Evaluation of Safety Exclusion Zone for LNG Bunkering Station on LNG-Fuelled Ships

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ABSTRACT

With increasing interests in using LNG as a marine fuel, safety issues for LNG bunkering have brought about global discussion on establishing a safety exclusion zone around LNG bunkering areas. However, international consensus has yet to be reached in determining an appropriate extent of the zone to ensure safe LNG bunkering.

The purpose of this study is to identify potential risks of LNG bunkering and to present a statistical method for determining the safe exclusion zone around LNG bunkering station with the help of a purpose-built computer program, Integrated Quantitative Risk Assessment (IQRA).

A probabilistic risk assessment approach was adopted in this study to determine the safety exclusion zone for two case ships: one, a 300,000 DWT very large ore carrier (VLOC) and the other a 32,000 DWT bulk carrier. The results are then compared with those obtained by a deterministic approach and the discrepancies are discussed.

It was found from this study that the frequency of bunkering is one of the key factors in determining the extent of safety exclusion zone. Thus a somewhat surprising result of 36 m radius safety exclusion zone for the 32,000 DWT bulk carrier compared to 6.4 m radius for the 300,000 DWT VLOC was obtained.

It was also found that the deterministic approach produced a much more extensive safety exclusion zone for the 300,000 DWT VLOC subjected to infrequent large scale LNG bunkering operations compared to the probabilistic approach, while it was reasonably consistent with the probabilistic approach for the 32,000 DWT bulk carrier which uses frequent small scale bunkering.

Keywords: quantitative risk assessment, LNG-fuelled Ship, LNG bunkering, safety exclusion zone

1. Introduction

For ships using LNG as a fuel, LNG bunkering is an unavoidable process. The most established method of LNG bunkering is to transfer LNG from an LNG terminal to a receiving ship in a similar way as LNG cargo is loaded. However, lack of terminal infrastructure has encouraged several alternative methods to emerge, such as using LNG tank lorries, LNG feeder ships or portable LNG tanks [1][2]. Since 2000 when the world's first LNG-fuelled ship, the *MV Glutra*, was put into service, small to medium scale LNG bunkering has taken place using some of these alternative methods by a total of 48 LNG-fuelled ships [3][4].

LNG bunkering requires careful attention to safe operations as it entails potential risks pertaining directly to the cryogenic liquid transfer and vapour returns, much more so than the conventional liquid fuel bunkering. According to a report of Norwegian Maritime Authority [5], four accidents associated with LNG spill have been reported – one of which led to an injury of a crew member on his hands and legs due to cryogenic burn. Moreover, in large scale LNG bunkering operations for large ocean going ships, significant uncertainties associated with massive accidental LNG release are present. In view of the possibly catastrophic consequence of such accidents, the risks associated with LNG bunkering merits careful studies.

It is not surprising, therefore, that several studies ([6] – [9]) related to the safety of using LNG as a marine fuel have been reported. An information document to the IMO's CCC Sub-Committee [10] addressed the explosion risk at an LNG bunkering station, presenting a result of computer simulation that showed the impact of an instantaneous explosion from a massive concentration of LNG vapour gas, using a CFD Code (FLACS)[1]. DNV [3] has conducted a site-specific quantitative risk assessment of LNG bunkering in an effort to determine a safe distance for passing ships at the Port of Rotterdam. However, the findings of these studies were too site-specific to be translated into general regulations directly. Moreover, current international/local regulations and rules concerning the safety in LNG bunkering are limited to operational guidelines, lacking quantified requirements.

On the other hand, ISO/TS 18683 [2] recommends establishing a safety exclusion zone around the LNG bunkering station access to which is to be restricted to all non-essential personnel during bunkering so as to minimise the probability of ignition and the threat to human lives in the event of an accident. Such a safety exclusion zone encompassing the supply point on the terminal side and the bunkering station on the ship is illustrated in Figure 1. This standard allows the extent of the safety exclusion zone to be determined either deterministically based on the worst case scenario or probabilistically using quantitative risk assessment.

In certain cases safety exclusion zone determined through a deterministic method may turn out to be impracticably large, because such a method is usually based on an extreme event regardless of the probability of its occurrence. The determination of the 'extreme' event is somewhat arbitrary as well.

DNV GL [11] has conducted a case study for proposed LNG bunkering ports in USA, estimating safety exclusion zones for the LNG terminals. However, since it focused on site-specific scenarios obtained from hazard identification, the findings may have limited general applicability.

Nevertheless, DNV GL [12] has developed a guideline for LNG bunkering facilities, which recommend establishing the safety exclusion zone under the frequency limit of

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[1] Flame Acceleration Simulator (FLACS), Ver.10.0, GexCon, Bergen, Norway

1.0E-6 per bunkering on condition that the minimum zone should not be less than 10 m. The frequency limit is defined as the contour of a cumulative frequency of an ignitable gas cloud (using 100% LFL). However, the DNV GL guideline has several issues. First of all, there are discrepancies between the ISO Standards and DNV GL guideline: the ISO Standards require all possible impacts of consequences such as radiation and blast pressure caused by fire or explosion to be considered, whereas DNV GL guideline only focuses on the consequence of flash fire. Secondly, it is reasonable to assume that the frequency of bunkering will have a great bearing on risks, but it can be argued that the DNV GL guideline does not fully consider the frequency of LNG bunkering.

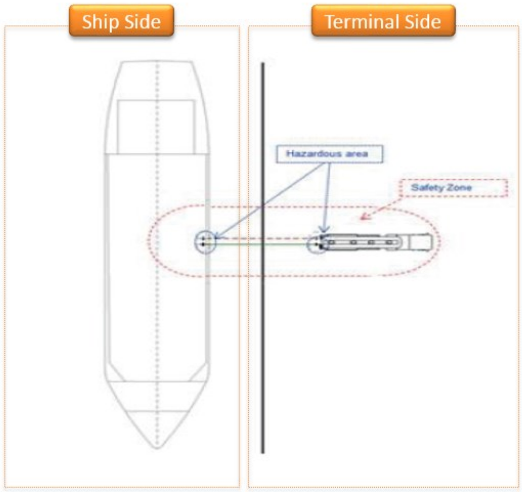

Figure 1 Illustration of a safety exclusion zone for LNG bunkering [2]

On the other hand, the safety exclusion zones for ships have yet to be studied probabilistically. As a result, sets of quantified guidelines for establishing the safety exclusion zone of LNG bunkering station for ships have not been firmly established as yet.

The current study addresses this shortfall and attempts to identify potential risks of LNG bunkering and key factors in determining the extent of the safety exclusion zone of LNG bunkering station for ships through case studies. Two case ships representing two rather different bunkering arrangements were studied. Since flag states have yet to provide the quantified risk criteria to establish the safety exclusion zone of LNG bunkering station, it is hoped that the findings of this can make some contributions in this regard.

A specially written IQRA program was employed for the case studies. The software features a built-in accident frequency calculator and a consequence estimator. Based on the numerical data thus produced, the program then evaluates the appropriate extent of safety exclusion zones for the case ships. A detailed description of the software including the methodologies applied in this study is given in Chapter 2.

2. Methodologies

A diagrammatic representation of the overall risk assessment procedure programmed in the IQRA software is shown in Figure 2. The procedure was based on the IMO's guidelines for Formal Safety Assessment (FSA) [13] and consists of four major steps: data input (system modelling); frequency analysis; consequence analysis; risk assessment. When the data of the system components, including type, size and working conditions, are input, the software estimates the frequency and the consequence, and, based on these, the overall risk level of the subject system is estimated. The overall program flow is given as an outline flowchart in Figure 2. The processes of frequency analysis, consequence analysis and risk assessment are given in Figures 4, 5 and 6. The main user interface of IQRA is shown in Figure 3.

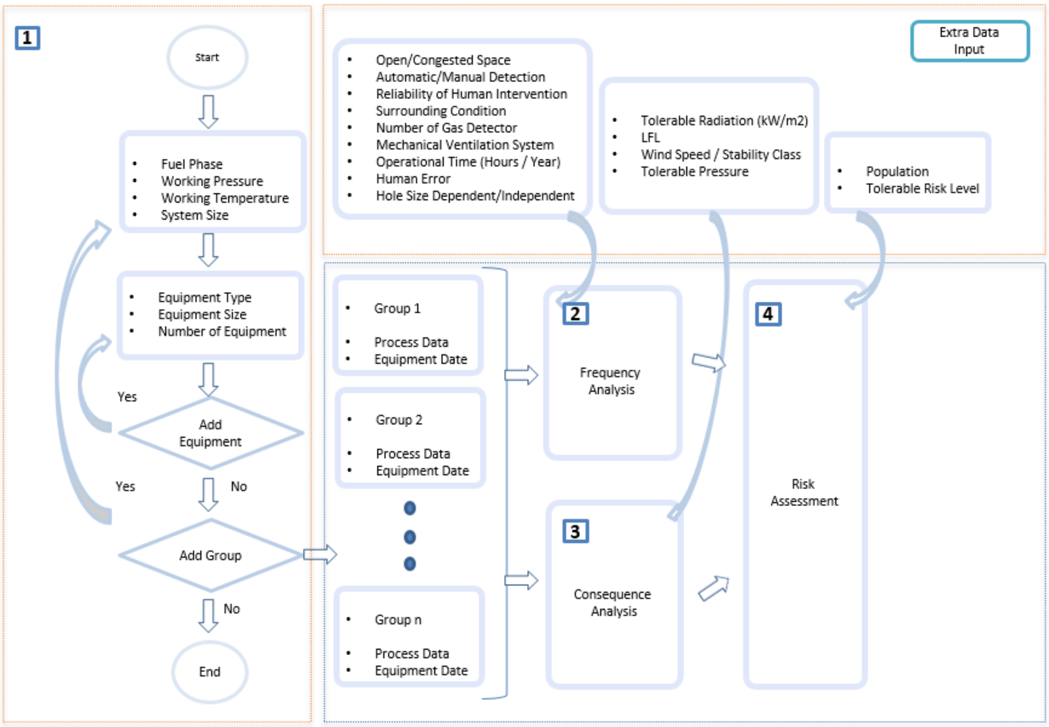

Figure 2 A flowchart of IQRA Software

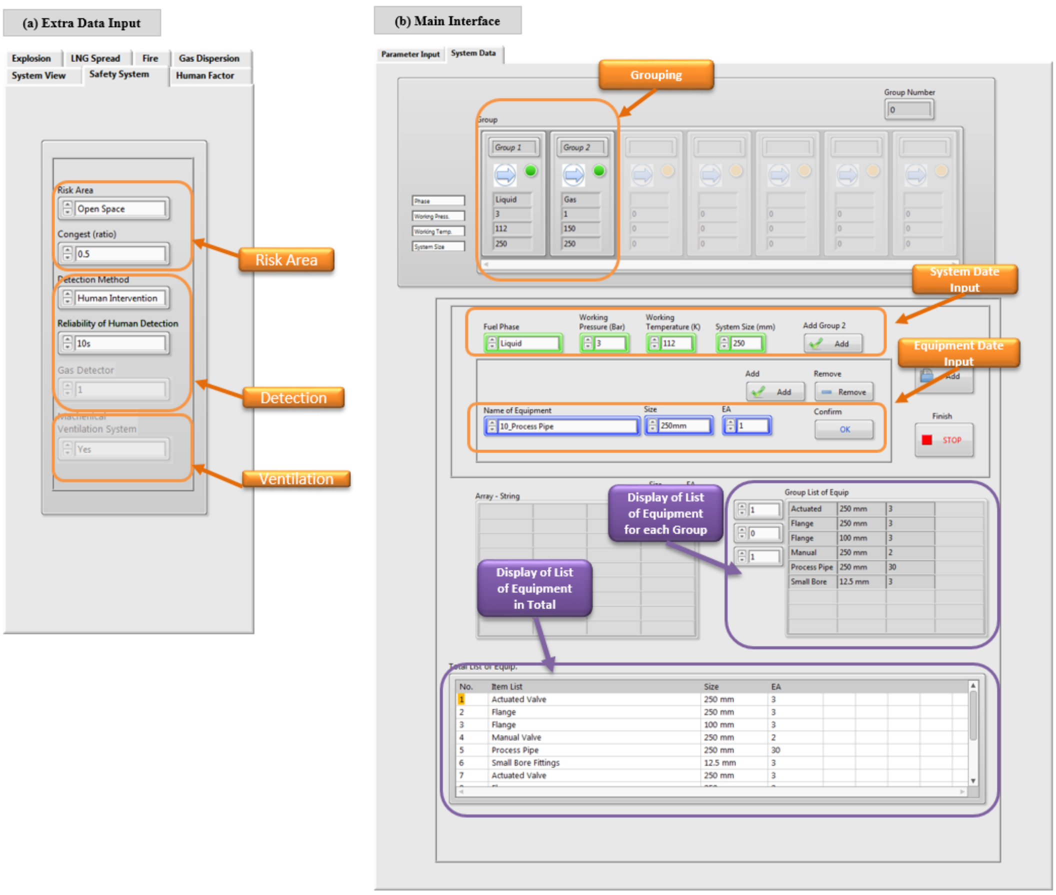

Figure 3 User interface of IQRA

2.1 Data Input

Users enter the system information into the software in a similar sequence to system design. Since a system may consist of a number of equipment/components with different working conditions, it can be split into several sub-systems and the program assesses the risk of each sub-system separately before summing them up to produce the overall risk of the whole system.

2.2 Frequency Analysis

Frequency analysis is a process of quantifying the likelihood of the unwanted events identified though the scenario analysis. The program carries out frequency analysis based on event trees. All possible hazards initiated by a leak are identified and their likelihood is estimated. The software also evaluates the contribution of escalating events leading to the final outcomes, taking into account the reliability of safety measures and the working conditions, which are specified by the user through selective parameters.

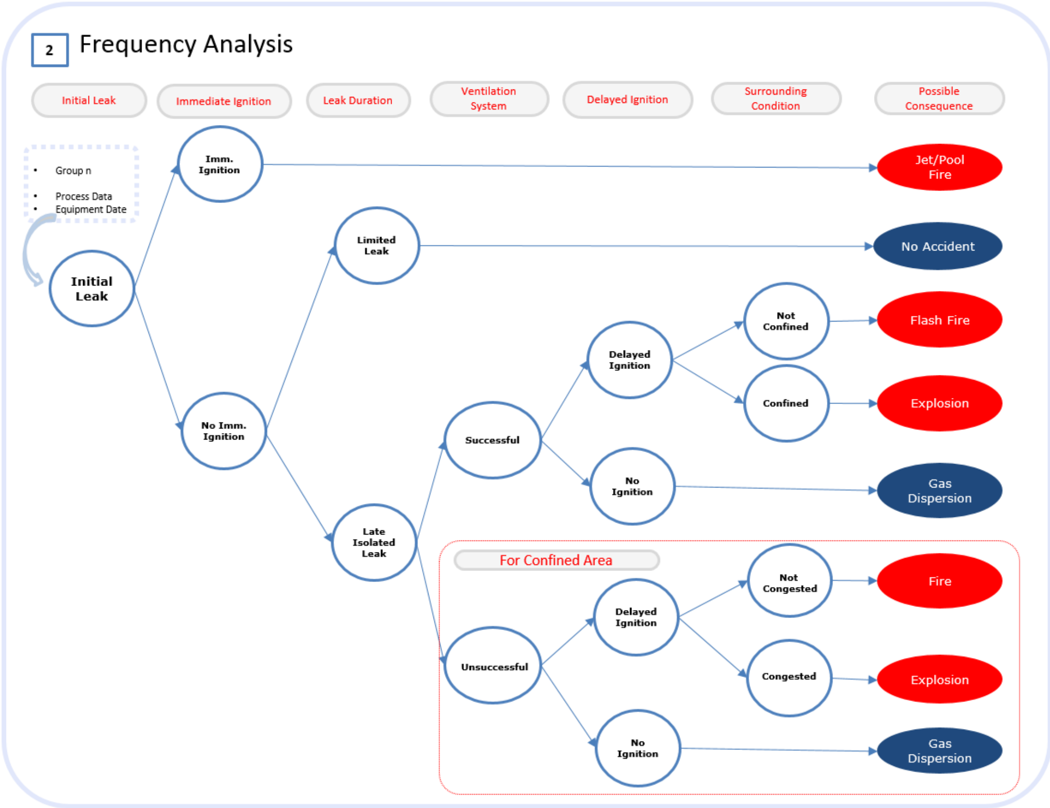

Figure 4 An example event tree for frequency analysis

Spilled LNG will undergo several physical processes simultaneously, such as pool formation, spread and boil-off. However, the final outcome can be diverse, depending on the nature of the leak and functioning of safety measures. Figure 3 shows an event tree of a series of accidental scenarios programmed in the software. Immediate ignition is assumed to be associated with jet fire (for gas release) and pool fire (for liquid release) whereas delayed ignition leads to other types of outcome. A leak of liquid fuel forms a liquid pool, possibly leading to a pool fire if ignited. Where the concentration of leaked material is between LFL and UFL (5%~15%), it is assumed that delayed ignition leads to a flash fire. A leak of liquid fuel forms a liquid pool, possibly leading to a pool fire if ignited. An explosion is likely to occur where gas is sufficiently enclosed, while a pool fire (which is only associated with liquid leak) and flash fire may occur in open conditions [14]. For open spaces, the frequency of each hazard is calculated as follows:

- $F_{\text{Jet Fire}} = F_{\text{Initial Leak}} \times P_{\text{Imm. Ignition}}$
- $F_{\text{Pool Fire}} = F_{\text{Initial\_Leak}} \times P_{\text{Imm. Ignition}}$
- $F_{\text{Flash Fire}} = F_{\text{Initial\_Leak}} \times P_{\text{Late\_Isolated\_Leak}} \times P_{\text{Suc. Ven.}} \times P_{\text{Del. Ignition}} \times P_{\text{Not Congested}}$
- $F_{\text{Explosion}} = F_{\text{Initial\_Leak}} \times P_{\text{Late\_Isolated\_Leak}} \times P_{\text{Suc. Ven.}} \times P_{\text{Del. Ignition}} \times P_{\text{Congested}}$

Where
F : Frequency (/year)
P : Probability

Since the bunkering systems are arranged in an open space for both case ships, leak is more likely to be detected by personnel than gas detection devices. Therefore, the probability of the full leak scenario is directly related to the probability of failure in watch keeping. An ignition results in several types of fire (flash, pool and jet) and explosion scenarios.

Using the 'Extra Data Input' tab shown in Figure 3, probable conditions of risk area and safety measures can be specified. In an open space, it is plausible that a fuel leak, either of liquid or gas, is detected by personnel while, in a confined space, gas detectors can be used. In addition, it can also distribute the congestion ratio of surrounding conditions and the effectiveness of ventilation system for confined spaces can be considered through this tab.

(a) Initial Leak Frequency

For the causes of initial leak, the software focuses on internally induced events, especially equipment failures.
The DNV Leak Frequency Datasheets contain 17 types of LNG equipment and various leak hole sizes: 3mm, 10mm, 50mm, 150mm and full (over 150 mm) [7]. Several failure databases are contained in the software, but the DNV frequency failure datasheets for LNG process equipment were used in this study as the database is commonly used for investigating hydrocarbon release including LNG.

The IQRA estimates the leak frequency of each piece of equipment and component using the built-in database in accordance with its size and annual operating time for various leak hole sizes in consideration. These frequencies are then summed to obtain the total leak frequency of LNG bunkering system.

(b) Probability of late isolated leak / Ventilation Failure

The full leak scenario represents a situation where the safety devices fail or appropriate actions are not taken to shut off the leak. To calculate the reliability of the safety measures including human factors, the software adopts generic failure data associated with safety system malfunctions and human errors from various sources such as KletzT [15], ORADA [16], EPRI [17], and CCPS [18]. It is assumed that limited leak scenarios, where safety systems function correctly, do not lead to adverse consequences. Natural dispersion takes place in open spaces, but the availability of mechanical ventilation system and the probability of its failure must be considered for confined spaces.

(c) Probability of Immediate Ignition and Delayed Ignition

Several models of ignition probability have so far been developed by various authors. For rigorous approaches, the default of this program for immediate ignition is the Dutch model [3], while for delayed ignition the Cox model [19] (P_{DI}) is used by default as those models have relatively higher ignition probabilities than other models. The probability of immediate ignition according to the Dutch model is shown in Table 1 and the Cox model for delayed ignition is given by Eq. (1).

Table 1 Probability of Immediate Ignition

Leak Rate (Q_{leak})	**Immediate ignition probability**
< 10 kg/s	0.02
10 ~ 100 kg/s	0.04

> 100kg/s	0.09

$$P_{DI} = 0.0158 Q_{leak}^{0.6415} \quad (1)$$

2.3 Consequence Analysis

The process of consequence analysis is outlined in Figure A4, showing the methods used in consequence modelling: calculation of liquid and gas release rate, modelling of LNG pool spread and evaporation, fires and explosion with respect to particular leak sizes.

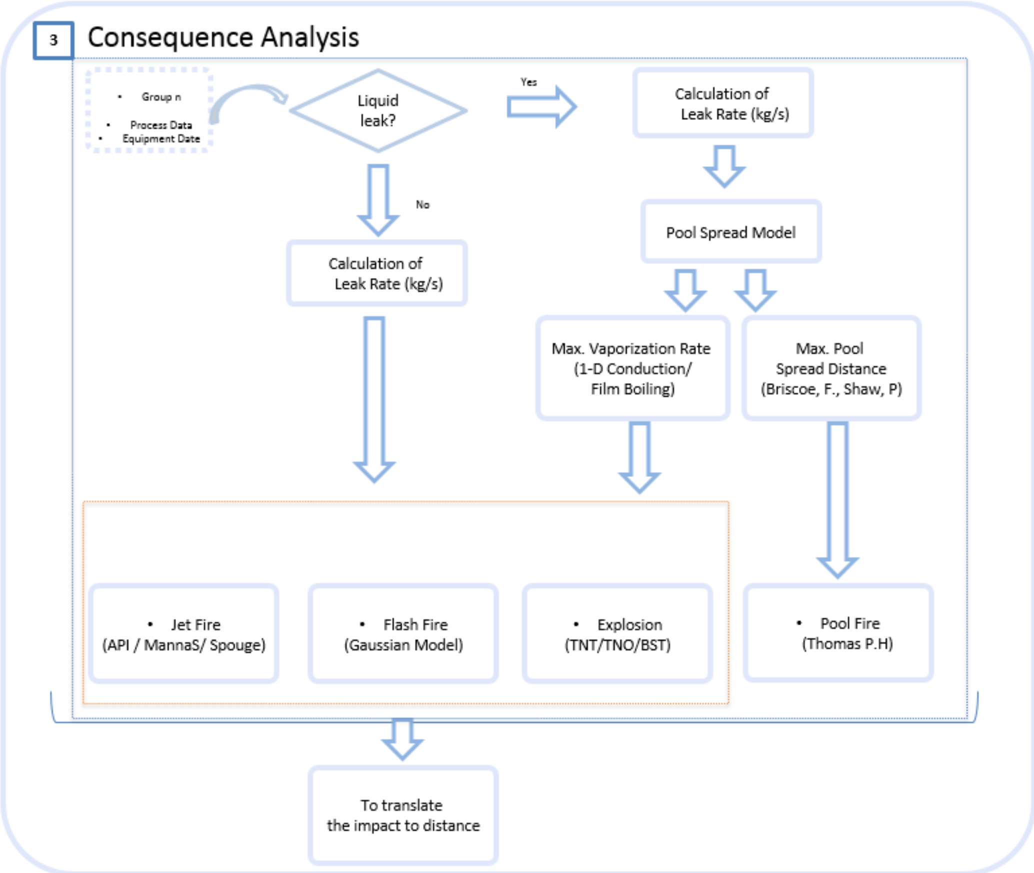

Figure 5 Layout for consequence analysis

(a) Leak Rate

Leak hole size as well as system conditions are used as the parameters to calculate the leak rate (kg/s) of the fluid. For liquid leak model, the initial leak rate of LNG is calculated based on the classical work of Bernoulli's equation. For gas leak model, the mass rate for sonic or subsonic discharges from a leak hole is calculated by means of the continuity equation and the law of ideal gases for an isentropic expansion. For both models, the discharge coefficient is set to 0.61 for default [20-22].

(b) LNG Spread/Evaporation

The Software adopts the pool spread model by Briscoe and Shaw [23] in conjunction with vaporization models of either 1-D conduction model of Carslaw and Jaeger [24] based on Fourier's law or film boiling model of Klimenko [25] based on Newton's law of cooling. For the present study, film boiling model was applied. Heat transfer by convection from ambient air or radiation is not included in this model, as this is assumed to be negligibly small.

(c) Jet Fire Model

The software calculates the length of jet fires using several semi-empirical models: Cook model [26], Mannan model [27] and Spouge model [28], all of which are based on the fact that the characteristics and impact of jet fires depend on the fuel composition, release conditions and release rate. Present study adopted Cook model to estimate the impact of jet fire. In addition, the jet fire radius at each length point is calculated with API RP 521 flare model [27]. The emissive power of a jet fire ranges from 50 to 220kW/m^2 and the impact of fire radiation can be assumed to be critical on any personnel working within the predicted length of the fire [29].

(d) Flash Fire (Dispersion Model)

In order to estimate flash fire ranges, the software adopts Gaussian gas dispersion models by predicting dispersion effect and the gas concentration [30]. Regarding the selection of coefficients applying to the dispersion models, two different methods - Briggs coefficients [31] or Van Buijtenen coefficients [32] – can be applied in this Software. For the current study, Briggs coefficients model was applied.

(e) Explosion Model

The software functions with three simplified empirical models (TNT equivalence model [33], TNO multi-energy [33-34] and Baker-Strehlow-Tang (BST) models [33][35]) to assess the magnitude of overpressure caused by explosion. TNT equivalence model uses empirical explosion efficiency having a range of 0.01 to 0.1 while TNO multi-energy model has various TNO numbers from 1 to 10 and BST numbers are set up with range between 0.037 and 5.2 [33][36]. All these parameters can be selected by the user. The present study adopted TNO model with TNO 7 which is widely acknowledged model for investigating LNG explosion [33].

(f) Pool Fire Model

The average visible plume length in relation to the diameter of a fire is estimated by means of the flame model derived by Thomas [37]. In addition, for calculating the mass burning rate, it adopts the correlation of Nedelka [38] or uses the mean value of 0.14 kg/m^{2}s [33] as default.

The radiation effect on personnel for a tilted flame by wind effect is estimated together with the view factors for vertical and horizontal receiving surfaces given by Hoftijzer [39] and Ramiro and Aisa [32].

2.4 Risk Assessment

Based on the critical distances estimated above, each consequence is put into a 'zone' Zone 1(below 5m), Zone 2(5-15m), Zone 3(15-25m), Zone 4(25-50m), Zone 5(50-100m), Zone 6(100-200m). And for each zone, the frequencies of all the consequences belonging to it are summed to produce the frequency of accidents which have the critical distance within the range of the zone. The safe exclusion zone is the nearest zone with less than the acceptable risk criteria. Alternatively, this software calculates the direct distance to meet the acceptable risk criteria.

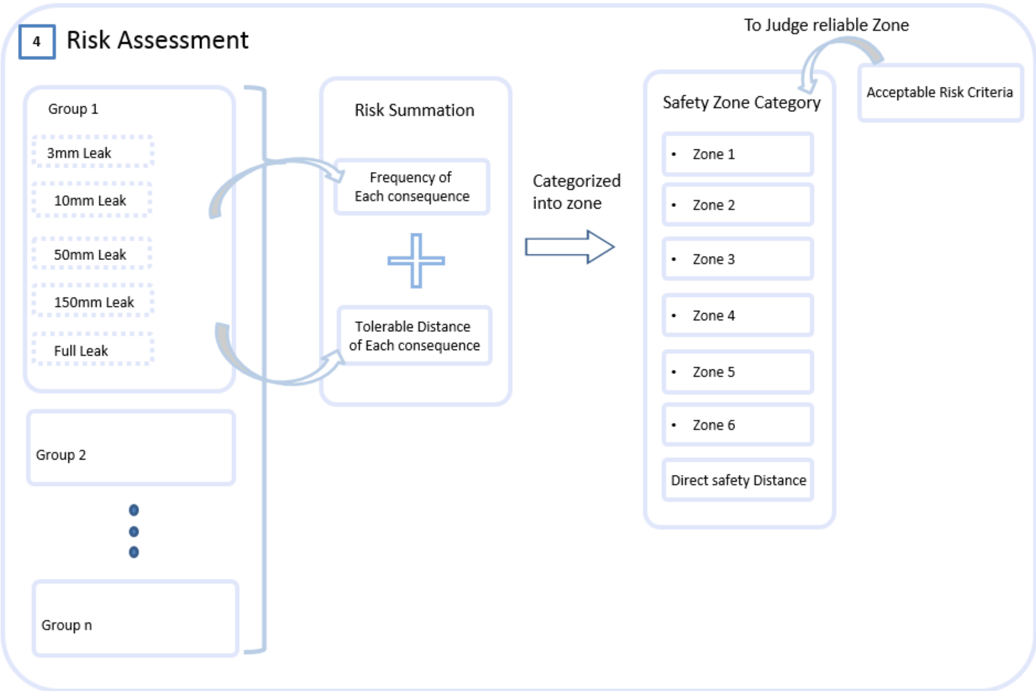

Figure 6 Layout for consequence analysis

The devision of zone enables users to observe risk levels in accordance with descrite distances, which may be convienient to parametric analysis where risks of several cases are compared. Therefore, it could be said that the purpose of using 'spatial zones' is related to the generalization of the present study. This will enable the rule-makers, for example, to specify a safety exclusion zone of radius at least so and so for such and such ships.

3. Case Ships

3.1 Particulars of Ships and Engines

In order to investigate rational safety exclusion zones required for LNG bunkering, two cargo ships were selected: a 300,000 DWT VLOC (referred to as Case Ship 1 hereafter) and a 32,000 DWT bulk carrier (referred to as Case Ship 2). These ships are presently the subject of 'LNG-Ready Ships'[2], a joint project of Korea Register of Shipping (KR), Hyundai Heavy Industries Co. Ltd and Hyundai Mipo Heavy Industries Co. Ltd. The

[2] Ships which can be easily retrofitted to use liquefied natural gas (LNG) bunkers.

main engines were modified to dual fuel and the LNG fuel system was designed in accordance with the IGF Code, class rules and other relevant guidelines in cooperation with KR. Table 1 summarizes general specifications and operational profiles of the case ships.

Table 2 General specifications of the case ships (*by courtesy of Korea Resister of Shipping*)

	Specifications	
	300K DWT VLOC (Case Ship 1)	**32K DWT bulk carrier (Case Ship 2)**
		
L x B x D	328.0 m x 55.0 m x 29.0 m	168.5 m x 28.4 m x 14.25 m
Main engine	Hyundai MAN B&W 6G80ME-GI-C9	MAN B&W 6S40ME-GI
MCR/NCR[3]	20,680 kW x 65.8 rpm/17,578 kW x 62.3 rpm	6,480kW x 139 rpm/5,832 x 134.2 rpm
LNG consumption	Abt. 67 tonnes/day	Abt. 19.8 tonnes/day
Cruising range	Abt. 25,000 miles per one voyage from Brazil to East Asia	Abt. 600 miles per one voyage from Donghae to Gwangyang South Korea
LNG fuel tank	11,000 m^3 (IMO B type)	125 m^3 (IMO C type)

Case Ship 1 is a typical ocean-going cargo ship engaged in international service routes, such as between Brazil and East Asia. The proposed NCR of the engine is 17,578 kW during service and LNG consumption is expected to be about 67 metric tonnes daily. This corresponds to the specific gas consumption (SGC) at NCR of 128.8g/kWh [40]. Given the ship owner's requirement of the capacity of the LNG fuel storage tank to be at least 10,000 m^3, bunkering needs to be carried out at least every 70 days, approximately five times each year.

Case Ship 2 is engaged in a domestic service between Donghae and Gwangyang in South Korea. The fuel consumption is estimated to be 19.8 metric tonnes daily corresponding to the SGC at NCR of 142.1g/kWh [41]. According to the voyage profile given, this ship has a voyage cycle of 102 hours spending about 42 hours at sea and about 60 hours in port. The capacity of the LNG fuel tank was proposed to be 125m^3, and therefore LNG bunkering needs to take place every voyage, approximately 84 times annually.

The Case Ships 1 and 2 represent generic large and small ships – they are realistic enough but do not represent case-specific ships. In this context, bunkering of Case Ship 1 can be characterised as 'infrequent large scale', while Case Ship 2 can be said to require 'frequent small scale' bunkering.

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[3] Maximum continuous rating/nominal continuous rating (85% of MCR)

3.2 Fuel System Design

The basic features of the LNG fuel systems and LNG bunkering systems were designed in accordance with the engine maker's specifications and the operational profile of the case ships.

(a) Case Ship 1

Figure 7 depicts the conceptual LNG fuel piping system and its arrangement devised for the Case Ship 1. It was agreed by all parties concerned that the best arrangement was to transform No.4 Cargo Hold into the space for LNG fuel systems, placing the LNG fuel storage tank, the tank connection space and the fuel preparation room inside the same hold.

The LNG bunkering stations are arranged on freeboard deck between Nos 3 and 4 Cargo Holds port and starboard. A ship-to-ship bunkering is considered to be the most likely for the time being.

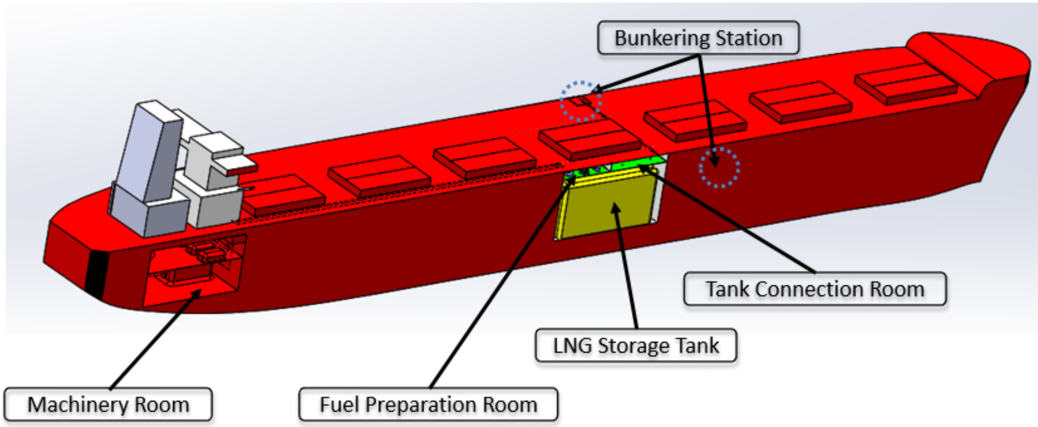

Figure 7 Conceptual arrangement of bunkering system for Case Ship 1

Figure 8 shows a conceptual piping diagram of the LNG bunkering system. Similar to LNG cargo transfer systems, fundamentally it consists of three lines: main line for LNG bunkering, vapour return line and N_2 inert line. In compliance with the LNG bunkering guidelines, emergency shut-down (ESD) valves are to be fitted to both main line and vapour return line. In addition, emergency release couplings (ERC) are to be fitted to the flange connections on the feeder side [2].

The pipes of the system are designed to be 250 mm in diameter and the length of piping engaged in the each side LNG bunkering is estimated to be 30 m, taking into account the ship's breadth. In order to keep the vapour return to a manageable proportion the maximum fluid velocity was assumed to be 5 m/s. This gives the time required to fill up an empty LNG storage tank (10,000 m^3) of 13 hours each time, or 65 hours per year.

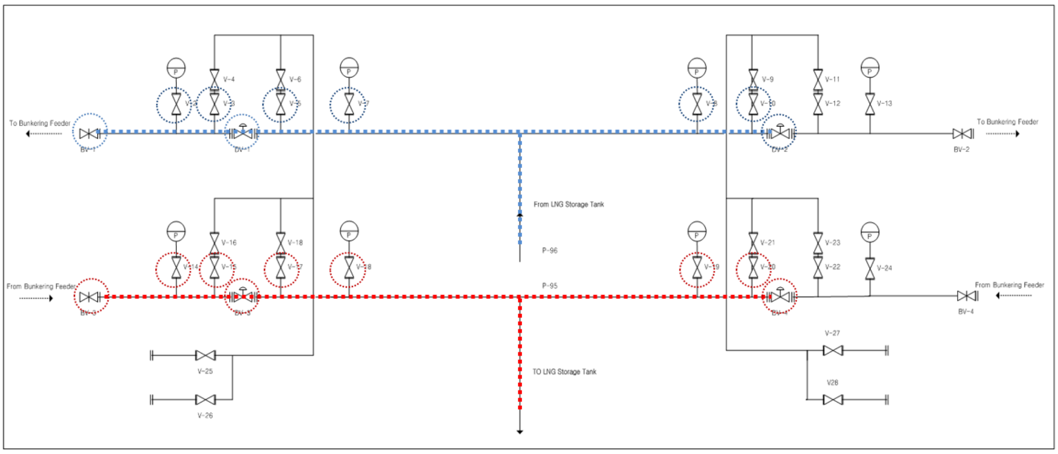

Figure 8 Conceptual design of bunkering system for Case Ship 1

(b) Case Ship 2

The conceptual LNG fuel piping system and its arrangement devised for the Case Ship 2 is outlined in Figure 9. The project team decided to install the LNG storage tank on an open space behind the accommodation block. The bunkering system is placed near the tank port and starboard as shown in Figure 8. Bunkering is likely to rely on tank lorries for the time being.

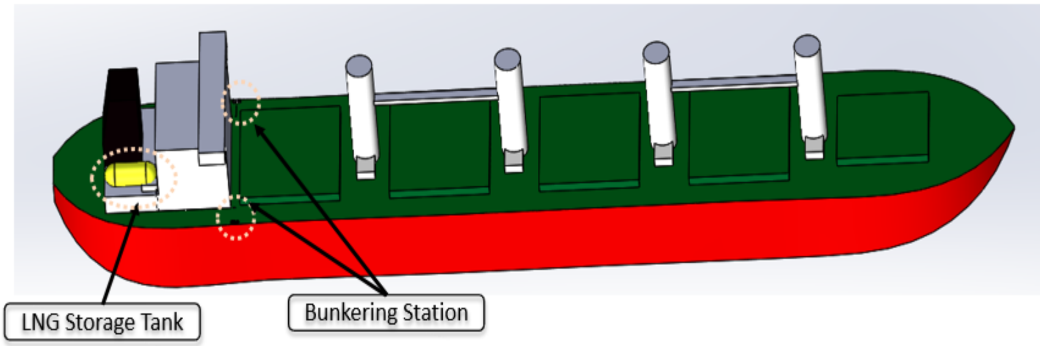

Figure 9 Conceptual arrangement of LNG fuel systems for Case Ship 2

Figure 10 shows a piping diagram of the conceptual bunkering system for Case Ship 2. Like to Case Ship 1, N_2 inert line as the inert system is assumed to be provided on board. Since the bunkering method used is not ship-to-ship and the system size is small, ERC is not practical.

The proposed size of the pipes in the LNG bunkering system is 25 mm in diameter and the length of piping engaged in the each side LNG bunkering is estimated to be 45 m. Since the IMO C type tank can contain the generated vapour inside the tank during bunkering, the vapour is not returned to the feeder side. For this reason an appropriate fluid velocity of 8 m/s is assumed, making the time to fill up the initially empty storage tank about 9 hours each time and about 773 hours per year.

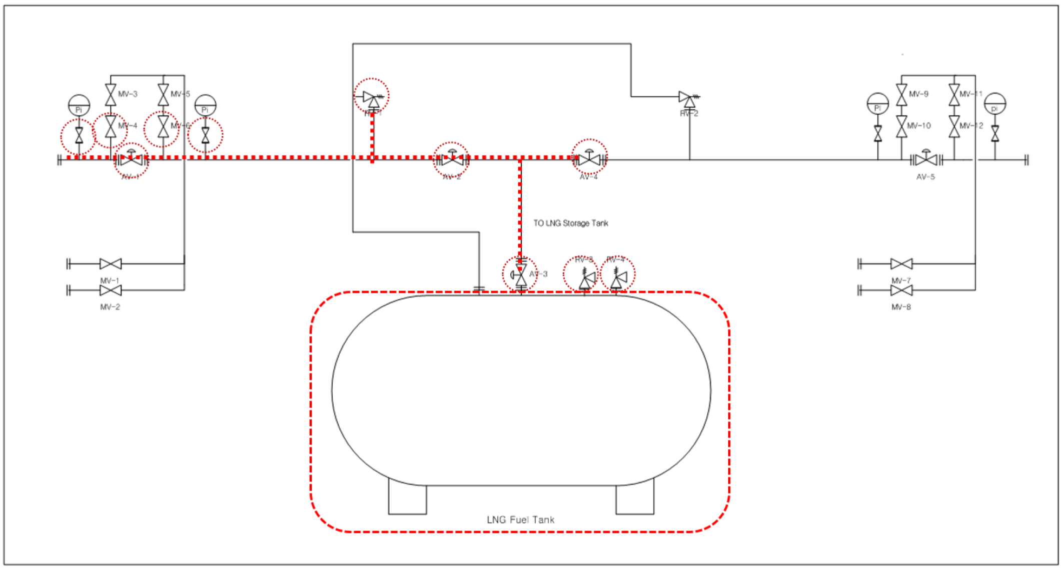

Figure 10 Conceptual design of bunkering system for Case Ship 2

The components included in the conceptual design of bunkering systems illustrated in Figures 8 and 10 are listed in Table 3. The equipment and the pipes serving the bunkering station on each side are marked with dotted circles and lines in the figures.

Table 3 List of components for bunkering system

Case	No.	Equipment	Size	Quantity	
				Main liquid	Vapour return
Case ship 1	1	ESD Valve	250mm	2	2
	2	ERC	250mm	1	1
	3	Flange for Main Line	250mm	3	3
	4	Flange for Inert Line	100mm	3	3
	5	Manual Valve	250mm	2	2
	6	Pipe (per 1m)	250mm	30	30
	7	Pressure indicator	12.5mm	3	3
Case ship 2	1	ESD valve	25mm	1	
	2	Flange for main line	25mm	12	
	3	Flange for inert line	12.5mm	2	
	4	LNG fuel tank	25mm	1	
	5	Manual valve	12.5mm	2	Not considered
	6	Pressure indicator	12.5mm	2	
	7	Pressure relief valve	25mm	3	
	8	Process pipe (per 1m)	25mm	45	
	9	Remote valve (exp. ESD valve)	25mm	3	

An accidental release of the fuel is the main danger associated with LNG bunkering. It is reasonable to consider that only the LNG main liquid line and the vapour return line are subject to risk of the fuel leak, but the N_2 inert line is not directly involved in LNG transfer. The two lines, however, are under different working conditions, and so they were separated into two groups in this study: one for main liquid system and the other for vapour return system. The working pressure for the main liquid line (hereafter referred to as Group 1) was assumed to be 3 bar(g) while that of the vapour return (hereafter referred to as Group 2) to be 1 bar(g) for both case ships. The working temperature of LNG flowing through the main line was assumed to be 112K whereas that of the vapour return was set to be 123K [3]. It is reiterated here that Case Ship 2 does not require a vapour return line.

4. Risk Analysis

4.1 Frequency Analysis

Figure 11 illustrates the calculated results. For Case Ship 1, Groups 1 and 2 are identical and consequently the initial fuel leak frequency is also the same. On the other hand, Case Ship 2 appears to have a higher leak frequency compared to Case Ship 1 due to the higher frequency of bunkering. It also shows that the occurrence of small leakage holes is more frequent than larger ones in both cases.

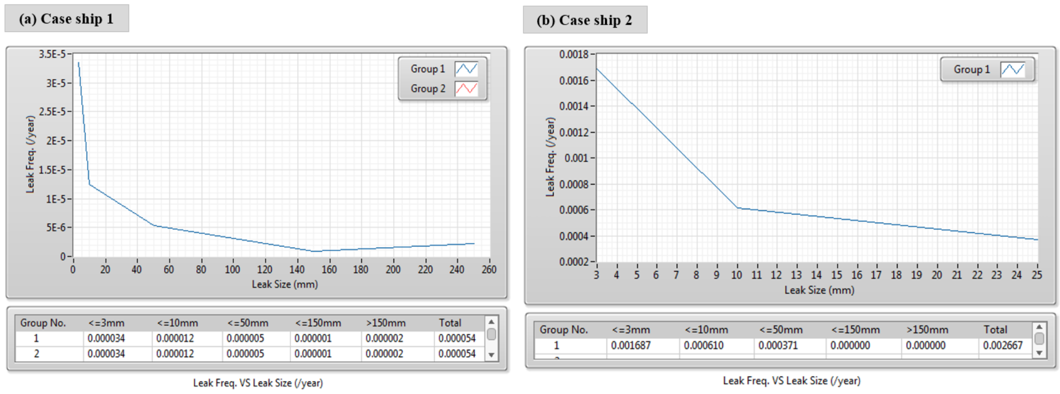

Figure 11 Leak frequency of proposed LNG bunkering system

A ‘late isolated leak’ scenario was defined as an isolation action not taken immediately (with probability of 0.1) [15]. In this study the maximum time to recognise and isolate the leak ‘immediately’ is 10 seconds, and thus a ‘limited leak’ with less than 10 seconds duration was assumed not to constitute an ‘accident’. DNVGL [20], for example uses 30 seconds to define limited leaks, and therefore the 10 seconds criterion used in this study is much shorter than that.

Safety measures are provided to ensure that, as long as they work effectively, all target accidents can be either prevented or contained with no serious consequence. For LNG bunkering in an open space, watch-keeping is the only practical safety measure that can be provided (since gas detectors will be ineffectual in such circumstances), and therefore the scenario of ‘limited fuel leak’ represents the situation in which the watch-keeper takes an appropriate action immediately to stop the leak. This means that we could assume that 90% of initial liquid fuel leak does not lead to an ‘accident’ as the leak can be contained to a ‘limited leak’ which was supposed to pose no danger.

According to IGF Code, Classification rules, ISO standards and other guidelines associated with LNG bunkering, ventilation in open space is ‘natural’ and not mechanical. Therefore, there is no probability of the ventilation failing. In this particular instance, given the fact that on-board LNG bunkering stations are situated in the open deck, namely the freeboard deck, albeit with some structures in the vicinity, we are indeed dealing with open spaces.

Surrounding condition, whether congested or open, is another important factor as it determines types of final accidents: fire or explosion. The usual structures near on-board bunkering stations include hatch coamings and covers, other pipes, cranes and so on with large variations between ships. However it is generally reasonable to consider that the surrounding conditions are closer to 'open' than 'congested'. After some discussion with ship designers and a classification society (Korean Register of Shipping), it was advised that 20% of occupancy ratio appears reasonable. In addition, it was decided to investigate how much this factor affects the final outcome. 10% and 50% in addition to the 20% were used in a sensitivity analysis.

Figure 12 shows an event tree analysis (ETA) for a 3mm initial leak for Group 1 of the Case Ship 1 with the frequencies of the final outcomes.

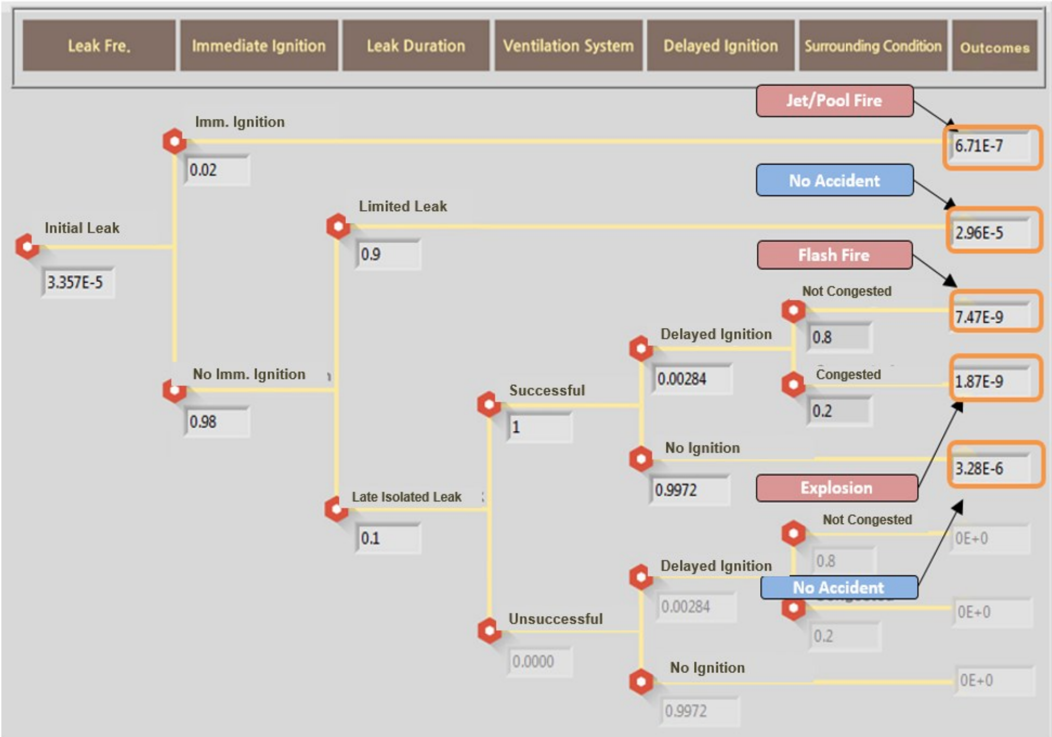

Figure 12 An event tree for 3mm leak hole from LNG bunkering main system for Case Ship 1

4.2 Consequence Analysis

Using the methods discussed in section 2.3 (a), the leak rates with respect to various hole sizes are estimated in Table 4.

Table 4 Leak rates for various leak hole sizes (unit: kg/s)

Case	Group	Leak hole size				
		3mm	10mm	50mm	150mm	>150mm
Case Ship 1	1	0.0688	0.7647	19.1	172.0	477.9
	2	0.016	0.0177	0.442	3.978	11.05
Case Ship 2	1	0.688	0.7647	4.791	-	-

Fire/explosion is likely to generate a significant amount of thermal radiation or overpressure which can adversely affect humans. The magnitude of radiation and overpressure is the highest at the ignition point and decreases as the distance from the origin increases. The safety guidelines from the Centre for Chemical Process Safety

(CCPS) [42] define critical thermal radiation at 37.5 kW/m^2 and critical overpressure at 1 bar(g), representing values exposure to which causes 100% fatality to a person. Based on this, the case study analyses critical distances using the safety parameters of radiation and overpressure. In addition, the length of jet fire and Lower Flammable Level (LFL) of methane (5% by volume) is considered to be the critical distance for the jet fire and flash fire respectively. For producing a generic understanding, a neutral weather condition with a wind speed of 5 m/s is assumed [3]. Less than 100% fatality does not imply absolute safety. This point is discussed later in this paper.

An example of critical distance of each consequence with respect to each representative leak hole size is featured in Figure 13. These results confirm that the impact of consequences has a direct correlation with leak rate of the fuel, and that the critical distance determined purely by the impact of accidents is, not surprisingly, much more extensive for a large scale LNG bunkering operation than a smaller one.

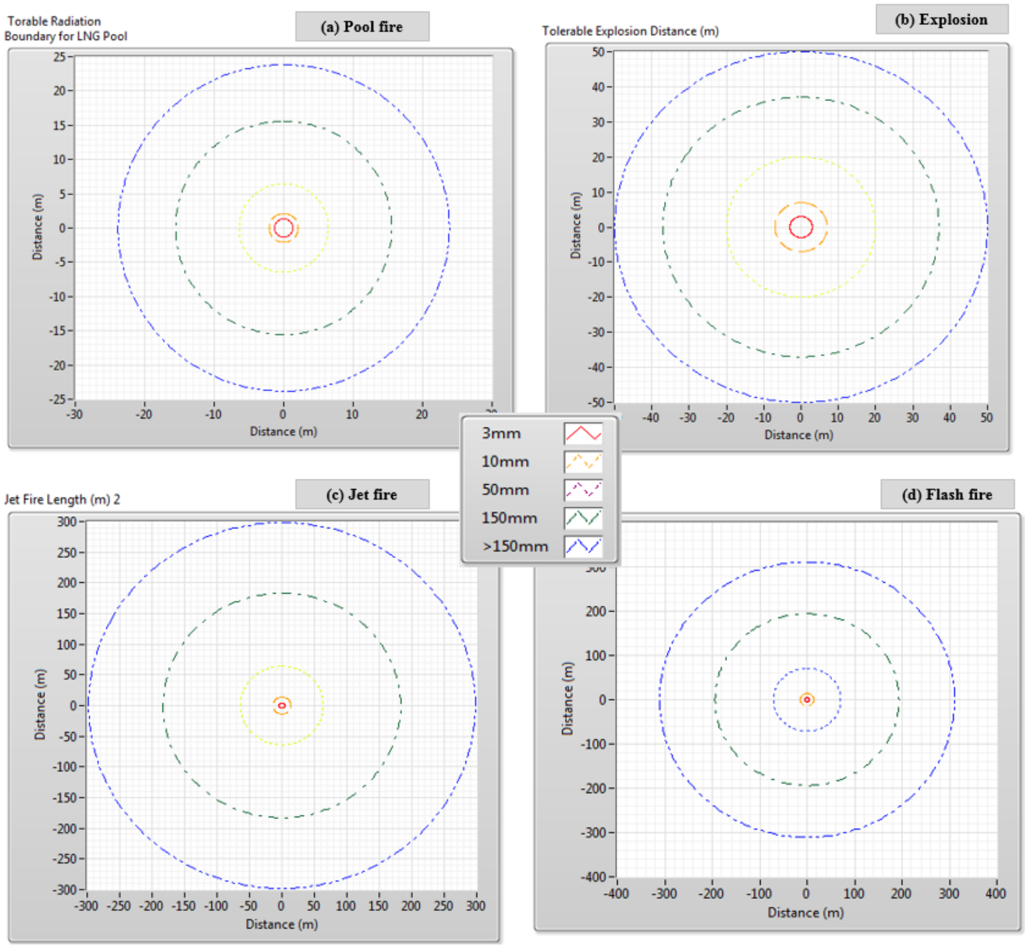

Figure 13 Example of critical distance for Group 1 for Case Ship 1

4.3 Risk Assessment

Risk is defined as the product of the probability of occurrence of an accident and its consequence which is usually expressed in terms of lives lost and injuries caused or financial losses suffered. However, the current case is independent of demographical conditions, and another relevant factor has to be found for establishing the safety exclusion zone. In this study it was decided to use the risk acceptance criteria (acceptable accident rate) for this purpose. Since presently there is no agreed probabilistic risk criteria available for LNG bunkering, as a purpose of observing severe condition, the Dutch risk criterion [3] (frequency limit of 1.0E-6/year) was applied to estimate the 'tolerably safe' zones for LNG bunkering stations.

The numerical results of frequency and consequence analyses are brought together as listed in Table 5. As discussed in Secion 2.4 with Figure 5, the areas around the bunkering stations are divided into discrete zones according to the distance from them: Zone 1(below 5m), Zone 2(5-15m), Zone 3(15-25m), Zone 4(25-50m), Zone 5(50-100m), Zone 6(100-200m) and Zone 7(over 200m). Based on the critical distance assessed by the consequence models discussed above, each accident is put into these zones and the frequencies of the consequences belonging to each zone are summed up. (For example, if an explosion has an impact up to 22m, the accident is included in Zone 1, 2 and 3). By this means the accident rate (risk level) of each safety exclusion zone can be evaluated. From this, the zone furthest to the bunkering station with the frequency higher than the acceptable limit can be taken as the safety exclusion zone. The results are shown in Figure 14 for Case Ship 1 and Figure 15 for Case Ship 2. It can be observed that the minimum safe exclusion zone is Zone 2(5-15m) for Case Ship 1, and Zone 4 (25-50m) for Case Ship 2. The minimum distances with less than the frequency limit are 6.4m for Case Ship 1 and 36m for Case Ship 2. This result does imply that the size of safe zone is more likely to be determined by bunkering frequency rather than the amount of LNG transferred.

On the other hand, the safety exclusion zone for Case Ship 2 includes accommodation areas which must be protected from any hazards. Consequently, it may be necessary to rearrange the bunkering systems away from this area. Alternatively, the safety exclusion zone can be made smaller by enhancing the safety system, such as using double walled piping.

Table 5 Numerical result of frequency and consequence analysis

Case	Line	Hole Size	Initial Freq.	Fire Type	Imm. Ignition	Leak Duration (Late isolation)	Del. Ignition	Surrounding Condition (Congestion ratio)	Ignition Probability	Consequence (distance, m)
Case Ship 1	Main Line - Group 1	3mm	3.36E-05	Pool Fire	0.02				6.71E-07	1.3
				Flash Fire	0.98	0.1	0.00284	0.8	7.47E-09	5
				Explosion	0.98	0.1	0.00284	0.2	1.87E-09	3
		10mm	1.24E-05	Pool Fire	0.02				2.48E-07	2.1
				Flash Fire	0.98	0.1	0.0133	0.8	1.29E-08	14
				Explosion	0.98	0.1	0.0133	0.2	3.24E-09	7
		50mm	5.41E-06	Pool Fire	0.04				2.16E-07	6.4
				Flash Fire	0.96	0.1	0.105	0.8	4.36E-08	71
				Explosion	0.96	0.1	0.105	0.2	1.09E-08	20
		150mm	8.76E-07	Pool Fire	0.09				7.88E-08	15.6
				Flash Fire	0.91	0.1	0.429	0.8	2.73E-08	194
				Explosion	0.91	0.1	0.429	0.2	6.84E-09	37
		Full (250mm)	2.20E-06	Pool Fire	0.09				1.98E-07	23.8
				Flash Fire	0.91	0.1	0.827	0.8	1.32E-07	311
				Explosion	0.91	0.1	0.827	0.2	3.31E-08	50
	Vapour Return Line - Group 2	3mm	3.36E-05	Jet Fire	0.02				6.71E-07	0.7
				Flash Fire	0.98	0.1	0.000253	0.8	6.66E-10	1
				Explosion	0.98	0.1	0.000253	0.2	1.66E-10	1
		10mm	1.24E-05	Jet Fire	0.02				2.48E-07	2.3
				Flash Fire	0.98	0.1	0.00119	0.8	1.16E-09	3
				Explosion	0.98	0.1	0.00119	0.2	2.89E-10	3
		50mm	5.41E-	Jet Fire	0.02				1.08E-07	10.6

			06	Flash Fire	0.98	0.1	0.00936	0.8	3.97E-09	14
				Explosion	0.98	0.1	0.00936	0.2	9.92E-10	7
		150mm	8.76E-07	Jet Fire	0.02				1.75E-08	30.2
				Flash Fire	0.98	0.1	0.0383	0.8	2.63E-09	41
				Explosion	0.98	0.1	0.0383	0.2	6.57E-10	14
		Full (250mm)	2.20E-06	Jet Fire	0.04				8.78E-08	49.2
				Flash Fire	0.96	0.1	0.0738	0.8	1.24E-08	69
				Explosion	0.96	0.1	0.0738	0.2	3.11E-09	19
Case Ship 2	Main Line - Group 1	3mm	1.69E-03	Pool Fire	0.02				3.37E-05	1.3
				Flash Fire	0.98	0.1	0.00284	0.8	3.76E-07	5
				Explosion	0.98	0.1	0.00284	0.2	9.39E-08	3
		10mm	6.10E-04	Pool Fire	0.02				1.22E-05	2.1
				Flash Fire	0.98	0.1	0.0133	0.8	6.36E-07	14
				Explosion	0.98	0.1	0.0133	0.2	1.59E-07	7
		Full (25mm)	3.71E-04	Pool Fire	0.02				7.41E-06	3.8
				Flash Fire	0.98	0.1	0.0431	0.8	1.25E-06	36
				Explosion	0.98	0.1	0.0431	0.2	3.13E-07	13

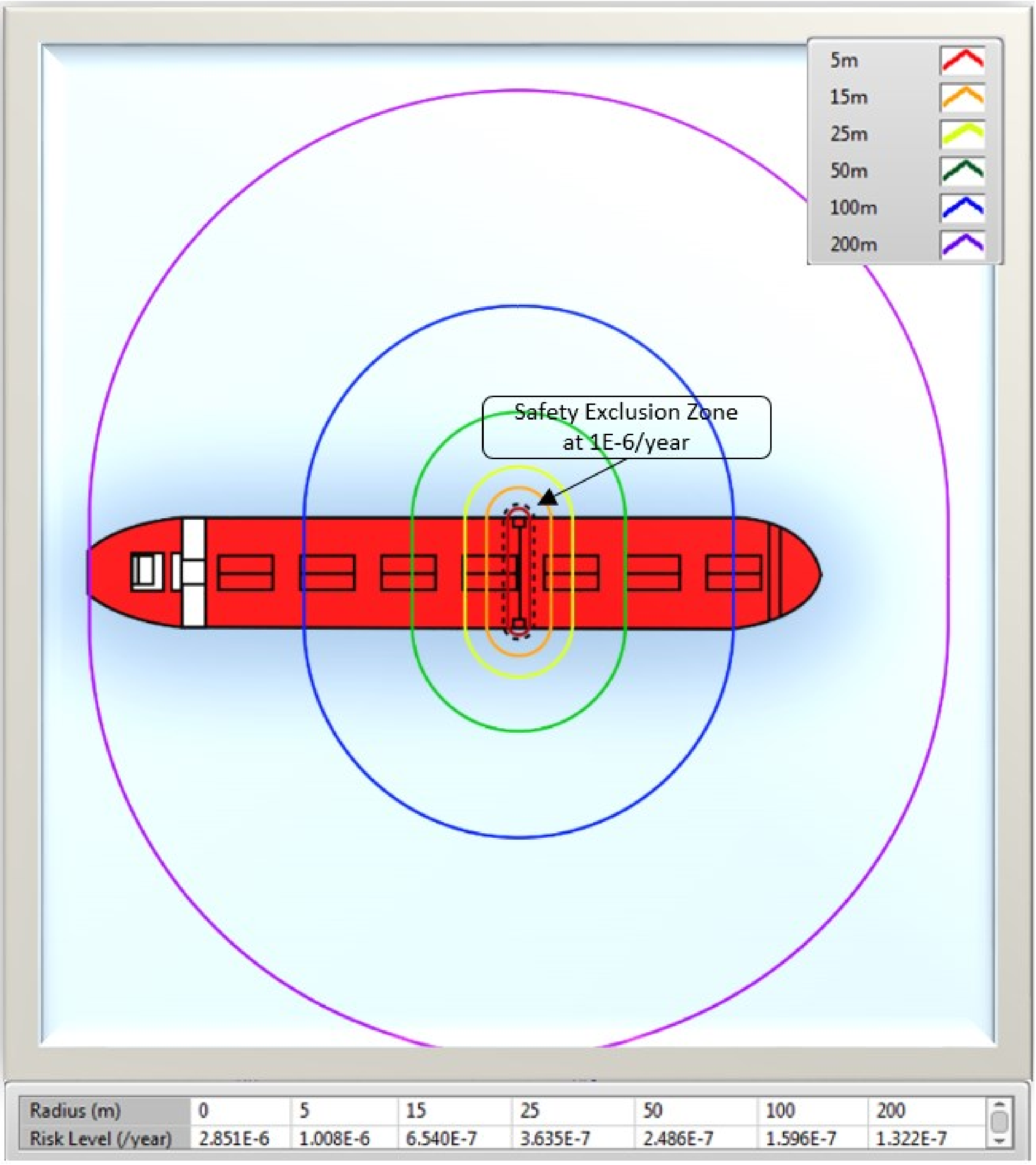

Figure 14 Risk level of safety exclusion zones for Case Ship 1

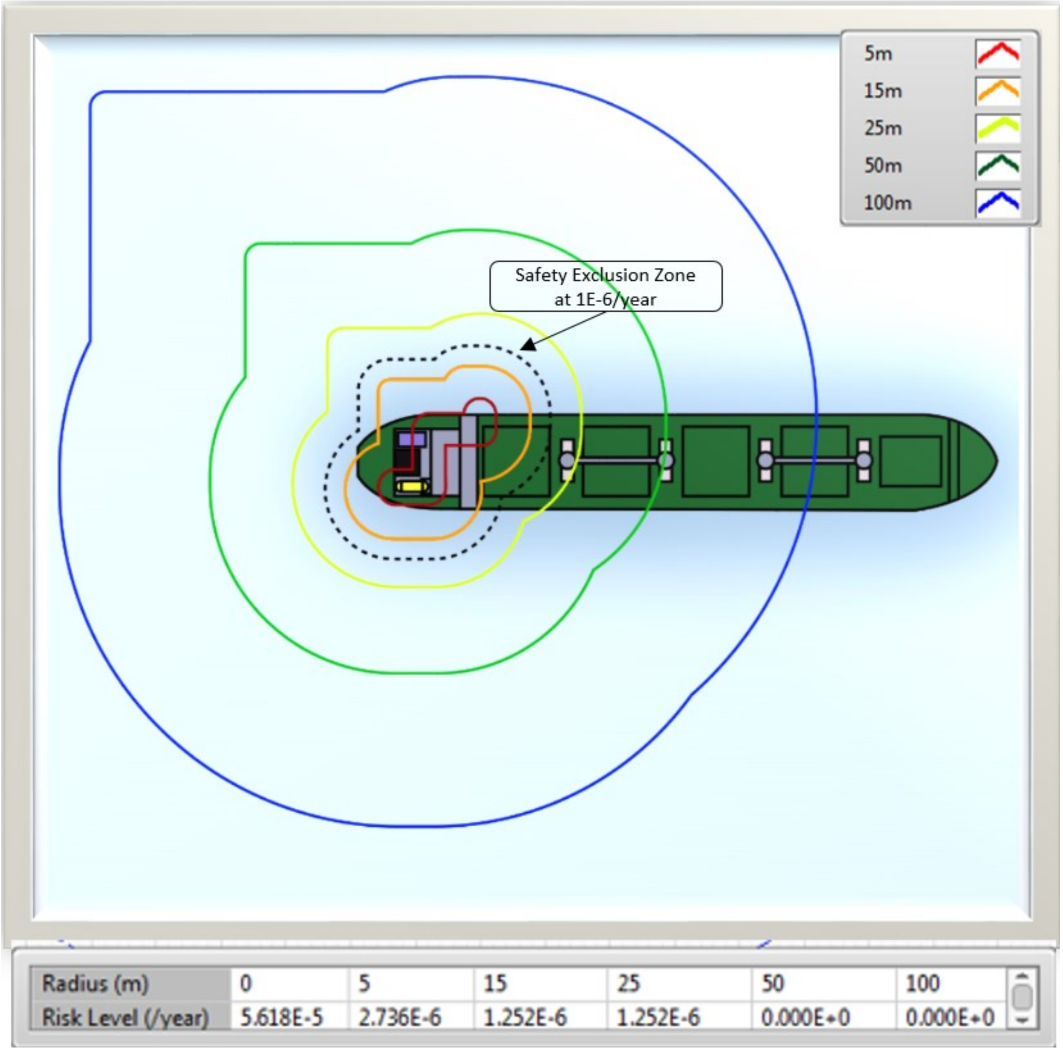

Figure 15 Risk level of safety exclusion zones for Case Ship 2

It was found from this study that the frequency of bunkering is one of the key factors in determining the extent of safety exclusion zone.

In order to evaluate the critical distance for pool fire and explosion, the original study was conducted based on the degree of radiation and overpressure corresponding to 100% fatalities. However, there still may be dangers outside the minimum safety exclusion zone with perhaps less than 100% fatality. For this reason two additional cases of 50% fatality and 10% fatality were also investigated. For radiation, 12.5 kW/m^2 and 5 kW/m^2, and for overpressure, 0.3 bar(g) and 0.1 bar(g) are used for 50% and 10% fatalities, respectively.[42][43]

Table 5 and Figure 16 show the analysis result of alternative cases. The regions shaded with red in Table 5 refer to the safety exclusion zones while the regions with green refer to the acceptable zones. In Figure 16, the horizontal line represents the limit of accident rate (1.0E-6/year) and the accident rates corresponding to each distance are drawn on the figure. It is observed that the application of the lower probability of fatalities resulted in the same safety exclusion zone despite slightly increased limits for both ships.

Table 5 Risk level of safety exclusion zones with respect to probability of fatalities (unit: /year)

Case Ship	Case		Distance (m)						
				Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
			0m	5m	15m	25m	50m	100m	200m
Case Ship 1	Original Case (100% fatalities)		2.85E-06	1.01E-06	6.54E-07	3.63E-07	2.49E-07	1.60E-07	1.32E-07
	Case 1	50% fatalities	2.85E-06	1.01E-06	6.59E-07	5.76E-07	2.66E-07	1.93E-07	1.32E-07
		Difference	0.00%	0.00%	0.76%	58.68%	6.83%	20.63%	0.00%
	Case 2	10% fatalities	2.85E-06	1.01E-06	6.61E-07	5.80E-07	2.70E-07	2.13E-07	1.72E-07
		Difference	0.00%	0.00%	1.07%	59.78%	8.43%	33.13%	30.30%
Case Ship 2	Original Case (100% fatalities)		5.62E-05	2.74E-06	1.25E-06	1.25E-06	0.00E+00	0.00E+00	0.00E+00
	Case 1	50% fatalities	5.62E-05	2.83E-06	1.72E-06	1.57E-06	0.00E+00	0.00E+00	0.00E+00
		Difference	0.00%	3.28%	37.60%	25.60%	-	-	-
	Case 2	10% fatalities	5.62E-05	2.83E-06	1.82E-06	1.72E-06	3.13E-07	0.00E+00	0.00E+00
		Difference	0.00%	3.28%	45.60%	37.60%	-	-	-

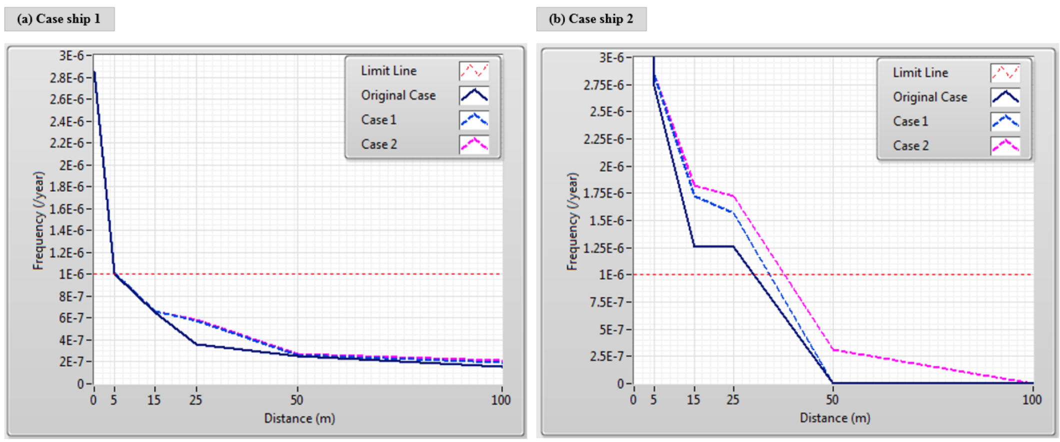

Figure 16 Risk level of safety exclusion zones with respect to probability of fatalities

4.4 Sensitivity Analysis

Since the history of LNG-fuelled ships is too short for any meaningful statistics to be compiled, this case study has relied upon DNV equipment failure frequency database that contains appropriate generic data associated with LNG process equipment in offshore and chemical industries. This generic approach may cause some uncertainties in the results of frequency in a quantitative sense. In this context, a sensitivity analysis was carried out to investigate possible differences due to different data sources. For this purpose, OGP hydrocarbon equipment failure frequency database [46] was used and the results are compared with the original results for the case ships obtained using the DNV source.

In addition, throughout the quantitative risk assessment for LNG bunkering, several parameters were uncertain and/or assumed. One of them was leak duration and it was thought to be important to establish how this parameter would influence the overall results. For this purpose a different scenario of delayed recognition and isolation time of 1,000 seconds combined with the failure of proper watch-keeping was also investigated [15]. To analyse the alternative scenario, a modified event tree is applied as shown in Figure 17.

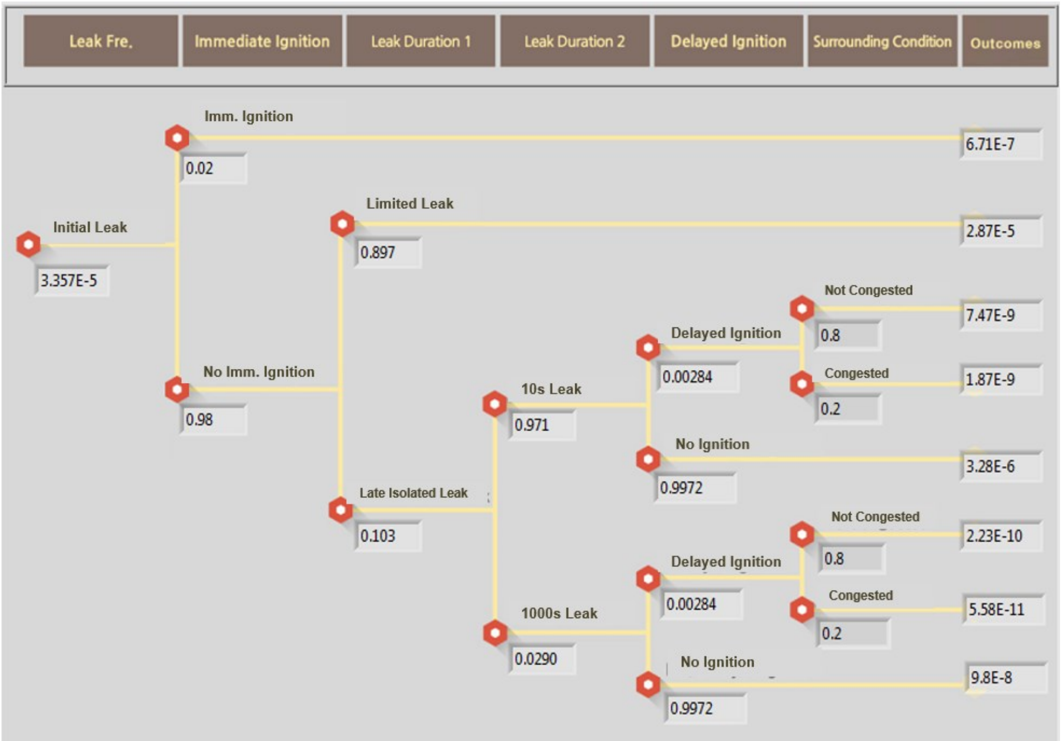

Figure 17 A modified event tree for 3mm leak hole from LNG bunkering main system for Case Ship 1

Table 6 and Figure 18 show the result of the sensitivity analysis. In the case of 10s leak duration for Case Ship 1, the OGP database reduces the minimum safety exclusion zone from Zone 2 to Zone 1 and the maximum difference of the accident rate in Zone 1 (below 5m) between DNV and OGP database is about 10%. Nevertheless, the discrepancy is relatively insignificant.

On the other hand, the scenario of the leak duration for 1,000s has higher accident rates than the original scenario for 10s. However, similar trends are observed between DNV and OGP database, and the differences are also marginal.

The results of sensitivity analysis for Case Ship 2 show relatively high differences between DNV and OGP database with over 50% in Zone 1 for the 10s and 1000s leak duration. Again the DNV database produces higher frequencies than the OGP database. Based on the findings, it can be concluded that the prolonged leak duration up to 1,000s does not appear to influence the extent of safety exclusion zone very much while the selection of leak frequency database does; this can be explained by the fact that, although the impact of each consequence of 1000 seconds leak would be significantly higher than 10 seconds leak, the probability of 1000 seconds leak is far too small to make noticeable difference to the safety exclusion zones for the case ships.

Table 6 Risk level of safety exclusion zones with different scenarios and databases (unit: /year)

Case Ship	Leak Duration	Case	Data Source	Distance (m)						
					Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
				0m	5m	15m	25m	50m	100m	200m
Case Ship 1	10s	Original Case	DNV (/year)	2.85E-06	1.01E-06	6.54E-07	3.63E-07	2.49E-07	1.60E-07	1.32E-07
		Case 1_1	OGP (/year)	2.58E-06	9.54E-07	6.19E-07	3.41E-07	2.03E-07	1.49E-07	1.20E-07

			Difference	-9.47%	-5.54%	-5.35%	-6.06%	-18.47%	-6.88%	-9.09%
	1000s	Case 2_1	DNV (/year)	2.86E-06	1.02E-06	6.69E-07	3.86E-07	2.65E-07	1.74E-07	1.38E-07
			Difference	0.35%	0.66%	2.23%	6.35%	6.33%	8.67%	4.69%
		Case 2_2	OGP (/year)	2.58E-06	9.69E-07	6.34E-07	3.64E-07	2.48E-07	1.63E-07	1.26E-07
			Difference	0.19%	1.59%	2.42%	6.62%	22.39%	9.69%	4.68%
Case Ship 2	10s	Original Case	DNV (/year)	5.62E-05	2.74E-06	1.25E-06	1.25E-06	0.00E+00	0.00E+00	0.00E+00
		Case 1_1	OGP (/year)	2.66E-05	1.30E-06	7.10E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
			Difference	-52.67%	-52.55%	-43.20%	-	-	-	-
	1000s	Case 2_1	DNV (/year)	5.63E-05	3.04E-06	1.54E-06	1.30E-06	9.35E-09	0.00E+00	0.00E+00
			Difference	0.13%	10.81%	23.26%	-	-	-	-
		Case 2_2	OGP (/year)	3.04E-05	1.86E-06	9.95E-07	8.43E-07	6.05E-09	0.00E+00	0.00E+00
			Difference	14.13%	43.24%	40.18%	-	-	-	-

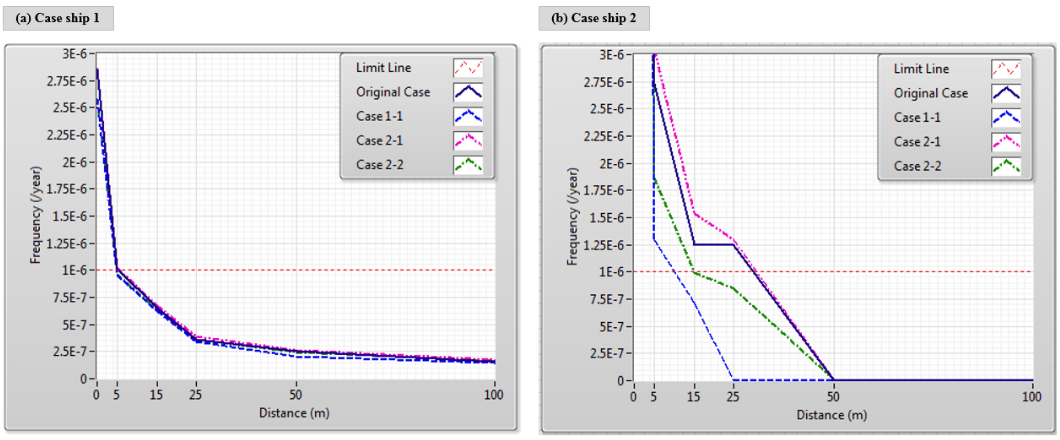

Figure 18 Risk level of safety exclusion zones with different scenarios and databases

It may be recalled that the original study assumed the degree of congestion to be 20%. In order to investigate the influence of this figure, two cases of 50% and 10% 'congested' conditions were investigated.

It is easy to conjecture that a higher congestion ratio increases the likelihood of explosion, but simultaneously reduces the likelihood of flash fire. Since the impact extent a of flash fire is wider than that of an explosion, a high congestion ratio must have lower overall risk as demonstrated by the results in Table 7 and Figure 19. For Case Ship 1, the congestion ratio is not significant while for Case Ship 2, high congestion ratio (50%) reduces the minimum safety exclusion zone. Nevertheless, realistically, the congestion ratio is more likely to be far less than 50%. When applied less congestion ratio (10%), the difference is insignificant for both case ships.

Table 7 Risk level of safety exclusion zones with respect to congestion ratio (unit: /year)

Case Ship	Case		Distance (m)						
			Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	
			0m	5m	15m	25m	50m	100m	200m
Case Ship 1	Original Case (20% congested)		2.85E-06	1.01E-06	6.54E-07	3.63E-07	2.49E-07	1.60E-07	1.32E-07
	Case 1	50% congested	2.85E-06	1.00E-06	6.53E-07	3.42E-07	2.17E-07	9.97E-08	8.26E-08
		Difference	0.00%	-0.99%	-0.15%	-5.79%	-12.85%	-37.69%	-37.42%
	Case 2	10% congested	2.85E-06	1.01E-06	6.54E-07	3.71E-07	2.59E-07	1.80E-07	1.49E-07

		Difference	0.00%	0.00%	0.00%	2.20%	4.02%	12.50%	12.88%
Case Ship 2	Original Case (20% congested)		5.62E-05	2.74E-06	1.25E-06	1.25E-06	0.00E+00	0.00E+00	0.00E+00
	Case 1	50% congested	5.62E-05	2.60E-06	7.83E-07	7.83E-07	0.00E+00	0.00E+00	0.00E+00
		Difference	0.00%	-5.11%	-37.36%	-37.36%	-	-	-
	Case 2	10% congested	5.62E-05	2.78E-06	1.41E-06	1.41E-06	0.00E+00	0.00E+00	0.00E+00
		Difference	0.00%	1.46%	12.80%	12.80%	-	-	-

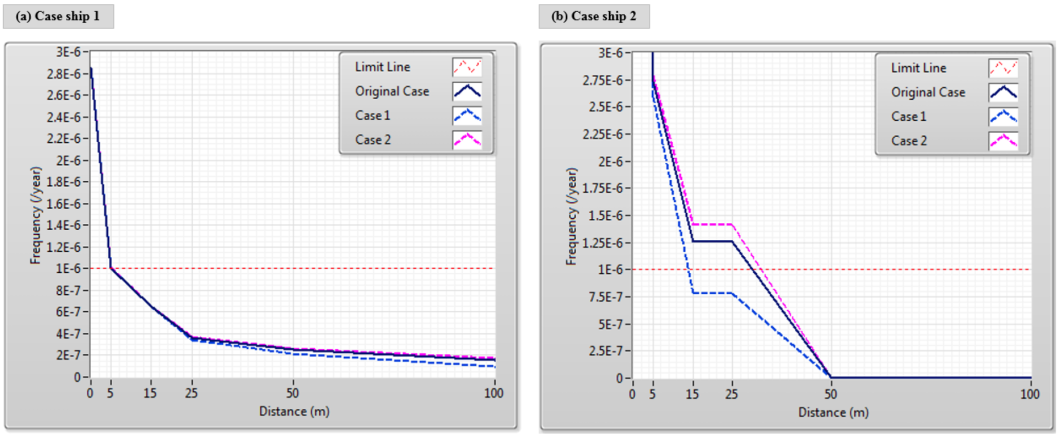

Figure 19 Risk level of safety exclusion zones with respect to congestion ratio

4.5 Parametric Analysis for Flow Rate

A flow rate is determined by the combination of the fluid velocity and the piping size. Where the total amount of the fuel to be transferred is fixed, a higher transfer rate will guarantee the reduction in the total time required for bunkering. Given bunkering time is an important factor which affects the frequency of equipment failure leading to leak, a study was undertaken to investigate how sensitive the safety exclusion zone is to varying velocities and piping sizes.

a) Velocity

Based on the DNV Class guidelines [12], the velocity of LNG transfer should not exceed 10 m/s in order to prevent static electricity from being generated. Accordingly four cases of differing velocities including the original one were compared: 3m/s, 5m/s 8m/s and 10m/s. The amount of LNG fuel to be shipped were kept the same as the original case study, i.e. 10,000 m^3 and 125 m^3 for the Case Ships 1 and 2 respectively. The annual bunkering time with respect to different velocity rates are summarized in Table 8 which highlights significantly reduced annual bunkering times for higher velocities.

Table 8 Annual bunkering time for varying fluid velocity

Case ship	Parameter	Flow Rate (m^3/h)	Annual bunkering time (hours)
Case Ship 1	Case 1 (3m/s)	529.9	108
	Original Case (5m/s)	883.1	65
	Case 2 (8m/s)	1,413.0	41
	Case 3 (10m/s)	1,766.3	32
Case Ship 2	Case 1 (3m/s)	5.3	2,061
	Case 2 (5m/s)	8.8	1,288
	Original Case (8m/s)	14.1	773
	Case 3 (10m/s)	17.7	687

As previously stated, the annual bunkering time is closely related to the frequency of initial leak as the increasing bunkering time leads to a higher probability of equipment failure. The findings of the parametric analysis are illustrated in Table 9 and Figure 20. It is observed that the Case 1 (3 m/s) with the highest annual bunkering times increases the frequency of the accident rate for the both case ships in all zones. As a result, the safety exclusion zone for Case Ship 1 moves up to Zone 3, while Cases 2 (8 m/s) and 3 (10 m/s) move safety exclusion zone down to Zone 1. Similar effects can be observed for Case Ship 2 but the safety exclusion zones remain the same, because the impact of fire and explosions associated with Case Ship 2 do not exceed Zone 4.

Table 9 Result of parametric analysis for velocity (unit: /year)

Case Ship	Case		Distance (m)						
			Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	
			0m	5m	15m	25m	50m	100m	200m
Case Ship 1	Original Case (5m/s)		2.85E-06	1.01E-06	6.54E-07	3.63E-07	2.49E-07	1.60E-07	1.32E-07
	Case 1	3 m/s	4.74E-06	1.67E-06	1.09E-06	6.04E-07	3.58E-07	2.65E-07	2.20E-07
		Difference	66.32%	65.35%	66.67%	66.39%	43.78%	65.63%	66.67%
	Case 2	8 m/s	1.80E-06	6.36E-07	4.13E-07	2.29E-07	1.36E-07	1.01E-07	8.34E-08
		Difference	-36.84%	-37.03%	-36.85%	-36.91%	-45.38%	-36.88%	-36.82%
	Case 3	10 m/s	1.40E-06	4.96E-07	3.22E-07	1.79E-07	1.06E-07	7.86E-08	6.51E-08
		Difference	-50.88%	-50.89%	-50.76%	-50.69%	-57.43%	-50.88%	-50.68%
Case Ship 2	Original Case (8m/s)		5.62E-05	2.74E-06	1.25E-06	1.25E-06	0.00E+00	0.00E+00	0.00E+00
	Case 1	3 m/s	1.50E-04	7.29E-06	3.34E-06	3.34E-06	0.00E+00	0.00E+00	0.00E+00
		Difference	166.90%	166.06%	167.20%	167.20%	-	-	-
	Case 2	5 m/s	9.36E-05	4.56E-06	2.09E-06	2.09E-06	0.00E+00	0.00E+00	0.00E+00
		Difference	66.55%	66.42%	67.20%	67.20%	-	-	-
	Case 3	10 m/s	4.99E-05	2.43E-06	1.11E-06	1.11E-06	0.00E+00	0.00E+00	0.00E+00
		Difference	-11.21%	-11.31%	-11.20%	-11.20%	-	-	-

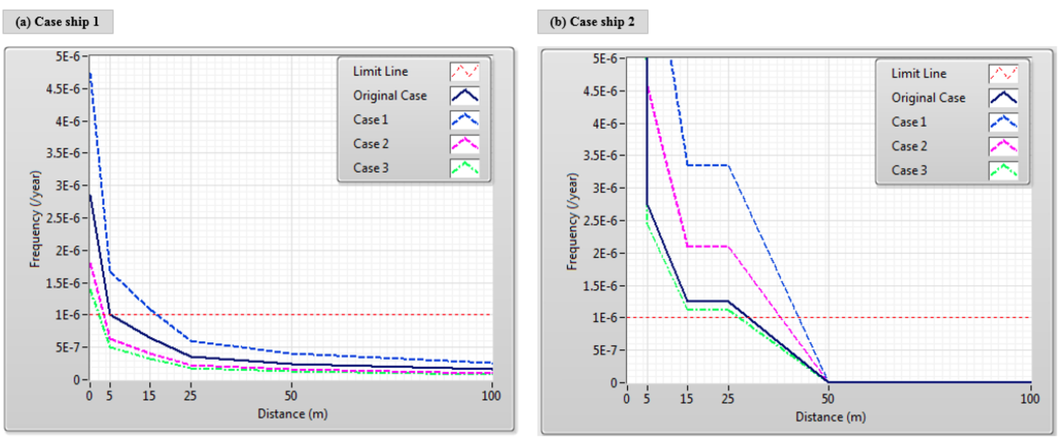

Figure 20 Result of parametric analysis for velocity

b) Pipe Size

The pipe sizes of 250 mm and 25 mm for Case Ships 1 and 2 respectively were chosen during the design stage. However, from the result of parametric analysis with fluid velocity, it can be deduced that similar results will be obtained if the pipe sizes are varied. To verify this, another parametric analysis was conducted using 150 mm, 350 mm and 500 mm pipes for Case Ship 1, and 12.5 mm, 50 mm and 100 mm pipes for Case Ship 2. The flow velocities were kept the same as the original case study, and the consequent annual bunkering time is summarise in Table 10.

Table 10 Annual bunkering time for varying pipe size

Case Ships	Parameter	Flow Rate (m^3/h)	Annual bunkering time (hours)
Case Ship 1	Case 1 (150mm)	317.9	180
	Original Case (250mm)	883.1	65
	Case 2(350mm)	1,730.9	33
	Case 3 (500mm)	3,532.5	16
Case Ship 2	Case 1 (12.5mm)	3.5	3,092
	Original Case (25mm)	14.1	773
	Case 2(50mm)	56.5	258
	Case 3 (100mm)	226.1	86

The bunkering time will obviously affect the failure rate. Moreover, different system size will also have different failure rate in the database. The results of the parametric analysis are summarised in Table 11 and Figure 21. As expected, they show a similar trend with the analysis results of velocity parameters. For Case Ship 1, the reduced system size of 150 mm (Case 1) leads to the safety exclusion zone moving up to Zone 4 while the increased system sizes of 350 mm (Case 2) and 500 mm (Case 3) result in Zone 2. Similar trend and results are observable for Case Ship 2.

Table 11 Result of parametric analysis for piping size (unit: /year)

Case Ship	Case		Distance (m)						
				Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
			0m	5m	15m	25m	50m	100m	200m
Case Ship 1	Original Case (250mm)		2.85E-06	1.01E-06	6.54E-07	3.63E-07	2.49E-07	1.60E-07	1.32E-07
	Case 1	150mm	7.77E-06	2.71E-06	1.75E-06	9.76E-07	6.69E-07	4.28E-07	3.56E-07
		Difference	172.63%	168.32%	167.58%	168.87%	168.67%	167.50%	169.70%
	Case 2	350mm	1.54E-06	5.46E-07	3.54E-07	1.96E-07	1.34E-07	8.61E-08	7.07E-08
		Difference	-45.96%	-45.94%	-45.87%	-46.01%	-46.18%	-46.19%	-46.44%
	Case 3	500mm	8.60E-07	3.09E-07	2.00E-07	1.11E-07	7.53E-08	4.85E-08	3.90E-08
		Difference	-69.82%	-69.41%	-69.42%	-69.42%	-69.76%	-69.69%	-70.45%
Case Ship 2	Original Case (25mm)		5.62E-05	2.74E-06	1.25E-06	1.25E-06	0.00E+00	0.00E+00	0.00E+00
	Case 1	12.5mm	5.46E-04	1.72E-05	4.29E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Difference	871.53%	527.74%	243.20%	-100.00%	-	-	-
	Case 2	50mm	1.34E-05	4.55E-06	8.70E-07	6.96E-07	6.96E-07	0.00E+00	0.00E+00
		Difference	-76.16%	66.06%	-30.40%	-44.32%	-	-	-
	Case 3	100mm	3.90E-06	1.51E-06	4.24E-07	3.96E-07	3.39E-07	2.26E-07	0.00E+00
		Difference	-93.06%	-44.89%	-66.08%	-68.32%	-	-	-

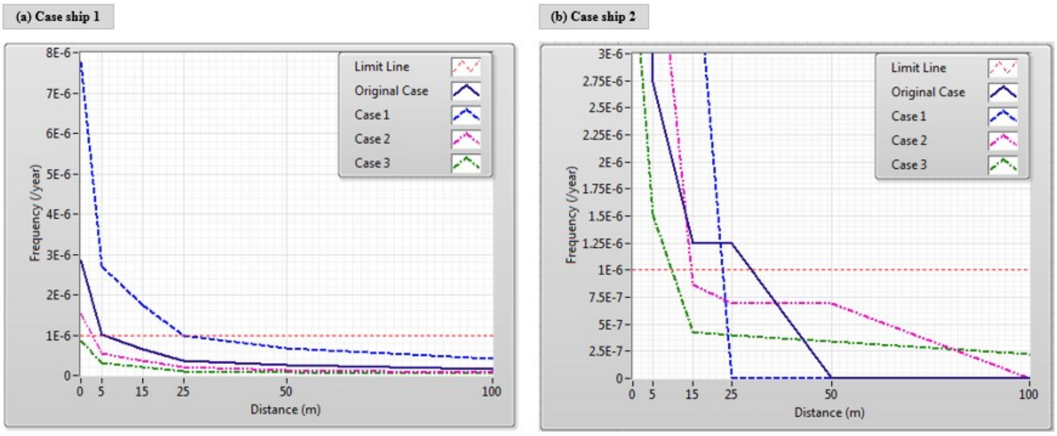

Figure 21 Result of parametric analysis for system size

Since the case ships are constrained on a number of operating issues including voyage profiles, it may be thought that some velocities and system sizes used for the parametric analysis are unrealistic. Nevertheless, the findings of this parametric analysis with varying flow rate helped conclude that bunkering frequency and time taken for the bunkering operations are the key parameters in probabilistically determining the safety exclusion zone. The result indicates that the most important parameter is the total duration of the bunkering operations required. Larger pipes and higher fluid velocity enables higher volumes to be transferred, thereby reducing the bunkering time required.

4.6 Comparison with Deterministic Approach

The deterministic approach of estimating the extent of safety exclusion zone uses a representative risk scenario (worst-case scenario). For Case Ship 1, the highest leak rate when fully ruptured is determined to be 477.9 kg/s from Table 3. As shown in Figure 22, the result of gas dispersion modelling with the software determines the safety exclusion zone at 514 m from the leak origin. This is longer than the ship's length, and is considerably larger than that obtained by the probabilistic approach.

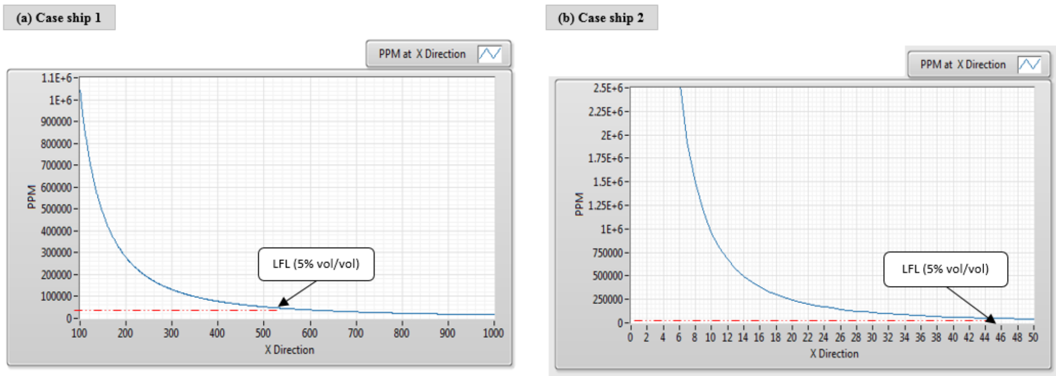

Figure 22 LFL boundary for deterministic approach – PPM over x direction

On the other hand, the maximum leak rate when fully ruptured is about 4.779 kg/s for Case Ship 2 as shown in Table 3. When the gas dispersion model was used, the safety distance became 45m from the leak origin, which is reasonably close to the result obtained from the probabilistic approach.

It is interesting to note that the Port of Gothenburg [44], which presently provides LNG bunkering services, established safety exclusion zones depending on the ship type: 15m for container ships and bulk carriers, 25m for other types of ships. In addition, an LNG bunkering guideline [45] presented in Swedish Marine Technology Forum, the safety exclusion zone was set up 10m for each side of bunkering station for a Ro-Pax vessel.

4.7 Comparison with DNV GL Risk Criteria

The minimum safety exclusion zones were calculated with DNV GL risk criteria (1.0E-6 per bunkering) for comparison with the results obtained from the probabilistic approach of this study. Case Ship 1 has 13 hours of operation time for each bunkering while Case Ship 2 has 9 hours. The annual frequency of bunkering is intentionally ignored, and the unit of frequency is transformed from 'per year' to 'per bunkering'. The analysis results are shown in Table 12 and Figure 23; for both case ships the overall accident rate is beneath the risk criteria.

According to the DNV GL guideline therefore, the safety exclusion zone needs to be set up at the minimum distance of 10 m for both case ships. This result is quite contrasting to the results from the probabilistic approach which produced the safety exclusion zone of 36m radius for Case Ship 2.

Table 12 Analysis results based on DNV GL guideline (unit: /bunkering)

Case ship	Distance (m)						
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	
	0m	5m	15m	25m	50m	100m	200m
Case Ship 1	5.70E-07	2.02E-07	1.31E-07	7.27E-08	4.97E-08	3.19E-08	2.64E-08
Case Ship 2	6.54E-07	3.19E-08	1.46E-08	1.46E-08	0.00E+00	0.00E+00	0.00E+00

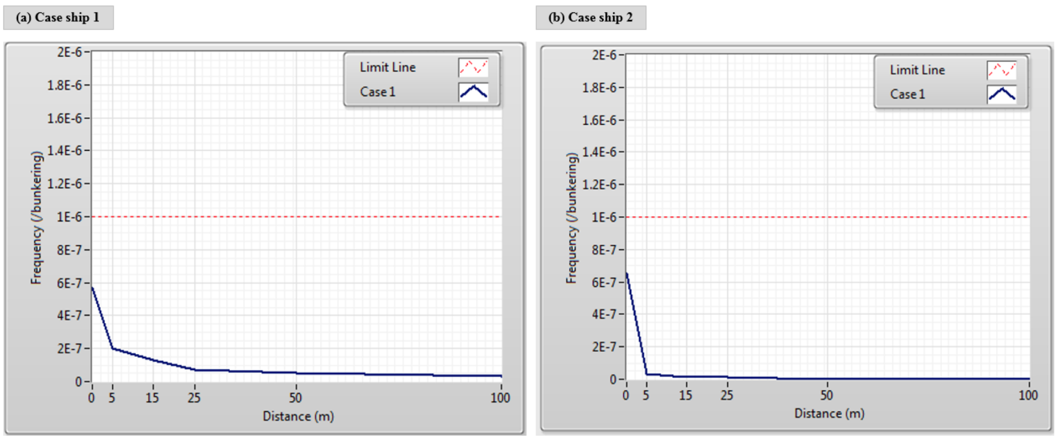

Figure 23 Analysis results based on DNV GL guideline

5 Discussion

The main purpose of this paper is to investigate the adequacy or otherwise of the safety provisions contained in rules and regulations concerning the relatively new practices of using LNG as a fuel for ships. As such, the investigation had to concentrate on typical situations to improve our understanding of where the risk is in LNG bunkering and how to minimise it so that the information generated can be used as a basis for future improvement of rules and standards,

This meant that we were not dealing with specific ships, but rather typical ships. Therefore, the so-called 'state-of-the-art' computational tools, such as CFD, is somewhat unnecessary. On the other hand, it is accepted that the rules and standards may require such tools to be used in establishing a safety exclusion zone while bunkering for each ship. If that is the case, consequence analysis will need to use micro-scale meteorological/geometrical models, since the impact of fires and explosion may be affected by geometry or metrological conditions of sites.

Whilst it is accepted that the LNG leaks during bunkering can occur due to external events, such as collision, excessive (relative) ship motions, extreme and unforeseen weather conditions and human error, they do not help in formulating a generic safety rules. That was why this study focussed on potential accidents associated with equipment failure only. With more experience with LNG bunkering in the future, a more accurate estimation of these factors may become possible in time, but at the present time there is no data, primarily due to the brevity of LNG bunkering history.

An attempt was made to generate additional information and aid general understanding of risks involved in LNG bunkering by carrying our rudimentary parametric analysis. However, it may be necessary to do this in more detail using more extensive ranges of parametric values.

6 Concluding Remarks

Using the IQRA Software, this study investigated the potential risk of LNG bunkering and evaluated the extent of indicative safety exclusion zones for LNG bunkering station for two contrasting case ships - one has low frequency but high consequence of risk while the other has high frequency but low consequence of risk - based on the risk criteria of 1.0E-6 /year. The result of the study shows that the minimum safety exclusion zone is 6.4 m radius, or Zone 2 for Case Ship 1 (high consequence) while 36m radius or Zone 4 for Case Ship 2 (high frequency).

This is opposite to what our common sense tells us, as it is, on the face of it, entirely credible to think that a large scale LNG bunkering (high consequence of risk) needs to have a more extensive safety exclusion zone, compared to small scale LNG bunkering (low consequence of risk). However, the result of this study clearly indicates that bunkering frequency and the total time taken for bunkering operations in a year are the key parameters in determining the risk level of LNG bunkering, while consequence less important. Larger pipes and higher fluid velocity enables higher volumes to be transferred, thereby reducing the bunkering time required.

It is thought that there may be a case for making the relevant rules and regulations more explicit and more stringent. However, as shown through sensitivity and parametric analysis, the overall results of risk assessment for LNG bunkering is influenced by some degree by parameters used in the analysis. It can be concluded, therefore, that the problem requires more extensive studies and discussion to draw a consensus on the standard database and scenarios to be used. It was also found that the safety exclusion zones set up through deterministic approaches may be over-extensive and impractical for large scale LNG bunkering. It is because the deterministic approach is based on the worst case scenario regardless of the likelihood. This problem appears to be overcome through using the probabilistic risk-based approach.

The current DNVGL guidelines specify safety exclusion zones based on risk per bunkering operation. However, the current study showed that this is incomplete as it does not take into account the total time the equipment and the system as a whole is used which governs the frequency of failure. In order to rectify this problem the current paper uses the frequency of failure 'per year'.

For a variety of reasons IMO member states have yet to develop their own explicit regulations concerning safety exclusion zones in LNG bunkering. The present study can therefore be viewed as a contribution towards safer uses of LNG as a marine fuel.

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References

1. ABS, *Bunkering of Liquefied Natural Gas-fueled Marine Vessels in North America,* Houston Texas USA*,* 2014.
2. ISO, *TS 18683: Guidelines for systems and installations for supply of LNG as fuel to ships*, Geneva Switzerland, ISO, 2015.
3. DNV, *Port toolkit risk profile LNG bunkering - Port of Rotterdam, Ministry of Infrastructure & Environment*, Port of Antwerp, Port of Amsterdam and Zeeland Seaport, Oslo Norway, 2012.
4. DNV, *LNG-fuelled fleet as of March 2014*, 2014.
5. Lasse K., *LNG (NG) Fuelled Shipping – Experience and regulations*, Norwegian Maritime Authority, 2015
6. Germany and Norway, *HAZID report*, London, IMO BLG, 2012.
7. ADN Administrative Committee, *Proposed text of a derogation regarding the use of LNG*, Geneva Swithland, ADN Administrative Committee, 2014.
8. ABS, *Bunkering of Liquefied Natural Gas-fuelled Marine Vessels in North America, Houston Taxas*, ABS, 2014.
9. Lee, S. and S. Seo and D. Chang, 'Fire risk comparison of fuel gas supply systems for LNG-fuelled ships', *Natural Gas Science and Engineering*, vol. 27, 2015, p. 1788-1795.
10. Republic of Korea, *Explosion analysis on the bunkering station for the LNG-fuelled ship*, London UK, IMO CCC, 2015.
11. DNV GL, *PP087423-4, Rev 3: Liquefied Natural Gas (LNG) Bunkering Study*, Oslo Norway, DNV GL, 2014.
12. DNV GL, *Recommended practice – DNVGL-RP-0006:2014-01: Development and operation of liquefied natural gas bunkering facilities*, 2014
13. IMO, *MSC/Circ.1023, MEPC/Circ.392: Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-making Process*, London UK, IMO, 2002.
14. Dan, S. et al., 'Quantitative risk analysis of fire and explosion on the top-side LNG-liquefaction process of LNG-FPSO', *Process Safety and Environmental Protection*, vol. 92, 2014, p.430-441.
15. Kletz, T., *An engineer's view of human error, The institution of Chemical Engineers*, 1st edn., Rugby UK, IChemE, 1991.
16. OREDA Participants, *Offshore Reliability Data Volume 1 Topside Equipment*, 5th ed., Trondheim Norway, OREDA participants, 2009.
17. Electric Power Research Institute (EPRI), *Advanced Light Water Reactor Utility Requirements Document (Volume III)*, California USA, EPRI, 1995.
18. Center for Chemical Process Safety of the American Institute of Chemical Engineers (CCPS), *Guidelines for Process Equipment Reliability Data with Data Tables*, New York USA, CCPS, 1989.
19. Cox, A. and F. Lees and M. Ang, *Classification of Hazardous Locations*, Rugby UK, IChemE, 1990.
20. DNV, *failure frequency guidance: Process Equipment Leak Frequency Data for use in QRA*, Oslo Norway, 2012.
21. Crowl, D. A., and J. F. Louvar, *Chemical Process Safety: Fundamentals with Applications*, New Jersey UAS, Prentice Hall, 1990.
22. John L. W. and R. M. Pitblado. *LNG RISK BASED SAFETY Modeling and Consequence Analysis,* New Jersey USA, A John Wiley & Sons, INC, 2010.
23. Briscoe, F., and P.Shaw, 'Spread and Evaporation of Liquid', *Prog. Energy Comb. Sic.*, vol. 6, 1980, p. 127-140
24. Carslaw H.S and Jaeger J.C., *Conduction of heat in solids,* 2nd ed., USA, Oxford University Press, 1986.
25. Klimenko, V. V. 'Film boiling on a horizontal plate - new correlation', *International journal of heat and mass transfer* 24(1), 1981, p. 69-79.

26. Cook, J. and Bahrami, Z and Whitehouse, R. J., ‘A comprehensive program for calculation of flame radiation levels’, *Loss Prevention Process Ind.*, vol. 3, 1990, p. 150.
27. Mannan, S., *Lee's Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control*, 3rd ed, Burlington, MA, Elsevier Butterworth-Heinemann, 2004.
28. Spouge, J., *A guide to Quantitative Risk Assessment for Offshore Installations, Bristol, Center for Marine and Petroleum Technology*, 1999.
29. Tweeddale, M., *Managing Risk and Reliability of Process Plants*, USA, Gulf Professional Publishing, 2003.
30. Perkins, H. C., *Air Pollution: Arizona*, USA, McGRAW-HILL BOOK COMPANY, 1974
31. Briggs, G. A., *Diffusion Estimation for Small Emissions, Atmospheric Turbulence and Diffusion Laboratory*, 1973.
32. Ramiro, J. M. S., and P. A. B. Aisa, *Risk Analysis and Reduction in the Chemical Process Industry, London*, UK, Blackie Academic & Professional, 1998.
33. John L. W. and R. M. Pitblado. *LNG RISK BASED SAFETY Modeling and Consequence Analysis,* New Jersey USA, A John Wiley & Sons, INC, 2010.
34. Frank, T., *Industrial explosion prevention and protection*, New York UAS, Mc Graw-Hill, 1980.
35. Baker, W., *Explosion in Air. Austin*, University of Texas Press, 1973.
36. Timothy, A. and D. Jeffrey, *A Systematic Method for Modelling Explosion Overpressures*, Norman, OK, Quest Consultants Inc, 2007.
37. Thomas, P., *Fire Spread in wooden cribs: Part III The effect of wind, fire research Note Nr. 600, in Fire Research Station*, England UK, Boreham Wods, 1965.
38. Nedelka, D., J. Moorehouse and R.F. Tucker, *The Montoir 35 m Diameter LNG Pool Fire Experiments*, Nice France, 1989.
39. Hoftijzer, G. W., *Heat radiation, in Methods for the Calculation of the Physical Effects of the Escape of Dangerous Material (Liquid and Gases),* KH Vooburg, the Netherlands, Directorate General of Labour, 1979.
40. KR, *LNG Fuel-Ready Ship For VLOC*, Busan South Korea, KR, 2015.
41. KR, *LNG Fuel-Ready Ship For 32K bulk carrier*, Busan South Korea, KR, 2016.
42. CCPS, *Guideline for Chemical Process Quantitative Risk Analysis*, 2nd ed, New York USA, Wiley-AlChe, 1999.
43. OGP, *Report No.434-14.1: Risk Assessment Data Directory – Vulnerability of humans*, 2010
44. Port of Gothenburg, *LNG operating regulations including LNG bunkering*, 2015
45. Linde Cryo AB. et al, ‘LNG ship to ship bunkering procedure’, *Swedish Marine Technology Forum*, Uddevalla, 2010
46. OGP, *Report No.434-1: Risk Assessment Data Directory – Process release frequencies*, 2010