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LNG regasification terminals: comparing the inherent safety performance of innovative technologies

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This study is aimed at the preliminary exploration of the safety performance of alternative technologies for LNG regasification terminals. Reference technologies applicable to on-shore and off-shore terminals are identified and reference schemes are defined. The potential hazards associated with the alternative technologies are assessed by the identification of the possible failure and consequence chains relevant for each unit. The definition and the application of leading KPIs was applied to assess emerging risks linked to alternative lay-outs and process schemes.

1. Introduction

The introduction of new LNG technologies in the current energy market allows for pursuing key goals as the diversification of the import sources, the exploitation of new productive fields, and the flexibility of the demand. The development of LNG terminals is of particular interest in countries, as Italy, that mainly depend on energy importation and which, due to favorable geographic positions, may become an import hub for gas distribution in nearby territories. More in general, the security of the supply, where the diversification of the sources plays an important role, is a key issue for the energy future of the entire Europe, which currently imports more than 50% of the natural gas. Presently, 13 LNG receiving terminals are operating all throughout EU, and approximately 20 more are currently planned or under construction. New technologies, mainly related to advanced floating and off-shore LNG terminals are now tackling the market of the new regasification plants.

Safety performance of the regasification plants is a core issue in the design and location of the facilities. Moreover, societal acceptability of these installations largely depends on the ability to soundly prove the negligible risk for the population and the environment. Especially with respect to new and emerging risks related to advanced technologies (e.g. floating or off-shore installations), these were not systematically explored to date, though the hazards associated to these installations is highly perceived as critical by the population.

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The current contribution introduces an approach to the systematic assessment and critical comparison of the safety and security issues related to new and existing technologies. Reference technologies applicable to on-shore and off-shore terminals were identified. Reference schemes were defined for each technology. The potential hazards associated with the alternative technologies were assessed by the identification of the possible failure and consequence chains relevant for each unit. The analysis of the expected consequences by conventional model runs allowed for the evaluation of reference severity values of possible accident scenarios. The definition and the application of leading Key Performance Indicators (KPIs) may allow a breakthrough in the assessment of emerging risks and in the identification of inherently safer solutions.

2. Definition of reference schemes for technologies

LNG regasification terminals may be classified depending on the facility set-up:

- On-shore terminals
- Off-shore gravity based structures (GBS)
- Off-shore floating storage and regasification units (FSRU)

The on-shore LNG regasification is currently the most common and developed technology (figure 1). This kind of plant is located nearby to the sea, usually within a seaport area. It basically consists of a docking area, supplied with loading/unloading arms, and of storage tanks, where LNG is temporarily stored. Pumping and vaporization equipment allow the LNG evaporation and the feed to high pressure transport pipeline systems (Tusiani and Shearer, 2007).

A more innovative technology is the off-shore gravity based structure. The first terminal applying this technology is currently in a start-up phase in Italy, while a few other are in design stage around the world (Adriatic LNG). It constitutes of a large concrete structure, which houses two self-supporting prismatic storage tanks, and includes a regasification plant on the deck with open rack vaporizers.

Finally, an effective alternative to this last technology are off-shore floating storage and regasification units (FSRU). This kind of terminal is obtained converting a LNG carrier by the installation of vaporization skids and of a connection to a sealine for natural gas export. One of the advantages is the independence from the sea bed, which provides an increased operational flexibility. Several projects concerning this set-up are currently under design. For this terminal Moss sphere tanks and intermediate fluid vaporizers are considered in the present study, although membrane storages may also be used.

Table 1 Reference set-ups considered for the LNG terminals

	On-shore	**Off-shore GBS**	**Off-shore FSRU**
Development stage	Operational	Start-up	Design
Potentiality (Nm^3/y)	$3.5*10^9$	$7.6*10^9$	$3.7*10^9$
Storage size (m^3)	2x 50,000	2x 125,000	4x 35,000
Storage tank technology	Double containment	Self-supporting prismatic	Kvaerner/Moss-Rosenberg
Vaporizer technology	SCV (Submerged Combustion Vap.)	ORV (Open Rack Vaporizers)	IFV (Intermediate Fluid Vaporizers)

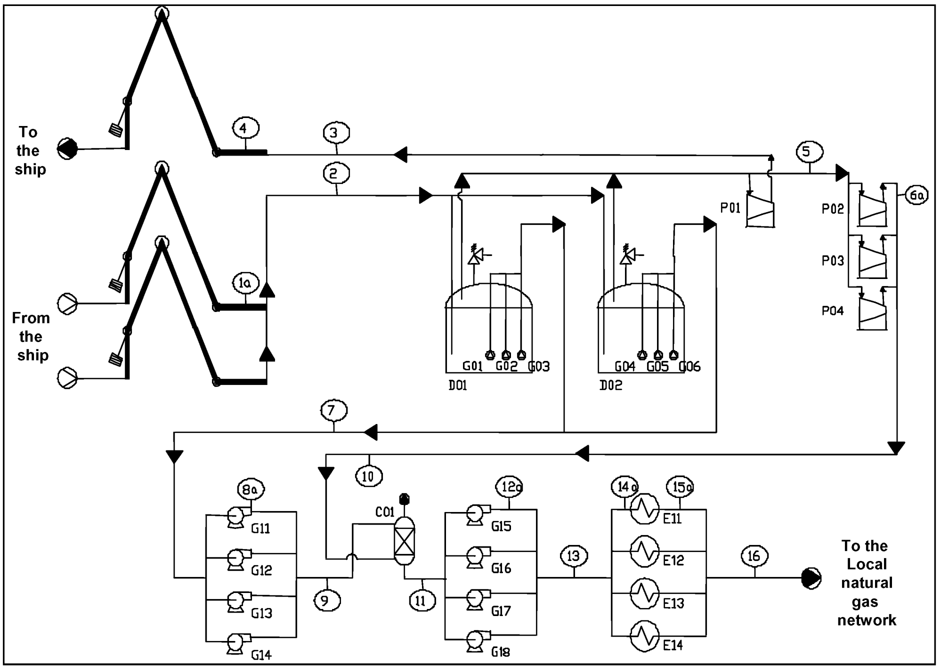

Figure 1. On-shore regasification technology scheme process.

For each of the above technologies a reference process scheme was defined (Table 1). Since the regasification process and storage conditions are substantially the same in all the set-ups, they differ mainly in the application of specific technologies to some pieces of equipment (e.g. storage tank, vaporizer, etc.). Thus a description of the regasification process can be inferred from the scheme in Figure 1. LNG is shipped by LNG carriers as a cryogenic liquid at about -160°C. At the terminal, the LNG is transferred by unloading arms (line 1a) to the storage tanks (D01-D02), where it is stored at the same cryogenic conditions of carrier (-160°C and pressure slightly above the atmospheric).
BOG management represents an important aspect of the terminal. During LNG unloading operations, the BOG is transferred to the ship by the BOG return arm (line 4), to avoid vacuum depressurization of carrier tanks. During normal operating conditions, BOG is collected and recovered at the recondenser (C01). In the recondenser, the BOG is contacted with LNG from a first pumping system (about 25 bar). The LNG to be vaporized is then compressed to the delivery pressure (about 80 bar) by pumps. LNG turns to the gaseous state thanks to the heat provided in the vaporizers (E11-E14). Finally, the Wobbe index is corrected by air injection, in order to meet the national network specifications.

3. Identification of the possible LOCs and consequences

The preliminary identification of accident scenarios in the 3 reference technologies was performed through the application of the MIMAH methodology (Methodology for the Identification of Major Accident Hazards), proposed within the ARAMIS project

(Delvosalle et al, 2006). The result of this analysis is a list of Loss Of Containment (LOC) events (or Critical Events, CE) and a set of correspondent event tree diagrams. The method required the division of the plant in plant units, PU (e.g. loading/unloading arms, tanks, compressors, recondenser, pumps, vaporizers and workpipes). LOCs were associated to the units by matrices, based on the equipment type and the physical state of the handled substance. The possible LOCs of concern in LNG plants are:

- Breach on the shell in vapor or in liquid phase
    - Large (e.g. 100 mm equivalent diameter)
    - Medium (e.g. 35 to 50 mm diameter or diameter of the fitting)
    - Small (e.g. 10 mm diameter)
- Leak from gas or liquid pipe
    - Large (full bore rupture)
    - Medium (22 to 44% of the pipe diameter)
    - Small (10% of the pipe diameter)
- Catastrophic rupture
- Vessel collapse

For each LOC an event tree was built, identifying all the possible consequences of final events. Also in this case the process of building an event tree in ARAMIS makes use of matrices, which, according to the physical state and hazardous properties of the substance, associate LOC to its consequences. In the current analysis the effect of active and procedural barrier is neglected, since the hazard is of concern. However inherent and passive characteristics of the technology are accounted for.

The standard event trees obtained for LOCs of “extremely flammable” substances were adapted to the specific situation of LNG regasification plants. For instance, LNG is stored in cryogenic tanks, whose pressure is roughly atmospheric, or handled in the state of sub-cooled liquid. The formation of a two phase-jets (and consequently of a jet-fire) from a continuous release from liquid phase is unlikely. In fact jet fires are conventionally considered for pressurized flammable gas or superheated/pressurized liquid (OTI, 1992). Moreover, final outcomes specific of off-shore LNG technologies, as Rapid Phase Transition (RPT) were included (Sandia, 2004; Luketa-Hanlin, 2006). Figure 2 reports an example of typical event tree considered for “breach on the shell in liquid phase” in an off-shore floating storage and regasification unit.

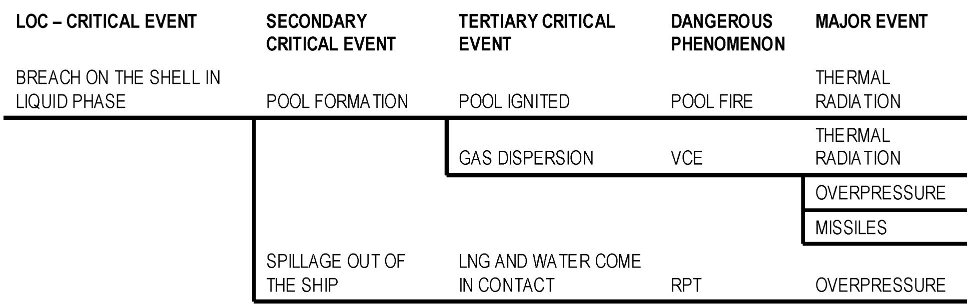

Figure 2. Event tree regarding "breach on the shell in liquid phase" in an off-shore floating storage and regasification unit (FSRU)

The comparison of the event trees for the alternative technologies evidences a great similarity among the results, even more evident for the two off-shore set-ups (GBS and FSRU), where the RPT phenomenon is possible. For each unit of the 3 set-ups, a gaseous release may lead to VCE, flash-fire or jet-fire, while a liquid release is generally followed by the events described in Figure 2 (except in the on-shore case where a contact between LNG and water is less probable). Thus results may seem more dependent on material properties and operative conditions (similar for every technology and set up) rather than on the technological options.

4. Evaluation of hazard KPIs

The inherent safety performance of alternative process schemes can be compared in detail by the assessment of quantitative hazard and risk Key Performance Indicators (KPIs). A few input data are required for each process: (i) substances and operating conditions (pressure, temperature, phase); (ii) input/output material flows; (iii) general technical specifications of units; and (iv) a preliminary estimation of inventories.

"Credit Factors" (*cf*) may be determined for the LOCs previously identified, in order to assess the credibility of the release. This parameter is expected to represent a fundamental element in the comparative assessment of the inherent safety performance of technological options for the units. In the present approach, the likelihood of the reference LOCs was used to quantify credibility. Standard reference failure frequency data may be easily derived from literature (Uijt de Haag and Ale, 1999). Specific failure frequency data can be introduced for technologies with higher safety standards.

The identification of scenarios allows for the calculation of areas potentially interested by expected accidents. The characteristic dimension of this area (e.g. maximum distance) is assumed as the severity parameter of the accident scenarios. Since different types of physical effects (thermal radiation, overpressure or toxic concentration) must be compared, damage distances were calculated for a reference physical effect (e.g. 1% fatality). Reference threshold values can be derived from conventional land use planning studies (Christou et al. 1999). Damage distances are calculated for each scenario using consequence analysis models. Several widely accepted models and commercial software tools are available for consequence analysis, and may be used for current purpose. However, coherent results ask for the use of the same model for the assessment of similar scenarios. Modelling the scenarios for each LOC yields an array of damage distances. The hazard vector ($h_{i,k}$) of a PU contains the maximum damage distances calculated for each LOC event.

Two types of Key Performance Indicators (KPIs) are introduced: the unit potential hazard index (UPI) represents effects which may derive from the worst case accidents; unit inherent hazard index (UHI) represents the effects which may derive from the worst credible accidents, accounting the safety performance (robustness to LOCs) of the PUs:

$$UPI_k = \max_i (h_{i,k})^2 \tag{1}$$

$$UHI_k = \sum_i cf_{i,k} \cdot h_{i,k}{}^2 \tag{2}$$

where the subscripts i and k refer to LOC mode and to PU respectively.

The overall indexes allow for the assessment of the expected global safety performance of a plant, based either on a direct assessment of potential worst-case scenarios (PI) or on the likely safety performance of the process units (HI). For *N* units they are:

$$PI = \sum_{k=1}^{N} UPI_k \tag{3}$$

$$HI = \sum_{k=1}^{N} UHI_k \tag{4}$$

Furthermore, domino escalation (i.e. accident propagation among the units inside and outside the plant) can be also accounted in the KPI analysis. A unit domino potential index, UPD, was defined similarly to eq.(1), substituting damage distances, $h_{i,k}$, with escalation distances (i.e. distance where the effect intensity reaches a predefined escalation threshold). Similarly the domino hazard index, UHD, can be defined modifying eq. (2) accordingly. Overall domino KPIs (PD and HD) can be defined summing up respectively the UPD values and the UHD values for all the units.

5. Conclusions

An approach to the assessment of safety performance was demonstrated in the assessment and comparison of new LNG regasification technologies. The preliminary application to reference schemes suggests that different tools are required to compare the expected safety performance of LNG technologies. The identification of expected accident scenarios yields final outcomes similar among the different technologies, since the regasification process, the material and the operative conditions are similar for all the set-ups. A further step in the analysis, based on the assessment of KPIs, allows for the evaluation of the alternative technologies, yielding a comparison of the possible LOC size and credibility.

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