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Accident type analysis and consequence simulation of LNG terminals equipment and facilities

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Abstract. A new round of energy change, energy clean and low carbon development become an inevitable trend. In the adjustment of energy structure, natural gas becomes the strongest growth carrier and LNG reserve peak regulation is of great significance. Building liquefied natural gas receiving center to secure domestic natural gas supply has become the main target, task and key work. Through the simulation of various equipment and facilities in the LNG terminal under different leakage scenarios, the accident scenarios are selected according to the protection distance criteria, the simulation of steam diffusion, pool fire, jet fire and explosion is carried out, and the influence range of consequences is obtained. The thesis provides a theoretical basis for the quantitative risk assessment for LNG terminal accident and the prediction of emergencies, having positive guiding significance for risk management and emergency disposal of new or operating LNG terminals.

Keywords: LNG；Liquid pool fire；Jet fire；Vapor cloud；shock wave.

1. Introduction

By the end of 2019, a total of 129 LNG terminals had been put into operation worldwide, with an annual receiving capacity of 816 million tons, and an average receiving capacity of each LNG terminal of 6.323 million tons[1]. Since China's first LNG terminal was put into operation on June 28, 2006, more than 20 LNG terminals have been built in China's coastal areas, including Shenzhen Dapeng, Fujian Putian, Shanghai Yangshan, Shanghai Wuhaogou, Zhejiang Ningbo, Jiangsu Rudong, Qingdao Dongjiakou and Tianjin Nangang. The storage and transportation medium of LNG terminal is mainly liquefied natural gas, which is volatile and easy to leak. The combustible vapor cloud formed by leakage may cause serious consequences such as fire and explosion[2], On February 9, 2009, the pipeline of an LNG terminal in Shanghai burst during a pipeline pressure test. The accident is the first explosion accident of LNG terminal in China. On November 2, 2020, the platform pipeline in front of the No. 2 storage tank of a terminal suddenly caught fire during construction. Among the 9 people working on the site, 6 people died and 3 people were seriously injured. But generally speaking, the probability of accidents at the terminal is low[3]. According to the statistics from the related reports, the frequency of accidents at LNG terminals is shown in Table 1.

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Table 1 Frequency of accidents at lng terminals

Type of accident	Accident size: kg / s	Medium accident size kg / s	Accident frequency / year
Jet fire	1	0.3	3.15×10^{-5}
Jet fire	1~10	3	5.77×10^{-5}
Jet fire	10~100	30	1.11×10^{-4}
Jet fire	＞100	300	3.65×10^{-5}
Liquid pool fire	1	0.3	2.60×10^{-5}
Liquid pool fire	1~10	3	5.49×10^{-5}
Liquid pool fire	10~100	30	1.00×10^{-4}
Liquid pool fire	＞100	300	3.37×10^{-4}
Vapor cloud	1	0.3	4.63×10^{-3}
Vapor cloud	1~10	3	3.19×10^{-3}
Vapor cloud	10~100	30	2.23×10^{-3}
Vapor cloud (including incomplete tank rupture)	＞100	300	4.20×10^{-4}

According to Table 1, the danger of LNG terminals to the surrounding facilities mainly comes from the danger of thermal radiation and blast shock wave overpressure caused by the fire after the LNG leakage. Many domestic and foreign literatures have simulated and the consequences of accidents in the process of LNG loading, unloading and storage, and assessed the risks of the consequences. Yang Zhaojun et al[4]analyzed and studied the consequences of leakage and diffusion of large LNG storage tanks as well as fire and explosion, showing that the distribution of fire and explosion risk area was greatly affected by wind speed and atmospheric stability. Du Jianmei[5], after deeply researching the problem of the quantitative calculation of LNG station diffusion range of LNG leakage proposed in the relevant specifications of domestic LNG stations, concluded that the scope of the diffusion isolation area was related with the working pressure, design leakage, storage tank form, LNG collecting tank and cofferdam area, wind velocity and atmospheric stability. Men Jinlong et al[6]studied the coupling relationship between leakage rate and time of horizontal tank by constructing the LNG tank car leakage accident, aiming at the limitations of the classical model of the leakage rate and the leakage model, and improving the leakage model combined with the gas state equation in the tank and the composite integral method. Tang Haiqi et all[7]conducted in-depth analysis on the main factors such as LNG tank container accident scenario, evaluation criteria and failure frequency, and calculated the personal risk and social risk of storing 192 LNG tank containers. The above researches, focusing on the influence of LNG leakage and diffusion as well as fire and explosion factors, lacking comprehensive control over the possible leakage points in LNG receiving station. Therefore, this paper takes a domestic LNG terminal as the research object, the accident scenarios according to the protection distance criteria to simulate the consequences of leakage, steam diffusion, fire, jet fire and steam cloud explosion at low pressure pump outlet, high pressure pump outlet, liquid tank(collecting tank, loading area, tank area), ship pump outlet, hoping to provide technical reference for the safety management of the terminal and scientific basis for accident emergency disposal.

2. Protection distance criteria

According to the Quantitative Risk Assessment Guide for Petrochemical Units, Hazardous Chemical Production Plant and Storage Facilities Risk Base GB36894, etc[8-11],combined with different accident types, including leakage, steam diffusion, steam injection fire, pool fire and steam cloud explosion, the judgment criteria of injury or damage are given to reflect different damage degrees.

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2.1 Thermal radiation criteria of liquid collecting tank

Within the boundary where the heat radiation amount reaches 4kW/m2 , there shall be no outdoor activity places with more than 50 people; within the boundary of where the heat radiation amount reaches 9kW/m2, there shall be no buildings in use such as activity places, schools, hospitals, prisons, detention centers or residential areas. Within the boundary where the heat radiation amount is up to 3kW/m2, there shall be no structures in use that can even resist fire and provide thermal radiation protection.[8]

2.2 Diffusion isolation criteria for liquid tank

The average gas concentration in the air at the boundary of the diffusion isolation zone should not exceed 50% of the lower limit of the methane explosion.[8].

2.3 Thermal radiation hazard criteria

The following thermal radiation damage criteria are selected[8-9]，See Table 2。

Table 2 thermal radiation hazard (injury) criteria

Thermal radiation intensity (kW / m^2）	Damage to equipment	Damage to people
32	The operating equipment is damaged	1% Death (10s) 100% Death (1min)
9	Minimum energy for wood burning and plastic melting when there is a flame	1-Degree burn injury (10s) 1% Death (1min)
4.73	-	Exposed for 16S, the exposed skin has pain; When there is no heat radiation shielding facilities, the operator can stay for several minutes in protective clothing

2.4 Overpressure hazard criteria

1.03kPa, 6.9kPa, 15.8kPa of overpressure are selected as the shock wave overpressure threshold of the low limit values of glass rupture (minor injury), partial damage of the house and inability to live (serious injury) and serious structural damage (death on the spot) caused by explosion overpressure[9]

3. Selection of accident scenarios

The scenarios of the leakage at the low pressure pump outlet (at the valve on the top of the tank), and high pressure pump outlet, as well as the steam diffusion, fire heat radiation and explosion at the liquid collecting tank and LNG storage tank top safety valve outlet of a domestic terminal. The selection of accident scenario is shown in Table 3 below.

Table 3 accident scenario

Device name	Outlet pressure	Outlet pipe diameter or size	Leakage caliber	Leakage time
Low pressure pump	1.2MPa	10 Inch	25mm	10min
High pressure pump	10.0MP a	10 Inch	25mm	10min
Liquid tank	-	5m×5m×5m	-	-
Release port of the LNG tank roof relief valve	29kPa	12 Inch	12 Inch	10min

According to the local meteorological data and relevant simulation requirements of the terminal, the meteorological data in Table 4 below are selected.

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Table 4. selection of typical meteorological conditions

Meteorological factor	Selected results
Wind speed	2.0m/s
Wind direction	direction of prevailing wind SE
Air temperature	The average annual air temperature is 15.2℃
Relative humidity	The annual average relative humidity is 81%
Atmospheric stability	F class
Mixed layer height	general conditions
Atmos	101.3kPa
Latitude	North latitude32°

4. Accident simulation

4.1 Calculation of leakage and steam diffusion scenario

4.2.1 Leakage

The pipeline enters and exits the LNG storage tank from the tank roof, and the LP pump outlet valve pipeline orifice leaks. When the outlet pipeline of the high-pressure pump leaks, the equivalent orifice leakage of the pipeline shall be calculated for 10min. The way of leakage collection of liquid tank in tank farm: after the leakage of the low-pressure pump pipeline, it is collected to the leakage collection pool in the tank farm through the collection tray. The process area and LNG transfer area with storage area and / or liquid collection tank are calculated according to the maximum credible leakage amount within 10min of a single leakage source. The loading pump exports liquefied natural gas from the top of the tank. The outlet valve of the loading pump leaks to the lower liquid pool and collects the liquid into the ground tank pool through the pipeline. When a large amount of BOG is produced due to heating or rolling of the storage tank, and the pressure of the storage tank reaches 29kpa, the tank roof safety valve jumps and the BOG is discharged into the atmosphere.

The calculation results of the leakage of low pressure pump outlet pipeline, the leakage of high pressure pump outlet, liquid tank collection amount and LNG tank roof safety valve leakage are shown in Table 5.

Table 5. calculation results of the leakage scenario

Leak position	Leak rate （kg/s ）	Leakage time （min）	Spillage （t）
Low-pressure pump outlet (1.2MPa)	9.493	10	5.723
High pressure pump outlet (10MPa)	28.269	10	17.04
Liquid tank (calculated based on the leakage liquid tank in loading area)	5.9276	10	3.574
Liquid tank (calculated based on the leakage liquid tank in process area)	27.928	10	16.834
Liquid tank (calculated based on the leakage liquid tank in the storage tank area)	9.493	10	5.723
Release port of the LNG tank roof relief valve	13.001	10	8.064
Ship-Pump Outlet (0.9MPa)	9.2309	10	5.565

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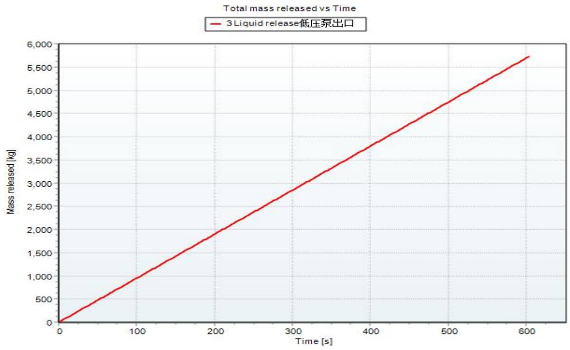

Figure 1 Relationship between leakage at LP pump outlet and leakage time

Figure 2 Relationship between the amount of leakage to liquid tank in loading area and leakage time

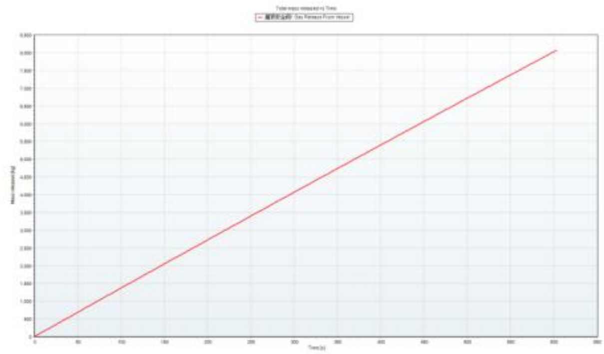

Figure 3 Relationship between overpressure discharge of safety valve on LNG tank roof and leakage time

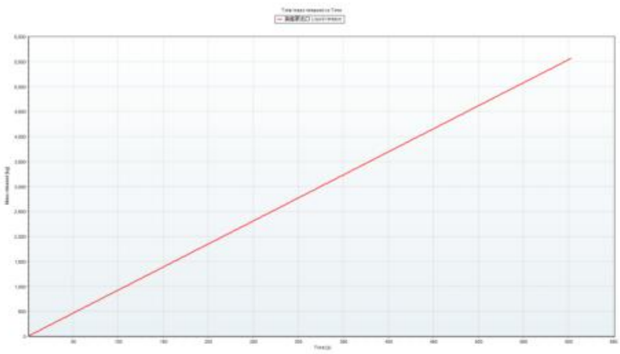

Figure 4 Relationship between the of leakage of loading pump outlet and leakage time

4.2.2 Evaporation and diffusion calculations

For LNG leaked into the liquid tank will be vaporized after absorbing heat and constantly diffused to the surrounding to form a vapor cloud. The vapor cloud diffusion isolation zone of

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liquid tank is calculated (50% LFL outer contour) through the simulation used "DENSE GAS DISPERSION" in TNO EFFECTS 10.1.5.

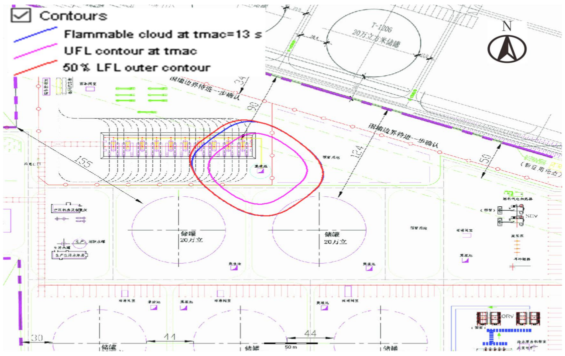

Figure5 Scope of liquid tank diffusion isolation area in tank loading area

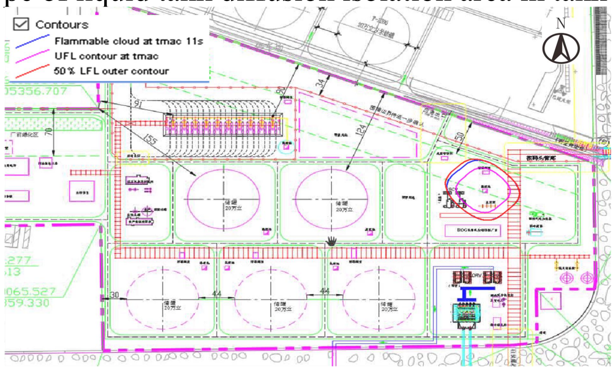

Figure6 Scope of liquid tank diffusion isolation area in process area

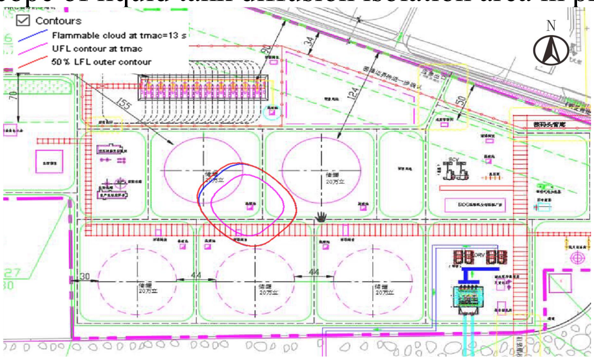

Figure7 Scope of liquid tank diffusion isolation area in tank area

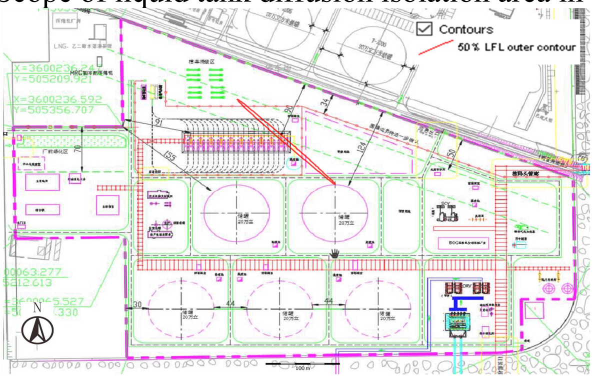

Figure8 Scope of LNG tank top safety valve discharge diffusion isolation area

4.2 Pool fire

Low pressure pump outlet valve (located on the tank roof valve platform) leaks and flows to the liquid collecting tray at its lower part. At this time, if an ignition source is encountered, a pool fire may occur. The leakage of high pressure pump outlet pipeline will flow to the ground. In the process of flowing on the ground, it may cause a fire when encountering an ignition source. After the liquid tank receives LNG, the low temperature detector and combustible gas alarm in the tank

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will alarm and interlock the high multiple foam fire extinguishing system to cover the tank to reduce the evaporation rate. However, fires may occur before high multiple foam covers. The thermal radiation coverage of the fire is simulated by the EFFECTS software of the National Institute of Applied Sciences in the Netherlands. See Table 5 below for details.

Table 5. calculation results of the pool-fire scenario

Position	Downward thermal radiation distance (m)				
	4.73kW/m^2	9kW/m^2	15kW/m^2	30kW/m^2	32kW/m^2
Low-pressure pump outlet leakage	40	30	22	13	13
High-pressure pump outlet leakage	54	40	30	18	18
Liquid tank (calculated based on the leakage liquid tank in loading area)	22	16	12	8	7
Liquid tank (calculated based on leakage liquid tank in process area)	22	16	12	8	7
Liquid tank (calculated based on leakage liquid tank in storage tank area)	22	16	12	8	7
Leakage from the loading pump outlet	40	30	22	13	13

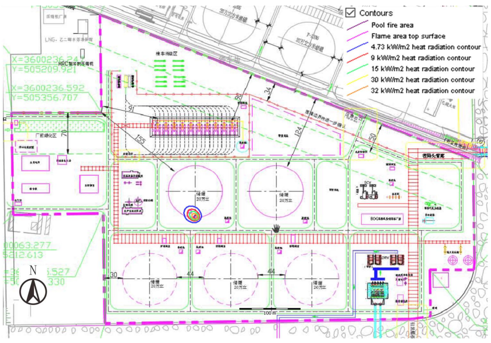

Figure 9 Simulation results of fire heat radiation after low-pressure pump outlet leakage

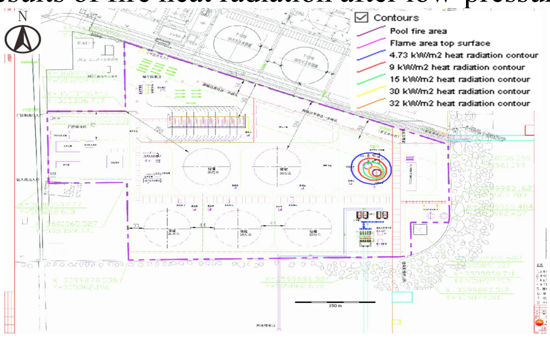

Figure10 Simulation results of fire heat radiation after high-pressure pump outlet leakage

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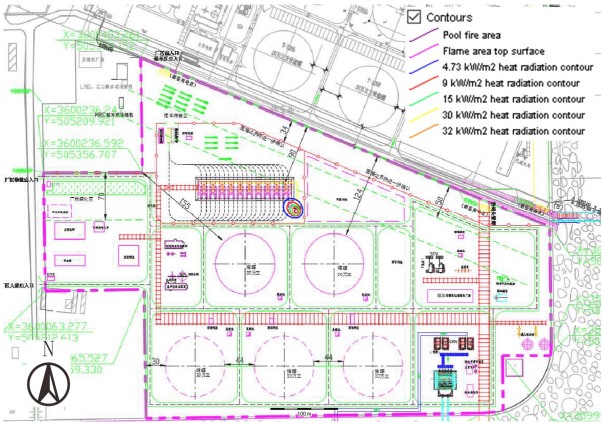

Figure 11 Simulation results of fire thermal radiation in loading area

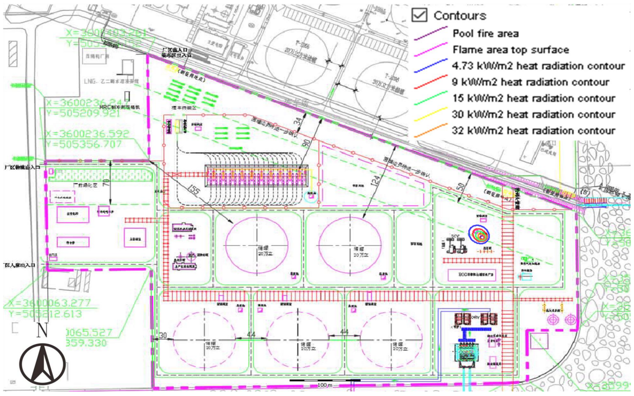

Figure 12 Simulation results of fire thermal radiation in process area

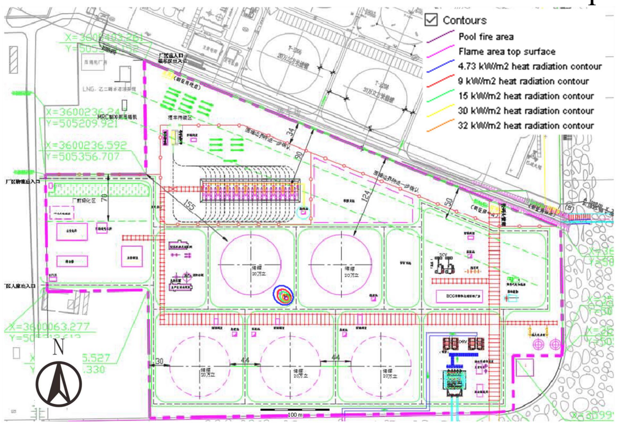

Figure 13 Simulation results of fire thermal radiation in tank reservoir

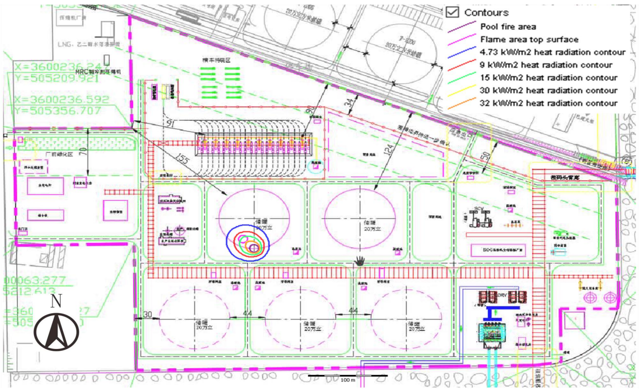

Figure 14 Simulation results of fire thermal radiation after leakage of loading pump outlet

As can be seen from the figures above, the thermal radiation covered area of the liquid tank does not include the places where people are concentrated.

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4.3 Jet fire

The outlet pressure of the high pressure pump of the terminal is high, When the outlet leaks, encountering an ignition source may cause jet fire. This is simulated by using the Jet Fire model in TNO EFFECTS 10.1.5, and the results are shown in Table 6 below.

Table 6 simulation results of leakage jet fire atthe highpressure pump outlet

Expended jet outlet velocity	5490.5m/s	Length of injection cone	14.394m
Bottom width of the injection cone	0.827m	Injection cone surface area	144.58m^2
Width of injection cone	4.719m	Heat radiation intensity	400kW/m^2

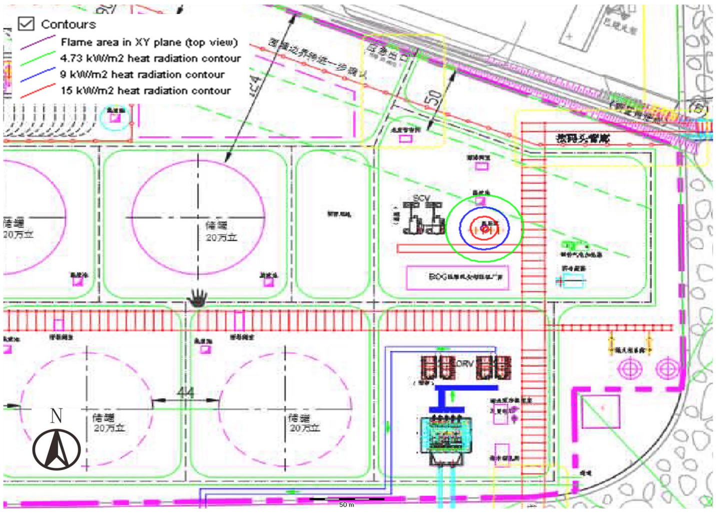

Figure 15 Simulation results of jet fire at high-pressure pump outlet

When LNG tank top safety valve discharge encountered ignition source, jet fire may be caused. This is simulated by using the Jet Fire model in TNO EFFECTS 10.1.5 and the results are shown in Table 7 below.

Table 7 simulation results of injection fire from lng tank roof

Expended jet outlet velocity	170.34m/s	Length of flame	26.037m
Bottom width of the injection cone	3.0268m	Injection cone surface area	726.55m^2
Width of injection cone	11.72m	Heat radiation intensity	206.93kW/m^2

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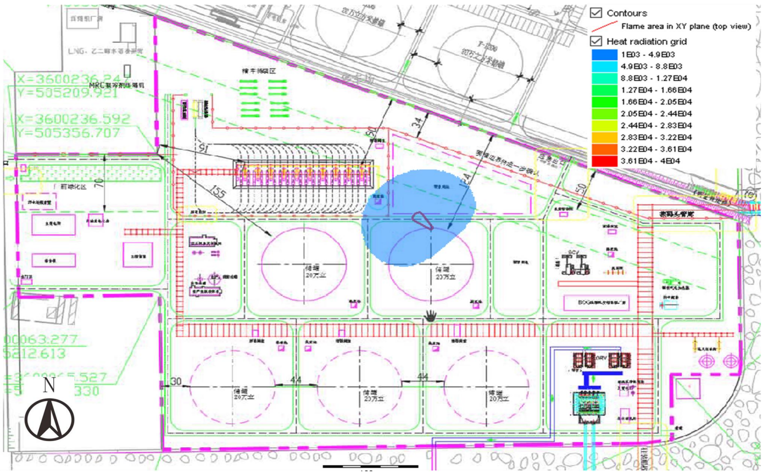

Figure 16 Simulation results of jet fire from LNG tank roof

4.4 Explosion

The leaked LNG can continuously volatilize and spread in the atmosphere, and may explode in case of ignition source. The damage of explosion to the surrounding includes thermal radiation and shock wave. The latter has a greater impact on the surrounding. Explosion in various leakage scenarios is simulated and the results are shown in Table 8 below.

Table 8 Statistics of simulation results of explosion accident consequences

Position	Downward thermal radiation distance (m)		
	1.03kPa	6.9kPa	15.8kPa
Low-pressure pump outlet leakage	1167	215	112
High-pressure pump outlet leakage	1665	306	159
Liquid tank (calculated based on leakage liquid tank in loading area)	433	80	41
Liquid tank (calculated based on leakage liquid tank in process area)	440	81	42
Liquid tank (calculated based on leakage liquid tank in storage tank area)	433	80	41
LNG tank head relief valve discharge	1478	272	141
Leakage from the loading pump outlet	1146	211	110

5. Conclusion

The leaked liquid of the liquid tank in loading area, process area, tank farm slowly volatilized under the high expansion foam. It diffuses after volatilization, the faster it volatilizes, the faster it diffuses and the more discontinuously the vapor cloud formed. During the simulation, the diffusion range was calculated by volatilization in a certain time, and the simulation results are: 3574kg, 1680kg, 2075kg. Diffusion simulation: the leaked liquid of liquid tank in loading area, process area and tank farm spreads after evaporation, the boundaries of the diffusion isolation area (average gas concentration in the air should not exceed 50% of the lower limit of methane explosion) are 67m, 50m and 60m. Diffusion simulation: after the LNG tank top safety valve discharge, the boundary of the diffusion isolation area (the average gas concentration in the air should not exceed 50% of the lower limit of methane explosion) is 188m.

According to the simulation results of the low pressure pump outlet, high pressure pump outlet, liquid tank (in loading area, process area, tank farm) and loading pump outlet, if the pool fire

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accident caused by LNG leakage at the high pressure pump outlet under the accident scenarios occurs, the thermal radiation distance of 4.73kw/m2 is 54m, and people will feel pain after more than 20s; the thermal radiation distance of 9kw/m2 is 30m, causing wood combustion and plastic melting, and people will suffer first-degree burns in 10s; 1% burn in 1min; and the thermal radiation distance of 30kw/m2 is 18m, and all the operating equipment of the wharf platform will be destroyed, and 1% of people will die in10s, and 100% will die in 1 min.

Thermal radiation is the main source of injury of jet fire. Thermal radiation at the outlet of high pressure pump causes death, second-degree burns and first-degree burns respectively within the range of 17.9m, 24.2m, 26.3m.

If the vapor cloud explosion accident is caused by the LNG leakage of the safety valve on the top of the LNG tank, the maximum distance between the 1.03kpa shock wave overpressure and the explosion point is 1478m; the maximum distance between the 6.9kPa shock wave and the explosion point is 272m and the maximum distance between the 15.8kPa shock wave and the explosion point blast wave is 141m. This shows that at 406.6m (0.21bar) from the explosion point, the shock wave overpressure may cause cracks in the building wall or damage to the window frame, and cause slight injury to the human body at the same time; At 437.7m (0.14bar) from the explosion point, the overpressure of shock wave may cause most of the door and window glass on the pressure surface to break; At 831.9m, the glass window may be damaged, but it is basically harmless to people.

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