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Including the human factor and environmental conditions in the reliability estimation of an LNG bunkering operation supply

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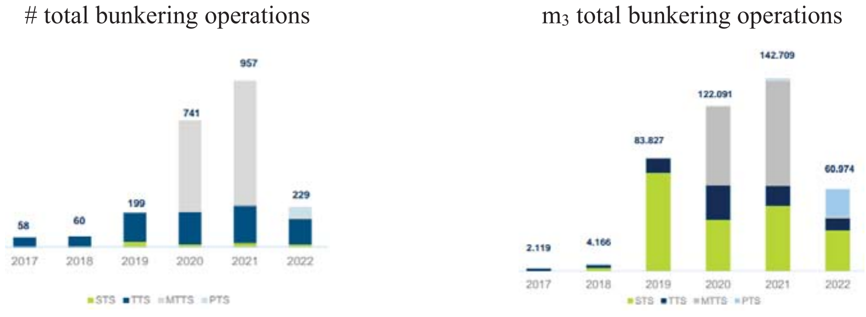
Liquified Natural Gas (LNG) has been recently used as a new fuel into the maritime sector. Besides the preceptive studies related to the safety in the use of LNG and its consequences on people, infrastructure, and the environment there have been released recent studies addressing the reliability of bunkering operations. In the following article, we have evolved these early reliability studies including the effect of surrounding conditions and the human behavior as a key factor for the reliability of the whole bunkering process. Results and key findings are supported by real bunkering truck to ship operations performed at ports of Spain.

Keywords: reliability, failure rate, human reliability, LNG bunkering, truck to ship.

1. Introduction and objectives

In June 2017 for the first time in Spain, a truck filled with Liquified Natural Gas (LNG) was unloaded into a ferry ship called Abel Matutes. LNG has been in use in the peninsula since 1966, however the novelty came on the fact that for the first time in the Iberian Peninsula this truck was not heading for an industrial customer but for a ship at port instead. From there on, the usage of LNG as a marine fuel has been increasing worldwide year after year as shown by statistics recorded by DNV and SeaLNG. Fig. 1 shows how, but for the pandemic effects, this increase had been steady both in the number of operations performed as well as in the amount of gas delivered.


total bunkering operations

m_3 total bunkering operations

Fig. 1. LNG Bunkering activity evolution in Spain by technology. Source, Bunkering activity in Spain. Stats from 2022 annual report. (GASNAM)

LNG bunkering rollout includes new achievements that are continuously challenged. Such is the case of the largest TTS bunkering operation performed in Huelva in 2021 unloading 10 trucks that soon was outperformed in Vigo in Oct 2022 with 12 trucks unloaded in 6.5 hours, which stands for the largest TTS LNG Bunkering operations performed in Spain to date. The numbers are clear, LNG has established itself as the alternative to traditional fossil fuels in the maritime sector.

Regulatory framework has a lot to do in the adoption of LNG as a marine fuel. In 2020 forcefully entered a resolution from the International Maritime Organization (IMO), which had forced shipping companies to reduce the SO2 emissions below 0.5% from the previous 3.5% allowed. This regulation represented a notable change that made the shipping companies act.

Future adoption of LNG and other alternative fuels are conditioned by the regulatory framework. The Initial IMO Greenhouse Gas Strategy ('the IMO Strategy') currently drives policy development within international shipping, and the new IMO 2023 regulation, effective from 1st January 2023, enforce two new indexes: the Carbon Intensity Indicator (CII) and Energy Efficiency eXisting ship Index (EEXI).

In addition, the EU has proposed to include shipping in the EU Emissions Trading System (EU ETS) and the FuelEU Maritime regulation which aims to increase the use of carbon-neutral fuels through an increasingly stringent well-to-wake GHG intensity requirement. These proposals take effect from 2024 and 2025, respectively. The regulatory and commercial drivers are enabled by supporting frameworks and standards specifying, for example, the setting of science-based, net-zero GHG emissions targets; taxonomies for sustainable activities; sustainability evaluation criteria and calculation methods for the well-to-wake GHG emissions of fuels; and supply-chain emission reporting requirements.

This regulatory framework points to a diverse future energy mix of carbon neutral and fossil fuels, with the latter gradually phased out by 2050. If we push towards full decarbonization by 2050, the fuel infrastructure needs to deliver around 270 million tonnes of alternative fuels. Responding to the drivers for decarbonization, shipowners will need to apply new technologies and fuels to reduce emissions. There is no single 'winner-takes-all' alternative fuel and technology. LNG is leading the change, but soon will be followed by other alternative fuels. Main engine manufacturers are already working on ammonia and methanol ship engines as the market is demanding for alternative solutions for the newbuild vessels. This includes hydrogen, battery/hybrid vessels and the use of biomethane and synthetic fuels.

Safety standards are beyond any doubt, but reliability levels remain still unexplored. The rapid and sudden growth in LNG bunkering operations shown in fig. 1 has forced the suppliers to adopt quick solutions to meet this new market appetite. Gas suppliers and logistic providers have adapted their traditional industrial solutions to the new surrounding environment at port. The differences are quite a few and may compromise the settled safety standards.

- "Just in time". No sooner is the ship at the dock than it is gone. LNG trucks must be prepared in advance.
- "SIMOPs" which stands for: simultaneous operations. In order to save time, suppliers would be asked to feed the ship at the same time than truck, cars and passengers are getting on and off the boat.
- ”Flexibility". Bunkering operations must adapt to different configurations related to which dock uses the ship, mooring port or starboard, motor tank and its hose, pump, skid and the rest of the equipment.
- "You always play as a visitor" Neither your facility nor the facilities of the shipping company, instead bunkering operations are always performed under the rules of the harbour facilities. Coordination is key; a forecast planning is required. 6 and 3 months planning updated weekly in addition to short time notice for daily operations.

To meet the requirements of this new scenario the supplying chain has necessarily adapted times, procedures, equipment, and labour force involved. It is time to check to what extend not only the safety standards, but also the reliability of the process is being granted. So far, there have been some good news in this adaptation process. The equipment used are brand new acquisitions and the personal involved in bunkering operations are skilled and experienced professionals. In addition, port authorities at each locations watch and care for the safety procedures. On the contrary, little can be said about the reliability of the whole bunkering process; as first assumption if the LNG has been delivered, the process works. But results might differ if we take a closer look. It is true that at port weather conditions and tight time schedules pop up as a new burden to overcome. Also, the human component can significantly vary from one operation to another. Yet the safety standards will not be compromised, but a natural question arises, what happen to the reliability of the process? So far, the bunkering operations are a black box. Every operation has a tailored design for each scenario considering the port, the ship, the mooring, the time allotted, and quantity of gas needed. The reliability of the whole process remines unknown once the ground configuration is defined. In other words, the supplier is at the port waiting for the ship, with the truck loaded of LNG and the ground configuration mounted. The ship will come, the loading process will start, and nobody knows what the chances are for the LNG transfer to be successfully completed.

Continuing the previous findings, the following research incorporates the effect of the human factor and the environmental conditions to complete a full reliability study of the LNG bunkering operations. We aim to answer the question, what the chances are that one specific ground configuration, performed by qualified professionals under certain surrounding environmental conditions might end successfully with the LNG delivered on time?

Results are expected to help understanding current configurations at port for LNG bunkering and what is more, these findings will also help configurate more reliable solutions for other alternative fuels.

2. Data Acquisition

The earliness at ports adopting LNG as an alternative fuel for shipping has allowed gathering relevant data and with these, make the subsequent first analysis. The behaviour of cryogenic equipment at bunkering operations remains still partially unveiled. Manufacturers are reluctant to share information about their new released equipment. As a result, the new specific failure data obtained from the field is received as gold mine for ulterior analysis. There are, however, some generic reliability data for some ground components already used with LNG on industrial configurations such as valves or hoses. This information has been collected from generic data bases of recognized prestige which is applicable to each component and processed using standard statistical techniques related to the operating experience of LNG bunkering facilities. Generic information on failures of the equipment involved has been collected from different research literature involving cryogenic and non-cryogenic equipment. Failure modes include among others: rip, drain, sensor fault, failure in automatic activation of vessel's ESD valve, human failure in a stress situation, leakage due to rupture leak in the pump (not in flanges), pump housing failure (body), leaking pump seals, controller fault.

This information has been merged with empirical results from some equipment involved in actual bunkering operation.

3. Methodology

3.1. *Equipment reliability*

Failures considering equipment can present three types of failure modes:

- Failures on Standby
- Failures on Demand
- Failures during Operation

In bunkering operations, we focused on the operational failure than includes, for example, leakage failure, rupture failure, spurious failure, etc. Unreliability, u, associated to failures during operation can be formulated as:

$$u_o(t) = 1 - e^{-\lambda_O * t} \approx \lambda_O * t \tag{1}$$

where λ_o is the component's operational failure rate and t stands for the time in which the bunkering operation must be performed. It is more particular for the present project; the aim is to obtain an equipment reliability index. Therefore, instead of using the equipment failure probability model, represented by equation (1), the aim is to directly represent the reliability of the equipment, which can be formulated as:

$$r = 1 - u_o \tag{2}$$

In addition to the equipment reliability, the impact of different environmental conditions on the performance of the bunkering activity has been assessed. Thus, the effect of the wind, wave height and visibility (rain) are considered. Tables 1 to 3 show the classification proposed in this study for the different environmental conditions and the Environmental Factor (EF) values which are used to penalize the probability of failure. The score and EF values were obtained using expert judgement.

Table 1. EF related to wind speed.

Intensity (knots)	Score	EF
7.5	100	1
15	50	2
20	10	4
>20	0*	-

* Recommendation to wait/stop the operation

Table 2. EF related to wave height speed.

Significant wave height (m)	Score	EF
0.2	100	1
0.75	50	2
1	10	4
>1	0*	

* Recommendation to wait/stop the operation

Table 3. EF related to rain.

Intensity (knots)	Score	EF
7.5	100	1
15	50	2
20	10	4
>20	0*	-

In such a way that, for each equipment belonging to the selected bunkering configuration, the value of u_0 obtained from equation (1) would be affected by the multiplicative factors corresponding to the meteorological conditions in which the operation is carried out, obtaining the value corresponding to the unreliability of the equipment u, value that will be used in the quantification of the reliability for a given configuration.

3.2. *Human reliability*

The effect of human factor is usually evaluated in terms of Human Error Probability (HEP). There are different types of human errors, both errors of omission and errors of commission in the performance of a planned action. In the case of bunkering operations we will focus on errors of commission in executing a given action, since the operation of the system is considered.

The most common model for modeling a human error in performing a given action can be represented as "on-demand" type. That is, such a model should represent the probability of human error in performing an action, so the following expression can be used:

$$u(HE) = \alpha \tag{3}$$

where $u(HE)$ or α represent such a fixed probability of human error (HEP) per action.

Different methodologies for human reliability assessment have been proposed in the literature (Akyuz et al. 2018). In this project, an adaptation of the SPAR-H (Human Reliability Analysis Method) methodology (NUREG/CR-6883, 2005) has been considered. The factors that constitute the elements considered in the model, called PSF (Performance Shaping Factors), are a total of eight and include: Time Available (TA), Stress (S), Complexity (C), Experience and training (ET), Procedures (P), Ergonomics (E), Motivation (M) and Process (P). The values corresponding to the different multipliers (M) of the eight FSPs presented in the (NUREG/CR-6883, 2005) are shown in Table 4.

Depending on the characteristics of the activity to be performed, the values corresponding to the multiplier of each PSF are selected, calculating the probability of human error, for a given activity, as:

$$\alpha = \frac{NPHE \cdot PSF_{compound}}{NPHE\ (PSF_{compound} - 1) + 1} \tag{4}$$

where $NPEH$ is the nominal human error probability which for the base case is equal to 0.001 and the $PSF_{compound}$ is evaluated as the product of the multipliers selected for each PSF.

Table 4. List of the Performance Shaping Factors considered and their values.

PSF	Level	M
Time available	Time inadequate	(1)
	Time available = required	10
	Nominal time	1
Stress	Extreme	5
	High	2
	Nominal	1
Complexity	High complexity	5
	Moderately complex	2
	Nominal	1
Experience/ Training	Training low	3
	Nominal	1
	High	0.5
Procedure	Unavailable	50
	Incomplete	20
	Available but "poor"	5
	Nominal	1
Ergonomics	Absent	50
	Poor	10
	Nominal	1
	Good	0.5
Motivation	Inappropriate	(1)
	Degraded	5
	Nominal	1
Process	Poor	2
	Nominal	1
	Good	0.8

(1) Failure probability=1; M Multiplier

Alternatively, one can decompose the $PSF_{compound}$ into a base PSF (PSF_{base}) by the PSF corresponding to the stress (PSF_{stress}), adapted to the specific case of bunkering, and a PSF of the available time (PSF_{td}) according to the selected availability. Considering this decomposition equation (4) is modified to:

$$\alpha = \frac{NPHE \cdot PSF_{base} \cdot PSF_{stress} \cdot PSF_{td}}{NPHE\ (PSF_{base} \cdot PSF_{stress} \cdot PSF_{td} - 1) + 1} \qquad (5)$$

The adaptation of the PSF corresponding to stress has been carried out with the aim of including the meteorological conditions during the bunkering operation in the probability of human error. The different levels corresponding to wind, wave height and visibility (rain) are the same as those considered in the probability of equipment failure (see Tables 1-3). Combining (multiplying) these levels and keeping the stress variability range between 1 and 5, as in the original method, the multiplier factors shown in Table 4 have been obtained.

3.2. *Reliability of a bunkering configuration*

Truck To Ship (TTS), along with multiple TTS configurations, when more than one truck are unloaded simultaneously, happens to be the more extended bunkering configuration according to the number of operations performed in Spain in the last (see Fig. 1). Its flexibility when adapting to the vessel's needs and the low infrastructure investment required are two of the main reasons for its widespread usage. So, in this paper, a TTS configuration is considered.

In a TTS configuration the different equipment are connected in series, then the failure of one of the equipment in the configuration causes the failure of the bunkering operation. However, in the case of spare parts availability for a given equipment, in a simplified way, it will be assumed that the availability of spare parts can be modeled as a parallel configuration, so that the equipment will fail if all the spare parts available for the equipment fail.

The reliability of a configuration, i.e., the probability that the bunkering operation will be performed successfully can be estimated, by considering the different contributions presented in the above subsections, as:

$$R = P(no\ failure\ of\ the\ configuration) = \prod_{i=1}^{n} r_i \prod_{i=1}^{n} (1 - \alpha_i) \qquad (6)$$

where r_i is the reliability of an equipment and α_i is the probability of human error. The value of r_i can be obtained, if spare parts for different equipment are available during the bunkering operation, such as:

$$r_i = 1 - \prod_{j=1}^{1+N_{rep}(i)} u_{ij} \qquad (7)$$

u_{ij} represents the probability of failure of a spare part j of equipment i, which can be calculated using equation (1), and $N_{rep}(i)$ represents the number of spare parts available for i equipment.

Substituting equation (7) into (6) the reliability of a configuration, called BUnkering Reliability Index ($BURI$), can be quantified as:

$$BURI = \prod_{i=1}^{n} \left[1 - \prod_{j=1}^{1+N_{rep}(i)} u_{ij}\right] \prod_{i=1}^{m} (1 - \alpha_i) \qquad (8)$$

where α_i is evaluated using equation (4) or (5).

4. Application case

Application case is focused on the estimation of the reliability of a typical TTS configuration. Fig. 2 shows the Reliability Block Diagram (RBD) corresponding to the configuration considered to carry out the bunkering operation. Basically, the configuration is composed of dry cryogenic couplings, cryogenic hoses, N_2 supply system, break away to prevent pull away accidents, insulation flange, flange adaptor and the emergency shutdown System. As shown in Fig. 2, the different components are connected in a series configuration. In addition, Table 5 presents the failure rates (λ_o)corresponding to the different components. These failure rates were obtained from (Miranda et al., 2022).

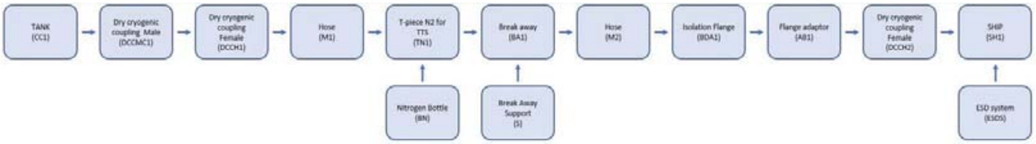


Fig. 2. Reliability Block Diagram (RBD) of TTS configuration

Table 5. Failure rate of the equipment.

Code	System	N_{spare}	λ_o
CC-1	Truck	0	2.08E-03
DCCMC-1	DCC mail	0	2.55E-04
DCCH-1	DCC female	0	5.11E-04
M-1	Hose	1	7.67E-04
BA-1	Break away	0	7.67E-04
BDA-1	Insulation flange	0	8.58E-09
M-2	Hose	1	7.67E-04
AB-1	Flange Adapter	0	1.80E-08
ESDS	ESD System	0	0

In addition, the probability of human error must be estimated. For this, previously, the Performance Shaping Factors, $PSFs$, must be determined. In this application case, the determination of the $PSFs$ have been carried out by means of expert judgment. In different sessions, the experts, technical personnel from companies that carry out bunkering operations, identified the activities that take place during the operation. Using Table 4, the value that corresponds to the multiplier, M, of each PSF is chosen for the different activities based on its characteristics. Then, the $PSF_{compound}$ is obtained by multiplying the values assigned to M. Finally, equation (4) is applied to calculate the probability of human error, α, using the $PSF_{compound}$. The results obtained for the $PSF_{compound}$ and α are summarized in Table 6 for the TTS configuration considered.

Table 6. $FSP_{compound}$ and the probability of human failure, α, for a TTS configuration.

System	Activity	$FSP_{compound}$	$NHEP$	α
CC1	Operations preparation	0.2	0.001	0.00020016
DCCMC-1	DCM tank flange installation	0.4	0.001	0.00040024
DCCH-1	Dry-coupling female-male connection (tank)	0.8	0.001	0.00080016
M-1	Transfer system connection	0.4	0.001	0.00040024
BA-1	Transfer system connection	0.8	0.001	0.00080016
M-2	Transfer system connection	0.4	0.001	0.00040024
BDA-1	Flange installation	0.4	0.001	0.00040024
DCCH-2	Dry-coupling female-male connection (ship)	0.8	0.001	0.00080016
TN-1	Connected	0.8	0.001	0.00080016

ESDS	Error of performance or performance involuntary	0.4	0.001	0.00040024

From the data in tables 5 and 6, the block diagram shown in Fig. 2, and equations (1), (4) and (8) the reliability of the bunkering operation has been estimated under different assumptions: a) considering only equipment malfunctions, b) including a spare equipment in the configuration and c) including the probability of human error. The reliability has been estimated considering normal environmental conditions and a bunkering operation duration of 1.25 hours. Results from calculations are summarized in table 7, stating the effect of human errors in the reliability of the bunkering operation.

Table 7. Quantitative effect of human factor on the reliability of a TTS bunkering operation.

BURI	With hose replacement	Without hose replacement
Not Considering Human Errors	0.9939	0.9929
Considering Human Errors	0.9870	0.9861

The BUnkering Reliability Index itself proves to be valuable, not as an absolute value, but as a comparation among different alternatives. Table 7 shows a clear example of the effect that human behaviour has in the reliability of the whole bunkeing process. Considering the human factor the same configuration has became less reliable. Still the spear components are a valuable option to improve the reliability when considering the human element.

5. Conclusions

The wide spread of LNG bunkering operations is allowing the first analysis of the information from the field provided by the different companies involved in the process: suppliers, logistic companies, manufacturers, ship owners. The adaptation of the SPAR-H (Human Reliability Analysis Method) methodology (NUREG/CR-6883, 2005) combined with the 8 Performance Shaping Factors chosen have yield to the following conclusions. First, As expected, the human factor happens to affect the reliability of a bunkering operations. At these early stages when the maritime sector is benefiting from the experience of industrial truck drivers, the human error introduces little variations in the whole reliability index.

Still, human factor happens to decrease the reliability of the whole process because the equipment considered is quite new and the different components show high reliability themselves.

The reliability index might not provide straight forward conclusions itself. However, it has been proven that some bunkering configurations are more reliable than others. And that is precisely what may be the best application of this reliability index, as a tool for undertaking improvements in the ground configuration of bunkering operations to improve their baseline reliability. The study provides the maritime companies and port authorities with a reference to determine how far from failure is the bunkering configuration offered by the supply company.

A BUnkering Reliability Index, BURI itself was first presented to GASNAM state holders on May 5th, 2022. The current study provides an improvement to this BURI reference introducing the environmental and the human factors. The objective is to make the tool available to shipping companies, logistic companies, and port authorities so that they can assess its usefulness when designing the shore configuration of LNG bunkering operations. The feedback received will be crucial to identify areas of improvement and assign priorities. However, apart from these considerations, some areas of interest have already been detected and are pointed out in the paper.

Further research might focus on evaluating the effect of time in the reliability of the procedures. Current calculations all yield extremely high values. These results are logical considering the short life of most of the materials that have been recently acquired in the last 2 or 3 years. It will be interesting to study the effect of the passing of time has compensated for the correct maintenance program to the reliability levels. In addition, alternative methods can be studied, such as Markov chains.

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