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Risk Assessment for Ship-to-ship LNG Bunkering

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In this paper risk assessment for ship to ship LNG bunkering is carried out by exploiting the results of the projects "Risk management system for design and operation of installations for LNG refuelling" (TRiTON) financed by the Greek government, and the "SUstainability PERformance of LNG-based maritime mobility – Plus" (SUPER-LNG PLUS) financed by Interreg-Adrion. Ship to ship bunkering constitutes a simple method when it is difficult to install new storage tanks in the port areas. In brief, risk assessment is conducted including five basic steps: a) hazard identification, b) accident sequence modeling and quantification, c) damage states identification, d) consequence assessment, and e) risk evaluation. First, the Master Logic Diagram (MLD) technique is used to identify the initial events that create a disturbance in the installation and may lead to an LNG release. Corrosion in tanks, pipelines and other parts, and excess external heat owing to a nearby external fire are some of the identified initial events. Moreover, safety functions and systems for preventing LNG release, such as emergency shut-down and pressure safety valves, are identified. Event trees are developed to describe the accident sequence from the initial event occurrence until the LNG release and define the final damage states. By exploiting available failure rate data, the frequency of each damage state is estimated. In parallel, the consequences of LNG release are assessed on the basis of the heat radiation or overpressure dose an individual receives. Finally, risk is calculated by combining the frequencies of the various damage states with the corresponding consequences. A case study for a Greek port is, herein, presented.

1. Introduction

Over the last few years there has been an increased demand of liquefied natural gas (LNG) as a marine fuel owning to the requirements for compliance with the international maritime legislation regarding the reduction of hazardous gas emissions (IMO, 2011). In order to enhance the use of LNG in the marine sector, specially designed port installations have been established worldwide providing some or all of the key bunkering methods; namely tank to ship, truck to ship, and ship to ship (Aneziris et al., 2020). Currently, Greece is examining the potential of implementing such port facilities, so as to contribute to the reduction of hazardous emissions from the shipping industry. Competent authorities and relevant stakeholders suggest the application of small-scale LNG bunkering stations providing effective bunkering solutions with the use of trucks, storage tanks or bunker ships. This paper focuses on the ship to ship bunkering method, proposed in several ports.

Ship to ship bunkering constitutes a favorable bunkering method for ports serving small to very large capacity ships with a short stay in the port, allowing also the simultaneous cargo or passengers handling (e.g. linear ships and ferries). In addition, it is a rational alternative for ports where fixed installations are prohibited or not preferred. Depending upon the port authority, ship to ship bunkering is allowed to take place either at pier or at anchorage on open sea. In both cases, a bunker ship is moored alongside the LNG fueled ship, is connected via flexible hoses or fixed arms and provides LNG to the LNG fueled ship.

A bunker ship is actually an LNG tanker obliged to comply with the International Maritime Organization (IMO) safety requirements, as defined in the international code for the construction and equipment of ships carrying liquefied gases in bulk (IGC Code) (IMO, 2014). A typical capacity of a bunker ship is 500 to 20,000 m^3 (Fluxys, 2012). When larger quantities of LNG are required, a feeder ship rather than bunker ship may be used. In case of small-scale installations, small bunker ships with a capacity of up to 3,000 m^3 may be typically applied. On the other hand, the LNG fueled ship can be any type of ship, including passenger ship, bulk carrier, containership, tanker and others. This ship shall comply with the provisions of the specially designed

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international code of safety for ships using gases or other low-flashpoint fuel (IGF code) (IMO, 2015). The LNG fueled ship typically carries one or more LNG fuel tanks reaching a total capacity of 50 to 20,000 m^3 depending on its size and therefore its type.

However, the presence of LNG in port areas poses risk, since a possible release and ignition of LNG is capable of adversely affecting both the facilities and the exposed people. For ensuring safety of LNG at ports, risk assessment should be performed as required by the IGF code (IMO, 2015). For enhancing and assisting implementation of risk assessment, various organizations have published useful guidelines; a comprehensive overview is presented by Aneziris et al. (2021). In addition, remarkable research has been conducted to develop and perform risk assessment in port infrastructures handling LNG. Zhang (2009) developed a quantitative risk assessment method for assessing risk of LNG tanks operating close to ports concluding that risk of LNG transportation was acceptable. Fu et al. (2016) performed an event tree analysis to investigate the hazards and the potential consequences and performed a computational fluid dynamics (CFD) simulation to quantify the risk of LNG leakage on a LNG fueled ship. Jeong et al. (2017, 2018) presented a quantitative method for demonstrating risk via F-N curves, estimating tolerable risk and determining safe exclusion zones for LNG bunkering operations for the three bunkering methods. Ovidi et al. (2018) developed risk matrix approach to assess the level of risk of LNG carriers approaching a bunkering terminal through port channels located in an industrial area. Within the published literature, limited analysis for ship to ship bunkering has been performed, as the hazard analysis for ship to ship LNG transfer by Sultana et al (2019). The current paper aims at performing a risk assessment for ship to ship bunkering in Greek ports.

The remaining of the paper is structured as follows. Section 2 describes the advocated risk assessment methodology and comprehensively analyses the major steps. Section 3 describes the case study and performs risk assessment for ship to ship LNG bunkering. Finally, section 4 presents the conclusions of this research.

2. Risk assessment methodology

LNG constitutes a hazardous substance consisting of a mixture of hydrocarbon gases, mainly methane (87–99 mol%), ethane (0.1–5.5 mol%), and propane (0–4 mol%) (Mokhatab et al., 2014). It is a natural gas that is cooled down to -162 °C in order to reduce its volume, thus facilitating its transport and storage as well. The accidental release of such a hazardous substance during the ship to ship bunkering process may pose significant risk leading to unintended consequences. This can occur in the following way: a) an initiating event occurs, as for instance leakage or external fire, that disrupts the normal bunkering operation; b) series of failures deactivate one or more existing safety systems preventing the release of LNG and c) LNG is released to the environment and may be ignited either immediately or after a delay, therefore causing undesirable consequences to the public. The probability of an LNG release and resulting consequences can be quantified by implementing risk assessment models. The quantitative methodology developed by Papazoglou et al. (1992) is utilized to conduct integrated risk assessment for ship to ship LNG bunkering. The key phases of this methodology are briefly presented in the next sections.

2.1 Phase I: damage states assessment

The first phase involves the assessment of damage states and their frequency of occurrence. As a matter of fact, the LNG port facility is thoroughly analyzed to identify potential initial events that may cause LNG accidental release and a Master Logic Diagram (MLD) is developed to determine all the initiators of potential accidents (Papazoglou and Aneziris, 2003). Next, Event Trees are constructed to describe specific accident sequences contributing to detect the damage states and prevent LNG release to the environment. These trees encompass the initial event identification, system failures and success, and human responses as well. Accident sequences that deduce similar release conditions are grouped into one damage state. Finally, systems failures in terms of basic component failures and human errors, and accident sequences are modelled. Frequencies of accident sequences and plant damage states are calculated with the aid of the Fault Tree- Event Tree analysis.

2.2 Phase II: consequences assessment

The second phase comprises the assessment of the consequences owning to the release of flammable LNG. First, all the types of physical phenomenon, such as pool fire, jet fire, flash fire or vapor cloud explosion, that may result in fatalities are determined. Assuming the LNG release and the associated physical phenomenon, the heat radiation or the peak overpressure is calculated. The calculation is achieved by using specially designed simulation models, as those developed by Papazoglou et al. (1996). Heat radiation and overpressure are integrated over time, so as to assess the dose of an individual to the hazardous LNG substance. Appropriate dose/response models are exploited to eventually estimate the probability of fatality of an individual receiving the assessed dose.

2.3 Phase III: risk integration

The third phase involves the integration of the results obtained so far. Indeed, the frequencies of the various damage states are combined with the corresponding consequences resulting in the quantified risk. Risk can be expressed by means of individual fatality at a specific location or group fatality in a given area.

3. Case study

3.1 General information

The case study examines the safety during LNG bunkering of a passenger ship, namely the LNG fueled ship, from a bunker ship. The passenger ship is equipped with two Type C storage tanks with a capacity to carry a total 800 m^3 LNG fuel and it is able to maintain LNG at pressure 4 bar. The bunker ship has a similar tank capable of carrying up to 3,000 m^3. In order to proceed with the bunkering operations, the passenger ship is moored at the pier, the bunker ship moors alongside, and the tank is loaded through 2 hoses with a diameter 4" at a rate 400 m^3/h. For handling emergency situations, an automatic Emergency Shut Down system (ESD) exists on both ships, and an emergency release system (ERS) is installed on the bunker ship for the release of the transfer hose and arm within a short time, thus minimizing LNG leakage.

3.2 Initial events identification

In the first phase of the risk assessment, two MLDs are constructed to determine the initial events that are likely to occur during ship to ship bunkering: one for the bunker ship, and one for the fueled ship. In brief, MLDs initiate with the top event "Loss of Containment" which is decomposed into the events required to occur for producing this top event. Loss of containment indicates the discontinuity or loss of the pressure boundary between the LNG and the environment, resulting in the release of LNG. Figure 1 presents the MLD developed for the bunker ship. As shown, there are two major categories of events leading to loss of containment: those resulting into a structural failure of the containment and those resulting into containment bypassing because of an inadvertent opening or an engineered discontinuity in the containment (e.g. valves). Loss of containment due to tank structural failure may be caused by corrosion, overpressure, high temperature, vibration, or external loading. Overpressure may be caused due to internal pressure increase. Internal pressure increase may be caused by inadequate purging, boil off gas removal malfunction or excess external heat. External loading may be achieved in the next two ways: a) natural phenomena such as high winds, earthquake, and tsunami, or extra loads owing to collision between the two ships, contact with large objects such as cranes, mooring line failure, or poor ballast. On the other hand, loss of containment resulting in a bypass of the containment may be caused either because operations start while the containment is open or because the latter is opened during operations. In addition, in case of the fueled ship tank, overfilling might further occur. Table 1 presents the list of the initial events, the identified damage states, and the LNG release quantities for the ship to ship bunkering of the case study.

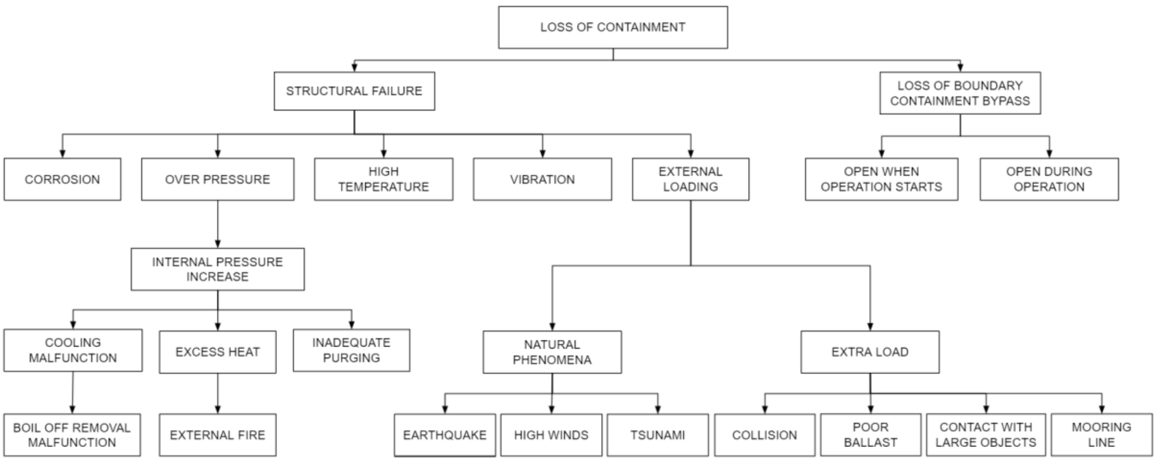

Figure 1: MLD for the bunker ship during ship to ship bunkering operations.

Table 1: List of the initial events, the identified damage states, and the LNG release quantities for the case study dedicated to ship to ship bunkering

Initial event	**Damage state**	**Bunker ship Release quantity**	**Fueled ship Release quantity**
Corrosion	Tank hole resulting in LNG leakage	Rate depends on hole diameter	Rate depends on hole size
High Temperature	Tank rupture resulting in LNG release	3000 m^3	400 m^3
Inadequate purging of loading arm pipes	Hose rupture resulting in LNG release	Release of LNG quantity in pipe	-
Overfilling	LNG release	-	400 m^3
Boil off removal malfunction	Tank rupture resulting in LNG release	3,000 m^3	400 m^3
Excess heat during unloading	Tank rupture resulting in LNG release	3,000 m^3	400 m^3
Vibration	Tank rupture	3,000 m^3	400 m^3
High winds, earthquake, tsunami,	Hose rupture resulting in LNG release	400 m^3/h	400 m^3/h
Collision	Tank rupture resulting in LNG release	3,000 m^3	400 m^3
Contact with objects	Tank rupture resulting in LNG release	3,000 m^3	400 m^3
Poor ballast	Hose rupture resulting in LNG release	400 m^3/h	400 m^3/h
Mooring line	Hose rupture resulting in LNG release	400 m^3/h	400 m^3/h
Valve closure after pumps	Hose failure resulting in LNG release	400 m^3/h	400 m^3/h
Valve left open before unloading starts	Hose failure resulting in LNG release	400 m^3/h	400 m^3/h

3.3 Major accident scenarios

Once the list of the initial events has been assembled the safety functions and the systems that serve these functions are determined. Safety functions are combinations of engineering systems and human actions aiming at mitigating the possible consequences of the initial events. The safety systems, or similarly frontline systems, are used to construct accident sequences that describe how the occurrence of an initial event, and the failure of safety systems result in the final damage state and the release of LNG. Accident sequences are graphically represented through Event Trees and their frequency of occurrence is calculated by using Fault Tree and Event Tree analyses, or previously calculated and reported frequencies. Accident sequences are constructed for the following six identified initial events: a) boil off removal malfunction during loading, b) overfilling of the tank of the fueled ship, c) inadvertent valve closure during loading, d) external fire on either ship, e) extra load in tank (collision, grounding, poor ballast, mooring line) and f) extra load in hose (earthquake, tsunami, high winds). Figure 2 presents the accident sequence for the initial event “mooring line failure”. As shown, the first action is to keep the ships at a safe distance and position by applying appropriate maneuvers from the bunker ship. The next action is to manually stop the send out and to automatically activate the ESD system to successfully end the process. In case that all these actions fail, the hose fails and LNG is released to the environment.

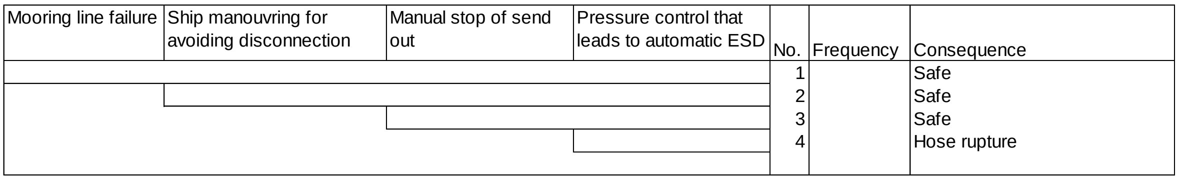

Figure 2: Event tree for the initial event “mooring line failure”.

3.4 Consequences quantification

Once the accident occurs, LNG is released during the two possible situations: a) immediate ignition occurs at the time of the release thus either a fireball, or a pool fire, or a jet fire will take place, and b) an immediate ignition will not occur at the time of the release thus LNG will evaporate, spread and eventually form a vapor cloud dispersing into the atmosphere that may result in flash fire or vapor cloud explosion if ignited. Figure 3 illustrates the possible paths, owning to LNG hose rupture. A number of accident sequences could result in case of hose rupture connecting the LNG bunker ship to the fueled ship. For this damage state, it is assumed that LNG is released at the unloading rate of 400 m^3/h for ten minutes. In case of hose rupture, an LNG release can result in either immediate ignition that will cause a pool or jet fire, or in delayed ignition whereby LNG will vaporize at a rate equal to the release rate and will produce a cloud denser than air spreading according to the weather conditions. If the cloud reaches concentrations between the upper and lower flammability level (5-15% by volume), the mixture can be ignited upon contact with an ignition source giving rise to either a flash fire or an explosion. Similar trees are developed for all the identified damage states. Table 2 presents the frequency of release events and the quantity released for all damage states. Subsequently, heat radiation or peak overpressure resulting from each release category is assessed for determining the dose that an individual will receive and their probability of fatality.

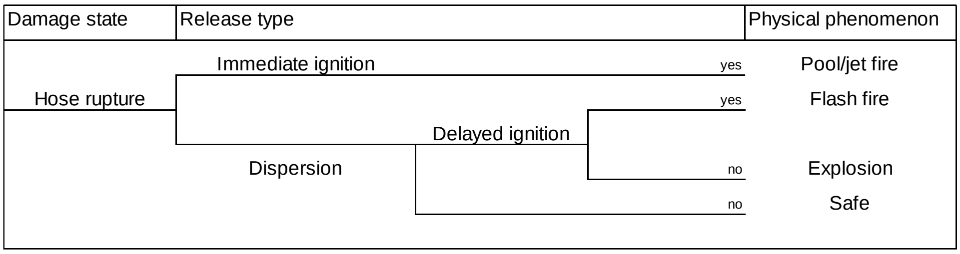

Figure 3: Event tree for the LNG release owning to hose rupture.

Table 2: Frequency of all damage states and release quantity or rate.

Damage state	Frequency (events/year)	Released quantity or rate
LNG fueled ship's tank rupture owning to overpressure/ overfilling	5 10^{-7} (RIVM, 2009)	400 m^3
BLEVE of fueled ship's tank	1 10^{-5} (HSE, 2019)	400 m^3
Bunker ship's tank rupture owning to overpressure	5 10^{-7} (RIVM, 2009)	3,000 m^3
BLEVE of bunker ship's tank	1 10^{-5} (HSE, 2019)	3,000 m^3
Hose rupture during bunkering	4 10^{-4} (RIVM, 2009)	400 m^3/h

3.5 Risk estimation

The final procedural step of the risk quantification is the integration of the results obtained in the various tasks that combines the frequencies of the various accidents with the corresponding consequences resulting in the quantification of risk, and the overall risk estimation. The measure used for risk quantification is the individual fatality risk at a location. This integration can be achieved with the help of computational tools. The SOCRATES (Papazoglou et. al, 1996) package has been used in this analysis. Table 3 presents all types of releases considered and the distances where conditional risk is equal to 1 10^{-2}. Accidents with the most serious consequences are: a) BLEVE of LNG bunker ship tank (3000 m^3) and rupture of the same tank followed by delayed ignition, and b) flash fire of the vapours contained in the tank.

Table 3: Distances where conditional risk is equal 1x10^{-2}.

Damage state	Distance in meters
LNG fueled ship's tank rupture and flash fire	170
LNG fueled ship's tank rupture and explosion	100
BLEVE of fueled ship's tank	170
Bunker ship's tank rupture and flash fire	800
Bunker ship's tank rupture and explosion	380
BLEVE of bunker ship's tank	1300
Hose rupture during bunkering and jet fire	70
Hose rupture during bunkering and flash fire	110
Hose rupture during bunkering and explosion	50

4. Conclusions

In the present paper the Quantitative Risk Assessment (QRA) methodology and models have been implemented in the studying of LNG ship to ship bunkering in a Greek port. The probability of an LNG release and the resulting consequences have been quantified by implementing risk assessment models. For the purpose of the present paper, the QRA methodology is utilized to conduct an integrated risk assessment for ship to ship LNG bunkering. The results obtained include the identification of the initiating events that can cause accidental scenarios together with the determination of accident sequences and damage states. Consequences of flammable LNG have been assessed and radiation and peak overpressure distances have been calculated; individual risk in the port area from the operation of the LNG storage facilities has also been assessed according to the procedures and assumptions presented in the main body of the paper. Total individual risk independent of all damage states has been assessed for the LNG ship to ship transfer and is equal to 10^{-5}, 10^{-6}/yr at a distance of 500 and 1000m respectively from the ships with the major contributors to be the accident scenarios for the LNG bunker ship releases.

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