CHEMICAL ENGINEERING TRANSACTIONS
VOL. 67, 2018
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Valerio Cozzani, Bruno Fabiano, Davide Manca

ISBN 978-88-95608-64-8; **ISSN** 2283-9216
DOI: 10.3303/CET1867021

Inherent Safety Assessment of LNG Fuelled Ships and Bunkering Operations: a Consequence-based Approach

Tommaso Iannaccone[a,*], Gabriele Landucci[b], Valerio Cozzani[a]

[a]Department of Civil, Chemical, Environmental and Materials Engineering – University of Bologna, Via Terracini 28, 40131 Bologna (Italy)
[b]Institute of Security and Global Affairs, Faculty of Governance and Global Affairs, Leiden University, Wijnhaven, Turfmarkt 99, 2511 DP, Den Haag (the Netherlands)
tommaso.iannaccone2@unibo.it

Liquefied natural gas (LNG) is becoming a viable, environmental-friendly alternative to marine fuel oil for ship propulsion. However, LNG flammability induces relevant safety concerns due to fire and explosion hazards. The present contribution is aimed at the safety assessment of onshore bunkering configurations for marine fuel systems, with particular reference to LNG technologies. A specific review of bunkering methods, including connection to the ship fuel system, is carried out to provide a knowledge background. Moreover, the conventional process configurations based on intermediate fuel oil (IFO) are taken into account for a comparison between process alternatives. A consequence-based approach is followed to develop a set of key performance indicators aimed at evaluating and comparing the inherent safety of LNG and IFO systems. The results obtained allow for a clear identification of critical process units and operations, indicating that conventional IFO bunkering is inherently safer when compared to LNG. Therefore, safety aspects need to be balanced with environmental benefits, in the perspective of sustainable development of LNG supply chain for marine applications.

1. Introduction

Increasing awareness of problems posed by air pollution caused by maritime traffic is leading toward substitution of traditional marine fuels. Transportation accounts for almost 25% of Europe's greenhouse gas emissions of which 13% is due to shipping activities (European Environment Agency, 2017). This transportation sector strongly depends on fossil fuels and significantly contributes up to 15% of global emissions of Sulphur (SO_x), Nitrogen oxides (NO_x) an particulate matter (PM) (Maragkogianni et al., 2016). International maritime organization (IMO) has recently tightened pollutant emissions limits, thus forcing shipping sector to rethink bunkering options. Moreover, the shift towards natural gas is driven by economical aspects, since the exploitation of new reservoirs and the extraction of shale gas have lowered liquefied natural gas (LNG) price, turning natural gas into an attractive fueling option (Lloyd's Register, 2014).
However, LNG is a highly flammable substance and, as such, consequences of a potential release might lead to severe fires and explosions. Therefore, in the stages of early development and selection of bunkering technologies and fuel system alternatives, safety aspects will become crucial to develop sustainable and reliable technologies involving LNG as marine fuel.
A number of previous studies investigated concerns over safety issues related to LNG utilization (Alderman, 2005) and storage (Scarponi et al., 2016) including a study about fire risk on board LNG fueled vessels (Kim et al., 2014) and a detailed report by DNV exploring LNG bunkering alternatives (Det Norske Veritas (U.S.A.), 2014). Despite the attention given to safe implementation of natural gas fueled vessels, a direct comparison between traditional and alternative bunker options is lacking.
In this work, a methodology for inherent safety assessment was implemented in order to compare fueling alternatives. The adopted methodology provides a quantitative metric, based on consequence assessment, which allows for the ranking of bunkering options based on inherent safety key performance indicators (KPIs). Following this approach, inherent safety is assessed in a physically sound and auditable manner. Reference

Please cite this article as: Iannaccone T., Landucci G., Cozzani V., 2018, Inherent safety assessment of lng fuelled ships and bunkering operations: a consequence-based approach, Chemical Engineering Transactions, 67, 121-126 DOI: 10.3303/CET1867021

schemes considered for bunkering options were defined along with relevant process conditions. Moreover, a general comparison was also carried out between the depicted scenarios for LNG supply and alternative scenarios based on conventional fuel oil utilization.

2. Ship bunkering alternatives and relevant regulations

Different LNG bunkering configurations are available for fuel delivery:

- LNG bunkering from ship to ship (STS)
- LNG bunkering from trucks to small vessels (TTS)
- LNG bunkering from terminal/pipeline to ship (PTS)

The choice between different fuel delivery configurations is dependent on various parameters, such as required bunkering volumes, bunker frequency, physical and logistical limitations. More specifically, the total LNG volume to be handled on a yearly basis in a harbor area, coping with possible time constraints for operations, drives the selection of the most suitable bunkering method. Critical safety aspects affect refueling operations, since large quantities of highly flammable substances are handled in proximity of passengers and port operators. Indeed, LNG bunkering activity is regulated according to requirements set out in international technical standard (CEN, 2017) and guidance provided by the European Maritime Safety Agency (EMSA), (EMSA, 2018).

Refuelling operations involving conventional fuels, such as Intermediate Fuel Oil (IFO), typically occur in port areas during passenger boarding in STS configuration. This bunkering operation needs to be conducted in accordance with IMO Recommendations on the safe transport of dangerous cargoes and related activities in port areas (Section 7.1.14 Bunkering), (International Maritime Organization, 2007) and the latest edition of the international safety guide for oil tankers and terminals guide (OCIMF, 1996). Each port authority can issue specific regulations for fuel bunker in addition to international agreed requirements.

In the following, the reference schemes for both LNG and IFO bunkering technologies are defined in order to support the inherent safety assessment.

2.1 LNG onshore storage facility

Onshore LNG deposits are a fundamental element of the fuel delivery chain. These sites can be used for loading operations of LNG bunker vessels or either for direct refueling in PTS configuration. A typical configuration scheme is reported in Figure 1.

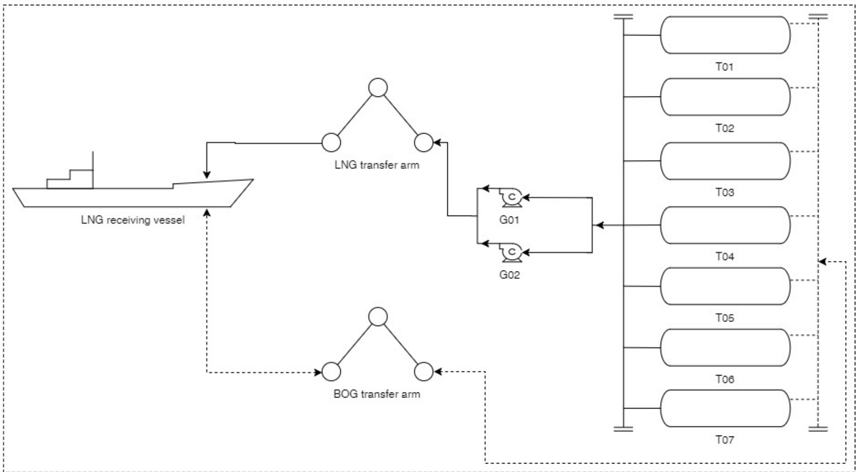

Figure 1: LNG bunkering facility reference scheme

Bunkering takes place at a quay equipped with LNG and boil-off gas (BOG) transfer arms that are special cranes which facilitate the handling of larger diameter hoses. Transfer arms are provided with rigid insulated pipe sections through which LNG is pumped through to the receiving vessel. Swivel joints provide needed flexibility for ship connection, allowing the necessary degrees of freedom.

The bunkering rate applied must be adapted to the fuel needs of the ships being supplied or the capacity of the bunker vessel. The reference scheme considered in this paper (Figure 1) features a LNG storage facility with a capacity of more than 4,500 t. Liquefied gas is stored in seven cryogenic tanks (T01 – T07 in Figure 1) connected to a common manifold. Cryogenic loading pumps G01 and G02 allow transfer of LNG up to the loading arm. Similarly, a BOG line connects tanks to BOG transfer arm, allowing tanks pressure regulation during bunkering. The LNG bunker line is typically featuring 10” (254 mm) nominal diameter, whereas vapour return line features 8” (203.2 mm) internal diameter. Process conditions considered are those typically encountered during loading operations of a medium scale LNG bunker vessel (around 1,000 m^3 capacity); a transfer rate of 250 m^3/h of LNG was considered. A summary of process operating conditions in the considered equipment and lines is reported in Table 1.

Table 1: Process conditions considered for LNG onshore storage facilities. For unit tags refer to Figure 1.

Parameter	Unit			
	Storage tank T01 – T07	Loading pump G01/G02	LNG transfer arm	BOG transfer arm
Inventory (kg)	648,648	-	-	-
Flow-rate (kg/s)	-	31.50	31.50	0.468
Pressure (MPa)	0.35	0.40	0.40	0.21
Temperature (K)	130	131	131	153
State	Liquid	Liquid	Liquid	Vapour

2.2 IFO onshore storage

The reference scheme considered for IFO bunker is shown in Figure 2 and is typically adopted on small storage facility. Fuel oil is stored in six atmospheric tanks (D01 – D06), for an overall storage capacity of 15,000 m^3, equivalent to approximately 14,800 t. Pumping station at the storage site comprises two centrifugal pumps (G01 and G02) each one with a capacity of about 130 m^3/h. Bunkering operations are carried out at a dedicated jetty using a flexible rubber hose with an internal diameter equal to 4” (101.6 mm). Fuel oil is usually delivered to bunker vessel tanks at pressures around 2 bar. A summary of process operating conditions in the considered equipment and lines is reported in Table 2.

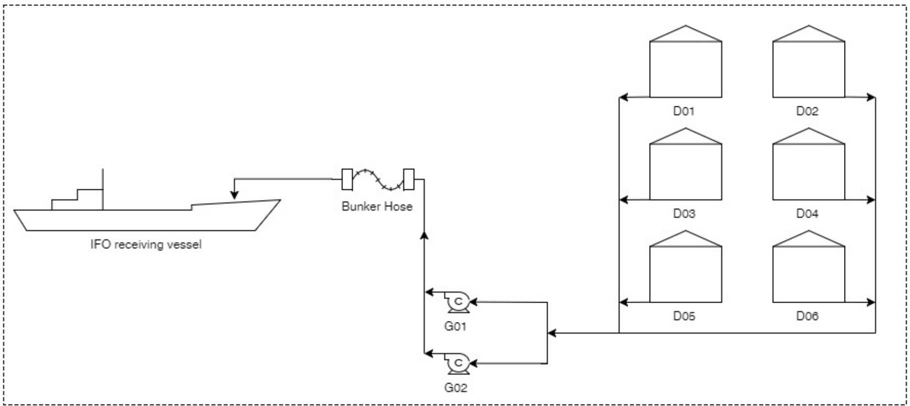

Figure 2: IFO STS bunkering facility reference scheme

Table 2: Process conditions considered for IFO onshore storage facilities. For unit tags refer to Figure 2.

Parameter	Unit		
	Storage tank D01 – D06	Bunker pump G01/G02	Bunker hose
Inventory (kg)	2,477,500	-	-
Flow-rate (kg/s)	-	35.39	38.54
Pressure (MPa)	0.12	0.20	0.20
Temperature (K)	318	318	318
State	Liquid	Liquid	Liquid

3. Methodology

The methodology is aimed at comparing the inherent safety of process alternatives for fuel supply chains based on the quantification of specific KPIs. The generic methodological framework for the assessment of fuel supply chains was developed in a previous work (Landucci et al., 2010) and was hereby adapted for the

specific features of harbour bunkering operations. In particular, KPIs quantification is based on the evaluation of expected damage distances of the credible accident scenarios associated with the considered reference schemes for bunkering alternatives (see Section 2).
The identification and characterization of equipment and lines are based on the definition of failure modes and expected release scenarios or loss of containment events (LOCs). A summary of the considered LOCs in the present work is reported in Table 3. For each LOC, a credit factor based on the available experience derived from past accident analysis is attributed. More details on LOCs definition and credit factors evaluation are reported elsewhere (Tugnoli et al., 2007). Accident consequences are evaluated by standard consequence-analysis models, such as those proposed by (Van Den Bosh and Weterings, 1996) to obtain damage distances that may be directly compared to acceptable damage threshold values.
The set of inherent safety KPIs includes:

- the unit potential hazard index (UPI), that is related to the maximum extent of the area that could be affected following a dangerous event,
- the unit inherent hazard index (UHI), that takes into account the likelihood of occurrence of the considered LOC, introducing a frequency value retrieved from technical literature (Uijt de Haag and Ale, 2005).

The above-mentioned indices are calculated according to Eq. (1) and Eq. (2), respectively:

$$UPI_i = \max_j \left(h_{i,j}^2\right) \quad (1)$$

$$UHI_i = \sum_{j=1}^{n_i} Cf_{i,j} \cdot h_{i,j}^2 \quad (2)$$

where ($h_{i,j}$) represents damage distance obtained for the j-th LOC of the i-th process unit considered, $Cf_{i,j}$ is the credit factor representative for the frequency of the j-th LOC event, and n_i is the number of LOCs considered for the i-th unit.
Summing over all process units involved in a certain bunkering configuration will give the overall value for the considered indicator:

$$PI = \sum_i UPI_i \quad (3)$$

$$HI = \sum_i UHI_i \quad (4)$$

where PI and HI are the overall potential and inherent hazard indexes, respectively. Either unit or overall KPIs are used to carry out the inherent safety comparison among the novel LNG supply chains and the conventional alternative based on fuel oil.

Table 3: Characterization of LOC events

LOC identification	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

4. Results and discussion

4.1 LNG bunkering

To avoid results variability due to different LNG composition, natural gas has been approximated as pure methane. Following an event tree analysis, credible accident events associated with the LNG release are: pool fires and jet fires, following immediate ignition; flash fires and vapour cloud explosions (VCE), considering the occurrence of delayed ignition. Table 4 reports a summary of the results obtained for the LNG onshore facility. The application of the proposed method points out that critical units involved in natural gas handling and refueling operations are the storage tanks (ID, see Figure 1) and the loading pumps (ID, see Figure 1). Storage tanks have the highest value of UPI, one order of magnitude greater than other equipment. This reflects the inherent hazard related to the storage of a large amount of LNG. On the other hand, LNG pumps are penalized by the higher credit factors assumed for the LOCs applicable to these equipment, and the calculated UHI is the highest among all process units.

Table 4: LNG onshore facility. Results of consequence assessment and calculated KPIs.

Unit	LOC	$Cf_{i,j}$ (1/y)	$h_{i,j}$ (m)	UPI (m^2)	UHI (m^2/y)
Storage tank T01 – T07	R1	1.00×10^{-5}	45.12	4.80×10^{6}	3.01
	R2	5.00×10^{-7}	2,190.32		
	R3	5.00×10^{-7}	1,085.55		
Bunker pump G01/G02	R4	5.00×10^{-4}	196.38	2.04×10^{5}	43.30
	R5	1.00×10^{-4}	490.10		
LNG Transfer arm	R4	6.00×10^{-4}	152.80	1.84×10^{5}	25.05
	R5	6.00×10^{-5}	429.00		
BOG Transfer arm	R4	6.00×10^{-4}	14.35	4.94×10^{4}	3.09
	R5	6.00×10^{-5}	222.19		

4.2 Intermediate fuel oil bunkering

Concerning IFO refueling, credible accident scenarios are limited to pool fires and flash fires, even if the latter scenario has little impact due to low volatility of the fuel, simulated as pure undecane.

The same approach used for the evaluation of LNG bunkering option was followed and UPI and UHI values were calculated for all the process units situated in the facility. The bunker hose employed during refueling activity is the item that shows the worst performance in terms of UHI, being about 2.5 times the one for storage tanks, which is the lowest. On the other hand, storage tanks are characterized by the highest value of potential hazard index, one order of magnitude greater than other units, highlighting the importance of the minimization principle in achieving inherent safety.

The results obtained are summarized in Table 5, along with calculated damage distances for all process equipment involved. The most critical units involved in fuel oil processing are the transfer hose and the storage tanks located within the onshore storage site.

Table 5: IFO onshore facility. Results of consequence assessment and calculated KPIs.

Unit	LOC	$Cf_{i,j}$ (1/y)	$h_{i,j}$ (m)	UPI (m^2)	UHI (m^2/y)
Storage tank D01 – D06	R1	1.00×10^{-4}	34.87	4.02×10^{5}	4.11
	R2	5.00×10^{-6}	633.88		
	R3	5.00×10^{-6}	629.43		
Loading pump G01/02	R4	5.00×10^{-4}	92.97	2.95×10^{4}	7.27
	R5	1.00×10^{-4}	171.70		
Bunker hose	R4	6.00×10^{-4}	152.80	8.57×10^{4}	10.46
	R5	6.00×10^{-5}	292.71		

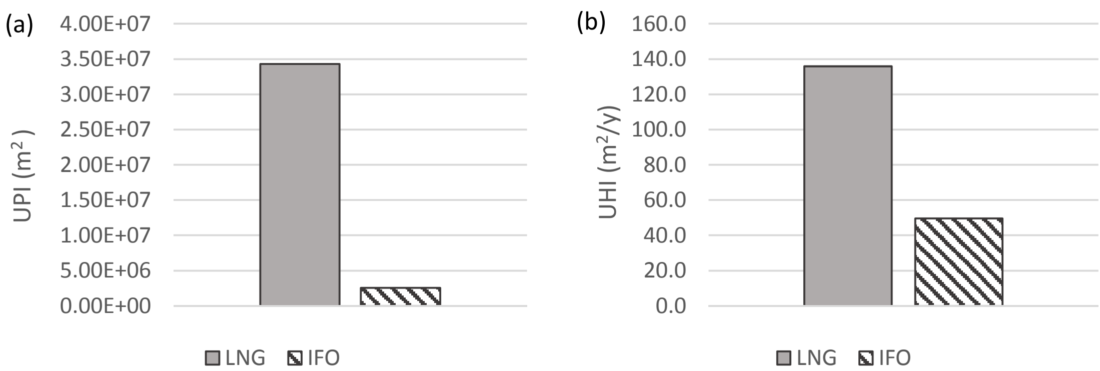

Figure 3: Comparison between overall PI values (a) and HI values (b) for the two reference schemes considered.

4.3 Comparison between bunker alternative technologies

The safety performance of the two bunkering facilities can be expressed in terms of overall inherent safety indices, namely PI and HI (see Eq. (3) and (4), respectively). The higher is the score, the worse is the inherent safety performance.
Figure 3 shows the evaluated PI (Figure 3a) and HI (Figure 3b) for the two alternatives. Despite a stored amount of LNG three times lower in mass terms than that of fuel oil, the value of PI calculated for LNG option is one order of magnitude greater than that of conventional marine fuel, making natural gas refueling a least inherent safe option, when considering only calculated damage distances extent for the storage facility and relative bunkering equipment. The trend is confirmed also when LOC likelihood is considered through credit factors: the IFO bunkering facility is characterized by a HI value that is slightly less than three times the one of LNG alternative. A possible explanation for such a wide difference in PI value could be the lager damage distances associated with LNG VCE that contribute the most to single UPI values and may not be excluded, due to the high level of congestion featured by harbor facilities resulting in potential overpressure effects.

5. Conclusion

A comparison between alternative marine fuels has been made analyzing inherent safety performance of bunkering facilities and refueling operations involving LNG and conventional bunker (e.g. fuel oil). A methodology based on KPIs calculation was applied to provide quantitative results and support safety assessment of a typical bunkering infrastructure. Critical process units were identified on the basis of equipment specific KPIs, highlighting the high hazard potential of storage tanks in both the considered alternatives. At the same time, when credit factors are introduced, transfer units (e.g., bunker pumps or transfer hoses) are more critical due to the increment in release likelihood. Overall indices indicate that marine fuel oil bunkering facility is inherently safer when compared to LNG, hence safety aspects need to be balanced with environmental benefits, in a sustainability perspective. This approach may be extended for the assessment of LNG fuel system onboard and comparison against traditional systems based on fuel oil, thus providing an overall evaluation at the supply chain level.

References

Alderman, J.A., 2005, Introduction to LNG safety, Process Saf. Prog. 24, 144–151.
CEN, 2017, Ships and marine technology - Specification for bunkering of liquefied natural gas fuelled vessels (ISO 20519:2017), Brussels, Belgium.
Det Norske Veritas (U.S.A.), 2014, Liquefied Natural Gas (LNG) Bunkering Study, Katy, TX, USA.
EEA, 2017, Greenhouse gas emissions from transport, European Environment Agency, Copenhagen, Denmark.
EMSA, 2018, Guidance on LNG Bunkering to Port Authorities and Administrations, Lisbon, Portugal.
International maritime organization (IMO), 2007, Revised recommendations on the safe transport of dangerous cargoes and related activities in port areas, London, United Kingdom.
Kim, K.H., Chang, K.P., Han, G.H., Kwak, J.M., Kim, S.T., 2014, Fire and explosion analysis for LNG fuelled ship, Safety, Reliability and Risk Analysis: Beyond the Horizon, 117–123.
Landucci, G., Tugnoli, A., Cozzani, V., 2010, Safety assessment of envisaged systems for automotive hydrogen supply and utilization, International Journal of Hydrogen Energy, 35(3), 1493-1505.
Lloyd’s Register and University College London, 2014, Global marine fuel trends 2030, London, United Kingdom.
Maragkogianni, A., Papaefthimiou, S., Zopounidis, C., 2016, Shipping Industry and Induced Air Pollution, Chapter in: Cham (Ed.), Mitigating Shipping Emissions in European Ports: Social and Environmental Benefits, Springer International Publishing, 1–9.
OCIMF, (fourth edition), 1996, International Safety Guide For Oil Tankers And Terminals, Witherby & Co., London, United Kingdom.
Scarponi G., Landucci G., Ovidi F., Cozzani V., 2016, A lumped model for the assessment of the thermal and mechanical response of lng tanks exposed to fire, Chemical Engineering Transactions, 53, 307-312.
Tugnoli, A., Cozzani, V., Landucci, G., 2007, A consequence based approach to the quantitative assessment of inherent safety., AIChE J. 53, 3171–3182.
Uijt de Haag, P.A.M., Ale, B.J.M., 2005, Guidelines for quantitative risk assessment (Purple Book), Committee for the Prevention of Disasters, The Hague (NL).
U.S. Energy Information Administration (EIA), 2018, Short-Term Energy Outlook, Washington, DC, USA.
Van Den Bosh, C.J.H., Weterings, R.A.P.M (third ed.), 1997, Methods for the Calculation of Physical Effects (Yellow Book), Committee for the Prevention of Disasters, The Hague (NL).