A realistic assessment of LNG hazards and consequences of release scenarios

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This paper tries to summarize the main aspects that characterize the hot debate about the risks of the LNG industry, and in particular those of the import (regasification) terminals, which represent a very attractive energy entry points for the economies of the industrialized and developing countries in search of an alternative to petroleum.
Unfortunately still a great divergence exists on the safety aspects between those who favour the new LNG plants and those who are scared by their impact: one of the most controversial point are the exclusion zones around such facilities in order to avoid that the consequences of an uncontrolled release can affect the people and the environment. This is often due to a poor understanding of the physical phenomena that may occur and to the intrinsic inaccuracies related to the model used for estimating such distances.
Both intentional and accidental release scenarios considered in many studies are here presented and the main assumptions of the models used to analyse the fire and flammable vapour cloud dispersion phenomena are highlighted. The intent of the paper is to provide a better understanding of the potential and credible hazards in order to contribute to a correct management of the risk associated with LNG installations.

1. Introduction

The main reasons of the renewed interest for LNG, and of the great number of newspaper articles and technical publications recently appeared on this topic, are:

- LNG import as a refrigerated liquid via large carrier ships is a convenient supply of natural gas, preferred in some cases (very long distances from producer areas) to the more traditional pipeline transport of pressurised gas;
- The socio-political climate generated after 11/09/2001, particularly in the United States, enormously increased the fear that a terrorist attack to LNG facilities would create a disaster possibly comparable to the explosion of a nuclear weapon;
- More often than not, the media fomented the dreads of the opponents, instead of diffusing a correct and balanced information;
- Scientific community - and in primis risk analysts – suffered the frustrating experience of not being able to affirm almost anything ‘beyond any reasonable doubt’, as far as hazard distances and probabilities of accidental events are concerned. The reassuring ‘objectivity’ of the science turned to extremely subjective. While many tools are available to analyse the hazards of potential accidents involving LNG, the results of different studies failed to portray a unique and uncontroversial picture of the risk.

Quoting a pamphlet on the topic (Melhem et al., 2005), it seems that “separating the facts from the myths” is still an important task to manage LNG risk on a rationale basis.

2. LNG Industry and History

The reasons for the resurgence and growth of the LNG industry are a combination of the increased demand for energy, the availability of natural gas reserves in locations around the world that provide new supplies, and advancements in LNG technology which lower the cost of the LNG value chain.

LNG facilities can be categorized as follows (AcuTech, 2007):

- Export Terminals/Liquefaction facilities – where LNG is liquefied, stored, and loaded onto carriers for shipment. There are presently (January 2007) over 19 export terminal/liquefaction facilities in the world.
- Import Terminals/Regasification facilities – LNG is received from carriers, stored, and, when needed, regasified for injection into the natural gas pipeline infrastructure. There are presently over 44 import terminal/regasification facilities in the world, and approximately the same number of new terminals have been proposed and are under approval of regulatory bodies.
- Peak shaving and other facilities to store and vaporize LNG, operating on an intermittent basis to meet short term peak gas demands.

In the modern LNG era (1970 to present day), all segments of the LNG chain have an exceptional record of no public fatalities and injuries (Pitblado, 2006); from 1941-2006, there have been few major incidents.

LNG shipments began in the late 1950s; the LNG world fleet can presently be estimated in 150 ships; about half of these are 20+ years old and around 60 more are on order. The current largest LNG vessel size is 125 – 138,000m^3 LNG, and concept designs exist for sizes up to 240,000m^3 of LNG. All these vessels (membrane or spherical designs) employ a double hull with additional barriers between the hull and the LNG cargo not present for crude oil tankers. While this is no absolute guarantee of safety, the current LNG fleet has substantial operating history with the usual scale of challenges (grounding, transfer accidents, etc.) with no bulk cargo loss of containment. All significant maritime incidents have occurred in international waters; none of these shipping incidents resulted in a catastrophic loss of cargo.

There have been only a few incidents involving LNG in operating LNG facilities that resulted in one or more fatalities: Skikda, Algeria, 2004 (export terminal); Bontang, Indonesia, 1983 (export terminal); Cove Point Maryland, 1979 (import terminal); Arzew, Algeria, 1977 (export terminal); and Cleveland, Ohio, 1944 (peak shaving facility), the most dramatic one: 128 people were killed and 225 injured.

The Cleveland accident stopped the development of the LNG industry in USA until the 1970s but, at the same time, set up the basis for the modern LNG regulations and design standards, giving an impulse comparable to the Piper Alpha accident for the offshore industry.

The excellent safety record of the LNG industry is mainly due to the result of the preventative, control and mitigation measures that are in place at LNG facilities, in compliance with the severe design and managing criteria established by the relevant industry's standards such as NFPA 59A, US DOT 49 CFR 193, and BS-EN 1473, CSA Z276-07.

Several safety studies have been completed or are near completion for LNG risks: Fay (2003), Lehr et al. (2004), ABS (2004), DNV (2004), Sandia National Laboratories (2004). Many earlier safety studies were completed in the 60's and 70's (USCG, 1980).

2. Safety concerns

The following is a summary of the main safety concerns raised by the opponents to the construction of LNG terminals, and propagated by the media and so-called 'experts', often in open contrast with factual data, scientific evidence and common sense.

a) A large amount of liquid LNG (a tanker contains more than one hundred thousand cubic meters of LNG) represents a potential hazard of explosion comparable to a nuclear bomb.
b) A terrorist attack to a LNG carrier ship entering a port can easily open a large breach in the hull causing the instantaneous spill of a large amount of the LNG cargo.
c) If the released LNG does not immediately ignite, the evaporating pool generates a flammable cloud that can travel for several kilometres, possibly involving populated areas where a delayed explosion has the potential to destroy a town.
d) The Cleveland disaster in 1944 and the recent Skikda accident (2004) demonstrates that LNG industry is unsafe.
e) The small craft attacks in Yemen on the USS Cole on Oct. 12, 2000, and the French oil tanker Limburg on Oct. 6, 2002, show that also LNG tankers are vulnerable to the assault of small boats carrying explosives, a relatively easy mean even for not very well organized terrorist groups.

The rebuttal of these statements will be briefly illustrated here below (Beale, 2006). Some further discussion of the possible accident scenarios that may involve LNG facilities will be given in the following sections of the paper.

a) Liquid LNG does not explode, i.e. it cannot release in a very short time its entire energy content, as explosives do. As refrigerated LNG is stored at an approximately atmospheric pressure, no BLEVE (boiling liquid expanding vapor explosion) is expected. The explosion scenarios sometimes observed when spilled LNG contacts the sea water are in fact RPTs (Rapid Phase Transition), i.e a violent vaporisation of the very cold liquid contacting the water, which develops modest overpressures with scarce damaging potential.
b) An LNG ship provides four layers of protections to the cargo: a double hull and two additional containment walls. It is required a very penetrating and destructive weapon to cause a large breach from which a substantial quantity of LNG may be released; under such circumstance the LNG will be surely ignited, so the resulting scenario will be a large pool fire, not a huge flammable cloud. The only way of discharging a large amount of not ignited LNG into the sea is by voluntary pumping (e.g. terrorist takeover of the ship) through the transfer line of the ship, and even in this case the release of the whole content will take more than 10 hours, allowing the control of the LNG cloud before it can reach vulnerable locations. In conclusion the

assumption of a large evaporating pool resulting from the massive release of LNG from a breach in the hull is not a credible scenario.

c) Both the Cleveland and Skikda accidents were due to conditions that cannot exist in the LNG installations designed according to the current standards and regulations. The former was due to cold embrittlement of the inadequate construction material (a low Nickel alloy) of one LNG tank; the latter to the suction of LNG vapors into the air intake duct of a steam boiler that was not provided with flammable gas detectors.

d) The assault by a small boat carrying explosives to the Limburg opened a 25 foot hole in the external hull and a series of much smaller holes in the inner hull; only 4% of the oil cargo was released through these apertures. Considering that an LNG ship will provide two additional walls of protection, one could presume that such an attack would not have been able to produce any spill at all from an LNG ship.
As far as the security aspects and the attractiveness of the LNG carriers as targets of a terrorist attack are concerned , the following quote from (AcuTech, 2007) offers a very clear opinion: "*LNG is one of numerous possible terrorist targets. However, LNG is also one of the more highly protected. The higher levels of protection make the degree of difficulty of attack more significant and reduce the attractiveness of LNG as a target. LNG also is judged to be a less attractive target based on the limited geographic use (generally remote location with limited potential impacts), the uncertain value of an LNG vessel as a weapon (due to the limited population that can be targeted), and the lack of symbolic importance of LNG vs. other assets*".

3. Credible accident events

The first step in any risk assessment is the identification of representative accident events. The importance of this step should be, if possible, even more emphasized when dealing with the safety of LNG facilities, as much of the circulating misinformation draws on the analysis of extreme events that are so unlikely that they can not be reasonably taken as 'reference accidents' for the design and the siting of LNG facilities.
On the other hand, a worst-case approach is still suggested or required in some national regulations, which do not embrace the more recent risk based approach that characterises most of the modern performance driven industry's standards.

A brief description of the principal approaches for establishing appropriate hazard separations between hazardous activities and nearby vulnerable installations or people, and their application to LNG facilities, is given in the following.

<u>Worst Case Approaches</u>
The Worst Case Event can be defined as the most severe incident, considering only incident outcomes and their consequences, of all identified incidents and their outcomes.
The Worst Case Approach appears attractive as a decision support tool as "whatever happens, it can't be worse than this" and those responsible for public protection can be assured that the nominated consequence levels will not be exceeded. In reality, for major energy sources, it is often very difficult for industrial facilities located in proximity to populated areas or infrastructure to demonstrate acceptability. This can

apply to nuclear facilities, refineries, chemical plants, LNG terminals, and dams. A catastrophic failure of any of these, without any regard to the safeguards or barriers in place, is unlikely to be able to demonstrate no impact to infrastructure or people within possible hazard zones. A disadvantage of the worst case approach is that ignoring safeguarding features tends to move public discussions away from safeguarding .
Several recent LNG studies consider a hole size in the range 5-20 m^2 and a volume spilled of 12,500-25,000m^3 in a time of 2-8 min. No specific mechanism is suggested for the breach size considered. Studies do not normally assess a rapid total loss of inventory from an LNG vessel (e.g. 125,000m^3 in 5 tank compartments).

Maximum Credible Event Approaches

A Maximum Credible Event can be defined as the most severe incident that is considered plausible or reasonably believable. By bringing in the aspect of plausibility, the ability of safeguarding to reduce the scale of possible events from the maximum possible to some lesser scale is allowed. Safeguarding can reduce the likelihood of the event (prevention) or reduce its potential outcome (mitigation). The judgment of plausibility is imprecise, but would take account of the level of threat, the number and quality of safeguards, and the number of installations.

Pitblado et al. (2006) describe a hazard identification approach that identified several maximum credible events (that actually have never happened) for different threats. These were:

a)	0.25 m	Maximum credible puncture hole
b)	0.75 m	Maximum credible hole from accidental operational events
c)	1.5 m (1.7 m^2)	Maximum credible hole from terrorist events
d)	7,000m^3/hr	Maximum credible operational spillage event (10 minutes)
e)	10,000m^3/hr	Maximum credible sabotage event (60 minutes)

The Hazard identification could not identify a credible mechanism leading to a 5m hole.

Risk Assessment Approaches

A risk assessment approach should include the entire range of potential events from frequent small events, through infrequent but credible events, to much rarer worst case events. It combines each event scenario's consequence with its likelihood of occurrence and the multiple possible outcomes. The advantage of a risk assessment approach is that safeguarding is explicitly included in a manner that allows cost-benefit to be established. A risk based approach is being gradually incorporated in many regulations traditionally characterised by a worst case, consequence driven, approach.

4. LNG characteristics and main hazards

LNG's principal hazards result from its:
- cryogenic temperature
- flammability, and
- vapor dispersion characteristics.

LNG is a cryogenic liquid stored and transported at approximately -160ºC. Contact with a cryogenic liquid can cause freeze burns and eye damage.
LNG is a flammable substance; it is not toxic and long-term environmental impacts from a release are negligible. Flammability limits of vapors in air are approximately 5 percent and 15 percent molar. If a flammable cloud from an LNG spill is ignited, the combustion results in a flash fire, unless the flame propagation occurs in confined/congested environments, where the flame may accelerate to the point of developing appreciable overpressure waves.
As a liquid, LNG will not burn nor explode. LNG vaporizes rapidly when exposed to ambient heat sources. The ignition of the vapors over an evaporating pool originates a pool-fire. When spilled onto water, LNG will initially produce a cold vapor cloud that is denser than air and will stay close to the sea surface or ground. As this cloud mixes with air, it will warm up and cause dispersion into the atmosphere. The downwind distance that flammable vapors might reach is a function of the LNG spill rate/volume, the evaporation rate, and the prevailing weather conditions. In order to disperse to significant downwind distances, a vapor cloud must avoid ignition, but an event of sufficient magnitude to rupture an LNG cargo tank is likely to provide ignition sources.

5. Modelling physical phenomena

The modelling of the physical phenomena involved in the evolution of an accidental release of LNG is based on standard software programs routinely used in risk analysis.
It is interesting to note that many of these programs, in particular those dealing with the dispersion of dense gases, have been developed within research project dedicated to improve the knowledge on LNG. Some of these (DEGADIS, FEM3A, LNGFIRE3) are currently ‘regulatory programs’ recognized by USA regulatory authorities, i.e. they are the preferred programs to be used in the safety studies included in the applications for the construction of new LNG terminals.
A great interest is obviously concentrated on the actual abilities of the available programs to provide reliable predictions of the hazard distances, and hence of the exclusion zones around a LNG facility. A substantial effort has then been devoted in recent years to the systematic reconsideration of the theoretical bases and the performance against experimental data of these models and codes. In addition, several protocols for the validation and the use of the programs have been proposed in order to enhance the understanding and the confidence in their results (Hanna, 1993).

Here, the main findings and some conclusions from the plenty of information available is presented.

- Several experimental tests on LNG vapour dispersion and fires were undertaken during 1970s and 1980s (Koopman and Ermak, 2007). Field data were extensively used to validate models and codes, which in general show reasonable agreement with the data. However it should be pointed out that: (1) An agreement within a factor 2 of the concentration results is considered typical of good programs, so it is not surprise that the predicted hazard distances may differ by such a factor in different studies. (2) The trials did consider LNG spills onto water, but the scale of LNG spilled was mostly 10-20 m^3, well below the size of spillages usually evaluated in recent studies. (3) Weather conditions covered unstable and neutral stability, but only one trial covered E stability, none F stability.

- Among the various linked phenomena that determine the extent of the LNG hazards (release rate from a given breach, pool spreading and evaporation, dispersion, ignition and flash-fire/pool-fire) the process of pool formation on water is probably one of the least accurately modelled. Most if not all available programs consider the sea as a flat surface of constant temperature where liquid LNG can freely spread, though in fact many complex phenomena determine the actual size, shape, position and vapour formation of the LNG pool. Just to name a few: marine currents, presence of sea waves, ship's movement after the spillage, ice formation, LNG composition, rapid phase transition of the cold liquid when contacting the sea. A continuous unconfined spill of LNG onto water will reach a nearly constant pool area in which the evaporation or burning rate equals the spill rate; the heat transfer to a burning pool is higher, so that an ignited pool will have a smaller diameter.
- CFD technology, though providing very detailed treatment of the physics and the geometry of an LNG loss-of-containment event, does not seem mature enough to completely substitute the standard simplified models, provided these receive accurate validation with a larger set of experimental data, more representative of the spillage conditions actually investigated.
- The most credible scenario in case of a massive LNG release is a large pool-fire over water. The thermal radiation hazard from a pool fire is largely determined by the visible flame size and flame brightness. Both these characteristics vary with pool diameter, but not in a simple way. From the series of LNG pool fire tests carried out thus far, the flame brightness, or Surface Emissive Power (SEP), appears to have reached a plateau, about 170 kW/m^2 for the largest diameter - 35m - tested so far during Montoir tests (Nedelka et a1., 2007). There is uncertainty how the SEP might vary thereafter for bigger pools, but there is strong theoretical evidence that there would be no further increase in SEP and indeed the SEP might start to decrease due to the shielding by soot from incomplete combustion. The limit seems to be about 20 kW/m^2 typical of hot smoke. Pool fires larger than 35m diameter would be required to confirm this trend.

6. Conclusions

This paper tried to provide an overview of the different arguments pertinent to the debate about the safety of the LNG import terminals.

The following main points have emerged from the recent vast literature on LNG risk:

- LNG industry demonstrated an excellent safety record during its 50 year history;
- LNG industry must comply with very stringent and detailed design standards and national regulations;
- LNG facilities are not very attractive targets for possible attacks of terrorist groups;
- The containers of very large amount of liquid LNG, both onshore storages and ship tanks, are designed with technology features that make accidental releases almost impossible to occur, so the concerns have concentrated on the effects of intentional breaches of the vessels;

- Only a very powerful penetrating weapon may produce a large breach and a massive release of LNG from a ship tanker. In this case a large pool-fire is the most credible scenario. According to the results of recent studies based on worst-case scenarios, the extension of the exclusion zone for fire should be about 1.5 km (most severe consequences within a 500 m radius);
- Failure cases selected need careful consideration and justification;
- Models and computer programs used to assess the hazard distances in case of LNG releases are variable in results but on the average have a good deal of validation data and show acceptable performance in reproducing the experimental trends. However available data are restricted to a scale much lower than that under investigation, so further experimental work is necessary to gain confidence on the results of the predictive tools;
- Topics affected by greater uncertainties are the dynamics of the pool formation on water, the distance travelled by the flammable cloud under stable weather conditions, the size and shape of the flame in a large LNG pool-fire over water;
- A risk based approach, taking into account likelihood of the events, severity of the consequences and safeguarding measures, should be preferred to a worst-case, hazard based approach.

7. References

Melhem, G.A., Kalelkar, A.S., Saraf, S., Ozog, H., 2005, Managing LNG Risk: Separating the Facts from the Myths, ioMosaic

AcuTech Consulting Group, 2007, Fire Service Guidance for Participating in LNG Terminal Evaluation, Siting and Operations

Pitblado, R., Baik, J., Raghunathan, V., 2006, LNG Decision Making Approaches Compared, Journal of Hazardous Materials, Vol. 130, Issue 1-2

Fay J.A., 2003, Model of spills and fires from LNG and oil tankers, Journal of Hazardous Materials, Vol. 96, Issue 2-3

Lehr, W. and Simecek-Beatty, D., 2004, Comparison of hypothetical LNG and fuel oil fires on water, Journal of Hazardous Materials, Vol.107, Issue 1-2

ABS Consulting Inc., 2004, Consequence Assessment Methods for Incidents Involving Releases from Liquefied Natural Gas Carriers, Report 131-04,

Sandia National Laboratories, 2004, Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water

DNV, 2004, LNG Marine Release Consequence Assessment, Project No. 70004197

USCG (1980) Safety aspects of Liquefied Natural Gas in the Marine Environment, DOT-CG-74248-A, 343pp, June 1980 (from NTIS).

Beale, J.P., 2006, The Facts about LNG, CH.IV International

Hanna, S.R., Chang, J.C. and Strimaitis, D.G., 1993, Hazardous Gas Model Evalutaion with Field, Atm. Environm., Vol. 27A, No15, pp. 2265-2285

Koopman, R.P. and Ermak, D.L., 2007, Lessons learned from LNG safety research, Journal of Hazardous Materials, Vol.140, Issue 3

Nedelka D., J. Moorhouse and R.F. Tucker (1989). The Montoir 35m Diameter LNG Pool Fire Experiments, Proc. 9th Int. Conf. on LNG, Nice, 17-20 Oct. 1989