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Safety of Cryogenic Storage Facilities of Flammable Gases

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In recent years, cryogenic storage of flammable gases spread beyond conventional applications. Actually, besides large-scale cryogenic transport by ship, loading/unloading and bulk storage, a number of smaller scale applications are proposed, in particular for liquefied natural gas (LNG). However, this growth comes with safety concerns arising from the flammable nature of natural gas and the amounts of this hazardous material stored and processed in LNG facilities. A long-lasting experience is present in the chemical industry concerning the medium and small-scale cryogenic storage of flammable gases as e.g. ethylene and propylene. In the present study, the operating experience deriving from such technologies is used as a basis to assess the safety of new supply chains based on small-scale storage of LNG and other cryogenic fuels. Preliminary hazard identification studies were used to identify credible accident scenarios. Based on current industrial practice and on proposed new installations, reference technologies were defined and considered in the study. A comparative analysis of the relevance and severity of reference accident scenarios was carried out. Safety key performance indicators based on the concept of inherent safety were defined, providing a simplified tool to support safety assessment and emergency response in cryogenic storage facilities.

1. Introduction

The limitation of pollutant emission related to navigation activities has favoured the use of alternative fuels; in particular LNG is a promising candidate for replacing fuel oil in specific sensitive areas subject to emission control (Baresic et al., 2018). The development of a small-scale distribution grid for LNG is a required step in order to foster the use of LNG as a fuel. This kind of installations are likely to be constructed in proximity of populated areas, such as coastal or harbour zones mainly due to logistic needs (e.g. ease of supply, access to main routes, etc.). As a result of heightened public concern, LNG onshore siting is strictly regulated, see e.g. NFPA 59A (NFPA, 2016). As outlined in a previous work (Tugnoli et al., 2010), the societal acceptability of newly-built storage and distribution facilities requires a proof that risk for population and environment is negligible.

However, a long-lasting experience is present in the chemical industry concerning the medium and small-scale cryogenic storage of flammable gases. For instance, storage, handling and transportation of refrigerated ethylene is a well-established industry practice that can be taken as a reference when considering risk mitigation solutions for cryogenic processes. A number of guidelines and recommendations concerning cryogenic ethylene have been issued, see (EIGA, 2017).The assessment of safety performance for process installations can be performed using a risk-based approach, also useful to support design solutions and to take into account accident scenarios that may arise when processing hazardous cryogenic substances, as illustrated in (Paltrinieri et al., 2011).

The aim of this work is to evaluate the inherent safety level of small-scale onshore LNG installation and compare the results with existing industrial ethylene storage plants. Possible accident scenarios were identified following a preliminary hazard analysis. A consequence-based methodology was used to produce an inherent safety score of the considered installation, then the possibility of accident escalation (Landucci et al., 2013) was questioned considering equipment damage thresholds for consequence assessment and

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calculating dedicated performance indicators that were used to quantify domino events impact for the evaluated cryogenic facilities.

2. Methodology

2.1 Overview

The methodology described allows the application of a consequence-based approach for the comparison of the inherent safety performance of different cryogenic onshore installations. Main concepts behind this approach are adapted from a previous work (Tugnoli et al., 2007). A set of key performance indicators (KPIs) was defined, based on results obtained from consequence assessment, providing an effective and reliable metric for the comparison. Flowchart reported in Figure 1 summarizes the main steps of the methodology.

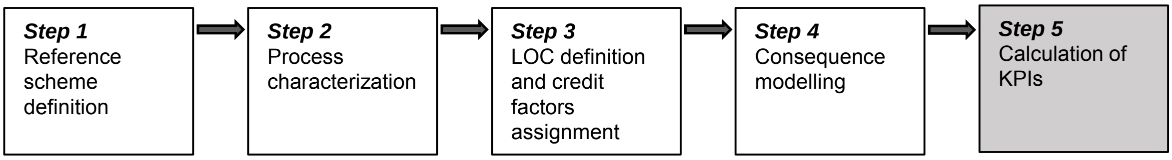

Figure 1: Proposed methodology flowchart

The first step is the definition of a reference process scheme representative for the small-scale onshore installation, outlining the required process units and the facility layout. Then, process data are gathered for each assessed unit, defining hazardous substance physical state and quantity present at the facility. Once having defined all process equipment needed, possible accident scenarios are identified following an event tree analysis: the initiating release events and the relevant frequencies (expressed by a credit factor) are defined on the basis of suggestions from recognized technical literature (Uijt de Haag and Ale, 2005). A damage distance is then calculated using well-known consequence analysis models, as those proposed by (Van Den Bosh and Weterings, 2005): the maximum distance at which dangerous effects threshold values (such as those proposed by national laws) are reached is the input for the following KPI calculation.
The set of indicators adopted in this work includes two main categories of indices, depending on the damage target considered:

1. Human hazard indicators,
2. Escalation hazard indicators.

The first category reflects hazards affecting plant operators and/or residential population, since damage distances are calculate using threshold values for humans, specifically intended for this purpose. The second group considers domino effect thresholds for the accidental scenario outcomes considered (Landucci et al., 2008). As reported in details in (Landucci et al., 2008), a potential hazard index and an inherent hazard index are defined. The first one expresses the maximum area that can be affected by the worst-case scenario dangerous effects originating from the i-th process unit, while the latter introduces the impact of the loss of containment event frequencies. Table 1 reports a summary of considered indicators, together with their definition.

Table1: Summary of considered key performance indicators

Indicator	Units	Equation	Target	Eq.
Unit Potential hazard	m^2	$UPI_i = \max_j(h_{i,j}^2)$	Human	(1)
Unit Inherent hazard	m^2/y	$UHI_i = \sum_{j=1}^{n_i} Cf_{i,j} \cdot h_{i,j}^2$	Human	(2)
Overall Potential hazard	m^2	$PI = \sum_i UPI_i$	Human	(3)
Overall Inherent hazard	m^2/y	$HI = \sum_i UHI_i$	Human	(4)
Unit Potential Escalation hazard	m^2	$UPE_i = \max_j(e_{i,j}^2)$	Equipment	(5)
Unit Inherent escalation hazard	m^2/y	$UHE_i = \sum_{j=1}^{n_i} Cf_{i,j} \cdot e_{i,j}^2$	Equipment	(6)
Overall Potential escalation hazard	m^2	$PE = \sum_i UPE_i$	Equipment	(7)
Overall Inherent escalation hazard	m^2/y	$HE = \sum_i UHE_i$	Equipment	(8)

The damage distance calculated for the j-th LOC of the i-th process unit considered is represented by ($h_{i,j}$), while $Cf_{i,j}$ is the credit factor of the j-th LOC event, and n_i is the number of LOCs considered for the i-th unit.

The overall values of the above-mentioned indicators are obtained summing over all process units identified for the considered reference scheme, as expressed by Equations 3 and 4 in Table 1. Similarly, the escalation KPIs are defined as indicated by Equations 5 and 6 in Table 1. The escalation vector ($e_{i,j}$) contains the domino damage distances calculated. Subscripts have the same meaning as for the human target KPIs.

3. Definition of the case study

3.1 Process description

The case study proposed in this paper covers a small-scale onshore terminal located in a coastal area. This facility can receive the liquefied gas directly from carriers thanks to a 2 km dedicated cryogenic pipeline installed on a jetty. The terminal features four tanker truck loading bays that can provide an overall loading capacity of 240 m^3/h. Liquefied gas is transferred using 3" diameter loading arms. Seven total containment cryogenic pressure vessels allow an overall storage capacity of 10,000 m^3 of cryogenic liquid. These tanks are connected with a 16" manifold and to a distribution pipeline which serves the loading bays. Cryogenic pumps and a boil-off gas (BOG) re-liquefaction system are also present. A simplified process flow diagram of the considered onshore facility is shown in Figure 2.

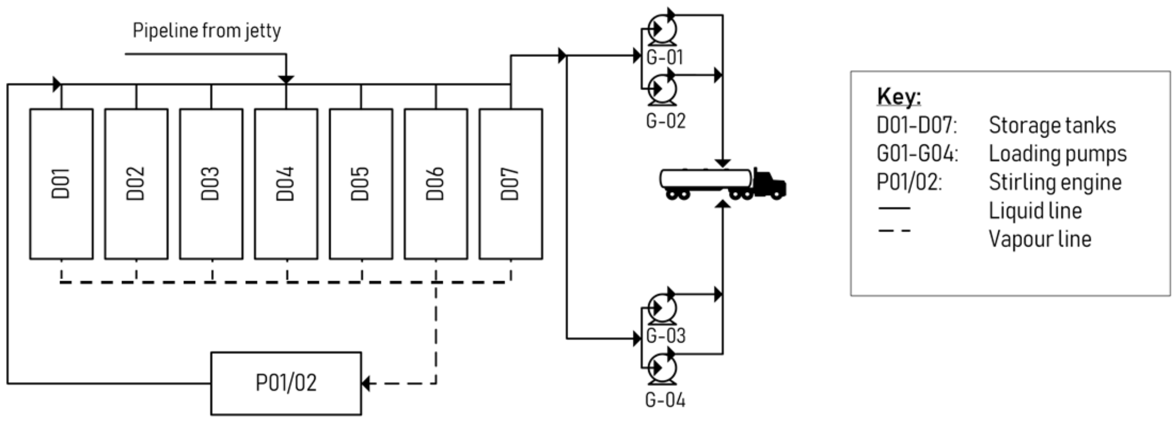

Figure 2: Simplified scheme considered for onshore storage & distribution facility. Continuous lines represent liquid pipelines, dashed ones are vapour lines associated with the BOG.

As mentioned in Section 1, two different substances, i.e. LNG and ethylene, have been considered as stored fluid for the small-scale terminal shown in Figure 2. Table 2 and Table 3 show the operating conditions implemented for the LNG and the ethylene case studies, respectively.

Table 2: Process conditions considered for LNG onshore terminal. For unit tags refer to Figure 2.

Parameter	Unit					
	Jetty pipeline	Storage tank D01 – D07	Tank manifold	Loading bay pipeline	Loading bay transfer arm	BOG pipeline
Inventory (kg)	-	648,648	-	-	-	-
Flow-rate (kg/s)	1,543	-	30.57	7.63	7.63	0.15
Pressure (MPa)	0.50	0.45	0.45	0.70	0.70	0.45
Temperature (K)	114	130	128	129	129	135
Nominal diameter (mm)	914.4	-	406.4	101.6	76.2	254.0
State	Liquid	Liquid	Liquid	Liquid	Liquid	Vapour

Table 3: Process conditions considered for ethylene onshore terminal. For unit tags refer to Figure 2

Parameter	Unit					
	Jetty pipeline	Storage tank D01 – D07	Tank manifold	Loading bay pipeline	Loading bay transfer arm	BOG pipeline
Inventory (kg)	-	746,031	-	-	-	-
Flow-rate (kg/s)	1,842	-	34.78	8.38	8.38	0.16
Pressure (MPa)	0.50	0.45	0.45	0.70	0.70	0.45
Temperature (K)	180	199	197	198	198	205
Nominal diameter (mm)	914.4	-	406.4	101.6	76.2	254.0
State	Liquid	Liquid	Liquid	Liquid	Liquid	Vapour

3.2 Definition of hazardous scenarios

A selection of loss of containment (LOC) events was considered following guidance provided by technical literature (Uijt de Haag and Ale, 2005). Each LOC event is associated with a credit factor that represents the frequency of occurrence of the considered release for a specific process unit. Frequency values were retrieved from technical literature (Uijt de Haag and Ale, 2005) and release frequency database (IOGP, 2010). Release frequency for the tanker truck loading arm (expressed in events per hour) was multiplied by the yearly operational hours of all the four loading bays (estimated in a total of 14000 hours per year), in order to consider the simultaneous use of all the bunker lots.

Depending on the category of evaluated process units, the release events reported in Table 4 were deemed possible.

Table 4: Definition of LOC events

LOC	Description
R1	Small leak, continuous release from a 10 mm equivalent diameter hole
R2	Catastrophic rupture, release of the entire inventory in 600 s
R3	Catastrophic rupture, instantaneous release of the entire inventory and release from the full-bore feed pipe
R4	Pipe leak, continuous release from a hole having 10% of pipe diameter
R5	Pipe rupture, continuous release from the full-bore pipe

The final dangerous outcomes originating from the considered release events were obtained performing an event tree analysis and following suggestion by (Vílchez et al., 2011). Dangerous scenarios evaluated in the present study were pool, jet, and flash fires, in addition to vapour cloud explosions (VCE). The latter scenario has been considered to account for the presence of potentially congested areas on small scale terminals, where confinement can result from the limited space available and may induce flame acceleration (Van Den Bosh and Weterings, 2005).

3.3 Consequence assessment

Accident scenario consequences were evaluated implementing well known integral models for the estimation of physical effects (Van Den Bosh and Weterings, 2005). The consequence modelling of hazardous LNG scenarios was carried out disregarding mixture composition, i.e. considering natural gas as pure methane, to avoid results variability. The cryogenic pipeline used for cargo ships unloading operations has a total length of approximately 5 km. Despite this, consequence evaluation for this piece of equipment only focused on the aboveground pipeline section, which is the one on the jetty, placed at a distance of about 3 km from the tank farm.

Damage distances refer to the worst case among that from the Pasquill weather categories 2F and 5D, that are typically considered in risk assessments. Release sources were set at 1 m height and modelled as non-impinging horizontal. Cryogenic liquid pool evaporation rates were calculated using available pool evaporation sub models; the resulting vapour cloud was used to estimate flash fires and VCE consequences. Explosions outcomes were estimated using the simplified approach provided by the TNT equivalency model (Van Den Bosh and Weterings, 2005), accounting for the different substance reactivity by changing the explosion efficiency parameter. According to what suggested by (Health and Safety Executive, 1986), explosion efficiency for natural gas was considered equal to 3%, whereas VCE resulting from ethylene were modelled using 6% efficiency.

4. Results and discussion

4.1 Inherent safety assessment

An overview of inherent safety KPIs estimated considering the physical effects on humans is given in Tables 5 and 6, respectively for LNG and ethylene. Among the LNG terminal units, jetty pipeline shows the largest values for both UPI and UHI (see Table 5). Instead, for the ethylene case, UPI value for storage tanks results the highest among all process equipment considered, while the jetty pipeline is still deemed as critical due to the highest value of UHI (Table 6). The relevant value of inherent hazard index for the jetty pipeline is mainly related to the combination of high credit factor and wide damage distances. The relative weight of the different accident scenarios considered over inherent human and escalation hazard is shown in Figure 3a. Flash fires and VCEs are the sole scenarios contributing to the overall value of HI. In particular, flash fires give the higher contribution in the LNG terminals, while VCEs consequences play a limited role. This trend is inverted when considering ethylene facility as a result of the higher severity of VCE, due to the higher ethylene reactivity.

*Table 5: Results of consequence assessment and calculated KPIs for LNG onshore facility. Values marked with a * were not considered for calculation of escalation KPIs.*

Unit	LOC	$Cf_{i,j}$ (1/y)	$h_{i,j}$ (m)	$e_{i,j}$ (m)	UPI (m^2)	UHI (m^2/y)	UPD (m^2)	UHD (m^2/y)
Storage tanks D01 - 07	R1	1.00×10^{-5}	48.08	44.21	5.43×10^{6}	5.07	4.55×10^{6}	2.84
	R2	5.00×10^{-7}	2,161	2,134				
	R3	5.00×10^{-7}	2,330	1,040				
Jetty pipeline	R4	1.00×10^{-3}	308.40	291.43*	6.96×10^{6}	1,487	-	-
	R5	2.00×10^{-4}	2,638	2,625*				
Tank manifold pipeline	R4	2.50×10^{-5}	248.74	239.13	1.58×10^{5}	2.34	1.54×10^{5}	2.20
	R5	5.00×10^{-6}	397.62	391.86				
Pipeline to loading bay	R4	2.00×10^{-4}	57.40	55.15	5.49×10^{4}	2.31	5.10×10^{4}	2.14
	R5	3.00×10^{-5}	234.37	225.85				
Loading bay arm	R4	4.15×10^{-3}	44.51	43.39	5.49×10^{4}	31.00	5.10×10^{4}	28.96
	R5	4.15×10^{-4}	234.37	225.85				
BOG pipeline	R4	5.00×10^{-6}	19.79	11.78	2.88×10^{5}	0.29	2.76×10^{5}	0.28
	R5	1.00×10^{-6}	536.45	524.93				

*Table 6: Results of consequence assessment and calculated KPIs for ethylene onshore facility. Values marked with a * were not considered for calculation of escalation KPIs.*

Unit	LOC	$Cf_{i,j}$ (1/y)	$h_{i,j}$ (m)	$e_{i,j}$ (m)	UPI (m^2)	UHI (m^2/y)	UPD (m^2)	UHD (m^2/y)
Storage tanks D01 - 07	R1	1.00×10^{-5}	76.03	72.05	6.83×10^{6}	5.66	6.72×10^{6}	5.37
	R2	5.00×10^{-7}	2,613	2,593				
	R3	5.00×10^{-7}	2,094	1,979				
Jetty pipeline	R4	1.00×10^{-3}	359.55	334.85*	4.56×10^{6}	1,040	-	-
	R5	2.00×10^{-4}	2,134	2,108*				
Tank manifold pipeline	R4	2.50×10^{-5}	288.25	239.13	8.94×10^{5}	6.55	4.67×10^{5}	3.77
	R5	5.00×10^{-6}	945.54	683.72				
Pipeline to loading bay	R4	2.00×10^{-4}	70.24	67.7	8.27×10^{4}	3.47	7.33×10^{4}	3.12
	R5	3.00×10^{-5}	287.55	270.79				
Loading bay arm	R4	4.15×10^{-3}	88.15	83.64	8.27×10^{4}	66.52	7.33×10^{4}	59.42
	R5	4.15×10^{-4}	287.55	270.79				
BOG pipeline	R4	5.00×10^{-6}	21.20	12.42	3.58×10^{5}	0.36	3.38×10^{5}	0.34
	R5	1.00×10^{-6}	598.42	581.44				

4.2 Accident escalation assessment

The evaluation of domino-potential consequences was performed disregarding all dangerous scenarios not capable to affect the tanks with hazardous radiation levels. In particular, all the accidental events investigated for the jetty pipeline were not able to affect the storage tanks; hence, they were not taken into account for calculation of the escalation indices. Tables 5 and 6 report the results of the analysis for the LNG and ethylene, respectively. On the basis of results, loading bay arms are deemed as critical units, in terms of inherent escalation hazard, due the high frequencies of loss of containment, although the escalation distances are not particularly extended. Considering only the maximum affected area, storage tanks are characterized by the highest values of unit potential escalation index for both the LNG and ethylene case. Considering the contribution of the single scenarios on the overall inherent escalation index, VCE scenarios account for the totality of HD index scores, due to large escalation distances. A minor contribution is related to jet fires for the ethylene facility, as can be seen in Figure 3b.

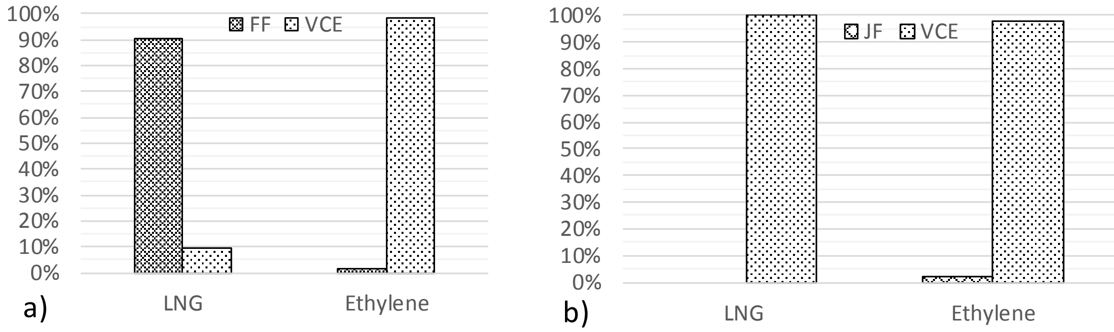

Figure 3: Accident scenario contribution for HI (a) and HD (b) indices. FF= Flash fire; JF= Jet fire; VCE= Vapour cloud explosion.

5. Conclusion

An inherent safety comparison of cryogenic substance storage and distribution facilities was made. A consequence-based method was implemented in order to calculate performance indicators. The aim was to identify the criticalities that need to be further investigated during the design stages. Comparison of an ethylene terminal with an equivalent LNG facility shows a lower safety performance of the former. The analysis of critical equipment identifies the loading bay transfer arms as most critical units. The presented method may serve as first guidance for addressing further accident escalation studies, highlighting the dangerous scenarios that may impact over storage tanks or tanker trucks. A further step, representing an important contribution for safety studies, may be the integration of the proposed methodology with computational models for prediction of thermal and mechanical response of fire-exposed vessels (Landucci et al., 2013).

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