SAFETY ASSESSMENT IN LNG TERMINALS: IDENTIFICATION OF ACCIDENT SCENARIOS BY AN IMPROVED IDENTIFICATION TECHNIQUE

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In spite of excellent safety records, LNG terminals are currently perceived as an emerging risk in the European scenario. The sound identification of reference accident scenarios is crucial for the future development of LNG technology, since the calculation of credible safety distances and the effective land use planning largely depends on the accident scenarios actually considered. The present contribution introduces a methodology for the identification of reference accident scenarios for LNG terminals, developed in the framework of FP7 iNTeg-Risk Project. The LNG regasification technologies, both current state-of-the art and innovative technologies, were revised. A reference process scheme was defined for the principal lay-out options. The state-of-the-art MIMAH methodology (FP5 ARAMIS Project) was used to obtain a preliminary set of reference accident scenarios. These scenarios were compared and validated with the results of past accident analysis and of HazOp studies. The work evidenced the importance of reference scenario selection in the management of the emerging risks.

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. 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. The new technologies (e.g. advanced floating and off-shore LNG terminals) which are now tackling the market of the new regasification plants, introduce further emerging risk aspects, not systematically explored to date. This is again highly perceived as critical by the population.

The present contribution focuses on the development of a methodology for the identification of reference accident scenarios for LNG terminals, carried out within the activities of FP7 iNTeg-Risk Project. The current state-of-the art technologies as well as proposed innovative designs for LNG regasification were revised. Three main categories of installations were identified (on-shore, off-shore gravity-based and floating) and for each a reference process scheme was defined. The MIMAH methodology, developed within the FP5 ARAMIS Project and featuring state-of-the-art with respect to hazard identification, represented the starting point to identify the reference scenarios that should be considered for each of the alternative design. A gap analysis was carried out comparing the MIMAH results with the outcomes of past accident analysis and of HazOp studies carried out on the reference schemes defined for each technology. The table of scenarios was thus integrated with the results of the gap analysis, thus obtaining a list of reference accident scenarios for each technology. Case-studies evidenced the importance of reference scenario selection and assessment in the management of the emerging risk and of land-use planning issues related to LNG terminals.

2. IDENTIFICATION OF REFERENCE SCHEMES FOR TECHNOLOGIES

2.1 The regasification process

The regasification of LNG consist of a purely physical process, where the liquefied natural gas is compressed and vaporized to the gas state, making it suitable for injection in the distribution grid. At the regasification terminal, other two operations are typically present: LNG tankers unloading and LNG storage. In some configurations (e.g. TRV regasification terminals) the storage function may not be present. The basic features of any regasification process are essentially the same, independently of the specific technologies and lay-outs adopted (Figure 1). LNG is transported in special double-hulled ships and the regasification terminal is therefore a marine installation (on the coastline or off-shore). The LNG is offloaded from the moored carrier by pumps onboard and delivered through unloading arms and transfer pipelines to the LNG storage tanks. Two or three of the arms are generally dedicated for unloading LNG to the transfer pipelines, one is for vapor return to the LNG carrier. The pressure in the LNG carrier during unloading is maintained through a system that allows vapor to flow back from the storage tanks to the carrier. The liquefied natural gas is stored at about -160ºC in double walled tanks specially designed for the purpose. In the vaporization stage, LNG is compressed to the desired final delivery pressure and then vaporized by dedicated heat exchangers (i.e. vaporizers). In the correction and measurement sections of the process, the quality of the gas is brought to the specification of the national grid. The correction usually consists in introducing dosed quantities of air or nitrogen-enriched air in the natural gas. This operation is usually located on-shore, but installation in floating units is technically possible. Liquefied natural gas is transported in special double-hulled ships and off-loaded at the terminal, that is therefore a marine installation (on the coastline or off-shore). The liquefied natural gas is stored at about -160ºC in double walled tanks specially designed for the purpose.

2.2 Alternative layout concepts

Current LNG regasification terminals may be grouped in 3 main categories with respect to the lay-out:

- *On-shore*. The plant is located on the coast, usually within a seaport area. It consists of a docking area, provided with a jetty and loading/unloading arms, a storage area and a vaporization section. This lay-out has been in vogue for decades, and some currently operative plants were built in the ‘60s. As a consequence the range of possible potentialities and storage capabilities is extremely wide (Table 1).
- *Off-shore gravity based structure (GBS)*. This is a more innovative technology. It is designed around a large concrete structure, which houses two modular self-supporting prismatic storage tanks. The Rovigo terminal in Italy of Adriatic LNG, is the first operating terminal based on this technology. The expected range of potentialities and storage capabilities is reported in Table 1 on the basis of ongoing projects.

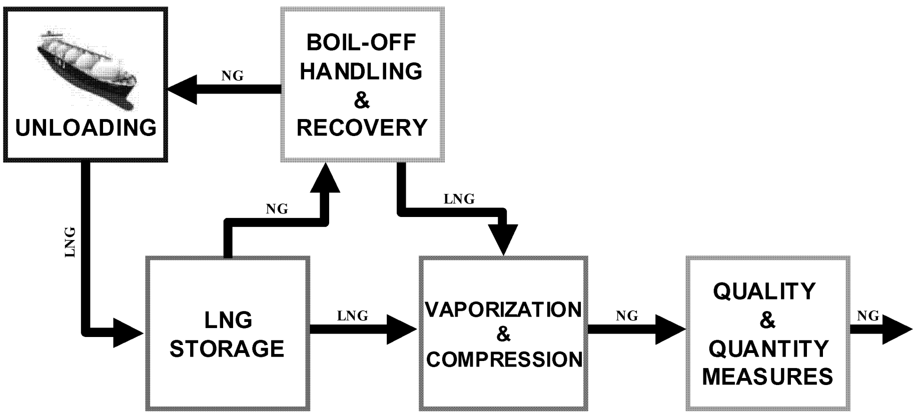

Fig. 1: The LNG regasification process

Table 1: LNG regasification terminal lay-outs: potentiality and storage capability

Lay out	State of Technology	Potentiality (Nm3/year)	Storage capability (m3)	Examples of locations
On-shore	Operative	$3*10^9$ - $20*10^9$	100,000 - 800,000	Panigaglia, Italy Sabine Pass, LA, USA
Off-shore GBS	In construction	$8*10^9$ - $14*10^9$	250,000 - 330,000	Rovigo, Italy Port Pelican, LA, USA Baja California, Mexico
Off-shore FSRU	Planned	$4*10^9$ – $5*10^9$	125,000 - 170,000	Livorno, Italy Porto Recanati, Italy

- *Off-shore floating storage and regasification unit (FSRU).* It is obtained by converting a LNG carrier into a floating platform permanently moored. One of the advantages is the independence from the sea bed, which provides a higher operational flexibility. LNG storage technologies suitable for this typology are those available for LNG carriers (Moss sphere tanks and membrane storage tanks). The range of storage capabilities is tied to LNG carrier models used for this aim (Table 1).

The current trend toward offshore layouts is justified by some advantages. Off-shore installations keep considerable safety distances between the process and the populated areas, positively contributing to cope the aversion of the population to regasification and storage terminals. The use of deepwater ports makes more easy mooring operation, generally allowing for larger class carriers. Moreover, some offshore layouts (e.g. FSRU) are suitable for meeting peak demands of natural gas on the national grid.

2.3 Alternative technologies available for process units of regasification plants

Alternative technologies exist for the different process units. The suitable technologies are obviously influenced by specific constraints deriving from the lay-out selected, and are briefly discussed in the following.

Carrier Unloading. As described earlier, the LNG carrier is unloaded by the unloading arms. New hose-based concepts have been proposed, but have not found application to date. Unloading arms are equipped with a Quick Connect Disconnect Coupler system (QC/DC), which allows a semi-automatic connection with the manifold of carrier ship. Furthermore, a release system consisting of 2 spherical valves (Emergency Release System ERS “no spill”) and a rapid release system PERC (Powered Emergency Release Collar) between the 2 ERS valves is provided on each arm. This system allows a safe and quick disconnection in emergency situations.

Boil-off gas Handling and recovery system. Ambient heat input into the LNG storage tanks results in vaporization of LNG, allowing the tank to remain at a constant temperature. The resultant vapour, referred to as BOG (boil-off gas), is removed by the BOG handling and recovery system to maintain the tank pressure. During unloading operations, BOG is displaced by LNG entering the tanks and needs to be removed.

The BOG handling and recovery system consists of pipework, compressors, and a condenser. In the compressor, BOG pressure is raised to a level at which the BOG could be condensed by the BOG condenser. The BOG compressors also controls the storage tank pressure during carrier off-loading and low sendout periods.

LNG storage. Different typologies are available for the LNG storage tanks:

- *Single containment storage tank.* The tank is typically constituted of a double-layer (inner nickel-steel; outer carbon-steel) tank, covered by an aluminium suspended insulation support deck.
- *Double containment storage tank.* It is essentially a single containment tank surrounded by a close-in, reinforced open top concrete container designed to contain any spill from the inner tank, but not to hold any vapour released during a spill.

- *Full containment storage tank*. It has a primary nickel-steel inner container with a suspended support deck like the single containment, but this is all enclosed in a secondary pre-stressed concrete wall container with a reinforced concrete bottom and a domed roof.
- *In-ground storage tank*. Even though all the above listed storage tank technologies can be built in-ground, only membrane tanks have been regularly built below grade, mainly in Japanese terminals.
- *Underground storage tank*. Similar to the previous, this technology regards tanks totally buried in the ground, where the dome roof is covered with over one meter of soil.
- *Self-supporting prismatic modular tank*. It is a newly developed technology for GBS off-shore terminal. It is a self-supporting prismatic tank, which has been made modular in order to be constructed in parallel with the GBS structure.
- *Moss sphere tank*. It is made up of an aluminum spherical shell, about 4 cm thick, surrounded by layers of insulating material.
- *Membrane storage tank*. It is built by installing a thermal insulating material into the inner hull of the LNG carrier and covering the surface with a metallic membrane layer.

The first 5 technologies can be built only in an on-shore terminal, whereas the self-supporting prismatic modular tank is an innovative technology designed for Gravity Based Structure off-shore terminal. The final 2 technologies (Moss sphere and membrane tank) are storage technologies applied on FSRU terminals.
Each storage tank is generally equipped with submerged in-tank LNG pumps, which transfer LNG to the BOG condenser or to other external pumps.

Vaporization System. There are several available technologies for vaporizers:

- *Submerged combustion vaporizer (SCV)*. LNG is circulated in stainless steel tubes submerged in a water bath. In the same water bath, a submerged combustion chamber burns a low-pressure natural gas stream. The exhausts bubble through the bath and vaporizing the LNG in the tubes. The SCV technology is a closed loop system that does not require water intake.
- *Open Rack Vaporizer (ORV)*. This technology is widely used where LNG facilities are located in close proximity to a readily available supply of relatively warm seawater (at least 10°C), that constitutes the sole source of heat for the process. The seawater is pumped to an overhead distributor, where it flows down over long-finned aluminum panels with the vaporizing LNG flowing inside. The seawater is collected in troughs at the bottom of the ORV before it is discharged back into the water source.
- *Intermediate Fluid Vaporizer (IFV)*. It is a counter-current heat exchanger, which use sea water as heat source and an intermediate heating fluid, such as propane, as heat vector. The circulation of propane is a closed-loop evaporation-and-condensation cycle, so pumping and restore are not needed.
- *Shell and Tube Vaporizer (STV)*. The system involves a heat exchanger in which tubes containing LNG pass through a shell containing a counter-current of heat exchange media, which may be a water/glycol mixture or seawater. This typology of vaporizer is remarkably flexible in its operation.
- *Heat Integrated Ambient Air Vaporizers (HIAAV)*. They use surrounding air as heat source. LNG flows in finned vertical bundles, either by natural convection or fan-forced circulation.

These technologies can be potentially applied to either on-shore or off-shore terminals, except the ORV vaporizers, which are not suitable for floating off-shore applications due to space issues. However the more compact technologies (e.g. IFV, STV, etc.) are usually considered only for application were size is critical.

Correction and quality and quantity measurement. The gas quality should be adjusted to the specifications required before the distribution. For this aim, pressure regulating systems and gas quality measurement (e.g. Wobbe index) systems can be found in regasification plants. A possible correction is performed through the addition of nitrogen-enriched air.

2.4 Definition of reference process schemes

Reference process schemes were defined for each of the set-ups considered. Table 2 reports the main characteristics of the reference schemes considered. Figure 2 reports one of the reference process scheme defined in this step. 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.) as earlier discussed. Thus a description of the regasification process that can be inferred from the scheme in Figure 2 is essentially equivalent for the other schemes.

Table 2: 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)

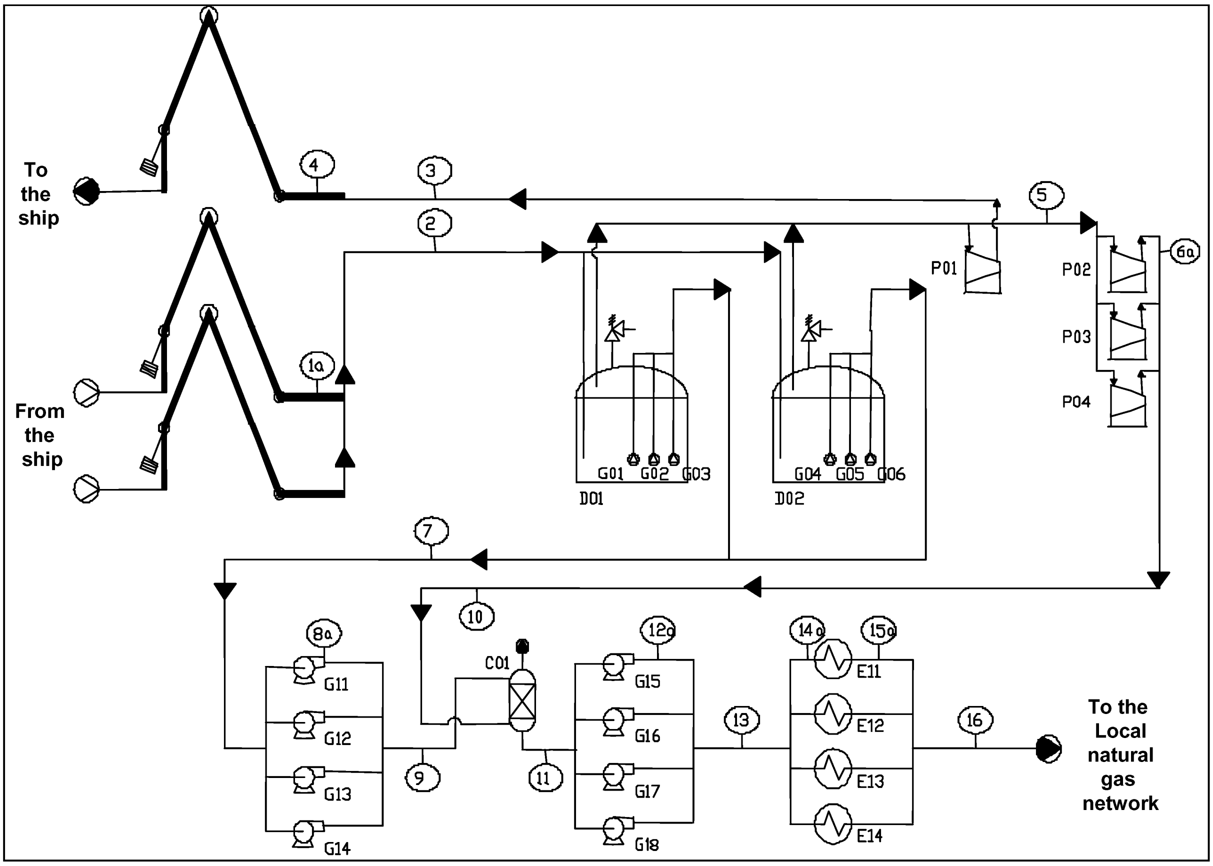

Fig. 2: On-shore regasification technology scheme process

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). A second validation step was based on the Hazard and Operability Analysis (HazOp) of the reference schemes and the analysis of the historical accidents. 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. In fact, in the present framework, the concept of accident scenario is characterized by two main elements: a release event and one or more than one possible final consequence.

3.1 Application of the MIMAH procedure

The MIMAH procedure consist of several systematic steps that eventually yield a bow-tie diagram (i.e. fault tree & event tree). Due to the specific goal of the current study, some of the steps of the original method were not relevant (e.g. selection of relevant hazardous equipment, building of a fault tree) and were skipped. The principal steps of interest are recalled in the following. Further details concerning the general features of the MIMAH procedure and the development of the technique are reported elsewhere (Delvosalle et al, 2006).

3.1.1 Classification of the installations according to MIMAH categories

The method required the division of the plant in plant units (e.g. loading/unloading arms, tanks, compressors, recondenser, pumps, vaporizers and workpipes). In the MIMAH approach equipment is classified according to a defined set of categories (EQ). As well the materials are classified according to the physical state (STAT). The ARAMIS documentation (Delvosalle et al, 2006) reports a detailed definition of the categories.
Table 4 reports the list of the units in the reference onshore layout (Figure 2) as classified according to MIMAH categories. In a few cases, the definition of the categories required specific assumptions:

- for cryogenic liquid, the physical state STAT3 (two phases) is considered in order to account for the phase change that may occur after release and/or in anomalous operating conditions. As a matter of fact the use of trees for liquid materials (STAT2) would have resulted in neglecting possible scenarios.
- the category "pipe network (EQ10)" is considered for loading/unloading arms, because, among the possible options, they have the highest taxonomical similarity to pipework.

3.1.2 Association of critical event to equipment

MIMAH procedure identifies the LOC events (critical events, CE) as a function of the equipment class and of the substance physical state. Table 3 summarizes the critical events relevant for the plants of interests. Table 4 provides a breakdown of the application in case of on-shore plant. In the MIMAH approach, the critical events from CE6 to CE9 concern all the possible continuous releases from pipes and breaches. Extending the approach to include loading/unloading units, the arms were considered as "pipes", thus, yielding CE8 and CE9 events.
The MIMAH procedure proposes a classification of continuous losses of containment in three classes of size:

- Large: 100 mm of breach diameter (CE6-7) and full bore rupture for pipe leaks (CE8-9)
- Medium: 35-50 mm or diameter of the fitting for breaches (CE6-7) and 22-44% of pipe diameter for

Table 3: Critical events considered by the MIMAH and of interest in LNG terminals (Delvosalle et al, 2006)

Code	Critical Event Description
CE6	Breach on the shell in vapour phase
CE7	Breach on the shell in liquid phase
CE8	Leak from liquid pipe
CE9	Leak from gas pipe
CE10	Catastrophic rupture
CE11	Vessel collapse
CE12	Collapse of the roof

leaks (CE8-9)

- Small: 10 mm of breach diameter (CE6-7) and 10% of pipe diameter for leaks (CE8-9)

This classification does not influence, in the MIMAH method, the selection of event trees. On the other hand, specific fault trees and, thus, different set of causes, are proposed for each pipe/breach size class.

3.1.3 Building an event tree for each critical event

The MIMAH methodology associates to each critical event a fault tree and an event tree. Generic reference event trees are provided by the method. Moreover, the method suggests to adapt the generic trees to the specific characteristics of the unit and to the properties of the material, but lacks in providing systematic methods to accomplish this goal. However, event tree adaptations directly linked to the characteristics of material and equipment are quite straightforward in this case. In particular:

- The properties of the materials allow for the exclusion of some final scenarios (e.g. toxic dispersion is excluded for LNG and natural gas)
- Conditional exclusions criteria can be identified, depending on specific evaluations in later phases of the safety study (e.g. the possibility of vapor explosion of a flammable gas cloud is strongly influenced by the presence of confinement)
- Notes are added for specific scenarios that may take place only in presence particular enabling conditions (e.g. RPT requires releases in water)

Table 4: Final table of Critical Events (CE) for the on-shore process schemes of Figure 2

Ref No.	Name	EQ Code	EQ Name	State Code	State	CE Code
D01-2	Tank	EQ7	Cryogenic storage	STAT 3	L+G	CE6, CE7, CE8, CE9, CE10, CE11
P01	Blower	EQ16	Other facilities	STAT 4	G	CE6, CE9, CE10
P02-3	Compressor	EQ16	Other facilities	STAT 4	G	CE6, CE9, CE10
P04	Compressor	EQ16	Other facilities	STAT 4	G	CE6, CE9, CE10
G11-2-3-4	Pump	EQ16	Other facilities	STAT 2	L	CE7, CE8, CE10
C01	Column	EQ12	Equip. devoted to the physical or chemical separation of substances	STAT 3	L+G	CE6, CE7, CE8, CE9, CE10
G15-6-7-8	Pump	EQ16	Other facilities	STAT 2	L	CE7, CE8, CE10
E11-2-3-4	Vaporizer	EQ14/16	Equipment designed for energy production and supply / Other facilities	STAT 3	L+G	CE6, CE7, CE8, CE9, CE10
1a	Loading arm	EQ10	Pipe network	STAT 2	L	CE8
2	Line (jetty)	EQ10	Pipe network	STAT 2	L	CE8
3	Line (jetty)	EQ10	Pipe network	STAT 4	G	CE9
4	Unloading arm	EQ10	Pipe network	STAT 4	G	CE9
5	Line	EQ10	Pipe network	STAT 4	G	CE9
6a ,10	Line	EQ10	Pipe network	STAT 4	G	CE9
7	Line	EQ10	Pipe network	STAT 2	L	CE8
8a, 9	Line	EQ10	Pipe network	STAT 2	L	CE8
11	Line	EQ10	Pipe network	STAT 2	L	CE8
12a, 13	Line	EQ10	Pipe network	STAT 2	L	CE8
14a	Line	EQ10	Pipe network	STAT 2	L	CE8
15a, 16	Line	EQ10	Pipe network	STAT 4	G	CE9

The standard event trees were modified accordingly to these criteria. 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-jet (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).

3.2 Validation of the accident scenarios

3.2.1 Analysis of past accident databases

The main European past accident databases (MHIDAS, MARS - limitedly to online open information, ARIA) were searched in order to obtain data on accidents that occurred. Applicable standards (e.g. EN 1473:2007; NFPA 59A: 2006, etc.) were screened. The details available in most accident records usually did not provide sufficient information to characterize the release event. However, the accident reports were analyzed in order to identify the final scenarios that actually took place and thus to indirectly validate the accident scenarios. Where significant, short accident reports were extracted from the more detailed past accident files, in order to have a description of a number of representative scenarios that actually took place.

The list of scenarios coming from MIMAH was integrated with results from the past accident analysis. An example of added scenario is rapid phase transition (RPT), that was added for the liquid releases on water. The relevance of such scenario is also confirmed by other technical sources (Sandia, 2004; Luketa-Hanlin, 2006).

3.2.2 Hazard and Operability Analysis

Hazard and Operability analysis was applied to the analysis of reference installations defined in the present work. The results of the HazOp analysis were used to obtain a list of “top-events” that was compared with the release modes identified for the reference installation by the MIMAH procedure. The comparison was aimed at the validation and/or the integration of the list of accident scenarios identified by the MIMAH approach. Where needed, further critical events identified were added to the event tree (e.g. collapse of the roof in on-shore storage tanks).

3.3 Results and discussion

The final output of the analysis was the definition of a table of possible scenarios for each possible layout. Table 4 reports the result for the reference on-shore facility. The possible LOCs of concern for corresponding units in other lay-outs were similar, due to the presence of similar materials and of similar process conditions.

For each LOC, the associated event tree identifies all the possible consequences of the final events. In the current analysis the effect of active and procedural barrier is not considered, since the potential hazard is of primary concern. However, inherent and passive characteristics of the technology were accounted for in the definition of the event trees. Clearly enough, frequency based criteria can be later applied to assess the credibility of such accident scenarios. At a later stage, some of the scenarios in the event tree may be excluded from the analysis, depending e.g. on a minimum frequency threshold or to other cut-off criteria adopted.

Figure 3-a reports an example of a typical event tree considered for “breach on the shell in liquid phase” in an off-shore floating storage and regasification unit, while Figure 4-b reports an event tree for a LOC from an on-shore booster pump.

As expected, the comparison of the event trees for the alternative technologies evidences a high 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 considered within the three set-ups introduced in the analysis, 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 3 (except in the on-shore case where a contact between LNG and water is less probable). Thus results seem more dependent on material properties and operative conditions (similar for every technology and set up) rather than on the technological options.

Nevertheless, the quantification of conventional damage distances expected for each of the final events identified by event trees as that shown in figure 3 may provide further elements for the selection among alternative technologies.

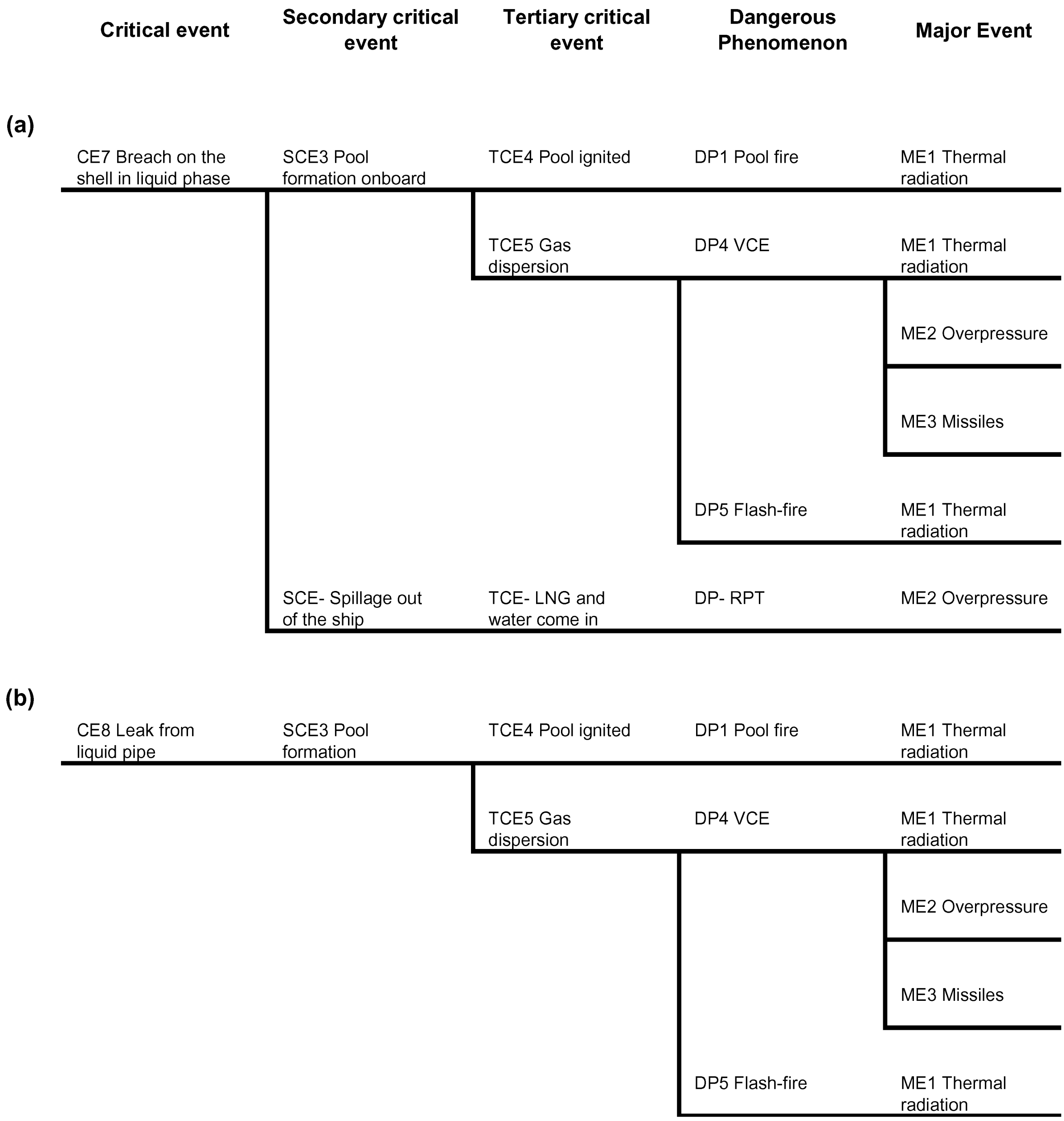

Fig. 3: Example of obtained event trees: a) "breach on the shell in liquid phase" in the storage of a FSRU terminal; b) "leak from liquid pipe" in a booster pump of an on-shore terminal.

4. CONCLUSIONS

An approach to the identification of reference scenarios for the assessment of safety performance of LNG terminals was developed and applied to the assessment and comparison of new lay-outs adopted for LNG regasification technologies.

The application to reference schemes suggests that an array of tools is required to compare the expected safety performance of LNG technologies: even the application of the state-of-the-art MIMAH approach needs to be integrated by customization to the specific problem and by the information from accident analysis and hazard identification techniques (e.g. HazOp). 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.

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