Analysing the risk of LNG carrier operations

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Received in revised form 15 January 2007; accepted 30 July 2007
Available online 17 August 2007

Abstract

This paper presents a generic, high-level risk assessment of the global operation of ocean-going liquefied natural gas (LNG) carriers. The analysis collects and combines information from several sources such as an initial hazid, a thorough review of historic LNG accidents, review of previous studies, published damage statistics and expert judgement, and develops modular risk models for critical accident scenarios. In accordance with these risk models, available information from different sources has been structured in the form of event trees for different generic accident categories. In this way, high-risk areas pertaining to LNG shipping operations have been identified. The major contributions to the risk associated with LNG shipping are found to stem from five generic accident categories, i.e. collision, grounding, contact, fire and explosion, and events occurring while loading or unloading LNG at the terminal. Of these, collision risk was found to be the highest. According to the risk analysis presented in this paper, both the individual and the societal risk level associated with LNG carrier operations lie within the As Low As Reasonable Practicable (ALARP) area, meaning that further risk reduction should be required only if available cost-effective risk control options could be identified. This paper also includes a critical review of the various components of the risk models and hence identifies areas of improvements and suggests topics for further research.

Keywords: LNG carriers; Marine transportation; Risk analysis; Maritime safety; Gas tankers; Formal safety assessment; Liquefied natural gas

1. Introduction and background

1.1. The SAFEDOR project

The study presented in this paper was carried out within SAFEDOR [1]. SAFEDOR is a research project co-financed by the European Commission as an integrated project (IP) in their 6th Framework Programme. One of the aims of this project is to encourage innovative ship design for cleaner and safer maritime transport. In order to facilitate this, concepts for a risk-based regulatory framework will be developed that will open for acceptance of novel design concepts based on risk analyses. These novel design solutions might have equal or better safety than conventional designs even though they may violate current prescriptive requirements.

As a part of the SAFEDOR project, generic Formal Safety Assessment (FSA) studies on various ship types have been initiated. The risk assessment of LNG carriers presented herein represents one part—step 2—of one of these generic FSAs.

1.2. Liquefied natural gas and LNG shipping

Liquefied natural gas (LNG) is composed of mostly methane and is a cryogenic liquid at approximately –162°C. When vaporized, its flammability range is between approximately 5% and 15% by volume, i.e. a mixture with air within this range of concentrations is flammable. Thus, in addition to possible damages due to its cryogenic temperatures, LNG spills are associated with hazards such as pool fires and ignition of drifting vapour clouds. In its liquid state, LNG is not explosive, and LNG...
vapour will explode only if ignited in a mixture with air within the flammability range and within an enclosed or semi-enclosed space. Natural gas may also present an asphyxiation hazard. LNG is not toxic and will not be persistent if spilled in a marine environment. LNG weighs less than water, thus LNG spilled on water will float.

In liquefied form, the volume of LNG is 600 times less than the same amount of natural gas at room temperatures. LNG shipping is therefore an economic way of transporting large quantities of natural gas over long distances. LNG is transported and stored at normal atmospheric pressure, and LNG carriers are purpose-built tank vessels for transporting LNG at sea.

The current world fleet of LNG carriers is relatively small; as of August 2005 it contained 183 ships, but it has been increasing steadily in recent years. A further increase is expected in the coming years. Fig. 1 illustrates the LNG fleet development, and includes a forecast until 2010. During the more than 40 years of LNG shipping, the total number of LNG carrier shipyears is 2838 (including 2005). Of these, 1857 are accumulated since 1990.

In addition to an increase in numbers, the size of LNG carriers is also increasing. The average size of the current fleet is almost 120,000 m³, whereas the average size of vessels currently in the order book is 156,000 m³. LNG super-tankers with capacities of 200,000–250,000 m³ are foreseen in the near future.

All types of LNG carriers are double-hull vessels, but there exist different cargo containment systems of independent or integrated cargo tanks. The current LNG fleet is dominated by two main types of vessel designs, i.e. the membrane tank designs and the spherical tank designs. In membrane tank designs, the cargo containment system consists of a very thin invar or stainless steel double-walled, insulated cargo envelope that is structurally supported by the ship’s hull. The spherical tank carriers, also referred to as Moss tankers, have spherical aluminium tanks or prismatic-shaped stainless steel tanks that are self-supporting within the ship’s hull. These tanks are insulated externally. Both tanker alternatives are designed, constructed and equipped with sophisticated systems for carrying LNG over long distances, stored at temperatures around −162 °C. Each of the main types of LNG vessel designs constitute about half of the fleet (the actual distribution is 50% membrane ships, 45% spherical tankers and 5% of other types of LNG tankers), but membrane tankers are dominant among LNG new buildings. LNG vessels are generally well designed, well maintained and operating with well-trained crew. Thus, LNG shipping so far has a good safety record. The two main types of LNG carriers are illustrated in Fig. 2.

1.3. The FSA methodology

FSA is a standard risk assessment, with the aim of developing maritime safety regulations in a structured and systematic way. It should not be mistaken for a risk assessment for a specific ship or a ship’s safety case. FSA may better be described as a safety case for the rules and regulations. FSA can be used in the evaluation of new regulations and for comparison between existing and possibly improved regulations, and it aims at balancing safety and environmental protection levels with costs. Both technical and operational issues, including the influence of the human element on shipping accidents, may be incorporated in an FSA. Various aspects and applications of the FSA methodology have been extensively discussed in different academic journals.

IMO has developed guidelines for FSA studies. By now, a number of FSA studies have been performed and reported to IMO according to these guidelines, and decisions have been made based on such submissions. The methodology is described as a 5-step process:

0. Preparatory steps
1. Identification of hazards
2. Risk analysis
3. Identifying risk control options

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4. Cost–benefit assessment
5. Recommendations for decision-making.

The study presented in this paper corresponds to the second step—risk analysis—of an ongoing FSA on LNG tankers.

2. Defining the scope of study

This paper describes a high-level, generic risk analysis of LNG carriers, and the scope of the study is the whole fleet of ocean-going LNG carriers. A generic LNG carrier is assumed representative for the various types of LNG vessels. Historic accident experience indicates that the risk level of the main types of LNG carriers is comparable, so this assumption seems valid up to a certain level of detail. It is noted that membrane tanks have experienced cargo tank leakage through its primary barrier, and are also believed to be more vulnerable to effects of dynamic loads and sloshing of LNG cargo, but risk contributions from such scenarios are assumed small in comparison with the main accident scenarios investigated in this study. Therefore, detailed studies of specific ships as well as specific trades and port environments are defined out of scope.

However, a particular reference vessel will be used where needed. For the purpose of this generic analysis, a 138,000 m$^3$ membrane LNG vessel currently under construction at Navantia was chosen. The cargo capacity of this reference vessel is within the main range of LNG carriers and its speed is typical for this type of vessels. It has a reversible geared, cross-compound steam-driven 28,000 kW × 83 RPM main turbine and a 5-blade fixed pitch-type propeller. The main characteristics of the reference vessel are given in Table 1.

Only the shipping phase of the LNG chain is considered, covering loading at the export terminal, the actual voyage and unloading at the receiving terminal. Risks pertaining to exploration, production, liquefaction, storage and regasification of natural gas are considered out of scope. Furthermore, only the operational phase of an LNG vessel is considered, and risks associated with construction, repairs in dock and scrapping of LNG vessels are out of scope.

![Fig. 2. Main types of LNG carriers: moss spherical tankers (top) and membrane tankers (bottom).](image)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Main characteristics of reference vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>284.40 m</td>
</tr>
<tr>
<td>Length between perpendiculars</td>
<td>271.00 m</td>
</tr>
<tr>
<td>Breadth (moulded)</td>
<td>42.50 m</td>
</tr>
<tr>
<td>Depth to main deck (moulded)</td>
<td>25.40 m</td>
</tr>
<tr>
<td>Depth to trunk deck (moulded)</td>
<td>32.20 m</td>
</tr>
<tr>
<td>Draft design (moulded) under keel</td>
<td>11.40 m</td>
</tr>
<tr>
<td>Draft scantling (moulded)</td>
<td>12.30 m</td>
</tr>
<tr>
<td>Double-bottom depth</td>
<td>2.9 m</td>
</tr>
<tr>
<td>Double-side width</td>
<td>2.32 m</td>
</tr>
<tr>
<td>Total displacement</td>
<td>98,500 t</td>
</tr>
<tr>
<td>Total cargo tank capacity</td>
<td>138,000 m$^3$</td>
</tr>
<tr>
<td>Total insulation thickness</td>
<td>0.530 m</td>
</tr>
<tr>
<td>Service speed at design moulded draft</td>
<td>19.50 knots$^a$</td>
</tr>
<tr>
<td>Accommodation capacity</td>
<td>40 persons$^b$</td>
</tr>
</tbody>
</table>

$^a$At NCR (90% of MCR) of main propulsion machinery.
$^b$Including 4 Suez canal workers.

Security issues are regarded as out of scope. The environmental risks associated with LNG shipping are assumed small since LNG is non-toxic and non-persistent, and is therefore not relevant to this study. Thus, the focus of this study has been on safety and risk to human lives. Third-party risks to people on shore are also left out of the study. It is argued that such risks should rather be investigated in specific risk analyses pertaining to specific LNG terminals or LNG trades, and these issues are more related to the siting of LNG terminals than to IMO regulations for maritime safety. Thus, this study only considers the risks to LNG crew as well as risks to crew and passengers onboard other vessels. Finally, the focus has been on accidents of a certain scale, and high-frequency, small-scale occupational accidents have not been emphasized.

3. Risk acceptance criteria

In order to evaluate the risk as estimated by a risk analysis, appropriate risk acceptance criteria should be established prior to and independent of the actual risk analysis. Among different principles of safety [13], the As Low As Reasonably Practicable (ALARP) principle will be employed, i.e. risk acceptance criteria should divide...
between three levels of risk: intolerable, ALARP and negligible. For risks within the ALARP area, cost-effectiveness considerations apply to the amount of resources that should be spent on risk mitigation. The IMO FSA guidelines [10] recognized this as the current best practice, although criticism of the ALARP principle has occurred [14]. For this risk analysis on LNG carriers, risk acceptance criteria for individual and societal risks were derived for crew as well as for passengers onboard other vessels that might be affected by a possible LNG accident.

3.1. Individual risk acceptance criteria

A thorough review of alternative risk acceptance criteria was presented in Skjong et al. [15]. Based on this review, the acceptance criteria for individual fatality risk to crew presented in Table 2 were adopted for the current study. This corresponds to the risk level experienced by an exposed crewmember. The individual risk to third parties (including passengers on other vessels) is intuitively assumed to be negligible, so only criteria for the LNG crew are deemed necessary.

3.2. Societal risk acceptance criteria

Societal risk acceptance criteria for crew were established based on the approach described in Norway [16]. According to this method, acceptance criteria are associated with the economic importance of LNG shipping, calibrated against the average fatality rate per unit of economic production. Based on reasonable estimates of daily rates, operational costs and capital costs due to initial investments, the economic value of LNG shipping was estimated to be USD 1.6 million per shipyear. The risk acceptance criteria that were derived based on these estimates are illustrated in Fig. 3. It should be noted that these criteria are somewhat stricter than the criteria proposed for tankers in general by Norway [16].

These societal risk acceptance criteria can be assumed appropriate also for crew onboard other vessels, but for passengers onboard other vessels more strict criteria might be appropriate. Thus, for the purpose of this study, societal risk acceptance criteria for passengers with anchor points that are one order of magnitude lower than for the criteria for crew will be used.

3.3. Cost-effectiveness criteria

The results from the risk analysis presented in this paper may be carried forward to support cost-effectiveness assessments of new as well as existing safety measures. If the risk level is found to lie in the ALARP area, all available cost-effective risk control options should be implemented according to the FSA philosophy. There exist various measures of cost effectiveness, and two that are often used in conjunction with FSA studies are the Gross Cost of Averting a Fatality (GCAF) and the Net Cost of Averting a Fatality (NCAF), defined by Eqs. (1) and (2). ΔC is the cost, ΔR is the risk reduction and ΔB is the economic benefit resulting from implementing the measure, respectively:

\[\text{GCAF} = \frac{\Delta C}{\Delta R},\]  
\[\text{NCAF} = \frac{\Delta C - \Delta B}{\Delta R} \cdot\]  

The risk analysis defines the baseline risk level and thereby also the potential for risk reduction. For a prospective measure, i.e. a regulatory option, the risk models developed in this paper can be used to investigate

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual risk acceptance criteria for LNG crew</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Risk level per year</th>
<th>Acceptance criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intolerable</td>
<td>&gt; 10^{-3}</td>
</tr>
<tr>
<td>ALARP area</td>
<td>10^{-6}–10^{-3}</td>
</tr>
<tr>
<td>Negligible</td>
<td>&lt; 10^{-6}</td>
</tr>
</tbody>
</table>

Fig. 3. Societal risk acceptance criteria for crew.
the expected risk-reducing effect. Further analyses would also be required in order to estimate the expected cost as well as any economic benefits that would result from implementing the measure. In accordance with current practice within IMO and the proposals presented in MSC 72/16 [10], a risk control measure will generally be recommended for implementation if $GCAF \leq USD 3$ million or $NCAF \leq USD 3$ million (note that by definition, $NCAF \leq GCAF$, so if $GCAF \leq USD 3$ million, $NCAF$ will always be $\leq USD 3$ million). For risk control options where the estimated cost effectiveness is close to USD 3 million, further scrutiny might be required.

4. Accident scenarios

4.1. Operational experience with LNG tankers

Marine transportation of LNG has gradually increased since the first LNG cargo was transported by an LNG tanker in 1959 and the first purpose-built LNG tanker was engaged in commercial trade in 1964. Thus, more than 40 years of operational experience with LNG carriers has accumulated over the years.

A literature survey on the history of LNG shipping reveals information of 182 events, with or without LNG spillage, involving LNG carriers larger than 6000 GRT [17]. Of these, 24 occurred to ships out of regular service (e.g. in yard during construction or repair or while in tow or during sea trials) and are considered out of scope. Thus, previous experience amounts to 158 known relevant accidents involving LNG carriers. The breakdown of LNG events on ship types according to these accidents is illustrated in Fig. 4. It is emphasized that this only illustrates the total number of accidents without considering the severity of the accidents or the relative population of membrane and spherical carriers.

The available material indicates that accidents have happened more often on spherical-type LNG ships during the history of LNG shipping, but that accidents have been more frequent on membrane ships during the last 20 years. Available statistics are too sparse to draw any definite conclusions, and conclusions cannot be drawn without considering the population of each LNG carrier type, but it is noted that accidents have occurred for all types of LNG carriers. For the purpose of this high-level study, the accident frequency is henceforth assumed independent of LNG carrier type.

4.2. Generic accident categories

The 158 known relevant LNG carrier accidents can be grouped into a few generic accident types. The breakdown of accidents into accident categories is presented in Table 3, and Table 4 presents the breakdown into accident categories and different periods of time.

This categorization of accidents is in general agreement with the scenarios identified during the hazard identification [18]. Some of the accident categories are not believed to be associated with severe consequences in terms of fatalities. For example, the accident category equipment and machinery failure is associated with incidents where the failure did not lead to any subsequent events such as collision, grounding or fire. For incidents where subsequent events occurred, e.g. for rudder failures leading to collision or grounding, it has been sorted under the accident category corresponding to this subsequent event. Hence, even though equipment and machinery failure is associated with the highest incident frequency, this accident category
is not believed to be very critical to crew safety. Also, incidents due to bad weather and failure of cargo containment system that are not leading to subsequent accidents such as collision, grounding and fire are considered to constitute a small risk compared with the remaining accident scenarios. Thus, the following five generic accident scenarios were selected for further study in the risk analysis:

- Collision
- Grounding
- Contact
- Fire and explosion
- Events while loading/unloading cargo
- Failure of cargo containment system

These are regarded as the main risk contributors, and risks from other scenarios are assumed to be negligible in comparison. It is noted that the accident categories listed above are general maritime accident scenarios that can occur for all types of ships, but the potential consequences and the possible further escalation of the scenarios are specific to LNG carriers due to the characteristics of its cargo.

5. Risk models

Selection of accident scenarios for further analysis corresponds to the overall risk model for LNG carriers as illustrated in Fig. 5. In the following, overall risk models for each accident category will be developed and the frequencies and consequences associated with each of the sub-models will be further investigated.

5.1. Frequency assessment

The frequency of an initiating event for each of the risk sub-models is based on the historic frequencies in Table 3. However, some adjustments to the estimates for the fire and explosion scenario and the loading/unloading scenario are made.

In all, 50% of the experienced fire and explosion accidents were vent riser fires and these do not constitute any significant hazard to the crew or the ship. Hence, these incidents were not regarded and the initiating frequency of fire and explosion is reduced accordingly, i.e. to $1.8 \times 10^{-3}$ per shipyear. A total of 22 loading/unloading incidents have been reported. However, only 9 of these reported any leakage of LNG, and only these events are assumed critical to safety. This corresponds to a frequency of $3.2 \times 10^{-3}$ for loading/unloading accidents, resulting in leakage of LNG, and this frequency will be used in the risk assessment. The initial frequencies used for each accident scenario are presented in Table 5. Comparing these frequencies with statistics for other generic vessel types, such as oil tankers, chemical tankers, LPG tankers and bulk carriers, they are found to agree reasonably well. In general, the accident frequencies are found to be somewhat lower for LNG carriers than for these other types of vessels, but this was expected considering the high focus on safety on these ships and the generally high competence of LNG crew.

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Table 3
Distribution of historic LNG accidents on categories

<table>
<thead>
<tr>
<th>Accident category</th>
<th>Accidents (#)</th>
<th>Frequency (per shipyear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision</td>
<td>19</td>
<td>$6.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>Grounding</td>
<td>8</td>
<td>$2.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>Contact</td>
<td>8</td>
<td>$2.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>Fire and explosion</td>
<td>10</td>
<td>$3.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Equipment and machinery failure</td>
<td>55</td>
<td>$1.9 \times 10^{-2}$</td>
</tr>
<tr>
<td>Heavy weather</td>
<td>9</td>
<td>$3.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Events while loading/unloading cargo</td>
<td>22</td>
<td>$7.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>Failure of cargo containment system</td>
<td>27</td>
<td>$9.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Total</td>
<td>158</td>
<td>$5.6 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Table 4
Breakdown of historic accident data based on accident categories and periods of time

<table>
<thead>
<tr>
<th>Exposure (accumulated shipyears)</th>
<th>64–75</th>
<th>76–85</th>
<th>86–95</th>
<th>96–05</th>
<th>64–05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision</td>
<td>1</td>
<td>10</td>
<td>4</td>
<td>4</td>
<td>19</td>
</tr>
<tr>
<td>Grounding</td>
<td>1</td>
<td>6</td>
<td>–</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Contact</td>
<td>–</td>
<td>4</td>
<td>–</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Fire and explosion</td>
<td>2</td>
<td>5</td>
<td>–</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Equipment and machinery failure</td>
<td>–</td>
<td>39</td>
<td>7</td>
<td>9</td>
<td>55</td>
</tr>
<tr>
<td>Heavy weather</td>
<td>–</td>
<td>6</td>
<td>3</td>
<td>–</td>
<td>9</td>
</tr>
<tr>
<td>Events while loading/unloading cargo</td>
<td>4</td>
<td>13</td>
<td>3</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>Failure of cargo containment system</td>
<td>7</td>
<td>15</td>
<td>5</td>
<td>–</td>
<td>27</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>98</td>
<td>22</td>
<td>23</td>
<td>158</td>
</tr>
</tbody>
</table>

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3Striking or being struck by any fixed or floating objects other than another ship or the sea bottom.
5.2. Consequence assessment

The expected consequences for each of the selected scenarios will be assessed by utilizing event tree techniques. First, a set of event trees will be constructed, one for each accident scenario, based on conceptual risk models. Then, these event trees will be quantified using a variety of different techniques for different branches. The estimates in Table 5 will be used as frequencies for the initiating events.

5.2.1. Constructing event trees

As the event trees tend to grow complex, it is not feasible to describe them in detail within the format of this paper. However, the conceptual risk model for each accident scenario will be presented in the following.

A typical collision scenario with an LNG carrier might develop in the following way. First, a collision occurs. The LNG vessel might be the struck or the striking ship. If the LNG vessel is the striking ship, the likelihood of further escalation of the accident is regarded as small as it will receive the collision impact in the bow in front of the collision bulkhead. Furthermore, the collision might occur when the LNG carrier is in ballast or when it is fully loaded. When the LNG carrier is the struck ship, the collision might cause a damage that penetrates the outer and inner hulls. If penetrating the inner hull, it might cause leakage of cargo. This might result in materialization of an LNG hazard such as pool fire. Cryogenic temperatures of LNG or heat generated from a pool fire might deteriorate the strength of the ship and may eventually lead to sinking. If LNG hazards materialize or the ship sinks, failure to evacuate in time may lead to a number of fatalities among the crew. Finally, for some of the possible LNG hazards, fatalities may occur among crew or passengers onboard the other vessel. Hence, the risk model illustrated in Fig. 6 describes a typical collision accident, and an event tree is constructed based on this.

The grounding and contact scenarios will resemble the collision scenario in many ways. First, a grounding/contact event might occur in either loaded or ballast condition. The grounding or contact will result in a certain extent of ship damage, and this damage might cause leakage of cargo and/or loss of stability. If LNG is released, one or more LNG hazards might materialize. Again, the LNG carrier might sink due to the damage or due to deteriorating strength caused by LNG leakage. Finally, if the crew is not able to evacuate in time, there might be fatalities due to LNG hazards or the sinking of the ship. The grounding and contact risk models that form the basis for event trees are illustrated in Fig. 7.

The fire or explosion scenario describes an accident where a fire or an explosion is the initiating event. It is distinguished between three types of fire scenarios, namely,

<table>
<thead>
<tr>
<th>Accident category</th>
<th>Initial frequency (per shipyear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision</td>
<td>$6.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>Grounding</td>
<td>$2.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>Contact</td>
<td>$2.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>Fire and explosion</td>
<td>$1.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>Leakage of LNG while loading/unloading</td>
<td>$3.2 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Fig. 6. Risk model for collision of LNG carriers.
fires that start in the machinery spaces, in accommodation areas or day rooms, and in the cargo area. For fires starting in machinery spaces or in accommodation areas, it is deemed highly unlikely that it will spread to the cargo area and no LNG-specific hazards are assumed. Thus, these scenarios will resemble similar fire accidents on other cargo ships such as oil tankers. The compressor room is the most likely place in the cargo area for a fire to break out, and such fires will be specific to LNG carriers. For a compressor room fire, the following scenario is assumed: the fire protection systems might fail in preventing or extinguishing the fire or explosion, which might lead to a breach in the cargo containment system and subsequent leakage of LNG. If there is leakage of LNG, an LNG hazard might materialize, and there will be a possibility that the ship will not survive. Finally, in the event of an escalating fire, the crew needs to evacuate and failure to do so in time might result in a number of fatalities. The fire and explosion risk model adopted in this study is illustrated in Fig. 8.

Spillage events during loading or unloading of cargo while in port are generally assumed to be of small scale, where only a limited number of the crew are exposed to risks of injuries or death. Fatal accidents are only deemed likely for crew members directly exposed to the cryogenic LNG. The resulting risk model is illustrated in Fig. 9, which was used to construct event trees for this scenario.

5.2.2. Quantifying the event trees

In order to assign probabilities for the various escalating events, and thereby quantify the probabilities and consequences associated with each scenario, a set of different approaches and techniques have been used. For each sub-model and for each branch of the event tree, the method that was found to be most practical was utilized and the information source that was assumed to be most relevant was exploited. Detailed descriptions of all these are not possible within the scope of this paper, but an outline describing the main approaches will be provided in the following.

The event tree for the collision scenario was quantified based on various techniques. First, some obvious general assumptions were made, e.g. the probability of being the striking or struck ship was assumed to be 0.5, and the probability of being loaded and in ballast was assumed to be 0.5 (since LNG shipping is principally unilateral in nature). The damage extent model contains several parts, describing the probability distribution of damage location, depth, length and height that again determines the probabilities of water ingress, receiving the damage in the cargo area, etc. For these probabilities, results from previous studies have been utilized, e.g. Olufsen et al. [19] and Skjong and Vanem [20], and in particular the damage database developed by the HARDER project have been exploited [21,22]. The extent of collision damage will determine the probability of cargo leakage. The remaining parts of the risk model, related to materialization of LNG hazards, survivability and evacuation, are associated with significant uncertainties and no amount of relevant data exist. Therefore, a workshop was arranged where expert opinion was elicited and incorporated in the event tree. A separate Delphi session was arranged in order to arrive
at consequence estimates related to number of fatalities on the LNG vessel as well as on the other vessel involved in the collision. All the estimates were inserted into the event tree in order to estimate the overall risk related to the collision scenario. The event tree for collision scenarios is illustrated in Fig. 10.

For the grounding and contact scenarios, similar approaches for quantification of the event trees were used as in the collision scenario, and the same sources of information were exploited. The event trees were quantified accordingly, as illustrated in Fig. 11 (grounding) and Fig. 12 (contact).

Due to its relatively small fleet, sufficient data on LNG carrier fires are not readily available. In the accident statistics for LNG carriers only five fires were reported (disregarding vent riser fires), and, of these, 3 started in the machinery spaces. This would correspond to 60% of the fires originating in the engine rooms, but it is realised that

![Diagram](image-url)

Fig. 8. Risk model for fire and explosion on LNG carriers.

![Diagram](image-url)

Fig. 9. Risk model for spill events during loading or unloading of LNG carriers.
A crew of 30 is assumed. Following table gives the risk contribution of collision frequency model:

<table>
<thead>
<tr>
<th>Consequence</th>
<th>Frequency</th>
<th>Risk</th>
<th>Consequence</th>
<th>Frequency</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG crew</td>
<td>0.0044</td>
<td>0.144</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd party</td>
<td>0.00157</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL RISK</td>
<td>0.00597</td>
<td>0.481</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10. Event tree: collision of LNG carriers.
A crew of 30 is assumed. A crew of 30 is assumed.

Fig. 11. Event tree: grounding of LNG carriers.
A crew of 30 is assumed.

Fig. 12. Event tree: contacts of LNG carriers.
A crew of 30 is assumed

Fire protection model
Cargo leakage model
LNG Hazard model
Survivability model
Evacuation model

Fire / explosion Model
Loading condition model

Fire and explosion distribution
In ballast (no LNG) at port
Fire Fighting systems successful
No leakage of LNG
No pool fire
Surviving
Probability of fatalities among crew
# fatalities

Probability of fatalities among crew

Consequence Frequency Risk contribution

Compressor room

0.03
0.5
0.1
0.85
1
1
1
0.37
1
0.15
0.9
1
1
0.37
1
0.1
0.1
0.989
8
0.9
0.85
1
1
1
0.37
1
0.15
0.9
1
1
0.37
1
0.1
0
1
0.989
16
0.81
0.37
1
0.81
0.37
1
0.16
0.37
1

Machinery space

Accommodation area

Sum Risk 0.000672088 fatalities per ship year

1 8.491E-07 8.491E-07
1 1.4985E-07 1.4985E-07
1 7.6424E-06 7.6423E-06
1 1.3487E-06 1.34865E-06
1 8.4915E-07 8.4915E-07
1 1.4986E-07 1.4986E-07
1 1.4986E-07 1.4986E-07
1 1.49869E-07 1.4986E-07
1 4.0055E-08 3.20436E-07
1 7.6424E-06 7.6423E-06
1 1.3487E-06 1.34865E-06
16 3.6049E-07 5.76785E-06
1 0.00053946 0.00053946
1 0.00010856 0.00010856

Fig. 13. Event tree: fire and explosion of LNG carriers.
the statistical base for this estimate is very weak. It was therefore assumed that the relative distribution of fires starting in machinery spaces, accommodation areas and cargo areas is similar to that of oil tankers, and recent results from a study on aframax tankers were utilized [23]. It may be argued that both the cargo area and the machinery spaces are very different for LNG tankers and oil tankers, and this suggests that probabilities arrived at from such comparison are not very accurate. Notwithstanding, fire statistics for LNG carriers are too scarce to be useful, and statistics from oil tankers are believed to be the best available source of information. The estimates used for the relative distribution of fires should be regarded with a high degree of uncertainty, but it is noted that the overall results are not overly sensitive to these uncertainties.

Furthermore, for fires in machinery spaces and accommodation areas, statistics from oil tanker accidents were assumed appropriate for LNG tankers and no further risk modelling was deemed necessary with regard to how these fires would potentially escalate. For quantification of the risk model for compressor room fires, different sources of information were used. For example, the assumed failure rate of the fire protection system was based on results from previous studies on other ship types [24,25]. Estimates on probabilities related to LNG leakage, LNG hazards survivability and evacuation performance were again based on expert judgement. The event tree for fire and explosion is illustrated in Fig. 13.

The event tree for spillage events during loading and unloading of cargo was quantified based on assumptions related to typical LNG trading patterns and normal cargo transfer operations. Furthermore, it was assumed that only relatively small-scale spillages would occur during loading and unloading, with the potential to harm only those members of the crew directly exposed to the spilled LNG. The event tree for loading and unloading events is illustrated in Fig. 14.

6. Risk summation

The risk modelling outlined in the previous sections results in the contributions from the various scenarios to the total potential loss of lives per shipyear from LNG shipping operations. This is presented in Table 6.

6.1. Individual risk

Intuitively, the individual risk for passengers onboard other vessels is not an issue in this context, and only the individual risk to LNG crew will be considered. Assuming a crew of 30 for a typical LNG carrier and a 50–50 rotation scheme (meaning that two complete crews are needed for continuous operation of the vessel), the individual risk to crew is assessed to be $1.6 \times 10^{-4}$ per person year. Compared with the individual risk acceptance criteria established in this study, it is seen that the individual risk falls within the ALARP area.

It should be noted, however, that this is the individual risk from ship accidents, and contributions from occupational accidents are not considered. Occupational accidents were not considered in the present study, but previous estimates of occupational fatality risks onboard gas tankers are presented by Hansen et al. [26] as $2.7 \times 10^{-2}$ fatalities per 10,000 days onboard. Assuming a 50–50 rotation

<table>
<thead>
<tr>
<th>Accident category</th>
<th>PLL (crew)</th>
<th>PLL (passengers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision</td>
<td>$4.42 \times 10^{-3}$</td>
<td>$1.59 \times 10^{-3}$</td>
</tr>
<tr>
<td>Grounding</td>
<td>$2.93 \times 10^{-3}$</td>
<td>0</td>
</tr>
<tr>
<td>Contact</td>
<td>$1.46 \times 10^{-3}$</td>
<td>0</td>
</tr>
<tr>
<td>Fire and explosion</td>
<td>$6.72 \times 10^{-4}$</td>
<td>0</td>
</tr>
<tr>
<td>Loading/unloading events</td>
<td>$2.64 \times 10^{-4}$</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>$9.74 \times 10^{-3}$</td>
<td>$1.59 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

![Fig. 14. Event tree: spillage during loading or unloading operations of LNG carriers.](image)
scheme, a crewmember will be on board for approximately 182 days per year, and 10,000 days onboard corresponds to 55 person years for a typical crewmember. Hence, according to the estimates presented by Hansen et al. [26], the occupational fatality rate onboard gas tankers is around \(4.9 \times 10^{-4}\) per person year. Assuming this estimate and adding this to the individual risk from ship accidents, the total individual risk for crewmembers is estimated to be approximately \(6.5 \times 10^{-4}\) per person year. This estimate is still within the ALARP area according to the risk acceptance criteria established in this study. On a final note, it is observed that the individual risk to crewmembers onboard LNG carriers is dominated by occupational accidents, with a ratio of 3 occupational fatalities to every fatality due to ship accidents according to the estimates above.

6.2. Societal risk expressed by FN curves

Detailed results from the risk analysis can be used to produce FN curves for the overall risk to crew and passenger (Figs. 15 and 16). Compared with the established risk acceptance criteria, it is found that also the societal risks lie within the ALARP region. An FN curve that shows the contribution from each of the main accident scenarios may also be produced (Fig. 17), and it is readily seen that the overall risk level is dominated by the collision, grounding and contact scenarios. However, fire and explosion are dominating the low-consequence risk contributions in the order of one fatality. The frequencies in all 3 figures are in terms of per shipyear.

It is observed that the FN curves resulting from this study lie slightly above the FN curves for gas tankers presented in MSC 72/16 [16], but in general the FN curves are found to be in reasonable agreement.

7. Uncertainties and suggestions for further research

When the various assumptions and other sources of uncertainties are reviewed, it becomes evident that some are conservative while others might be optimistic. Thus, the overall results might in principle be skewed in either way.
However, upon further evaluation of the various assumptions, it is believed that the net effect tends to be conservative, and it is believed that the overall results are more likely to be conservative than optimistic. Hence, the risk analysis presented in this paper might be regarded as somewhat conservative. Table 7 lists some of the assumptions made in this study that might be conservative or optimistic.

All in all, there are a number of uncertainties associated with this study, and improvements in any areas would always be favourable. It is also emphasized that a generic FSA such as this should be considered as an on-going process where the results are continuously updated according to new knowledge, developments in technology, environment and trading patterns, refinements of underlying assumptions, etc. Nevertheless, in spite of the subjectivity and inherit uncertainties, on a high level, the results from the current study are believed to be meaningful and robust for the world fleet of LNG carriers.

Even though the risk assessment presented in this paper is believed to be based on the best available information, approaches and estimates, parts of the study should undoubtedly be regarded as somewhat subjective. In some areas of the analysis there have been sufficient statistical data available to draw meaningful conclusions, whereas in other areas no sources of information have been available. In the latter areas, quantitative estimates have been based on qualitative considerations and expert judgement, although it is acknowledged that this is generally associated with a certain degree of subjectivity [27]. However, this risk analysis is modular by design and, if new knowledge becomes available in any area, it should be rather straightforward to replace or update relevant modules accordingly. It is therefore recommended that such amendments to the risk models should be made when appropriate.

Uncertainties have been particularly salient in some areas of this analysis, and it is suggested that further studies should be carried out in order to bridge the gaps in fundamental knowledge and available statistics pertaining to hazards and risks related to LNG shipping. These are in most cases represented towards the right-hand side of the event trees, describing events in the later stages of a scenario. In particular, it is suggested that further studies related to the following parts of the risk model are initiated: LNG hazard model, damage extent models, survivability model, evacuation model and third-party...
model. These studies could be in the form of experiments, calculations or simulations.

8. Conclusions and recommendations

The overall risk associated with LNG carriers was found to be in the ALARP area. Thus, all risks should be made *As Low As Reasonable Practicable* by implementing any cost-effective risk reduction measures that may be identified. Further work on identifying, selecting and assessing prospective risk control options in terms of cost effectiveness is therefore a logical continuation of this risk analysis. These issues will be addressed in subsequent SAFEDOR tasks.

Three generic accident scenarios are together responsible for about 90% of the total risk related to LNG carriers, i.e. collision, grounding and contact. These scenarios are related in that they all describe a situation where an LNG vessel is damaged because of an external impact from, e.g., another vessel, floating objects, the sea floor, submerged objects, the quay or other structures. Upon closer investigation of the risk models associated with these scenarios, four sub-models in particular stand out where further risk reduction could be effective. These are the accident frequency model, the cargo leakage frequency model, the survivability model and the evacuation model. Therefore, it is recommended that further efforts in the next steps of this on-going FSA on LNG carriers focus on measures related to:

- Navigational safety
- Manoeuvrability
- Collision avoidance
- Cargo protection
- Damage stability
- Evacuation arrangements.

The above list should by no means be considered as exclusive, and possible cost-effective risk control options related to, e.g., cargo handling and fire protection should also be investigated. However, it is believed that the most cost-effective risk control options will be those addressing the high-risk areas identified in this risk analysis.

Acknowledgements

The work reported in this paper has been carried out under the SAFEDOR project, IP-516278, with partial funding from the European Commission. The opinions expressed are those of the authors and should not be construed to represent the views of the SAFEDOR partnership or that of DNV, IST, LMG Marin or Navantia.

The authors wish to acknowledge valuable contributions to this study in the form of discussions, expert opinion, management or general support from the following individuals: R. Skjong, S. Valsgård and S.E. Jacobsen (DNV) and C. Suedes Soares (IST).

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