliminary Hazard Analysis (PHA) were used, results from other studies of HAZID to LNG fuelled ships are referred.

Preliminary Hazard Analysis (PHA) is a qualitative technique to identify the hazards, assess the severity of potential accidents that might happen in a system, and identify measures for reducing or eliminating the risks associated with the hazards. It mainly focuses on identifying the weaknesses and problems of a system in its early stage of design, in the condition of little detailed information or few operating procedures. PHA is a broad and preliminary study for further detailed risk analysis (Mullai, 2006, p.112).

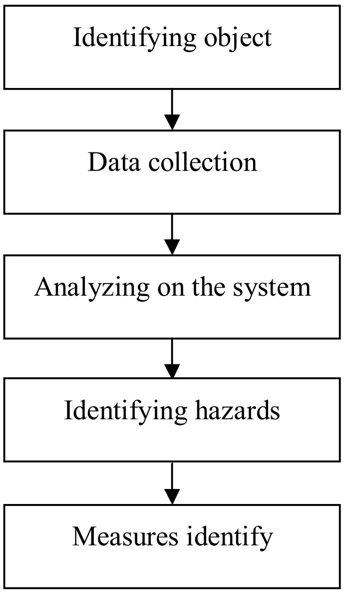

Figure 7 Framework of Preliminary Hazard Analysis (PHA)

3.3 The background of LNG safety incidents

Since 1964, the LNG carriers have used the boil off gas of LNG as fuel onboard. Many LNG carriers have long and good experiences with the use of natural gas as fuel for the propulsion machinery, mainly steam turbines (Danish EPA, 2010, p.58). The maritime incidents with severe LNG releases in the history of the LNG industry are rare. During the 60-year history of 59,000 voyages of the industry, no spillage of LNG from a ship into the water which resulted from collision or grounding has occurred (Foss, 2012, p.64). The good design and maintenance of LNG ships reduces the risks of severe incidents. The containment systems also prevent the breach of cargo tanks and the spill of LNG.

Based on the statistics of the U.S. Department of Energy, there are only 8 marine incidents worldwide that resulted in spillage of LNG in the 60 years history of the industry, some caused deck-plating damage under the manifold piping due to brittle fracture. There has never been LNG cargo related fires and LNG related fatality on board, all LNG-related injuries and fatalities have occurred within an LNG facility or ashore (Foss, 2012, p.65). The major marine LNG incidents are listed in Table 3 below.

In 2000, the first LNG fuelled car and passenger ferries “Glutra” was launched in Norway, and up to now there are about 30 LNG fuelled ships in operation worldwide excluding LNG carriers. Good safety record has been kept and no injuries or fatalities occurred during the more than 10 years’ experience. No reported or recorded accidents , only some backfire in engine manifolds due to sudden change in load and 2 cases of blackout on new ferry's and consequential anchor dropping– reason not known but possible unstable gas heating. There was one heavy crash with quay due to failure in maneuvering system, but no problem with the LNG tank or gas system (Norwegian Maritime Authority, 2012).

Table 3 Major marine LNG Incidents (source: the U.S. Department of Energy)

Incident Date	Ship / Facility name	Location	Ship status	Injuries/ fatalities	Ship/ Property damage	LNG spill/ Release	Description
1965		Canvey Island, UK	A transfer operation	1 seriously burned		Yes	
1965	Jules Vernet		Loading	No	Yes	Yes	Overfilling. Tank cover and deck fractures.
1965	Methane Princess		Disconnecting after discharge	No	Yes	Yes	Valve leakage. Deck fractures
1971	LNG ship Esso Brega	Italy	Unloading	No	No	Yes	First documented LNG Rollover incident. Tank developed a sudden increase in pressure. LNG vapor discharged from the tank safety valves and vents. Tank roof slightly damaged. No ignition
1974	Massachusetts		Loading	No	Yes	Yes	Valve leakage. Deck fractures
1974	Methane Progress		In port	No	Yes	No	Touched bottom at Arzew.
1977	LNG Aquarius		Loading	No	No	Yes	Tank overfilled.
1979	Mostefa Ben-Boulaid Ship		Unloading	No	Yes	Yes	Valve leakage. Deck fractures.
1979	Pollenger Ship		Unloading	No	Yes	Yes	Valve leakage. Tank cover plate fractures.
1979	El Paso Paul Kayser Ship		At sea	No	Yes	No	Stranded. Severe damage to bottom, ballast tanks, motors water damaged, bottom of containment system set up.
1980	LNG Libra		At sea	No	Yes	No	Shaft moved against rudder. Tail shaft fractured
1980	LNG Taurus		In port	No	Yes	No	Stranded. Ballast tanks all flooded and listing. Extensive bottom damage.
1984	Melrose		At sea	No	Yes	No	Fire in engine room. No structural damage sustained– limited to engine room.
1985	Gradinia		In port	No	Not reported	No	Steering gear failure. No details of damage reported.
1985	Isabella		Unloading	No	Yes	Yes	Cargo valve failure. Cargo overflow. Deck fractures.

1989	Tellier		Loading	No	Yes	Yes	Broke moorings. Hull and deck fractures.
1990	Bachir Chihani		At sea	No	Yes	No	Sustained structural cracks allegedly caused by stressing and fatigue in inner hull.
2002	LNG ship Norman Lady	East of the Strait of Gibraltar	At sea	No	Yes	No	Collision with a U.S. Navy nuclear-powered attack submarine, the U.S.S Oklahoma City. In ballast condition. Ship suffered a leakage of seawater into the double bottom dry tank area.
2010	Montoir de Bretagne terminal	France	Unloading	No	Yes	No	The incident occurred when liquid passed into the gas take-off line during discharge operations. The damage sustained extended to part of the ship's manifold and its feed lines.
2010	Withnell Bay facility	Australia	Loading	No	Yes	Yes	The ship suffered cryogenic burns when 2,000 to 4,000 liters of LNG were spilt.
2011	Yung An LNG terminal	Taiwan	Unloading	No	No	No	The vessel's master decided to suspend the discharge and move the ship off the berth but the problems were eventually rectified and the vessel returned to complete the discharge of its cargo.
2011	Pyeongtaek LNG terminal	South Korea	Unloading	No	Yes	Yes	The ship disconnected from the berth after what was described as a very small leak of LNG was reported around the top of one emergency release coupler shortly after a scheduled overhaul of the unloading arms had been completed. Seals and ball valves were replaced on the unloading arms and discharge recommenced using the remaining two arms.

3.4 The generic model of LNG fuelled passenger ferries

A generic model of LNG fuelled passenger ferries needs to be developed according to the IMO's guideline for Formal Safety Assessment (IMO, 2007, p.7), taking into consideration of the particular ship structure and characteristics of LNG fuelled propulsion of the passenger ferries.

The design and arrangements of LNG fuelled passenger ferries are assumed to satisfy the requirements of the IMO interim guidelines on the gas fuelled ships as well as the other requirements of IMO regulations to the passenger ships. The LNG fuel storage tanks are assumed to be located in the enclosed space. The ships are engaged in the short sea voyage in the coastal water.

For a generic LNG fuelled passenger ferries, the following assumptions are followed:
1. The average number of operational days per year: 330 days.
2. The average number of passengers on board each trip: 500 persons.
3. The average number of crew on board: 30 persons.
4. Operational hours per day: 16 hours.
5. Period for bunkering of LNG: every 4-5 days, bunker operation is assumed to be carried out by truck load LNG when the ship alongside the berth after operation and with no passengers on board.

3.5 Identification of fire/ explosion Hazards

Peachey suggest that one way to identify hazards is to develop a flow chart of the operations which are decided to assess. It is necessary to list each overall function or activity being performed for developing the flow chart (Peachey, 1999).
The process of daily operation of LNG fuelled ferries could be divided in to the following steps (Figure 5):
1. Prepare for sailing
2. Departing Quay
3. Under way
4. Arriving at port, mooring and preparing for unloading
5. Unloading

Each step of operations includes the following activities:

Preparation for sailing:
(1) The ferries moors alongside the quay, and crew keep watch on board.
(2) Passengers embark the ships and the tickets are checked before embarkation.
(3) The cars and trucks are driven onto the vehicle deck, and lashed by the crews.
(3) All equipments of ships related to the safety of navigation are checked and tested before sailing, and the conditions of lased vehicles and cargoes are inspected.
(4) Whether forecast on the route line is received and analyzed, the voyage plan are

checked and ensured.

(5) Information is exchanged between the master and officers by a meeting or by radio for the understanding of the voyage.

(6) The passengers come into the passenger cabins for a seat; drivers also leave their cars or trucks for a rest.

(7) Safety instruction is introduced to the passengers after the passengers embarking on board.

Departing quay:

(1) All preparation works for departure and sailing have been finished, and ramp is heaved up or removed and the bow door is closed.

(2) Unberth operation: The officers and crew are in position for the unberth operation, and departure is reported to the VTS or port authority according to the local regulations.

(3) The main engine was started and the mooring lines are cast off, the ferries usually leave the berth by its own thrusters and maneuverability, and the telegraph of engine is frequently changed for maneuvering.

Under way:

(1) Navigation in the port area: The ferry departs the quay and sails in the port area which is a limited space.

(2) Navigation in the open water: The ferry leaves the port and sails to the open water and the speed of ship turns to be fixed.

(3) Passenger services are provided such as catering and entertainment by videos, and the passengers are free to visit the non- restricted public areas of the ship.

(4) Patrols are carried out by the crew to the areas of the ship, especially the passenger cabins, vehicle decks, LNG storage rooms and engine rooms.

(5) The conditions of ship such as the indicators and alarms of the LNG fuelled propulsion systems are monitored from the bridge and control rooms by the officers.

(6) The deck officers and/or captain keep watch on the bridge for the safety of

navigation, take actions to prevent the collision, ground, contact and other accidents from happening.

Docking:

(1) Arriving is reported to the VTS or port authority according to the local regulations.

(2) Related Information of docking operation is exchanged between the master, officers and crew before arriving.

(3) Inspections to the related equipments and prepare works are conducted before arriving.

(4) The ferry enters the port and all the crew are in position for the operation of docking.

(5) The ferry berths alongside the quay, the bow door is opened and the ramp is laid down for unloading.

Unloading:

(1) The passengers disembark the ferry, and the vehicles on the ferry are unlashed and driven to the shore.

(2) The crew keep watch on the ferry to ensure the ship mooring alongside the berth safely.

Bunkering:

(1) Information related to the operation is exchanged between the crew on board and workers ashore before the bunkering.

(2) The critical equipments are inspected, preparing works such as blowing of the pipelines by inert gas is conducted according to the procedure requirements of bunkering.

(3) The situation of bunkering is monitored during the operation to prevent the over pressure of bunkering system or overfill of the LNG storage tanks and leakage of LNG fuel.

(4) After the finish of bunkering, the pipelines are blown out with the inert gas and disconnected according to the procedure of bunkering operation.

Based on the above operation activities of LNG fuelled ferries, refer to the SAFEDOR HAZID reports for RoPax and TNO report for Assessment of hazard identification study MTS Argonon, potential hazards related to the fire/ explosion of LNG fuelled passenger ferries are identified according to the operation phrases.

Table 4 Potential hazards related to the fire/ explosion of LNG fuelled passenger ferries

Operation	Hazards	Cause	Consequence
loading	Fire/Explosion	Fire starting in car because of hot breaks, internal electric failure and petrol leakage. Fire starting in refrigerating units connected to the ships electrical system.	
loading	Petrol leakage	Leakage from cars and trucks.	Fire, explosion.
loading	Uncontrolled dangerous cargo aboard	Improper cargo and luggage inspection	Fire, explosion.
Departing quay	Collision with other ships/quay	Current and wind. Inadequate port control. Poor knowledge of pleasure crafts/Sail ships. Weather conditions and swell. Technical failure.	Damage and puncture of the ship hull and LNG fuel tank containment, leakage of LNG and fire/ explosion.
Departing quay	Grounding	Current and wind. Swell and bad weather. Collision avoidance.	Damage and puncture of the ship bottom and LNG fuel tank containment, leakage of LNG and fire/ explosion.
Under way	Collision with ships	Crossing traffic in certain areas. Collision avoidance. Technical and Human failure. Improper training on use of bridge equipments. Communication problems, such as hard to reach the other ship on radio.	Hull damage and puncture of the ship hull and LNG fuel tank containment, leakage of LNG and fire/ explosion.
Under way	Collision with fixed objects	Loss of control Technical failure Human error Bad navigational information. Incorrect information. Buoy out of position	Hull damage and puncture of the ship hull and LNG fuel tank containment, leakage of LNG and fire/ explosion.
Under way	Grounding	Current and wind. Swell and bad weather. Human error/Interaction between officers and Captain. Navigation equipment failure. Collision avoidance. Propulsion of steering failure (technical) during acceleration or deacceleration.	Break and puncture of the ship bottom and LNG fuel tank containment, leakage of LNG and fire/ explosion.

Under way	Fire/Explosion in machinery spaces	LNG leakage and accumulation, technical failure, hot surfaces, Engine room design. Hydraulic systems in casing.	Fire/Explosion and spread to other areas; Loss of maneuverability and power; Damage to crewmembers and panic on ship.
Under way	Fire in accommodation	Use of naked flame/Cigarettes in waste bins, Laundry activities, Fire in galley/pantry. Portable electrical equipment	Fire/Explosion and spread to other areas. More complex problem for the master and crew such as fire fighting and organization for preparing evacuation.
Under way	Fire in cargo area	Electrical problems in vehicles Hull vibration may cause electrical problems on cars or connection between ship and trailers (refrigeration plants). Gas/Petrol leakage. Electric magnetism. Open fire from such as smoking of crews	Free surfaces. Fast fire escalation. Smoke ingress in accommodation. Injuries to crew members
Docking	Fire/Explosion in machinery spaces	LNG leakage and accumulation, technical failure, hot surfaces, Engine room design. Hydraulic systems in casing.	Fire/Explosion and spread to other areas; Loss of maneuverability and power; Damage to crewmembers and panic on ship.
Docking	Fire in accommodation	Use of naked flame/Cigarettes in waste bins, Laundry activities, Fire in galley/pantry. Portable electrical equipment	Fire/Explosion and spread to other areas. More complex problem for the master and crew such as fire fighting and organization for preparing evacuation.
Docking	Fire in cargo area	Electrical problems in vehicles Hull vibration may cause electrical problems on cars or connection between ship and trailers (refrigeration plants). Gas/Petrol leakage. Electric magnetism. Open fire from such as smoking of crews	Free surfaces. Fast fire escalation. Smoke ingress in accommodation. Injuries to crew members
Docking	Contact to the quay	Loss of control, - Technical failure, - Human error, - Bad navigational information. - Incorrect information. - buoy out of position	Hull damage and puncture of the ship hull and LNG fuel tank containment, leakage of LNG and fire/ explosion.
Unloading	Fire/Explosion	Spill from cars accumulated during journey	High congestion of people on deck. Damage to cars, ship and passengers
Bunkering	Bunkering failure.	Electrical "transmitters" such as mobile phones or ambulances. Human error. Fatigue for personnel. Mechanical failure	Fire/Explosion. Damage to ship and crew.

3.6 Ranking of the hazards

According to the IMO guideline on the FSA, the identified hazards and associated scenarios should be ranked for prioritization, a risk index could be established by adding the probability/ frequency and consequence indices as follows:

Risk = Probability ×Consequences

Log (Risk) = Log (Frequency) + Log (Consequence)

The probability index and consequence index are defined in the following tables:

Table 5 Definition of Frequency index

PI	Frequency	Definition	F (per ship year)
7	Frequent	likely to occur once per month on one ship	10
5	Reasonably probable	likely to occur once per year in a fleet of 10 ships	0.1
3	Remote	Likely to occur once per year in a fleet of 1000 ships	10^{-3}
1	Extremely remote	Likely to occur once in the lifetime (20 years) of a world fleet of 5000ships	10^{-5}

Table 6 Definition of consequence index

SI	Severity	Effects on human safety	Effects on ship	S (Equivalent fatalities)
1	Minor	Single or minor injuries	Local equipment damage	0.01
2	Significant	Multiple or severe injuries	Non-severe ship damage	0.1
3	Severe	Single fatality or multiple sever injuries	Severe damage	1
4	Catastrophic	Multiple fatalities	Total loss	10

The following table is the risk matrix based on the above tables.

Table 7 Risk index (RI)

		Severity (SI)			
		1	**2**	**3**	**4**
FI	**Frequency**	Minor	Significant	Severe	Catastrophic
7	Frequent	**8**	**9**	**10**	**11**
6		**7**	**8**	**9**	**10**
5	Reasonably probable	**6**	**7**	**8**	**9**
4		**5**	**6**	**7**	**8**
3	Remote	**4**	**5**	**6**	**7**

2		**3**	**4**	**5**	**6**
1	Extremely remote	**2**	**3**	**4**	**5**

After the identification of accidents, the causes could be grouped in terms of human error, hardware failures, external events, and so on. The ‘‘fire’ accident subcategories are listed as follows:

1. Bridge
2. Accommodation areas
3. Vehichle deck
4. Machinery spaces

The ranking of hazards of fire/ explosion of LNG fuelled passenger ferries in the different phrases of operation could be carried out using the Probability and Consequence Scales defined before and results is shown in the Table 8 as follow:

Table 8 Fire Subcategories rankings by the Risk Matrix

Operation **Accident subcategory**	Loading	Departing Quay	Under way	Docking	Unloading
Bridge	F1/S1=2	F1/S1=2	F1/S1=2	F1/S1=2	F1/S1=2
Accommodation	F2/S2=4	F4/S3=7	F4/S3=7	F4/S3=7	F2/S2=4
Vehicle deck	F3/S3=6	F3/S2=5	F3/S2=5	F3/S2=5	F3/S3=6
Machinery spaces	F2/S2=4	F3/S3=6	F3/S3=6	F3/S3=6	F2/S2=4

Based on the above table, the fire subcategories with risk index less than RI=5 would not be investigated further as their level is considered to be acceptably low.

3.7 Summary

According to the analysis above, the top rank hazards to the fire/explosion of LNG fuelled passenger ferries could be identified as follows:

1. Fire or explosion during loading.

2. Fire in accommodation while in open sea or navigating in coastal waters.

3. Fire in machinery spaces while in open sea or navigating in coastal waters.

4. Fire on vehicle deck while unloading due to accumulation of fuel spills during journey.

5. Gas leakage and accumulation due to over pressure, technical failure or operational errors.

6. Gas leakage due to damage to the LNG fuel tank containment caused by collision, ground or contact.

7. Fire or explosion due to the bunkering failure.

Chapter Ⅳ Risk Analysis to the High Ranking Hazards and Associated Scenarios

4.1 Scope of study

Based on the results of HAZID of fire/explosion to the LNG fuelled passenger ferries in the last Chapter, the high ranking hazards and associated scenarios would be investigated in more detail. The risk of loss of life among the passengers and crew on board would be estimated to the possible extend by calculating of Individual Risk, the Potential Loss of Life in each identified scenario.

4.2 Method and techniques

The Risk Contribution Tree (RCT) of fire/ explosion on LNG fuelled passenger ferries would be established, techniques of Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) would be used in the session. Due to limited accident and failure data of the LNG fuelled passenger ferries, statistics of LNG carriers and RoPax Ships with similar feature would be referred.

4.3 Risk model

A Risk Contribution Tree (RCT) of fire/explosion is established as follows (Figure 8), the top-half above “fire/ explosion” is a graphical representation of the accident sub-category with the direct causes initiated and combined to cause the sub-category accidents by using fault trees, and the bottom-half below “fire/explosion” is an event tree representation of the development of the accident and its final results in different magnitudes of loss (IMO, 2007, p.40).

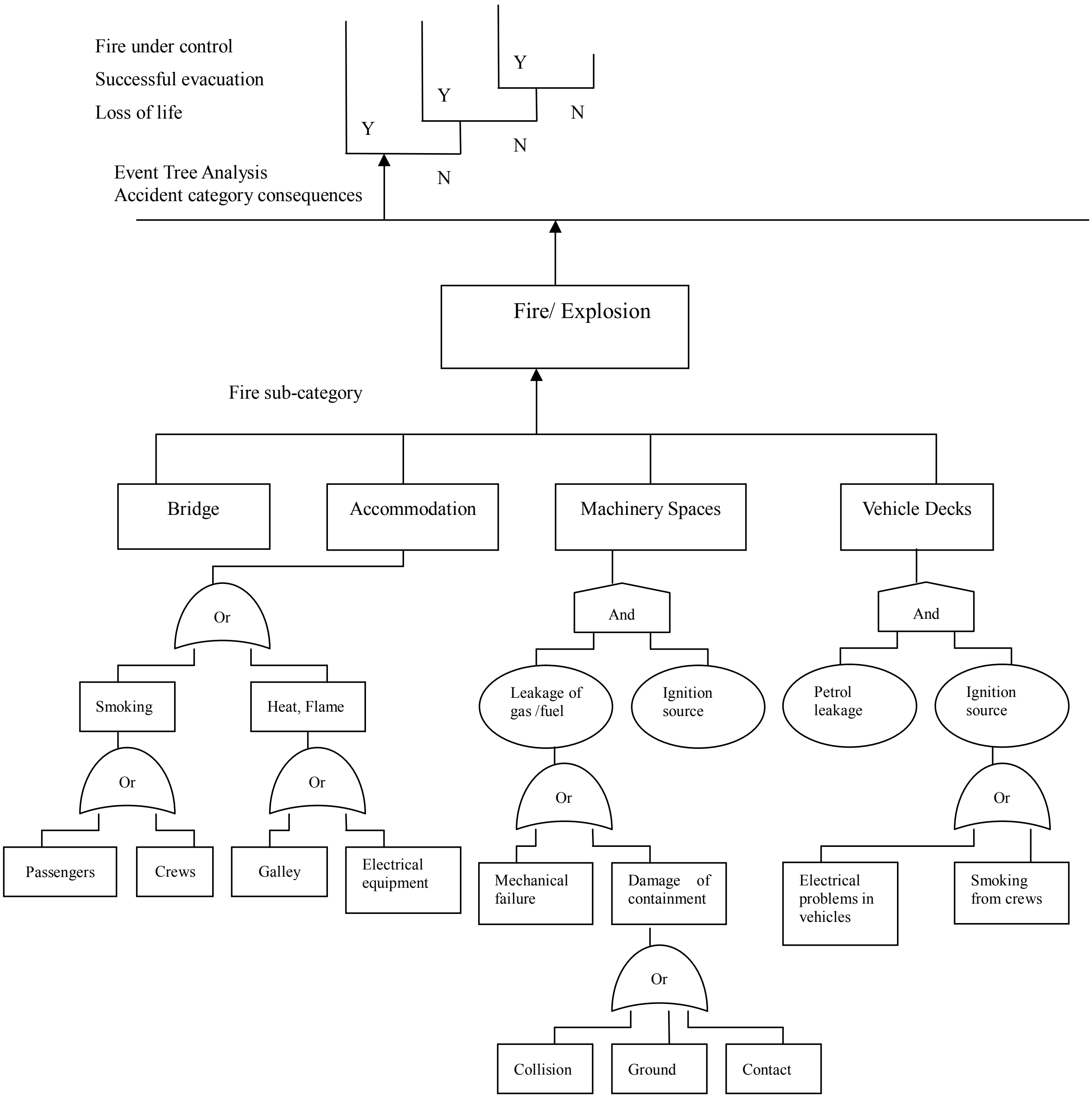

Figure 8 The Risk contribution tree of fire/explosion of the LNG fuelled passenger ferry

4.4 Consequence assessment

The total risk of fire/explosion of LNG fuelled passenger ferry is assumed to be the sum of risk contribution from the following selected accident sub-category scenarios (Figure 9). The risk contribution from the "fire/ explosion in bridge" is assumed to be negligible in comparison based on the previous analysis. The risk contribution from each of sub- category scenario would be estimated based on detail risk models and event trees.

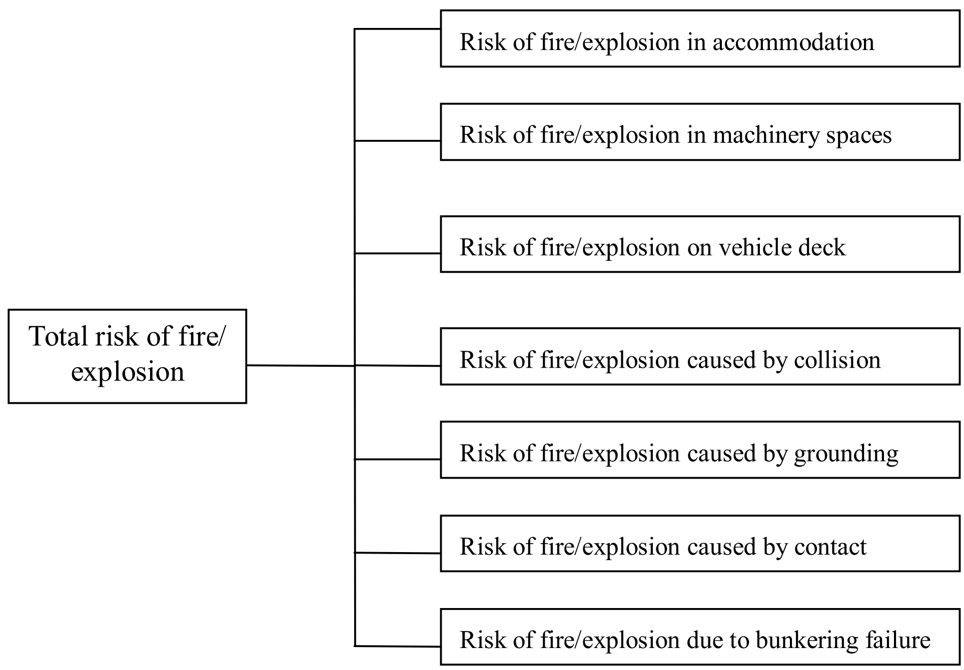

Figure 9 Overall risk model of fire/explosion on LNG fuelled passenger ferries

Due to the scarce accident records of LNG fuelled passenger ferries, and the probability of fire/explosion in accommodation and vehicle deck spread to the machinery spaces and lead to the leakage and ignition of LNG is regarded as negligible (IMO, 2007, p.42). Therefore the fire/ explosion in accommodation and vehicle deck on the LNG fuelled passenger ferries is assumed to resemble similar fire incidents on the oil fuelled Ro-Pax ships, the results from a review of Ro-Pax ships would be used (IMO, 2008, p.44) .

4.4.1 Fire/ explosion in accommodation

According to the report of FSA on RoPax ships submitted by Denmark, the overall frequency for fire/explosion incidents estimated for RoPax of 1,000 GRT and above is 8.28 E-03 based on the 1994-2004 world-wide experience, and the percentage of fire/explosion incidents in accommodation is 24%. So the frequency of fire/ explosion in accommodation on LNG fuelled passenger ferries is assumed to be 1.99 E-03. The percentage of non-escalation and escalation for fire incidents in accommodation is 81% and 19% respectively, and the percentage of unsuccessful evacuation is 20 % in this category (IMO, 2008, p.44).

An event tree is established as follows and the frequency of different situations in the fire/explosion at accommodation is identified:

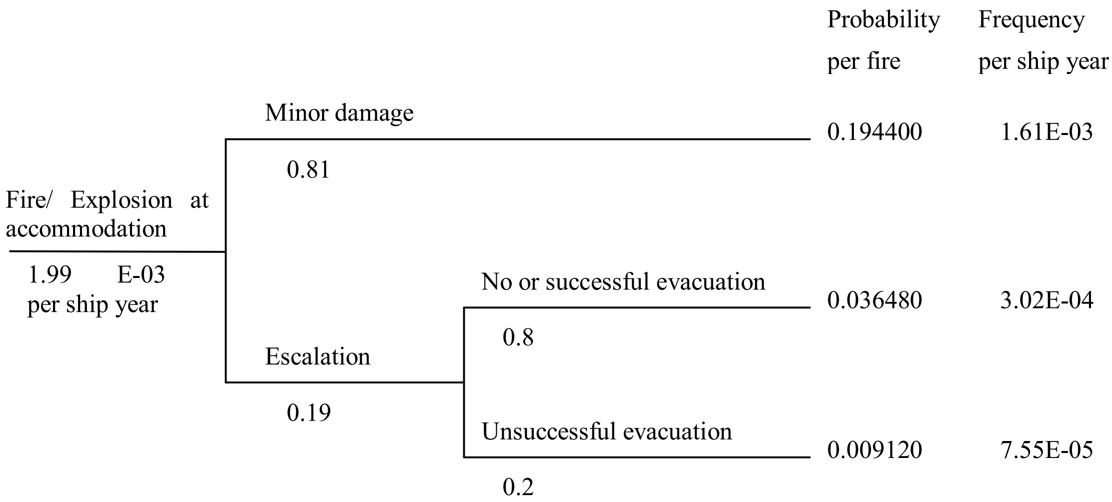

Figure 10 The Events Tree of Fire/Explosion at accommodation

Based on the above event tree, the outcomes of fire/ explosion in accommodation could be identified as follows:

The average number of passengers on the LNG fuelled ferries is assumed to be 500 persons each trip and the average number of crew is assumed to be 30 persons in the generic model in section 3.4. The average fatality rates for the fire incidents in accommodation with unsuccessful evacuation is assumed to be 8% which had been used during the North West European project study (IMO, 2008, p.45), it will also be used in the calculation of this study.

Individual Risk (per year) = 7.55E-05 × 0.08 = 6.04 × E-06

PLL (per ship year) = 530 × 7.55E-05 × 0.08 = 3.2 × E-03

4.4.2 Fire/explosion on vehicle deck

According to the report of FSA on RoPax ships submitted by Denmark, the estimated overall frequency for fire/explosion incidents is 8.28 E-03 and the percentage of fire/explosion incidents on vehicle deck is 12%, so the frequency of fire/ explosion on vehicle deck of LNG fuelled passenger ferries is assumed to be 9.94 E-04. The percentage of non-escalation and escalation for fire incidents in accommodation is assumed to be 71% and 29% respectively, and the percentage of unsuccessful evacuation is 25 % in this category (IMO, 2008, p.44).

An event tree is established and the frequency of different situations in the fire/explosion on vehicle deck is identified as follows:

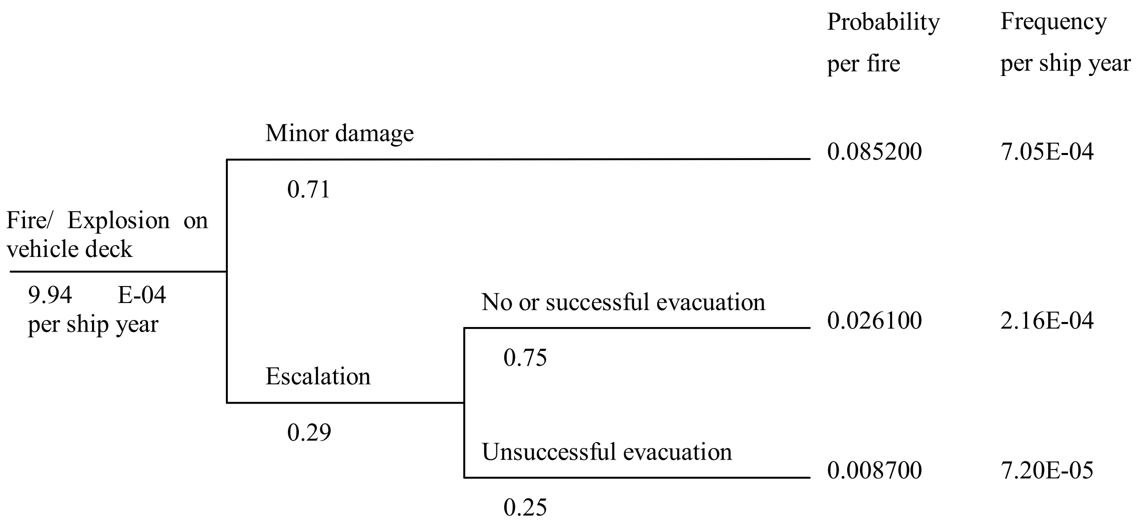

Figure 11 The Events Tree of Fire/Explosion on vehicle deck

The assumption of average fatality rates used in the North West European project study for the fire incidents on vehicle deck with unsuccessful evacuation also is 8%

(FSA, 2008, p.45), it is used in the following calculation of outcomes:

Individual Risk (per year) = 7.20E-05 × 0.08 = 5.76 × E-06

PLL (per ship year) = 530 × 7.20E-05 × 0.08 = 3.05 × E-03

4.4.3 Fire/explosion in machinery spaces with no LNG leakage and ignition

In this scenario, the fire/explosion with no LNG leakage and ignition in machinery spaces of LNG fuelled passenger ferries is similar to oil fuelled passenger ferries, so the results from a review of Ro-Pax ships will be used in this study.

The frequency of fire/ explosion in machinery space of LNG fuelled passenger ferries is assumed to be 5.30 E-03. The percentage of non- escalation and escalation for fire incidents in accommodation is assumed to be 71% and 29% respectively, and the percentage of unsuccessful evacuation and fire uncontrolled is 5% respectively in this category (IMO, 2008, p.44).

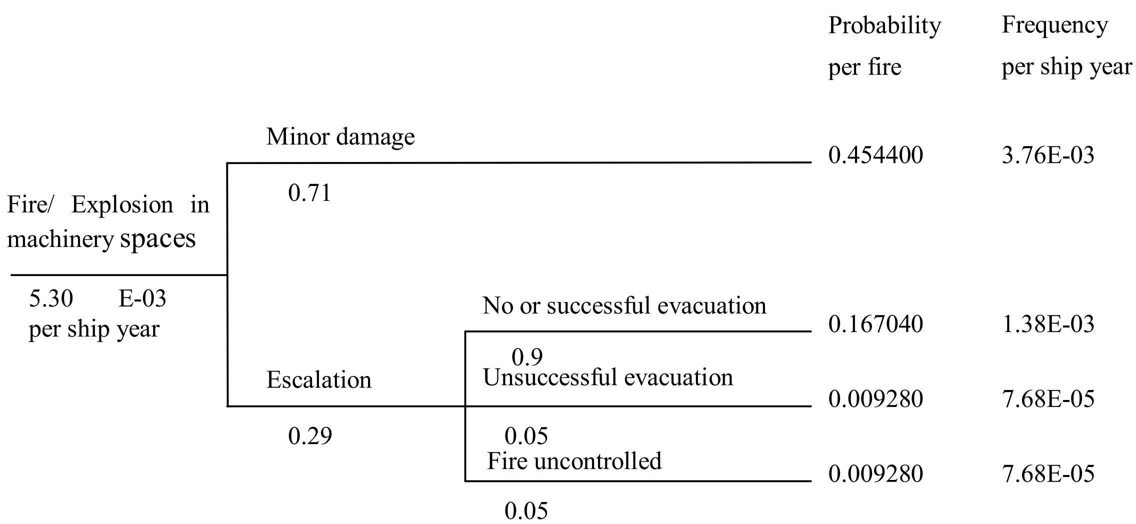

Figure 12 The Event Tree of Fire/Explosion in machinery spaces

The assumption of average fatality rates used in the North West European project study for major fire incidents in machinery spaces is 0.7% and average fatality rates for the engine room fire uncontrolled is 75% (FSA, 2008, p.45). The outcomes are obtained form the following calculations.:

Individual Risk (per year) = 7.68E-05 × 0.007 + 7.68E-05 × 0.75= 5.81 × E-05

PLL (per ship year) = 530 × (7.68E-05 × 0.007 + 7.68E-05 × 0.75) = 3.08× E-02

4.4.4 Fire/explosion due to damage of containment caused by collision

In this scenario, the frequency of collision of LNG fuelled passenger ferries is assumed to the same as RoPax ships, 1.25E-02 per ship year which is based on the statistics of RoPax of 1000GRT and above during the period 1994-2004; the percentage of collisions under way is 63% and 37% of the remaining are striking while at berth; in the collision incidents under way, 84% of the incidents are recorded as minor damage and 16% of the remains are recorded as serious casualty (IMO, 2008, p.25). These percentages and probabilities would be used in the event trees.

During the collision scenario, the LNG fuelled passenger ferry could be a striking ship or a being struck ship, the possibility is assumed to be 50%-50% based on the conclusion on analysis of collision casualty data (IMO, 2004). And for a striking ship, the probability of receiving critical damage is assumed to be negligible, so the distribution of this scenario to the consequence of collision is discounted.

In the damage extent model, there are two situations: the collision damage location in the LNG fuel tank areas and out of the LNG fuel tank areas. According to the IMO guideline on the LNG fuelled ships, there are no requirements of location of LNG fuel tank on the distance from fore or aft of ships on the longitudinal direction. In the study, the location of LNG fuel tank(s) on passenger ferries is assumed to resemble the location of cargo tanks on a typical LNG vessel, in the following area: Between the foremost 2/15 of the ship and the aft 1/5 of the ship. Based on the previous study (Laubenstein & Mains, 2001), the probability of collision damage location distribution could be estimated: P (foremost 2/15) = 0.2 and P (aft1/5) = 0.15. So the probability of collision damage locates in the LNG fuel tank areas is 0.65.

Based on a couple of previous studies, the possibility of critical damage caused by collisions with penetration of outer hull is P=0.38 for passenger ships (Olufsen & Spouge, 2003), and the result is assumed to be applicable to the LNG fuelled passenger ferries.

Even if there is a penetration of outer hull by collision, it will not necessary be a damage to the containment of LNG fuel tanks. According to the IMO guideline for gas-fuelled ships, the LNG fuel storage tank in enclosed spaces should be placed as close as possible to the centerline of ship and no less than B/5 from the ship side (IMO, 2009, p.19). So if the depth of a critical damage to ship side is more than B/5 in the transverse direction, it is assumed the LNG fuel tank would be penetrated. From the damage statistics collected by the HARDER project in the previous study (Laubenstein & Mains, 2001), the damage penetration: P (b> B/5) = 0.35.

In the condition of penetration of LNG fuel tanks and LNG leakage caused by collision, the LNG specific hazards might materialize, and the Rapid Phase Transition (RPT) is the hazard most likely happens. There are three possible scenarios following the Rapid Phase Transition: First, there is no ignition of the LNG vapour and the gas disperse into the atmosphere due to the concentration is below the lower flammable limit; secondly, the LNG vapour is ignited during collision by ignited source such as sparks from steel; Thirdly, a vapour cloud is formed and drifted away from the collision area, gets ignited and burns back to the LNG pool and form a pool fire. Based on the expert judgment, the possibility of first scenario is 80% and the possibility of second and third scenario is 10% respectively (IMO, 2007, p.38).

Based on the above analysis, an event tree could be established as follows:

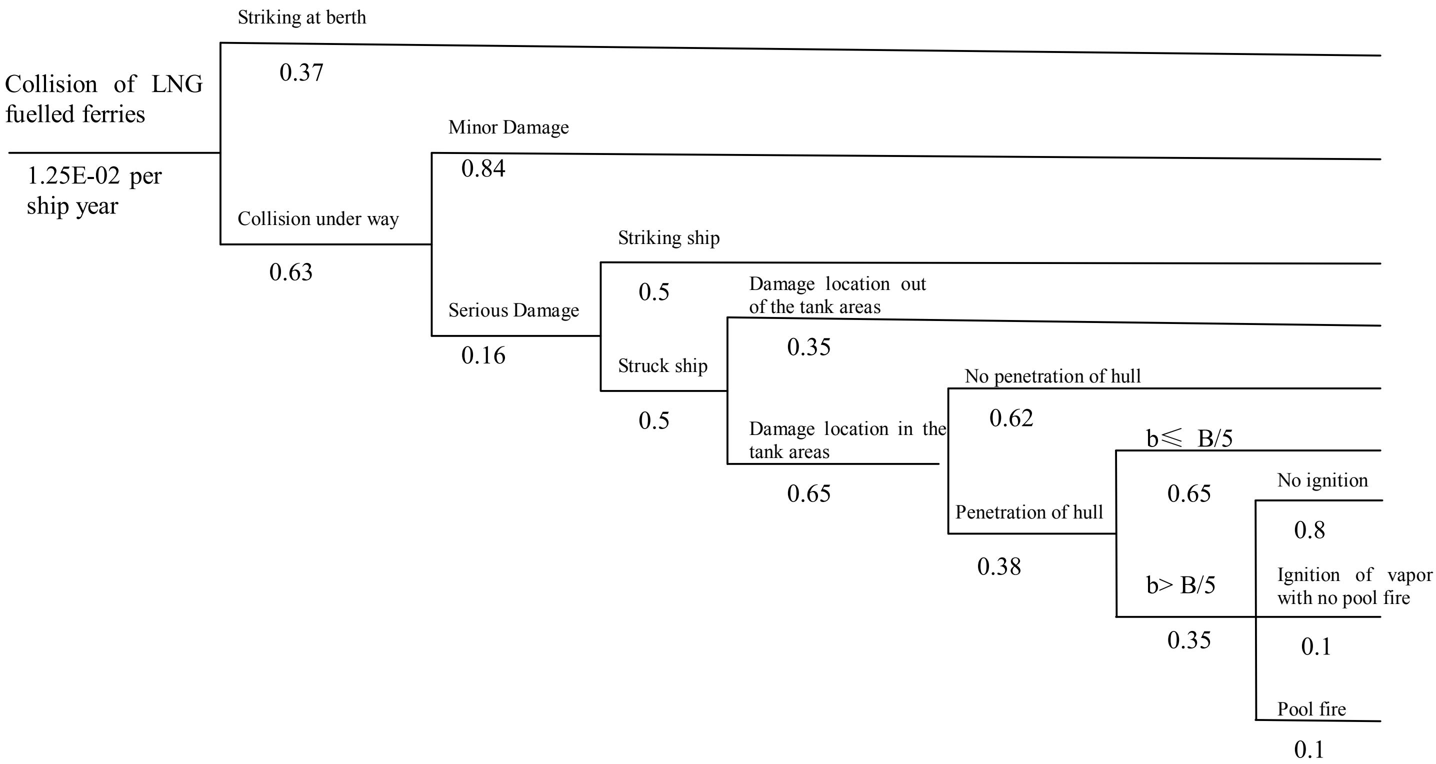

Figure 13 The Event Tree of Fire/Explosion caused by collision

The possibility and frequency of different scenarios after the penetration of containment of LNG fuel tank caused by collision could be identified as follows:

Table 9 Possibility and frequency of different scenarios caused by collision

Scenarios	Possibility	Frequency
Leakage of LNG vapor with no ignition	0.003485664	4.36 E-05
Ignition of LNG vapor with no pool fire	0.000435708	5.45 E-06
Ignition of LNG vapor with pool fire	0.000435708	5.45 E-06

Consequences of LNG accidents on the ferries are difficult to be estimated as no statistics are available. In the study, the average fatality rates of the scenario that ignition of LNG vapor with no pool fire is assumed to be 0.7% as used for the major fire incidents in machinery spaces in the North West European project study. And the fatality rates in the scenario of ignition of LNG vapor with pool fire would refer to the results from the study of LNG carriers, it is 52.5% and based on the expert judgment from a Delphi session (IMO, 2007, p.39). The calculation of consequence is illustrated as follows:

Individual Risk (per year) = 5.45 E-06× 0.007 + 5.45 E-06× 0.525= 2.90 × E-06

PLL (per ship year) = 530 × (5.45 E-06× 0.007 + 5.45 E-06× 0.525) = 1.54× E-03

4.4.5 Fire/explosion due to damage of containment caused by grounding

In this scenario, the frequency of grounding of LNG fuelled passenger ferries is assumed to be the same as RoPax ships, 9.57 E-03 per ship year. According to the statistics, 68% of the grounding incidents were recorded as minor incidents and 32% of the incidents were recorded as serious casualty (IMO, 2008, p.30). These frequency and probability would be used in the following event tree.

The LNG fuel tank location areas in the longitudinal direction are assumed to be similar to those in the collision scenario, between the foremost 2/15 and the aft 1/5 of the ship. According to the grounding damage location distributions collected by the HARDER project, the probability of receiving damage in the foremost 2/15 of ship is P (foremost 2/15) = 0.2 and in the aft 1/5 of the ship is P (aft 1/5) = 0.1, so the possibility of damage location within the LNG fuel tank areas is 0.7 in the grounding.

In the grounding damage extend model, the possibility of critical damage with the crack of outer hull is estimated to be 0.76 for passenger ships based on the previous study (Olufsen & Spouge, 2003). Even if there is a crack of outer hull of the ship by grounding, it is not necessarily for the penetration of LNG fuel tank. And according to the requirements of IMO guideline on the LNG fuelled ships, the location of LNG fuel tank in enclosed spaces should be no less than the lesser of B/15 and 2 m from the bottom plating (IMO, 2009, p.19), so LNG fuel tanks is assumed to be penetrated if the damage depth is more than 2 m. Based on the statistics collected by the HARDER project, the probability of damage depth more than 2m is : P (d> 2 meters)

= 0.12 (IMO, 2007, p. 40), it is used in the event tree of this study.

If there is LNG leakage in the grounding accident, the LNG hazards would materialize similar to the collision scenario. The difference is that LNG will leak from the bottom of ship compared to the leak from side of ship in the collision. Possible scenarios following the Rapid Phase Transition in the grounding are similar to the scenarios in collision: LNG vapor disperse into the atmosphere with no ignition because the concentration is below the lower flammable limit; LNG vapour is ignited but with no pool fire; LNG vapour leakage form a cloud and is ignited, burns back to cause a fire pool. The probability of the above three scenarios are assumed to be similar to that in the collision, which are 0.8, 0.1 and 0.1 respectively. An event tree could be established as follows based on the above analysis:

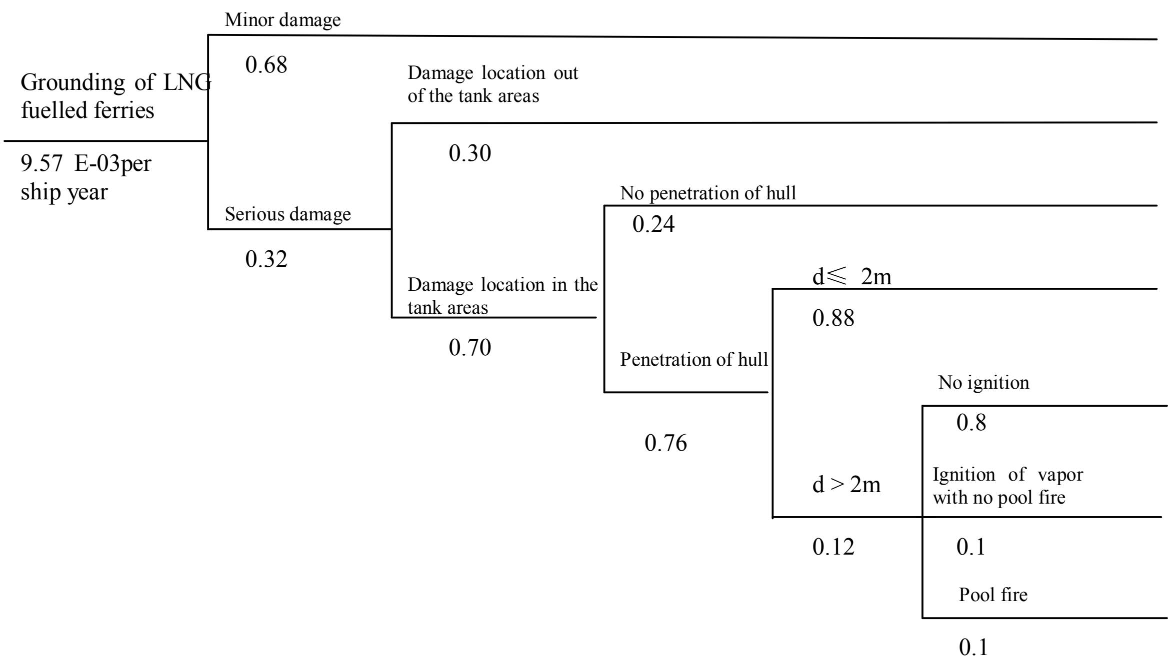

Figure 14 The Event Tree of Fire/Explosion caused by grounding

The possibility and frequency of different scenarios after the penetration of LNG fuel tank and RPT caused by grounding could be identified as follows:

Table 10 Possibility and frequency of different scenarios caused by grounding

Scenarios	Possibility	Frequency
Leakage of LNG vapor with no ignition	0.01634304	1.56 E-04
Ignition of LNG vapor with no pool fire	0.00204288	1.96E-05
Ignition of LNG vapor with pool fire	0.00204288	1.96E-05

In the study, the average fatality rates of the scenarios in grounding are assumed to be similar to those in the collision: the fatality rate of ignition of LNG vapor with no pool fire is assumed to be 0.7% and 52.5% in the scenario of ignition of LNG vapor with a pool fire. The calculation of consequence is illustrated as follows:

Individual Risk (per year) = 1.96 E-05× 0.007 + 1.96 E-05× 0.525= 1.04 × E-05

PLL (per ship year) = 530 × (1.96 E-05× 0.007 + 1.96 E-05× 0.525) = 5.53× E-03

4.4.6 Fire/explosion due to damage of containment caused by contact

In this scenario, the frequency of contact of LNG fuelled passenger ferries is assumed to be the same as RoPax ships, 1.25 E-02 per ship year; according to the statistics, 89% of the contact incidents were recorded as minor incidents and 11% of incidents were recorded as serious casualty (IMO, 2008, p.34). These frequency and percentage would be used in the event tree.

In the study, the contact scenario is considered to be very similar to the grounding scenario, except for the probability of flooding, other risk distributions and probabilities from the contact scenario are assumed to be identical to the grounding scenario. And according to the previous study (Olufsen & Spouge, 2003), the probability of flooding in the contact is assumed to be 0.38. An event tree could be established as follows:

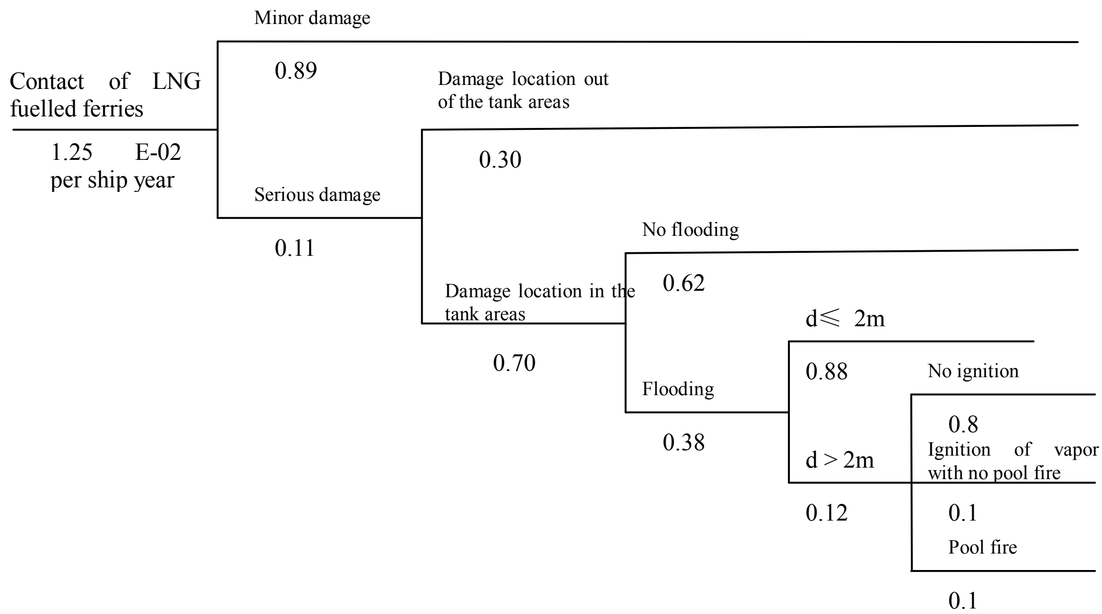

Figure 15 The Event Tree of Fire/Explosion caused by contact

The possibility and frequency of different scenarios after the penetration of LNG fuel tank and RPT caused by contact could be identified as follows:

Table 11 Possibility and frequency of different scenarios caused by collision

Scenarios	Possibility	Frequency
Leakage of LNG vapor with no ignition	0.00280896	3.51 E-05
Ignition of LNG vapor with no pool fire	0.00035112	4.39 E-06
Ignition of LNG vapor with pool fire	0.00035112	4.39 E-06

The average fatality rates of the scenarios in the contact are assumed to be similar as in the grounding: the fatality rate of ignition of LNG vapor with no pool fire is assumed to be 0.7% and fatality rate in the scenario of ignition of LNG vapor with a pool fire is assumed to be 52.5%. The calculation of consequence is illustrated as follows:

Individual Risk (per year) = 4.39 E-06× 0.007 + 4.39 E-06× 0.525= 2.34× E-06

PLL (per ship year) = 530 × (3.99 E-05× 0.007 + 3.99 E-05× 0.525) = 1.24× E-03

4.4.7 Fire/explosion due to bunkering failure

According to the statistics (IMO, 2007, p.43), a LNG carriers conduct 12 roundtrips a year on average and spend about 2 days of loading/unloading cargo per roundtrip. There have been 22 loading/ unloading incidents recorded in the industry history, and 9 of the incidents had leakage of LNG. The frequency of loading/unloading accidents with leakage of LNG is estimated to be 3.2 E-03 per ship year (Vanem & Antão, 2008, p.1333).

As for the bunkering operation of the LNG fuelled ferries, it is similar to the loading/unloading operation of LNG carriers. Based on the experience of LNG fuelled ferries in Norway, the most common bunkering method is truck to ship, the ship is refueled every 4-5 days , the bunkering rate is about $40m^3$/hour and about 2 hour for the bunkering peroration each time (DNV, 2013, p.23). The bunkering operation of LNG fuelled ferries is much more frequent compared to the LNG carriers loading/unloading operation, but the potential consequences of LNG bunkering failure might be less severe than the LNG carrier accidents as the small scale of volume (Algell & Bakosch, 2012, pp.106-107).

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As the bunkering operation of LNG fuelled ferries is conducted when out of service with no passengers on board, and the related accident statistics are not available, so the quantitative consequences of fire/ explosion caused by bunkering failure is not taken into account in the study.

4.5 Risk summation

Based on the calculation of above risk models, the consequences of fire/ explosion risk from different scenarios of the LNG fuelled passenger ferries could be summarized as follows (Table 12):

Table 12 Summary Risk Calculations of fire/explosion

	Individual Risk (per year)	PLL (per ship year)	PLL (%)
fire/explosion in accommodation	6.04 × E-06	3.20 × E-03	7%
fire/explosion on vehicle deck	5.76 × E-06	3.05 × E-03	7%
fire/explosion in machinery spaces	5.81 × E-05	3.08× E-02	68%
fire/explosion caused by collision	2.90 × E-06	1.54× E-03	3%
fire/explosion caused by grounding	1.04 × E-05	5.53× E-03	12%
fire/explosion caused by contact	2.34× E-06	1.24× E-03	3%
Total	**8.55×E-05**	**4.54×E-02**	**100%**

The total individual risk of fire/explosion calculated by the risk models is 8.55×E-05, based on the assumption that the vessel at sea and the person on board for a full year. From the above table, we can conclude that the fire/explosion in the machine spaces has the highest frequency of occurring; the fire/explosion due to damage of containment caused by collision, contact has relatively low frequency but high fatality rate, and the fire/explosion caused by grounding has relatively high frequency of occurring.

4.6 Summary

The consequences of fire/explosion risk from several major scenarios on the LNG fuelled passenger ferries are calculated based on the risk models of event trees. Some of the assumptions and results from the research reports of RoPax ships and LNG carriers are used in the calculation of the risk models, so the outcomes of the study still contain uncertainties. However, due to the limited statistics of LNG fuelled passenger ferries, best efforts are made to provide a rational estimation of the risk models to the possible extend.

Chapter Ⅴ Recommendations

5.1 Identified high risk areas and recommended measures

Based on the above analysis on risk models of different fire/explosion scenarios, the high risk areas could be identified and potential measurements could be recommended as follows:

1. Navigation safety. The improvement of navigation safety could reduce the frequency of collision, grounding and contact, would also reduce the risk of damage of LNG fuel tank containment and fire/explosion caused by the leakage of LNG. According to the previous study (Antão & Soares, 2006, p.115), human factors are the dominant factors towards the accidents of groundings and collisions of RoPax vessels, so the measurements for reducing the human errors such as the navigator training could be taken; on the other hand, the improvement of bridge design and navigation equipments such as ECDIS (Electronic Chart Display and Information System), AIS (Automatic Identification System) integration with radar could be cost efficient options for promoting the navigation safety of passenger ships (IMO, 2004, p.2).

2. Gas detecting and ventilation system. The flammable limit of natural gas is in a small range (5%- 15%), so the gas detecting system is very important to discover the leakage of LNG and give alarms to the crew timely; ventilation system is very critical for reducing the concentration of natural gas to below the lower flammable limit (LFL) if the leakage happened.

3. Fire protection. The fire protection could prevent or slow down the fire/ explosion escalation from the ignition source to the other compartments or areas of the ship, providing more time for the evacuation of passengers as well as crew and the fire fighting operation.

4. Evacuation operation and arrangements. According to the previous study (Melhem & Ozog, 2007, p.10), the fatality rate of personnel on board in the pool fire is largely

determined by the distance from the ignition source and exposure time to the thermal radiation of the pool fire. So the evacuation drills are needed to be carried out frequently to improve the efficiency of evacuation operations after the fire/ explosion of LNG leakage, the safety distance from the potential pool fire point to the evacuation point should be taken into account in the design and arrangement of evacuation equipments.

5. Crew training. The LNG has specific hazards compared to conventional fuel oil, so the crew serving on the LNG fuelled passenger ferries should receive professional training on familiar with the LNG specific hazards, learn how to manage and utilize the LNG fuel safely in daily operation.

6. Bunkering operation. Because of the high frequency of bunkering operation, it is a high risk area for the leakage of LNG and result in fire/explosion , so good practice, safety standards and procedures should be set up for the bunkering operation , the personnel involved in LNG bunkering including crew onboard and operators onshore should receive related training.

7. Source of ignition. The fire/explosion is caused by the combining the flammable materials and ignition source, so control to the ignition source is critical to the reduction of fire/explosion risk on the LNG fuelled ferry. The naked fire such as smoking of cigarette and could be prohibited by set up no-smoking area; the electrical equipments fitted in the gas atmospheres should satisfy the related standards and prevent the sparks during operation; heat sources could be controlled or separated from the flammable materials.

5.2 Suggestions for the safety administration

The development of LNG fuelled ships is a new trend of green ships, and it also brings new challenges to the maritime administration, especially for the LNG fuelled passenger ferries which would result in a large amount of deaths if the fire/explosion occurs on board. Some suggestions are put forward for the maritime administration of LNG fuelled ferries as follows:

1. Specific guidelines and standards should be made for the safety of application of LNG fuel on board. Although the IMO Interim guidelines on the gas-fuelled ships has established a framework of requirements for the safety of LNG propulsion ships, there are still a number of specific issues such as bunkering configuration and operation that haven't been covered by the regulations. International regulations may be developed for the specific issues during the application of LNG fuel on board, and the class society and maritime administration of each contating state also play a key role in making rules for the developing of LNG fuel.

2. Risk assessment should be carried out for the new type of LNG fuelled ships. As a new type of ships, safety standards and experience for the vessel design, construction, installation and operation would not be available enough, so related risk assessments are essential to be carried out for the reduction of potential risks and improvement of safety.

3. Promoting the education and training to the crew and the public. Compared to the conventional fuel oil, the LNG fuel is not much familiar to the crew, ship owners, passengers and other stakeholders of the public. On one hand, the crew serving on the LNG fuelled ships should receive training on LNG hazards, correct operation and maintenance to the gas-related equipments as well as emergency exercises. On the other hand, the stakeholders of the public should be aware of the LNG hazards correctly, and the administration should eliminate their excessive worries on the application of LNG fuel on board, and protect their personal safety and properties efficiently.

Chapter Ⅵ Conclusions

According to the calculation of risk models in this study, the fire/explosions in the machinery spaces of LNG fuelled ferries have the highest frequency and fatality while the fire/explosions due to the damage of LNG containment caused by collision, grounding and contact have relatively low frequency, however the results might be very serious. Bunkering operations of LNG fuel is also a high risk area of fire/explosion to be concerned. Evacuation is very critical to the fatalities in each fire/explosion scenario, especially when the pool fire caused by the leakage of LNG. Standards and guidelines related to the specific issues of ship design, construction and operation should be established as the development of application of LNG fuel on board. Human factor is a key point to the safety of the LNG fuelled passenger ferries, and related training and education should be conducted to the crew and the public.

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