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Containment of Spills on LNG Fuelling Stations – a Critical Evaluation

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According to the international standards ISO 16924, EN 13645 and NFPA 52, LNG fuelling stations need to include a means of containing spilled LNG in order to reduce the possible consequences of a spill. This can be accomplished by placing the LNG-containing installations inside a bund or by draining spills to a retention area remote from the storage area. In some standards, however, an exception to this requirement is provided. The ISO 16924 standard states, for example, that containment of LNG spills from the storage tank and associated equipment is not required if it is demonstrated that the consequences of LNG spills can be safely mitigated without the use of a containment. The EN 13645 standard specifies, on the other hand, that a containment system must only be provided if leaks of flammable liquids are considered to be a possible scenario. As a result of this ambiguity in international standards, local legislation will sometimes prescribe that the construction of a bund or equivalent containment system on LNG fuelling stations is not required, while it is mandatory in other European regions. In this paper, the effectiveness of a bund or containment system on LNG fuelling stations is assessed based on consequence and risk calculations. However, the paper will also point out some pitfalls that occur when using standard risk calculations to assess the effectiveness of safety measures such as a bund.

1. Introduction

For about ten years LNG (liquefied natural gas) has been on the rise as an alternative eco-friendly fuel – replacing diesel – for heavy-duty vehicles. LNG is mostly delivered to fuelling stations by road tankers from nearby import terminals, where LNG is stored at near-atmospheric pressure and at a temperature close to its normal boiling point (-160 °C). Upon arrival at the fuelling station the cold LNG at low pressure (typically 1 barg) is unloaded in a double walled vacuum insulated pressure tank. As most LNG-fuelled vehicles require a fuel supply pressure in the range of 5 to 8 barg (Wiens et al., 2001), there is a need to increase the pressure of the LNG. If the vehicle does not have an on-board system to increase the fuel pressure, the LNG is heated at the fuelling station, thereby increasing the saturation pressure. This process is known as LNG conditioning and the resulting fuel is called ‘saturated LNG’ as opposed to ‘cold LNG’ or ‘unsaturated LNG’. (Sharafian et al. 2017)

There are two main design strategies for LNG conditioning: bulk conditioning and on-the-fly conditioning (Sharafian et al. 2017). Bulk conditioning entails heating the whole inventory of the storage tank immediately after delivery, implying that the LNG is stored at a minimum pressure of 5 barg. When using on-the-fly conditioning, the LNG is stored at lower pressures (1 – 5 barg) and the conditioning is done while delivering fuel to the vehicle. This has the advantage of increasing the holding time and allowing more LNG to be stored in a unit volume.

The difference in LNG storage conditions that may occur at fuelling stations leads to a somewhat ambiguous situation as to whether it is needed to provide containment for LNG spills or not. At high saturation pressures, LNG behaves more like a gas and when released will form a vapour cloud and only small to no pools. Hence, there may be no need to contain any spills. At low saturation pressures, however, LNG behaves more like a volatile liquid and when spilled will form an evaporating pool.

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This ambiguity is reflected in the international standards. NFPA 52 (2016) states that retention of spilled LNG within the limit of the plant property is needed for ASME tanks containing saturated LNG (2.45 barg and above). For other aboveground or mounded LNG tanks, a bund is needed. ISO 16924 (2016) states that “LNG fuelling stations shall include a means of containing spilled LNG in order to reduce the consequences of a spill.” Containing the spill can be accomplished by placing the LNG-containing installations inside a bund or by draining spills to a retention area remote from the storage area. If, however, it is demonstrated that the consequences of LNG spills can be safely mitigated without the use of a containment, the containment can be omitted. In the Netherlands, the guidance given in PGS 33-1 (2013) is that it is not needed to place a bund around the LNG storage tank as placing a bund would not lower the risk. This guidance was based on calculations of the rain-out in case of an LNG release. The assumptions underlying these calculations are, however, not documented.

This paper addresses the question if and how placing a bund around the storage tank influences the risk of an LNG fuelling station. First, the influence of the storage and release conditions on the calculated rain-out fraction is studied. Next, effect distances and risk profiles are calculated for different storage and release conditions, both with and without a bund placed around the storage tank.

2. Parameters influencing the LNG rain-out fraction and pool formation

When a liquefied gas is released, it will break up in liquid droplets. These droplets will partly evaporate. The release, thus, leads to the formation of a two-phase jet, comprised of vapour and liquid droplets. Typically, the larger droplets will rain-out while the smaller ones remain airborne (VROM, 2005). The vapour mass is called the flash fraction, whereas the liquid mass is divided between the rain-out fraction and the spray fraction. When considering the need for a bund, knowledge of the rain-out fraction is indispensable since the size of a pool is directly related to the rain-out fraction.

The amount of rain-out from a two-phase release of a gas liquefied by cooling it to sub-ambient temperatures (such as LNG) depends upon a number of parameters, the most important of which are summarised in Table 1. Obviously, an increase in storage temperature and pressure will lead to a reduction of the amount of rain-out as more of the liquefied gas will flash at higher temperatures. For the same reason, a release from a storage tank through a long, uninsulated pipe will lead to less rain-out as the product flowing through the pipe is heated and therefore is released at a higher temperature than the storage temperature. An increase in the release height will lead to less rain-out since more time is available for the droplets to evaporate before hitting the ground. Similarly, a horizontal release will lead to less rain-out than a release directed towards the ground. Finally, if the release is directed towards a wall (or another obstacle) there will be more rain-out than when the release is unobstructed. This is borne out by experiments (Cleaver et al., 2007).

Table 1: Expected influence of different release parameters on rainout fractions and pool sizes

Release parameter	Extent of the rain-out fraction and pool formation
Storage temperature and pressure (↑)	↓
Length of release pipe (↑) and degree of insulation (↓)	↓
Release height (↑)	↓
Release direction, downward angle from horizontal plane (↑)	↑
Presence of obstacles in release direction (↑)	↑

When doing a quantitative risk analysis (QRA), the rain-out fraction can be estimated by using a variety of methods. In some of these methods, such as the one described by the Flemish QRA guidelines (Handboek Risicoberekeningen, 2017), the flash fraction is calculated first and subsequently the rain-out fraction is calculated from the flash fraction by using a predefined function. Different functions can be used for instantaneous and continuous releases. When using these methods, the rain-out fraction is mainly determined by the ‘thermodynamic’ release conditions (temperature and pressure). The results of calculating the rain-out fraction for different storage conditions and for both instantaneous and continuous releases following the Flemish QRA guidelines are given in Table 2.

Table 2: LNG rain-out fractions as function of the storage conditions and the extent of the release [%]

Failure type	Release conditions	saturated LNG @ 1 barg	saturated LNG @ 3 barg	saturated LNG @ 5 barg	saturated LNG @ 7 barg
Instantaneous release	n/a	87.4	70.4	56.9	46.7
Continuous release	n/a	67.6	30.0	5.5	0

Other methods take the complex behaviour of the liquid jet into account by including models for the break-up of the jet into droplets, the motion of these droplets under the influence of drag and gravity, and their simultaneous evaporation. One of these methods is the 'trajectory' method of DNV in which the mass of a liquid droplet is calculated along its trajectory. The part of the initial droplet that hits the ground determines the rain-out fraction (Witlox et al., 2014). When using this method, the rain-out fraction is determined by many factors in addition to the thermodynamic release conditions, such as the release height and orientation (horizontal or vertical) and the presence of obstacles (obstructed or unobstructed flow). The obvious advantage of the more complex methods is that they can more accurately predict the rain-out when the precise conditions of the release are known. The rain-out fractions are calculated by using Phast 7.2. Calculations are done for different failure types, different storage pressures and two meteorological conditions, namely stability class D and 5.0 m/s wind speed (D5) and stability class F and 2.0 m/s wind speed (F2). Different release conditions are considered, namely releases at 0 m, at 1 m directed downwards (1 m ↓), at 1 m directed horizontally obstructed (1 m →|) and unobstructed (1 m →). The results are given in Table 3.

Table 3: LNG rain-out fractions as function of the storage and release conditions (Phast 7.2) [%]

Failure type	Release conditions	saturated LNG @ 1 barg		saturated LNG @ 3 barg		saturated LNG @ 5 barg		saturated LNG @ 7 barg	
		D5	F2	D5	F2	D5	F2	D5	F2
Catastrophic rupture	n/a	87.6		70.3		56.1		45.2	
Release of full content in 10 min.	0 m or 1 m ↓	93.8	93.8	86.8	86.8	82.2	82.2	78.7	78.7
	1 m →|	74.2	80.0	30.0	40.9	0	9.8	0	0
	1 m →	14.8	22.7	0	0	0	0	0	0
Leak (50 mm)	0 m or 1 m ↓	93.8	93.8	86.8	86.8	82.2	82.2	78.7	78.7
	1 m →|	58.8	70.5	9.9	26.4	0	0	0	0
	1 m →	0	5.85	0	0	0	0	0	0
Leak (10 mm)	0 m or 1 m ↓	93.8	93.8	86.8	86.8	82.2	82.2	78.7	78.7
	1 m →|	0	22.4	0	0	0	0	0	0
	1 m →	0	0	0	0	0	0	0	0

3. Influence of release conditions and containment on maximum effect distances

As the storage conditions and the circumstances of the release can have an impact on the rain-out fraction and the pool formation, they can also affect the calculated consequences of the possible incident outcomes. This is illustrated below for the scenario of a 50 mm leak on a vertical LNG storage tank with a volume of 80 m³. In the event of an LNG release, the possible incident outcomes are: a pool and/or jet fire in case of an immediate ignition, and a flash fire or vapour cloud explosion (VCE) in case of a delayed ignition.

For the 50 mm leak scenario, the maximum effect distances for the various incident outcomes are calculated. Calculations are done for different storage pressures, ranging from 1 to 7 barg, and for two meteorological conditions, namely stability class D and 5.0 m/s wind speed (D5) and stability class F and 2.0 m/s wind speed (F2). The calculations are done in accordance with the Flemish QRA guidelines with one exception: since we want to study the influence of the release circumstances on the rain-out fraction and the pool formation, the rain-out is calculated by means of the trajectory method. Two different release orientations are considered, namely horizontally and vertically downwards both at 1 m height. The results are presented in Table 4 for a storage tank without a bund.

Table 4: Maximum effect distances for a 50 mm leak on a 80 m³ LNG[1] storage tank (without a bund) [m]

Assumptions about rain-out	Incident outcome	saturated LNG @ 1 barg		saturated LNG @ 3 barg		saturated LNG @ 5 barg		saturated LNG @ 7 barg	
		D5	F2	D5	F2	D5	F2	D5	F2
Droplet Trajectory model (1 m →)	Pool fire	-	-	-	-	-	-	-	-
	Jet fire	80	90	90	105	95	110	100	115
	Flash fire	60	115	70	115	75	125	80	130
	VCE	140	245	165	245	175	260	185	265
Droplet Trajectory model (1 m ↓)	Pool fire	120	125	125	130	130	135	130	135
	Jet fire	-	-	-	-	-	-	-	-
	Flash fire	40	110	60	155	70	180	80	200
	VCE	100	240	140	310	160	345	180	370

[1] The consequences have been calculated with pure methane, being the main component of LNG.

It is seen that the maximum effect distances increase with an increasing pressure in the LNG storage tank. This is mainly caused by the higher outflow rate at higher storage pressure. For neutral atmospheric conditions (D5) the maximum effect distances are the largest for a horizontal unobstructed release. For very stable atmospheric conditions (F2), however, the maximum effect distances of a downward impinging release – resulting in the formation of a boiling pool – extend beyond those of a horizontal emission.
In Table 5, the results are presented for a storage tank placed in a bund with a (net) surface area of 100 m².

Table 5: Maximum effect distances for a 50 mm leak on a 80 m³ LNG[1] storage tank (in a 100 m² bund) [m]

Assumptions about rain-out	Incident outcome	saturated LNG @ 1 barg		saturated LNG @ 3 barg		saturated LNG @ 5 barg		saturated LNG @ 7 barg	
		D5	F2	D5	F2	D5	F2	D5	F2
Droplet Trajectory model (1 m →)	Pool fire	-	-	-	-	-	-	-	-
	Jet fire	80	90	90	105	95	110	100	115
	Flash fire	60	115	70	115	75	125	80	130
	VCE	140	245	165	245	175	260	185	265
Droplet Trajectory model (1 m ↓)	Pool fire	55	55	55	55	55	55	55	55
	Jet fire	-	-	-	-	-	-	-	-
	Flash fire	25	50	40	80	50	95	55	105
	VCE	60	115	90	155	105	175	120	195

[1] The consequences have been calculated with pure methane, being the main component of LNG.

Since the trajectory model predicts little to no rain-out for a horizontal unobstructed release of LNG at a height of 1 m, the containment system will have no impact on the calculated effect distances. For a downward impinging release, however, calculations with the trajectory model result in large rain-out fractions (see Table 3) and consequently large boiling pools regardless of the LNG storage conditions. By restricting the pool size, the consequences of the incident outcomes will be reduced. This is seen from a comparison of the results shown in Tables 4 and 5. The calculated effect distances for the situation with a bund are about 1.5 to 2.5 times lower than those for the situation without a bund.

4. Influence of a containment system on the calculated human risk

In various European countries, the human risks posed by installations with large quantities of hazardous substances are calculated by means of a quantitative risk analysis (QRA) and evaluated against predefined risk criteria. In QRA studies, different loss of containment (LOC) scenarios are taken into account, ranging

from the catastrophic rupture of a storage tank to small leaks in the tank. For each LOC scenario, the consequences of all possible incident outcomes are determined. In order to limit the number of incident scenarios and the accompanying calculations, specific assumptions are made in the development of the scenarios that are expected to result in a conservative risk profile. When analysing the risk of storage tanks for flammable liquefied gases, the risks are mostly calculated for the highest storage temperature and pressure occurring in practice. Moreover, leaks are modelled as unobstructed horizontal releases through a hole at 1 meter above the ground. These assumptions result in high flow rates and small rain-out fractions for which it is expected that the risks at larger distances are the highest. However, when QRA results are used to assess the effectiveness of a safety measure such as a containment, one must be aware that the assumptions made in the QRA are not representative for all incident circumstances that may actually occur.
To illustrate this, risk calculations are done in accordance with the Flemish QRA guidelines for an 80 m³ vertical storage tank containing LNG at two different storage pressures, namely 1 and 7 barg. The calculations are done on the one hand using the assumption of an unobstructed horizontal release at 1 m and on the other hand using the assumption of a downward release at 1 m impinging on the ground. The results are presented in Figures 1 and 2, respectively.
The risk profiles calculated for the unobstructed horizontal release indicate that the presence of a bund or containment system has no risk-reducing effect for the storage of LNG at high saturation pressures. For the storage of LNG at low saturation pressures, the bund has a limited risk-reducing effect (reduction factor: 1.1 – 1.5) at large distances from the tank (100 – 200 m). The risk profiles calculated for the downward impinging release, however, indicate that the presence of a bund or containment system also has a relevant risk-reducing effect (reduction factor: 1.4 to 1.9) at distances of 35 to 70 m from the storage tank, regardless of the LNG saturation pressure.

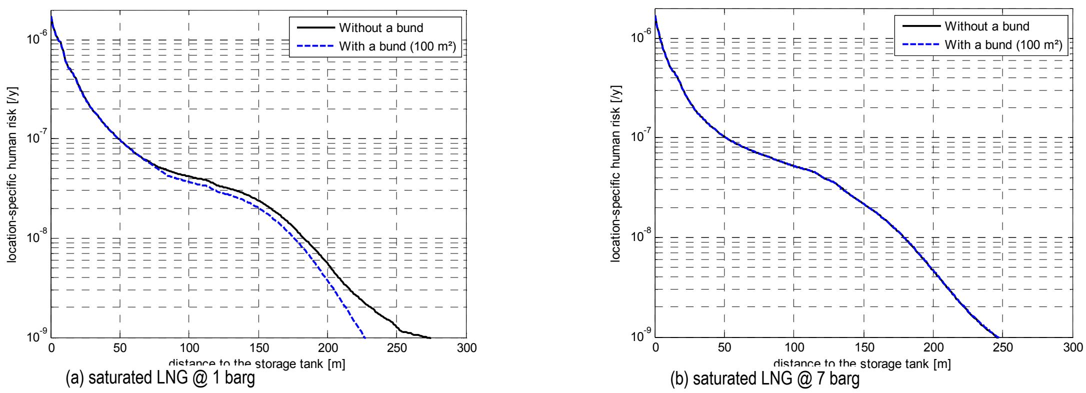

Figure 1: Calculated location-specific human risk profiles for an 80 m³ LNG storage tank with and without a bund containing LNG at a saturation pressure of 1 and 7 barg, assuming a horizontal unobstructed release.

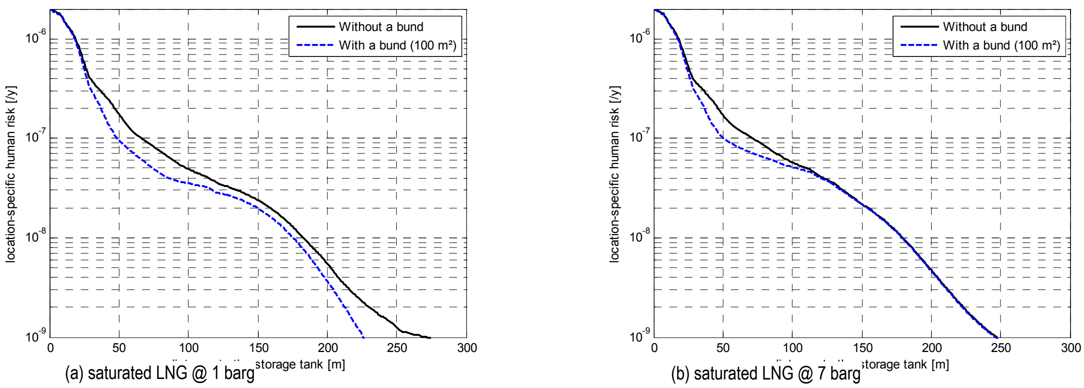

Figure 2: Calculated location-specific human risk profiles for an 80 m³ LNG storage tank with and without a bund containing LNG at a saturation pressure of 1 and 7 barg, assuming a downward impinging release.

5. Conclusions

It is concluded that for LNG fuelling stations with bulk conditioning where the LNG is stored at relatively high pressures placing a bund around the storage tank will only have a limited impact on the calculated human risk. For LNG fuelling stations with on-the-fly conditioning the impact on the human risk is expected to be larger.
More generally, it is concluded that care should be taken when assessing the effectiveness of risk reducing measures based on the results of a QRA using a narrow set of release scenarios. For some release scenarios, such as incidents resulting in downward releases of LNG impinging on the ground, it is found that a bund will reduce the risk at small distances from the storage tank. Hence, if it is expected that many people will be present on or in the immediate neighbourhood of the LNG fuelling station, placement of a bund will reduce the risk for these people and, therefore, is recommended.

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