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Quantitative risk assessment on loading and unloading ships exclusively carrying LNG tank containers

Qing Xia[a], Hui Song[*,b]

China Waterborne Transport Research Institute Beijing, China

[a]e-mail: xiaqing@wti.ac.cn, [b]e-mail: songhui2014@wti.ac.cn

Abstract. Quantitative risk assessment (QRA) on protocol that allows maximum 96 40ft heavy LNG containers carried by a single ship in a dock was performed using applications EFFECTS and RISKCURVES, to investigate the hazard while loading and unloading ships exclusively carrying liquefied natural gas (LNG) tank containers in a dock. Through analyzing typical accident scenarios, the simulation predicted the range of the accident impact. Individual and social risk levels during loading and unloading were calculated to determine the hazard level while loading and unloading ships exclusively carrying LNG tank containers. The results show that the individual and social risk levels while loading and unloading ships exclusively carrying LNG tank containers are acceptable and meet the requirement of existing regulations.

Keywords: exclusively carry, LNG tank container, loading and unloading in dock, quantitative risk assessment

1. Introduction

LNG tank containers are great supplement to traditional liquefied natural gas (LNG) industry, and their transportation is integrated with storage and can be done via water or land. The transportation is characterized by large quantity, long distance, wide coverage and long storage time. It delivers to end users in a door-to-door way and may even supply areas that natural gas pipeline network cannot reach. LNG tank containers will be an important measure to guarantee the national economy and people's livelihood and national energy security, and further secure China's natural gas supply.

To ensure the security in transporting LNG tank containers, the Ministry of Transport of the People's Republic of China issued the Regulations on Safe Transportation of Ships Exclusively Carrying Mobile Tank Containers of Liquefied Natural Gas on July 2nd, 2020. The Regulations specified requirements on safety supervision. Ship exclusively carrying LNG tank containers is defined in the Regulations as: i. ships carrying only LNG tank containers; ii. a ship carrying both LNG tank containers and other cargos, among them the quantity of LNG tank containers (as measured in standard container) exceeds 50% of the deck cargo capacity of the ship, or ≧ 100 LNG tank containers by sea or ≧ 50 by inland river.

The capability of the simulated dock and ship allows maximum 96 40ft heavy containers to be shipped out by a single ship. Since there is no approved container yard for hazardous cargo in the dock, LNG tank container must be loaded and unloaded directly. When LNG tank containers enter the port, their temperature should be ≦ -100 ºC and pressure should be < 0.3 MPa, and maximum 2 LNG tank container transporting trucks should present in the port area simultaneously. After LNG tank containers are loaded on ship, the hazard level increases since multiple hazardous goods are transported together. To determine if the hazard of the protocol described above is acceptable, quantitative risk assessment on loading and unloading operations of a ship exclusively carrying LNG tank containers in the dock was carried out in this study.

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2. Assessment model and method

2.1 Tank container data

LNG tank container is transporting equipment consisting of frame and vacuum multi-layer insulation tanks intended for low temperature liquid. Its data is given in Table 1.

Table 1 LNG tank container data

Projects	Inner container	Outer container
Effective volume (m^3)	40	10.2 (interlayer)
Maximum design pressure (MPa)	0.87	-0.1 (external pressure)
Maximum working pressure (MPa)	0.7	＞ -0.1 (external pressure)
Minimum design temperature (ºC)	-196	50
Working temperature (ºC)	-162 - 50	Room temperature
Body material	0Cr18Ni9	16MnR
Insulation	vacuum multi-layer insulation	
Nominal filling rate	90%	
Liquid tube diameter	50 mm	

2.2 Meteorological data and population

The meteorological data for quantitative risk assessment include typical Pasquill stability of the wind speed, incidence of the wind speed, and probability of the wind direction. Typical meteorological conditions of the area are as following. The average temperature in several years is 24.7 ºC, the atmospheric pressure is 101.3 kPa, and the relative humidity is 82%. The atmospheric stability is class F with a wind speed of 1.5 m/s and normal wind direction being east by north east (ENE).

There are villages and communities, industries, restaurants and a night market in the vicinity of the dock project, and the whole area is intensively populated, as can be seen in Table 2. Employees of this project such as gate operators, container truck drivers and safety management are active risk takers and not included in the risk calculation.

Table 2 Population in the vicinity

Direction	Surrounding places/area	Population		Distance (m)
		Day	Night	
W	Villages	300	600	566
N	Office building 1	80	10	340
NE	Freezing factory	5	1	25
NE	Port office	40	10	100
NE	Warehouse	20	5	119
NE	Restaurants	20	60	250
NE	Night market	50	200	425
NE	Office building 2	110	20	500
NE	Shops	100	200	427
NE	Community 1	1500	3227	431
NE	Community 2	250	562	407
E	Repair workshop	20	5	450

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2.3 Accident consequence analysis

The main component of LNG is methane, which is characterized by flammability, explosion, and rapid phase change, and the explosive limit is 4.8-13.4%. In LNG fire disaster, the flame spreads very fast and has high temperature, the mass burning rate is high, and there is strong radiant heat. Therefore, it is prone to cause massive fire with potential re-ignition and re-explosion, and the fire is difficult to extinguish [1][2].

According to the working parameters of LNG tank containers, they have certain level of vapor pressure during normal transportation. Therefore, under the critical condition acceptable to the dock, i.e. the vapor pressure is around 0.3 MPa, the temperature of the LNG is approximately -146.5 ºC. Once loss of containment (LOC) happens, combustible gas vapor cloud or LNG liquid pool will form depending on the leakage scale. As the ignition condition and degree of space obstruction vary, different types of accident may occur [3]:

a. In case of continuous leakage, immediate ignition will lead to jet fire, and delayed ignition will cause vapor cloud explosion or flash fire depending on the degree of space obstruction. If there is no ignition, the gas will gradually dissipate.

b. If leakage happens instantaneously, immediate ignition will cause boiling liquid expanding vapor explosion (BLEVE) and fireball, whereas delayed ignition will result in vapor cloud explosion or flash fire depending on the degree of space obstruction. If there is no ignition, the gas will gradually dissipate.

c. During leakage, cloud may form droplets and pool may appear on the ground. Early or late pool fire may break out depending on ignition time.

A BLEVE scenario may be, when a tank container catches fire, it may heat the adjacent tank container and cause BLEVE.

2.4 Loss of containment event and incident

As suggested by Guidelines for Quantitative Risk Assessment [4], taking consideration of catastrophic rupture of LNG tankers, liquid phase tanker breakage, and 200 mm aperture leakage caused by collision or other reasons, the LOC scenarios are defined in Table 3.

Table 3 Loc Scenarios And Incidences

Scenario	Leaking point	Situation	Leaking type	Outcome	Probability
LOC-1	Tank body	Catastrophic failure (complete rupture)	Instant leakage	Pool fire, BLEVE, vapor cloud explosion	5×10^{-7}
LOC-2	Liquid phase tube	Breaking (50 mm aperture breakage)	Continuous leaking in 10 min	Jet fire, vapor cloud explosion	5×10^{-7}
LOC-3	Tank body	200 mm aperture breakage	Continuous leaking till empty tank container	Jet fire, vapor cloud explosion	5×10^{-7}

2.5 QRA methods and risk acceptance criteria

Applications EFFECTS and RISKCURVES developed by the Netherlands Organization for Applied Scientific Research (TNO) were used for QRA and plotting the individual risk contour and social risk curve. EFFECTS was used to calculate and simulate the physical influence of leakage, and RISKCURVES was applied for individual and social risk assessment.

According to Chinese national standard GB 36894-2018, Risk criteria for hazardous chemical production unit and storage installations [5], the criteria for individual risks of highly sensitive

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protected targets, important protected targets and general protected targets are listed in Table 4, and the tolerable social risk can be seen in Figure 1.

The ALARP (as low as reasonably possible) principle was used as the acceptable principle for social risk criterion. The ALARP principle divides risk into 3 regions by two risk margins, namely the unacceptable region, the ALARP region and the broadly acceptable region.

a. If the social risk curve enters the unacceptable region, safety improvement measures should be taken immediately to reduce social risk.

b. If the social risk curve enters the ALARP region, all possible safety improvement measures should be taken to reduce social risk within the achievable range.

c. If the social risk curve entirely falls into the broadly acceptable region, the risk is acceptable.

Table 4 Individual risk criteria

Newly built hazardous chemical production unit and storage installations	Individual risk criteria /(incidence/year)
1. Highly sensitive protected targets, including cultural centers, colleges and universities, medical facilities, welfare facilities, etc. 2. Important protected targets, including public libraries, museums, etc. 3. General protected targets (class I, such as rural settlements, tall residential buildings, etc.)	$\leq 3\times10^{-7}$
General protected targets (class II, such as residence with less than 100 residents, office building, etc.)	$\leq 3\times10^{-6}$
General protected targets (class III, such as residence with less than 30 residents, industrial office building with less than 100 employees)	$\leq 1\times10^{-5}$

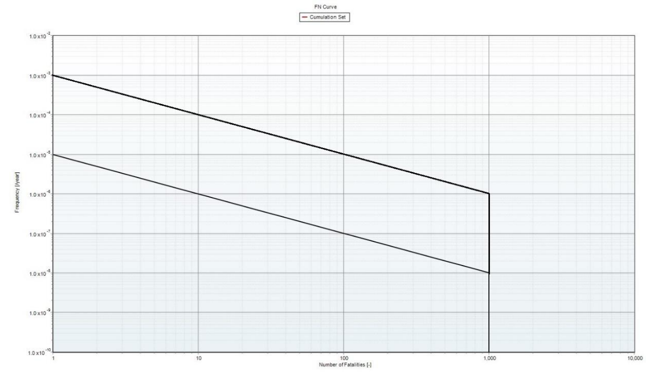

Figure 1. Social risk criteria

3. Risk calculation and analysis

3.1 Accident outcome simulation and analysis

(1) Range of leakage diffusion

The longest distance the flammable vapor resulted by leakage can spread is listed in Table 5. Under the influence of the wind, the hazardous area after LNG leakage is a roughly oval-shaped area in the downwind direction. When the vapor concentration is in the range of flammable or explosive limits, it will burn or explode in case of fire (deflagration).

Table 5 The diffusion range of flammable vapor

LOC		LOC-1	LOC-2	LOC-3
Downwind diffusion range (m)	LFL	84	18	157
	UFL	114	58	245

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(2) Range of fire impact

The thermal radiation damage range determined by fire and explosion simulation can be seen in Table 6. Once fire breaks out, personnel, equipment and facility getting into contact with fire will obviously first suffer from deadly injury or disastrous damage. Secondly, those in the vicinity will suffer from certain degree of thermal radiation hazard from the flame.

Table 6 Range of thermal radiation impact

Thermal radiation (kW/m^2)	The largest downwind distance (m)			
	LOC-1		LOC-2	LOC-3
Fire accident type	Pool fire	Fire ball	Jet fire	Jet fire
37.5	37	172	66	296
25	49	211	69	310
12.5	77	296	74	337
4.7	124	469	85	392

(3) Range of explosion impact

The range of shockwave damage determined by explosion simulation is shown in Table 7. The exploding spot of vapor cloud is hard to locate, thus hindering accident prevention. If the vapor cloud gathers in a low-lying area or an area crowded with equipment, facility and containers, it may be relatively more obstructed and constrained, and thus releases stronger shockwave while exploding. Shockwave may cause severe damage and injury to equipment, facility, and personnel in the vicinity. Besides, blast fragments and the heat from explosion are also hazardous, and the danger of blast fragments is unpredictable.

Table 7 Range of explosion overpressure

Scenarios	Overpressure (kPa)	Max downwind Distance (m)	Diameter of explosion impact range (m)
LOC-1	9	75	111
	6.9	97	155
	4.8	129	221
	2.07	274	510
LOC-2	9	42	18
	6.9	45	26
	4.8	51	37
	2.07	75	84
LOC-3	9	186	85
	6.9	203	119
	4.8	228	169
	2.07	339	391

3.2 Individual and social risk analysis

To determine if the transportation plan keeps a compliant distance from protected targets in the vicinity, individual and social risks should be evaluated to determine if they are within the acceptable range specified in Table 4 and Figure 1. Less favorable scenarios should be used to assess risk. It was presumed that the carrying ship was loaded with 94 heavy containers, and there are tank containers in the emergency depletion area and both transporting routes. The results show that no specified protected targets were present in areas with individual risks ≤ 3×10-7, ≤ 3×10-6 and ≤1×10-5, and the individual risk was acceptable, as shown in Figure 2. The social risk fell in the acceptable region and was acceptable, as shown in Figure 3.

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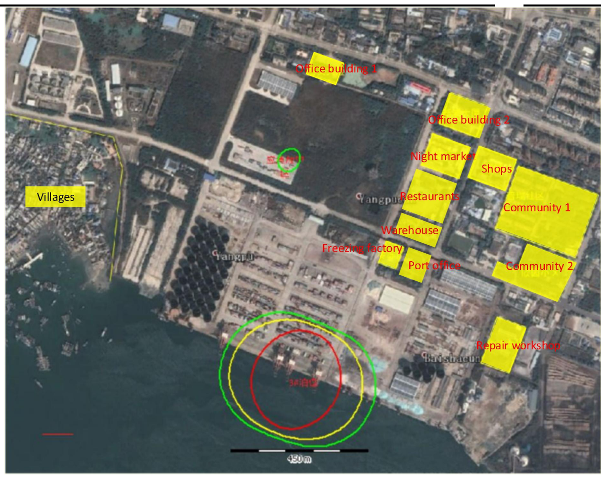

Figure 2.Individual risk contour

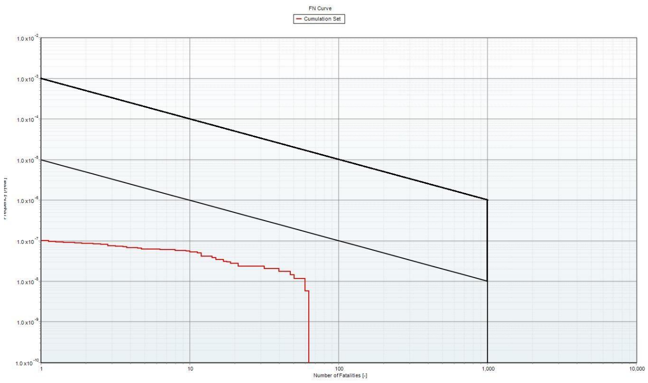

Figure 3. F-N curve

4. Conclusion

The hazard of a single ship carrying maximum 96 40ft heavy containers in a dock was calculated through quantitative risk assessment. Both the individual and social risks met the requirements of regulations and standards. It is worth noticing that when regular leakage happens to a single LNG tank container, the fire and explosion are constrained to the port. However, large scale leakage and BLEVE have relatively larger range of impact. Once uncontrollable situations such as a tank container being completely ruptured and massive LNG leakage happen, at the same time of on-site management, the intensively populated areas in the vicinity must be informed to take necessary precautions, such as emergent evacuation and closing the port area, to minimize the influence on personnel caused by explosion. Emergency drills should be carried out against such accidents to improve handling capability.

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[5] GB 36894-2018, Risk criteria for hazardous chemicals production unit and storage installations [s].
[6] Corresponding author Hui Song .Tel:+86-010-65290307; E-mail address: songhui2014@wti.ac.cn