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Analytical Study of the Potential Consequences for LNG Release on Typical Floating Liquefied Natural Gas (FLNG) Facility

Haidar Ibrahim*, P. J. Rao
Department of Chemical Engineering, Andhra University, Visakhapatnam, India

ABSTRACT

Floating Liquefied Natural Gas (FLNG) is the most recent mobile unit that currently designed for evolution of natural gas production from distant offshore fields. It is multifunctional technology as developed to perform the exploiting, processing, liquefying and storing of LNG on board. To do so, it is equipped with complex subsystems within congested area. So, any process failures may lead to unfavorable incidents. Natural gas leaks are a widespread incident in offshore gas processing facilities which subsequently propagate to the major accidents such as pool fire, jet fire and VCE. Thus, it is necessary to conduct consequence analysis of the LNG leaks on the typical FLNG facility. For this purpose, the present analytical study includes the graphical and numerical analysis of potential consequences for set of leak scenarios of LNG on typical FLNG facility. In the graphical analysis, the sequences of the typical accidents due to LNG leaks have been analyzed graphically by drawing consequence analysis flowcharts for two cases: one for unpressurized release and another for pressurized release. The numerical analysis has been done for likely consequences and in which the selected release scenarios have been modeled using Aerial Location of Hazardous Software (ALOHA). Consequently, the threat zones for physical effects such as heat radiation intensity, blast overpressure and toxic dispersion have been obtained and possible impacts on human and assets also have been estimated. This study is useful to control the possible risks effectively in the early design stages or operational phase of the FLNG facility aiming to avoid the occurrences of the serious accidents or to mitigate their severity on human and structures.

Keywords: FLNG facility, consequence analysis, ALOHA software, threat zones.

I. INTRODUCTION

The rapid growth of industrialization has sharply raised the demand for natural gas as clear energy and environmental friendly. So, to meet the world energy needs, the exploration and exploitation of the natural gas has been pushed to the gas reserves located at remote and hostile offshore environments using extremely complicated and sophisticated facilities. Floating Liquefied Natural Gas (FLNG) is a fascinating and quickly evolving enterprise that specifically designed for natural gas production [1].It consists of complex subsystems, distributed processes, control and operating systems. FLNG is integrated technology as it combines LNG tanks with a gas liquefaction process plant so, it can be used for natural gas processing, liquefaction, storage and offloading activities [2], typical FLNG plant is presented in **(Figure1)**.FLNG facility has significant financial benefits as it give the ability to produce LNG on site which helps to avoid lying of long gas pipelines or installing the land processing plants. Furthermore, it also has no risks to the public due to its remote offshore gas resources. However, due to the limited space, less ventilation, congested layout, concentrated equipment, wave and wind effects, the potential risks to workers and structure are higher than onshore LNG facility [3]. As a

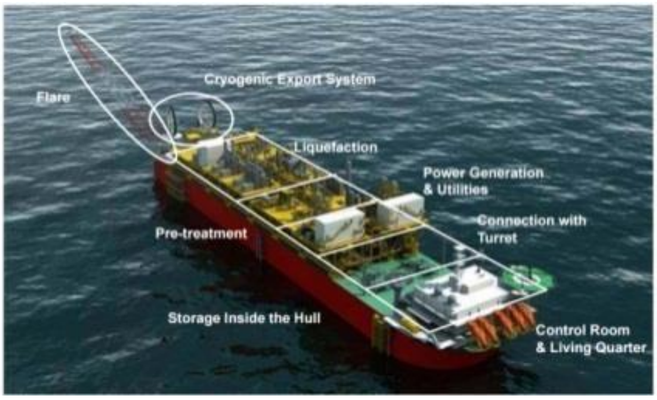


Figure 1: Typical FLNG plant [4].

result, many important safety issues and technical challenges associated with this new facility have appeared must to be well considered and addressed. The extraction of hydrocarbons in the offshore oil and gas industry is risky and has the likelihood for major accidents like fires and explosions[5].Thus so , offshore oil and gas industry is more prone to serious incidents that have led to catastrophic accidents in the past such as the Piper Alpha accident which have attracted the public attention to the offshore safety domain[6].Accident occurrences in LNG and LPG process facilities are well explained and addressed in literature[7].Most of the researches on FLNG facilities are focused on operational challenges[8]. As the FLNG ship is handling with the LNG and its hazardous properties involving cryogenic nature, and characteristics of the vapour flammability and dispersion, the FLNG structure is riskier than conventional production platform [9]. The majority of past LNG accidents have been initiated by the release of LNG [10]. This may occur due to any process deviations from intended operating conditions, human and management errors and organizational issues which make the plant extremely oversensitive to malfunctions and failures [11]. Aronsson has found out that hazardous units in an FLNG facility are gas treatment, liquefaction and offloading processes [12]. Fire, explosion, cryogenic release and gas dispersion are considered the most frequent risks on FLNG processing facility [2]. These catastrophic events will not only result in significant fatalities and economic losses but also cause serious pollution and damage to surrounding environment [6]. As, the cost of offshore structures is high, consequence severity and complexity of offshore fields strongly seeking to the necessity of the hazard and risk analysis[13].Safety is the most important aspect in offshore operations especially during design phase of structures, which is often measured in terms of risk. Risk can be analysed and evaluated by many techniques to determine the level of personal and process safety in the work place. In addition, Risk analysis is also powerful and essential tool for developing strategies for accident prevention and mitigation and one of the prime steps of safety management as well. Khan and Abbasi [14] briefly discussed the advantages and disadvantages of the past and present methods for risk analysis and assessment and also presented variety of developed tools for conducting efficient and optimal risk analysis process. LNG leaks are the most frequently incident in offshore gas process facilities and this event may be propagated to unfavourable accidents. So, it is essential to concentrate on the potential consequences of the LNG release event. Consequence analysis is a master part of the QRA in which the physical effects of probable hazards are quantified and estimated. According to the statistics, fires and explosions are the most frequently occurred on the offshore production facilities [15].A few studies and researches related to risk assessment in the offshore oil and gas industry have focused on the consequences and impacts analysis: Krueger and Smith has proposed approach for fire risk assessment by estimating the potential impacts of worst scenarios on the oil and gas platforms [5]. In recent years, CFD softwares are deemed as one of the best tools for identifying the action characteristics of hydrocarbon explosions and fires [16]. It is able to simulate the obstacles and represent the real operation conditions as well [9]. Consequence analysis depends upon many parameters such as released volume, release rate, release direction and time of ignition [17]. So, performing the consequence analysis becomes so necessary for efficient evaluation and powerful control the risks regarded to the serious accidents that caused by plausible LNG release which in turn improves the safety level in the design and operations [18]. In order to assess the possible associated risks, appropriate modelling approaches of consequences can be applied. Areal location of Hazardous Atmosphere (ALOHA) is one of the fastest and most accurate modelling software for the consequence analysis. It can be used to model and analyse the likely hazards due to LNG leaks on typical FLNG for worst case scenarios .ALOHA software is specifically designed for hazard evaluation of the hazardous material releases[19]'[20]. ALOHA is commonly employed to estimate the main accidental scenarios such as toxicity, flammability, thermal radiation and explosion over pressure. On other hand, the ALOHA is unable to model the risks of the LNG cryogenic spillage and its impacts on personnel and steel structure. The inputs of ALOHA involves the data about location, type of chemical, atmospheric conditions, source of release and its properties .The outputs of ALOHA are the footprints of impacts and hazardous zones for escalation factors such as (thermal radiation, blast wave and toxic or flammable vapour concentration contours) for each release scenario as well as the potential impacts on human and assets within each threat zone. For more information about inputs selection and running ALOHA read instructor guide and examples

[19]' [20].This analytical study for consequence analysis on the FLNG installation will greatly pay attention and focusing to the possible worst scenarios to reduce or prevent probability of process deviations which may lead to major accidents and eventually contributes in process and personal safety level improvement.

FLNG processes

LNG is natural gas that has been cooled and liquefied to a cryogenic liquid with temperature about (-162 ºC) under atmospheric pressure [21].LNG contains about (85-95 %) methane so, the methane has been used in the current software simulation. Its flammability range is (5-15Vol %) concentration in air and also ignited spontaneously at (540 °C) without catching any ignition source.

FLNG plant is capable to extract, process, liquefy, store and offload LNG to the tankers which transfer it directly to the market [22]. The FLNG facilities are particularly designed for handling of natural gas with accompany liquid components, which will be treated, liquefied, fractionated and stored as Liquefied Natural Gas, Liquefied Petroleum Gas and condensate products [23].The primary units of FLNG facility are feed gas treatment, natural gas liquefaction, fractionation and storage unit. A typical FLNG block flow scheme is provided in **(Figure 2)** with the main process flow proceeding from top to bottom.

The overall processes on FLNG are descried in nutshell in this paper as below [2]' [23]' [24]: Feed natural gas is received from the gas wells via pipelines and passes through gas/liquid separation system to separate gas from condensate liquids. The separated gas will subject to further treatment to remove the acid gas such as CO2 and H2S which may cause corrosion or freeze and create solids in subsequent cryogenic processes. Thereafter, the sweetened gas will be dried by passing through the dehydration separator which removes the water to avoid the formation of ice in the subsequent cryogenic process in the liquefaction unit so, the moisture content have to meet the typical requirement. The dry natural gas way out the dehydration system and enters the mercury removal system in which any impurities of mercury will be removed to avoid corrosion of the downstream cryogenic unit. After that, the treated gas will pass through the liquefaction system. The liquefaction unit consists of the propane coolers, fractionation column and cryogenic heat exchangers. After the treatment of the gas, the treated NG is pre-cooled in the chilling unit to about (-30°c to -70 °c) by passing within propane compressor. Then, the precooled gas is subjected to multiple cooling stages in the cryogenic heat exchanger by cryogenic refrigerants in which the heat will be effectively transferred from the feed gas to the refrigerant. The natural gas will be cooled below methane boiling point of approximately -163c, as natural gas is converted into liquefied natural gas with 600 times reduction in its original volume to be stored in the LNG atmospheric tanks for marketing purposes.

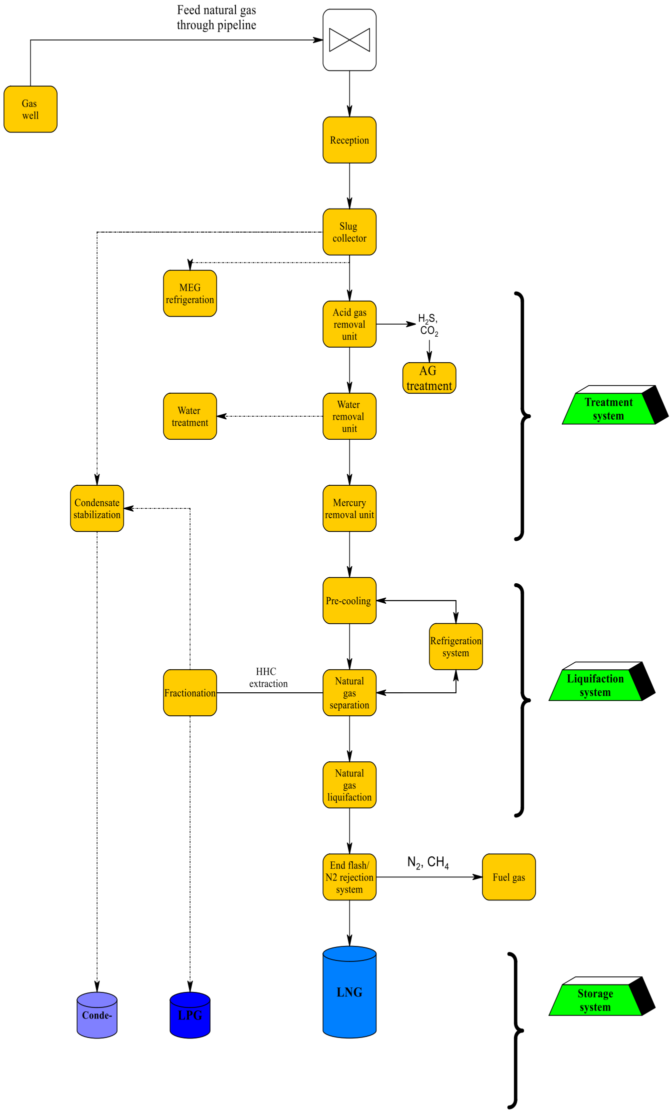


Figure 2: FLNG operations flow chart.

II. GRAPHICAL ANALYSIS

Loss of inventory is the common initiating incident in the offshore gas industries due to the failure of the tanks or pipes, this incident can be evolved in various sequences leading to major accidents.

Each one of these sequences will lead to a final accidental scenario. Within the topsides of a FLNG, the occurrence of one or more of these hazards depends on many parameters such as the properties of released material , phase of the released gas, the source of release, the ignition (immediate or delayed) and pressure of release[15]. The consequences resulting from a LNG leak leading to major hazards can be divided into two categories based on the operating pressure weather the LNG unpressurized (storage tanks) or under pressure (processing and liquefaction units).The sequence of the potential consequences and accident scenarios for both categories are given in the **(Figure 3)** and **(Figures 4)** respectively.

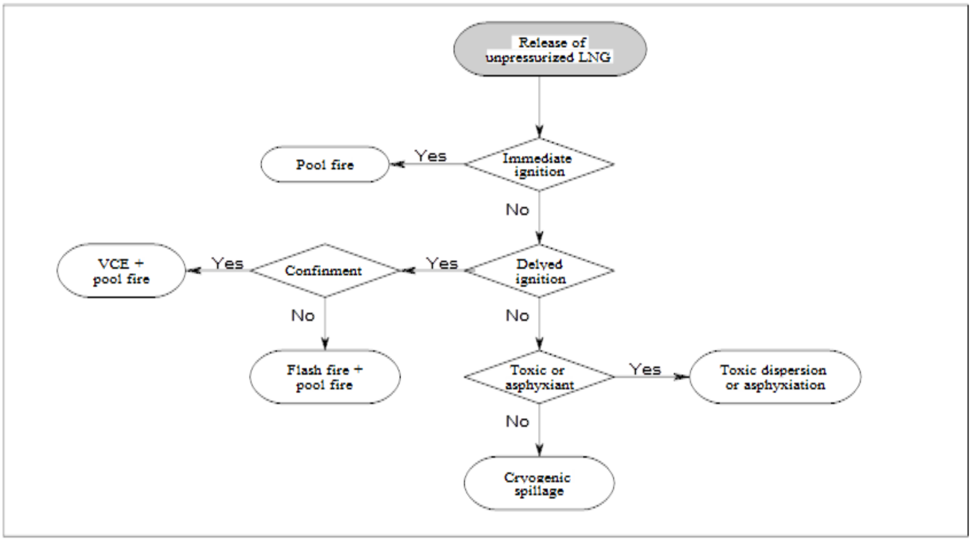


Figure 3: Typical accident scenarios of unpressurized LNG leak (consequence analysis).

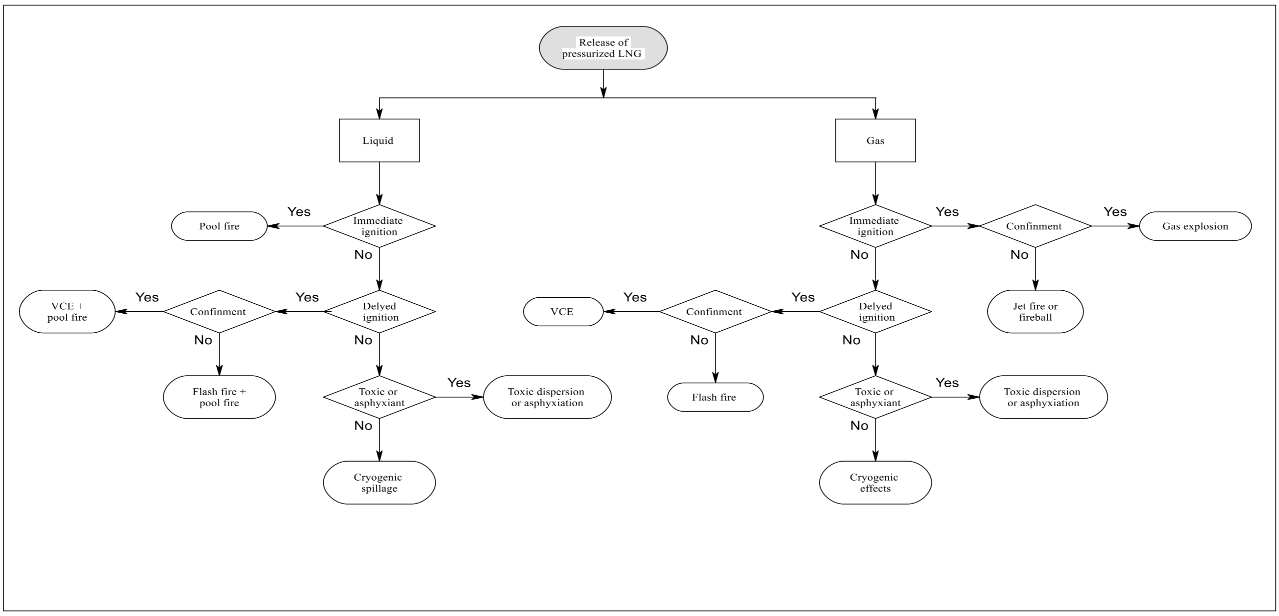


Figure 4: Typical accident scenarios of pressurized LNG leak (consequence analysis).

III. NUMERICAL ANALYSIS

Consequence analysis is primary aims to model and quantify of physical effects in terms of threat zones and distances in order evaluate the probable impacts on the personnel and material exposed to the escalation factors such as thermal radiation intensity and explosion overpressure based on tables of the effects criteria and risk rates. In this analytical study, the numerical analysis has been carried out of potential consequences arising from a LNG spillage on typical FLNG plant leading to major hazards.

Release scenarios

Four different scenarios are considered and analyzed using ALOHA software, the outcomes for each scenario has been identified and the threat zones are plotted as contours for thermal radiation, blast waves and toxic vapour dispersion over the process area. The worst case scenario in each basic unit has been considered according to the source of release, the most vulnerable targets in a process facility are LNG storage tanks and gas pipes during processing[25].So, the cases used in this study are classified as following:

- Release of unpressurized cryogenic LNG (liquid phase) with temperature equals to -163°c and atmospheric pressure from the spherical storage tank with typical diameter is 70 m. LNG is released from hole or valve in liquid state as following:

1. **The first scenario** is LNG release from storage tank from hole with 100 mm diameter (in the body of the tank due to any mechanical failure).
2. **The second scenario** is LNG release from storage tank from valve with 500 mm diameter (discharge or filling valve which its diameter equals to the diameter of filling pipe that connected to the tank).

- Release of pressurized natural gas from gas pipes (gas phase) with typical diameter is 0.5 m. According to the gas temperature in the release location, two scenarios have been specified:

3. **The third scenario** is release of the feed natural gas under pressure from a valve with hole diameter 500 mm, the process parameters are: the temperature is 30 °c and pressure is 7atm. This may occur during processing in treatment system.
4. **The fourth scenario** is release of precooled treated gas under pressure from a valve with hole diameter 500 mm, the process parameters are: the temperature is -70 °c. This may occur during chilling in liquefaction system.

The weather parameters which are necessary to run the ALOHA software for consequence estimation: Wind speed and direction, the ground roughness, cloud cover, air temperature and humidity. Visakhapatnam weather conditions have been used in this software. The average wind speed is 3 m/s, the prevailing wind direction is southwest, the average humidity is 70 % and the average ambient temperature is 30°c.

Rate and level of the risk

To simplify the consequence assessment process, consequence severity can be converted to corresponding risk score. This score demonstrates the level of risk due to the consequences severity of at any location in the process area .The human and assets effects caused by exposure to the thermal radiation are given in the **Table 1** and the effects caused by blast overpressure are given in the **Table 2**.These effects have been derived and obtained according to the resulted footprints of the ALOHA software which are used for consequences modeling in this study. Moreover, this derivation is based on the literature publications such as Hazardous Industry Planning Advisory Paper [26], AICHE Guidelines [27], and the effects tables presented by Dadashzadeh [28].

In addition, the level of risk needs to be known. To do that, the effects of thermal radiation and blast overpressure have been rated on severity scale from 1to 10 as shown in table. The scale starts from 1 for the minor impact (safe zone) and increase to 10 for the lethal impact (potential death zone). Then, each risk rates corresponds specific level of risk for specific release scenario.

Table 1: Effects by thermal radiation.

Radiant heat flux (kw.m^{-2})	Effect on human	Effects on assets	Risk rate	Risk level
Less than 1.6	Minor pain	No significant effect	1	Insignificant
Greater than 2	First degree burn(pain within 60 sec)	No significant effect	4	Low
Greater than 5	Second degree burn within 60 sec	No significant effect	7	Medium
Greater than 10	Third degree burn (potentially lethal in 60 sec)	Thermal stress of unprotected steel and melting of plastic tubes.	10	High

Table 2: Effects by blast overpressure.

Pressure (psi)	Effects on human	Effects on assets	Risk rate	Risk level
Less than 1	Loud noise and Very low probability of injury	90% glass breakage	1	Insignificant
Greater than 1	Probability of injury is 10%. and threshold of eardrum damage	Damage to confined partitions but can be repaired	4	Low
Greater than 3.5	Serious injury , 50% fatality chance and threshold of lung damage	Reinforced structures distort or Storage tanks fail	7	Medium
Greater than 8	100% chance of fatality for a person and head damage	destruction of equipment	10	High

IV. RESULTS AND DISCUSSION

The consequences parameters have been estimated using ALOHA software. (Burn Duration or release duration or evaporating duration in ALOHA is limited to 1 hour) for each aforementioned scenarios. The consequences are presented as impact zones, each zone corresponds specific level of concern based on type of consequences. Red zone for hazardous area, orange zone for mid-hazardous area and yellow zone for less hazardous area. The threat distances and risk levels for identified scenarios are presented in the **Table 3**.

A. **The first scenario** is LNG release from spherical storage tank (Typical diameter is 70 m, 85% full) from hole with 100 mm diameter (in the body of the tank due to any mechanical failure). The possible consequences are:
   1. Released LNG is burning and forms a pool fire .Threat zones for thermal radiation are shown in (**Figure 5).**
   2. Released LNG is not burning and forms evaporating pool. There are three possible hazards of vapour cloud dispersion based on vapour concentration in the air, level of congestion, time of ignition etc. There are toxic and flammable vapour dispersion and blast overpressure of cloud explosion. Threat zones are shown in **(Figure 6).**

B. **The second scenario** is LNG release from spherical storage tank (Typical diameter is 70 m, 85% full) from valve with 500 mm diameter (discharge or filling valve which its diameter equals to the diameter of filling pipe that connected to the tank). The possible consequences are:
   1. Released LNG is burning and forms a pool fire. Threat zones for thermal radiation are shown in **(Figure 7).**
   2. Released LNG is not burning and forms evaporating pool. There are toxic and flammable vapour dispersion and blast overpressure of cloud explosion. Threat zones are shown in (**Figure 8)**.

C. **The third scenario** is the feed natural gas release from pipeline (typical diameter is 0.5 m , length is100 m) under pressure from a valve with hole diameter 500 mm, the operational parameters are temperature is 30 °c and pressure is 7 atm . This may occur during processing in treatment system. The possible consequences are:
   1. As natural gas escapes from pipe, the gas is burning: Threat zones for thermal radiation are shown in (**Figure 9).**
   2. As treated natural gas escapes from pipe, the gas is not burning. There are toxic and flammable vapour dispersion and blast overpressure of cloud explosion. Threat zones are shown in (**Figure 10)**.

D. **The fourth scenario** precooled treated gas release (-70 °c) from a valve with hole diameter 0.5 m. This may occur during freezing in liquefaction system. The possible consequences are:
   1. As precooled natural gas escapes from pipe, the gas is burning: Threat zones for thermal radiation are shown in (**Figure11)**.
   2. As chemical escapes from pipe, the gas is not burning. There are toxic and flammable vapour dispersion and blast overpressure of cloud explosion. Threat zones are shown in **(Figure 12).**

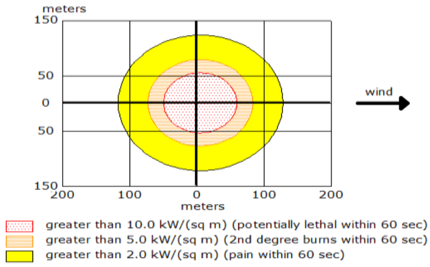
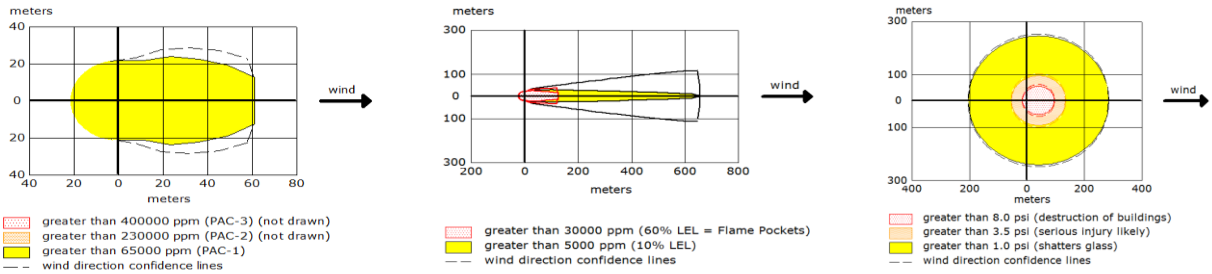


Figure 5: Thermal radiation threat zone for pool fire (unpressurized LNG release from hole with 100 mm diameter).



(a) **(b)** **(c)**

Figure 6: Threat zones for vapour cloud (unpressurized LNG release from hole with 100 mm diameter).
(a) Toxic dispersion**, (b)** Flammable dispersion**, (c)** blast overpressure of cloud explosion.

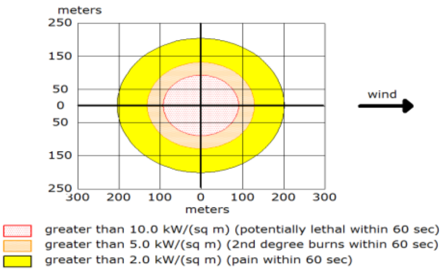
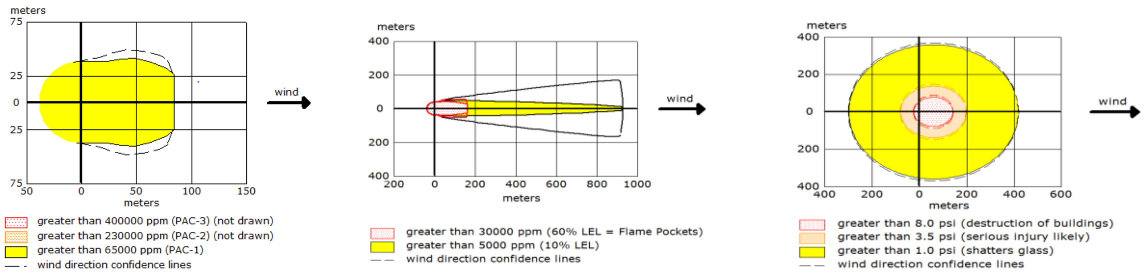


Figure 7: Thermal radiation threat zone for pool fire (unpressurized LNG release from hole with 500 mm diameter).



(a) **(b)** **(c)**

Figure 8: Threat zones of vapour cloud (unpressurized LNG release from hole with 500 mm diameter).
(a)Toxic dispersion, (b) Flammable dispersion, (c) blast overpressure of cloud explosion.

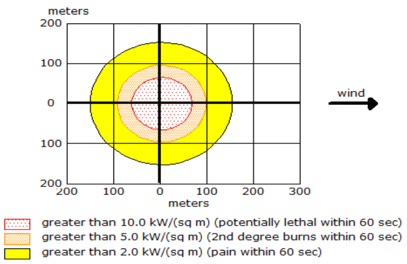
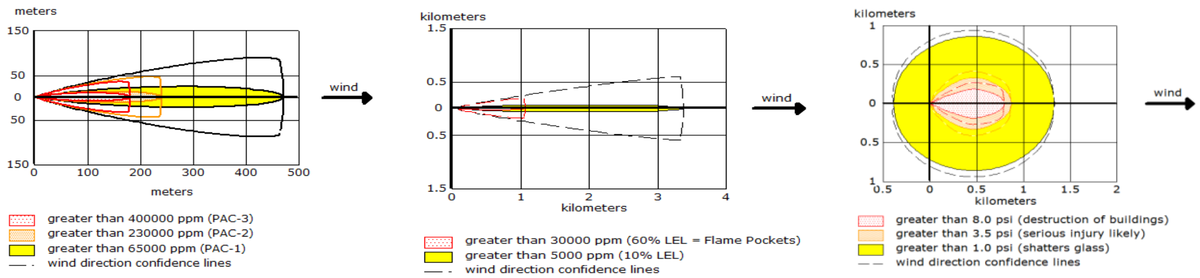


Figure 9: Thermal radiation threat zone for jet fire (pressurized LNG release from pipe with 500 mm diameter, temp is 30°c).



(a) (b) (c)

Figure 10: Threat zones of vapour cloud (pressurized LNG release from hole with 500 mm diameter, temp = 30°c). (a)Toxic dispersion, (b) Flammable dispersion, (c) blast overpressure of cloud explosion.

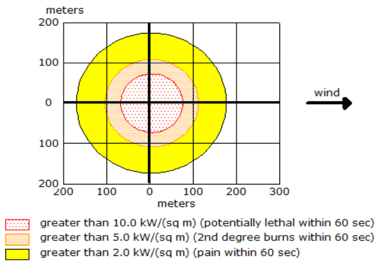
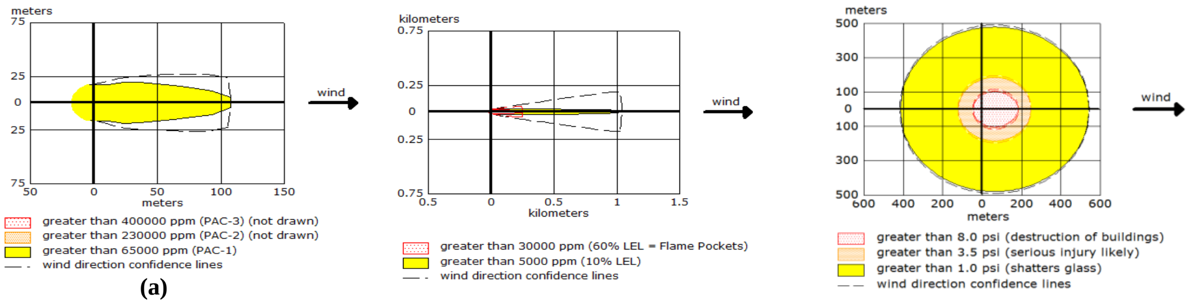


Figure 11: Thermal radiation threat zone for jet fire (pressurized LNG release from pipe with 500 mm diameter, temp is -70 °c).



(a) (b)

(c)

Figure 12: Threat zones of vapour cloud (pressurized LNG release from hole with 500 mm diameter, temp is 70°c). (a)Toxic dispersion, (b) Flammable dispersion, (c) blast overpressure of cloud explosion.

According to summary in **Table 3**, the comparison among obtained results for identified scenarios indicate that the 2nd scenarios in the LNG tank "LNG release from spherical storage tank (Typical diameter is 70 m, 85% full) from valve with 500 mm diameter" has the maximum red zone (high risk zone) greater than another scenarios in case of fire accident occurrence. So, the maximum thermal radiation (10 **Kw.m**$^{-2}$ or more) will extend for the longest distance (92 m) as compared to red zone extension for other scenarios. In case of vapour cloud explosion occurrence, the comparisons among results found out that the 3rd scenario in the treatment system "The feed natural gas release from pipeline (typical diameter is 500 mm) under pressure from a valve with hole diameter 500 mm, the operational parameters are: temperature is 30 °c and pressure is 7 atm" has the maximum red zone (high risk zone) as compared with other scenarios. So in this scenario, the maximum blast overpressure (8 psi or more) will reach to the distance (801 m) further than other case scenarios. Moreover, the obtained results have found out that, 3rd scenario red zone for toxic and flammable vapour cloud dispersion in the downwind direction and will extend to greater distance than others. The possible impacts of fire and explosion on personnel and assets can be obtained from the **Table 1** and **Table 2**. Potential death zone for thermal radiation is maximum for the 2nd LNG release scenario from the tank .The human exposed to thermal radiation within the red zone would be prone to third degree burn and potentially death in 60 second. The impact on structure inside the red zone would be as thermal stress of unprotected steel and severe damage of plastic tubes. The severity of damage depends on value of thermal loads and level of protection of equipment. Whereas the 3rd treated gas release scenario from pipes poses the maximum potential death zone for blast overpressure. The human exposed to blast overpressure within the red zone would be prone to severe head impact and high chance for death. The impacts on structure inside the red zone would be severe and destructive for huge blast force value. Two LNG release scenarios from tank (1st and 2nd) have been considered, but the 2nd scenario is more severe than 1st one. This is due to the release hole in 2nd scenario (500 mm) is greater than release hole in 1st scenario (100 mm). The bigger hole size, the longer red zone distance (high risk zone) because of the quantity of LNG released and involved in the fire will be greater which in turn increase the quantity of heat released and transferred around the flame.

Table 3: Threat distances for each release scenario and risk level due to fire and explosion.

Release scenario Description	Source and leak size of release	Consequence modelled	Threat zones (distance)					
			Red	Risk	orange	Risk	Yellow	Risk
1st scenario Liquefied natural gas release	Spherical tank (Hole diameter is 100 mm)	Thermal radiation from pool fire	60 m	High	84 m	Medium	129 m	Low
		Toxic area of vapour cloud	28 m		33 m		61 m	
		Flammable area of vapour cloud	126m		No LOC selected		656 m	
		Blast area of VCE	98 m	High	136 m	Medium	286 m	Low
2nd scenario Liquefied natural gas release	Spherical tank (Valve diameter is 500 mm)	Thermal radiation from pool fire	92 m	High	130 m	Medium	203 m	Low
		Toxic area of vapour cloud	46 m		49 m		84 m	
		Flammable area of vapour cloud	163 m		No LOC selected		932 m	
		Blast area of VCE	143 m	High	198 m	Medium	420 m	Low
3rd scenario Pressurized feed natural gas release (30 °c)	Gas pipeline (Hole diameter is 500 mm)	Thermal radiation from jet fire	69 m	High	99 m	Medium	156 m	Low
		Toxic area of vapour cloud	182 m		243 m		473 m	
		Flammable area of vapour cloud	1.1 km		No LOC selected		3.4 km	
		Blast area of VCE	801 m	High	877 m	Medium	1.3 km	Low
4th scenario Pressurized precooled treated gas release (-70 °c)	Gas pipeline (Hole diameter is 500 mm)	Thermal radiation from jet fire	78 m	High	113 m	Medium	178 m	Low
		Toxic area of vapour cloud	26 m		35 m		108 m	
		Flammable area of vapour cloud	259 m		No LOC selected		1 km	
		Blast area of VCE	185 m	High	251 m	Medium	545 m	Low

V. CONCLUSION

Consequence analysis of the LNG leaks has been conducted graphically and numerically for identified LNG release scenarios from storage tank and gas pipes on the typical FLNG facility. In the graphical analysis, the flow charts of consequence analysis and typical sequence of accident scenarios have been drawn for unpressurized LNG release and pressurized LNG. From this analysis, it was found that the type of accident depends on process pressure, phase of release and time of ignition. The main outcomes are the pool fire, jet fire, flash fire, VCE and toxic dispersion .The numerical analysis has been carried out using ALOHA software for the worst release scenarios and the threat zones for heat radiation, blast overpressure and toxic dispersion have been modelled. It is found out that the fire accident is most severe in case of unpressurized LNG release from storage tank and has the greatest threat distance and the human exposure to the thermal loads within it may result in third degree burn and potentially death in 60 second. The risk of heat radiation increases when the release hole size and exposure duration increase. Furthermore, it is discovered that the vapour cloud explosion accident is more risky in the case of pressurized feed natural gas release from pipes in the treatment system. So, it has the greatest threat distance (high risk zone) and the human exposed to blast overpressure within it would be prone to severe head impact and high chance for death. The risk of blast overpressure increases when the degree of compression of the released gas increases. Moreover, the pressurized feed natural gas release from pipes in the treatment system poses the maximum red zone for toxic and flammable vapour cloud dispersion in the downwind direction and will extend to greatest distance due to the initial pressure of the released gas. Cryogenic effects are not modelled by ALOHA software so, further researches are needed for studying risks associated with cryogenic spillage of LNG and estimation of the potential impacts on human and structures.

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