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FORMAL SAFETY ASSESSMENT

FSA – Liquefied Natural Gas (LNG) Carriers
Details of the Formal Safety Assessment

Submitted by Denmark

SUMMARY

Executive summary:	This document is related to document MSC 83/21/1 entitled "FSA – Liquefied Natural Gas (LNG) Carriers" and contains further details of the FSA study.
Action to be taken:	Paragraph 2
Related document:	MSC 83/21/1

Introduction

1 As referred to in document MSC 83/21/1 submitted by Denmark, a high level FSA application on conventional LNG carriers has been performed. The reports providing further details on this study are contained in the annexes to annex to this document:

.1 Annex I: Risk Analysis of LNG Tankers;

.2 Annex II: Risk Control Options and Cost Benefit Analysis; and

.3 Annex III: Recommendations.

Action requested of the Committee

2 The Committee is invited to consider the information provided in this document in relation to its consideration of document MSC 83/21/1.

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ANNEX

FORMAL SAFETY ASSESSMENT OF LIQUEFIED NATURAL GAS (LNG) CARRIERS

Contents

Annex I: Risk Analysis of LNG Tankers

1 Introduction

1.1 FSA – Step 2: Risk Analysis

This annex presents the second step, the risk analysis, in a high-level FSA on ocean going LNG carriers according to the FSA guidelines issued by IMO [1]. The purpose of this risk analysis is a more detailed investigation into the causes and consequences of the most important scenarios identified and prioritized in step 1, the HAZID [2]. The risk level associated with LNG shipping will be assessed, and one of the aims of the risk analysis is to identify high risk areas where further attention can be focused, e.g. by proposing new risk control options (RCOs).

Various methods will be employed in order to investigate the causes and consequences of the scenarios selected for further study. A risk model will be built using standard risk assessment techniques such as construction and quantification of event trees. In order to establish frequencies of incidents developing into the different scenarios, various methods will be utilized as deemed appropriate, e.g. construction of fault trees, investigation of historical accident data, calculations, simulations, comparison with similar ship types and techniques for using expert judgement.

1.1.1 Scope of study

In general, different types of risks should be considered in a risk analysis, i.e. risk to people, the environment and property. However, for the purpose of the current study, only the risk to life and health of people will be considered. Environmental issues will be left out of the study because LNG is not representing any notable hazard to the marine environment. The local environmental risks associated with LNG carriers are thus similar to all other ocean going vessels and limited to that of accidental or operational release of marine bunker oil, black water, grey water etc. In a global perspective, it might be argued that natural gas contributes to the greenhouse effect and global warming, but this is considered out of scope of this risk analyses. Furthermore, property risk is considered out of scope as the main focus will be on safety issues.

Security issues have gained a lot of attention in recent years, but only safety related hazards will be considered in this risk analysis. Even though LNG carriers might be exposed to security risks, it is not believed that this type of vessels is obvious targets for terrorist attacks, partly due to the difficulty of deliberately causing an LNG catastrophe. One study on LNG security concluded that a deliberate attack on an LNG carrier can result in a threat to the ship, its crew and members of the public, but it also concluded that the fire hazard from an LNG tanker would be less than that of a gasoline or LPG tanker [7]. Different studies on LNG security hazards have reached different conclusions, and there are uncertainties related to how dangerous a real LNG tanker terrorist attack could be. However, much attention has been directed towards security issues in recent years, and extensive measures are in place to prevent terrorist attacks. These measures are assumed to be sufficient to ensure a reasonable security level for all types of shipping activities, including LNG shipping. At any rate, security risks are considered out of scope of the current study.

Furthermore, the scope is to investigate credible accidents of a certain scale involving LNG carriers. Thus, occupational hazards with the potential of injuring, or in special circumstances even kill, individual crewmembers are not within the scope of this risk analysis.

This risk analysis on LNG carriers will be limited to study the operational phase of an LNG carrier's life cycle. Thus, risk associated with LNG vessels at yards or in dock during construction, repair or maintenance or in the decommissioning and scrapping phase is considered out of scope. Furthermore, only the shipping stage in the LNG value chain will be considered. A typical LNG value chain consists of the following stages:

- Exploration and production of natural gas, where the natural gas is found and produced.
- Liquefaction, where the natural gas is converted into liquid form so that it can be transported in ships
- Shipping, where the LNG is shipped in special purpose vessels

Storage and regasification, where the LNG is stored and converted back to its gaseous state, ready to be sent to the final destination at the end users, e.g. through a natural gas pipeline system.

Thus, by limiting the scope of the study to the shipping stage, the study is restricted to study the risk associated with the LNG vessels only. Risks associated with LNG exporting or receiving terminals are out of scope, apart from hazards related to the interface between the terminals and the ships during loading/offloading of LNG while the carriers are at the terminals. This is illustrated in Figure 1.

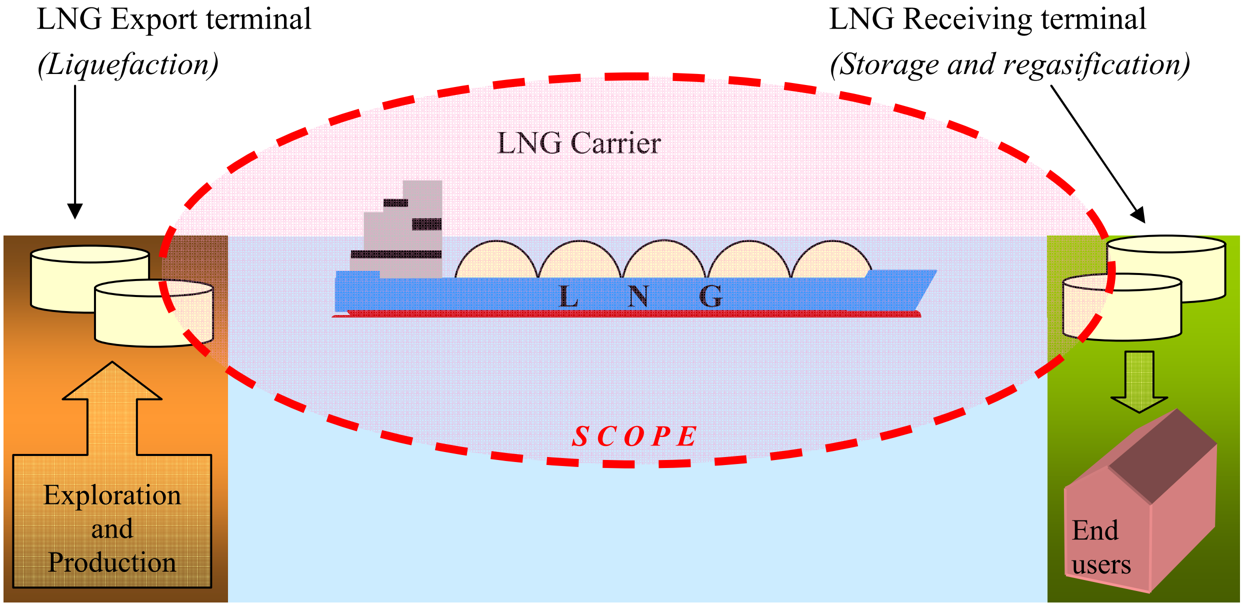

Figure 1: LNG Value chain and scope of study

The characteristics of different waterways and port environments will be different and unique to every LNG terminal. Particular factors might have a significant influence of the risk associated with LNG shipments in these waterways, e.g. the local marine traffic loads, possible obstacles, water depth, waterway width, local emergency preparedness, distance to populated areas, local aids to navigation, nearby infrastructure etc. However, detailed investigations of specific routes are out of scope of the present study, and some kind of generic waterways are assumed. Detailed risk assessments for specific areas have previously been carried out on several occasions, e.g. as reported in [3].

In certain scenarios, LNG carrier operations might pose a threat to public ashore or people onboard other vessels. Specifically, if e.g. a serious grounding or collision accident occurs that results in spillage of LNG, this has the potential for formation of a vapour cloud that may drift some distances before reaching the lower flammability limit. This would represent a hazard to everyone within this distance, and if the vapour cloud encounters an ignition source when concentrations are in the flammable region, it will ignite. The distance associated with this hazard will depend on a number of factors such as local conditions at spill site, size of the spill, weather conditions etc., and it will not be possible to assess this risk in a generic, global risk analysis such as this. Thus, this kind of third party risks is out of scope of the current study. This risk should rather be assessed in specific risk analyses pertaining to specific LNG terminals or LNG trades.

1.2 Risk Acceptance Criteria

1.2.1 Individual risk acceptance criteria

Criteria for individual risk to crew were established by SAFEDOR D.4.5.2 [4]. These are deemed appropriate for LNG carriers and will be adopted for the purpose of this study. The acceptance criteria for individual risk are reproduced in Table 1. This corresponds to the risk levels experienced by an exposed crewmember.

Table 1: Individual risk acceptance criteria for crew	
Boundary between negligible risk and the ALARP area	10^{-6} per year
Maximum tolerable risk for crew members (risks below this limit should be made ALARP)	10^{-3} per year

1.2.2 Societal risk acceptance criteria for crew

Societal risk acceptance criteria for crew will be established based on the approach presented in MSC 72/16 [5], now included in MSC83/INF.2. According to this method, acceptance criteria will be associated with the economic importance of the maritime transportation of LNG, calibrated against the average fatality rate per unit of economic production. An average acceptable potential loss of life (PLL_A) based on the economic value of LNG shipping (EV_{LNG}) may be defined as in equation (1.1).

$$PLL_A = q \cdot EV_{LNG} \tag{1.1}$$

In this equation, q denotes an aggregated indicator for occupational accidents in terms of the average fatality rate per gross national product (GNP), as defined in equation (1.2).

$$q = \frac{\#\ occupational\ \_\ fatalities}{GNP} \tag{1.2}$$

Based on data from USA and Norway, a value of q = 1.5 fatalities per billion British pound (£) were suggested in [5], and this will be adopted for the current study. In US dollars, the indicator takes the value of q = 1.0 fatalities per billion USD. Thus, the task of estimating an average acceptable PLL for LNG shipping is reduced to obtaining a reasonable economic value for the activity.

In line with the discussion in D.4.5.2 [4], acceptance criteria will be presented in terms of FN criterion lines with slope of -1. Hence, the average acceptable PLL corresponds to a reference point F_1, corresponding to the frequency of accidents involving one or more fatalities, with value according to equation (1.3). N_u denotes the upper limit of the number of fatalities that can occur in one accident. For accidents not involving third parties, this upper limit will be the size of the crew and possible other persons onboard such as Suez Canal workers, repair workers etc. For the purpose of this study, a conservative upper limit of 40 will be assumed.

$$F_1 = \frac{PLL_A}{\sum_{N=1}^{N_u} 1/N} = \frac{q \cdot EV_{LNG}}{\sum_{N=1}^{N_u} 1/N} \tag{1.3}$$

Estimates of the economic value of LNG shipping are based on estimates of the daily rates, operational costs and initial investments, described in more detail in appendix A.2. In this appendix, the economic value of a typical LNG carrier was assessed to be about USD 19 million per year.

Using these values, an F_1 value of 4.5 x 10^{-3} is arrived at, corresponding to the average acceptable frequency of accidents with one or more fatalities. The ALARP area can be defined around this value by assuming that risks are intolerable if more than one order of magnitude above this average acceptable and negligible if more than one order of magnitude below this value. The resulting societal risk acceptance criteria are illustrated in Figure 2 as a set of FN curves. *1.2 Risk Acceptance Criteria*

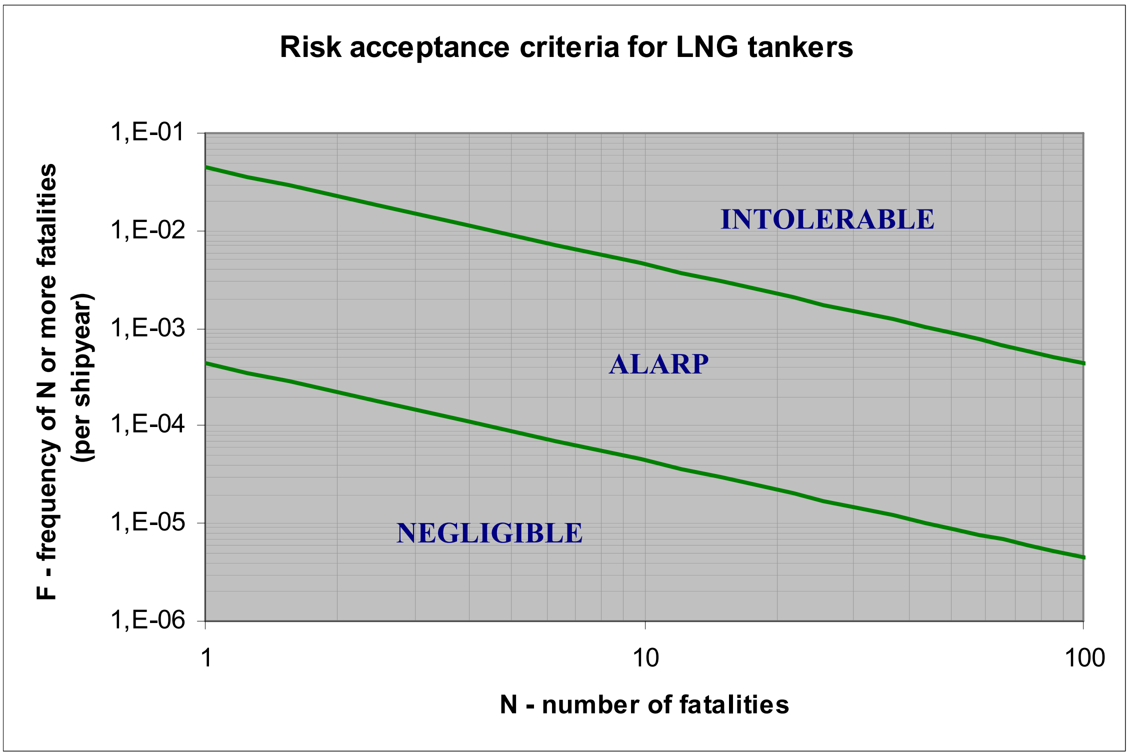

Figure 2: Societal risk acceptance criteria for LNG carriers

It could be noted that these risk acceptance criteria are somewhat stricter than the criteria presented in [5] for tankers in general. This is because the economic value associated with LNG tankers was estimated to be lower than the average for different tankers. Nevertheless, the risk acceptance criteria for LNG carriers as established by this study are believed to be appropriate and will be used in order to assess the results from the subsequent risk analysis.

2 Background

2.1 Liquefied Natural Gas

LNG is short for Liquefied Natural Gas, and is produced by liquefaction of natural gas. Natural gas produced from wellhead consists of methane, ethane, propane and heavier hydrocarbons as well as small quantities of nitrogen, helium, carbon dioxide, sulphur compounds and water. The liquefaction process includes pre-treatment of the natural gas stream to remove impurities (e.g. water, nitrogen, carbon dioxide and sulphur compounds) so that solids cannot be formed as the gas is refrigerated. Then, the pre-treated natural gas, now in a composition of mostly methane with small amount of other hydrocarbons and nitrogen, is cooled and liquefied at cryogenic temperatures at approximately ÷162 °C. In this form, the LNG is ready for storage and shipping.

In liquefied form, the volume of LNG is 600 times less than the same amount of natural gas at room temperatures. Thus LNG shipping is an economical way of transporting large quantities of natural gas over long distances. LNG is not pressurized during transport and storage, and is a colourless, odourless, non-corrosive, non-toxic and cryogenic liquid at normal atmospheric pressure. Natural gas (primarily methane) is not toxic, although natural gas that is vaporized from LNG can cause asphyxiation due to lack of oxygen if concentration of gas develops in an unventilated, confined area. The weight of LNG is less than the weight of water, thus LNG spilled on water will float.

When vaporized, LNG forms a flammable, visible vapour cloud (visible because temperature is lowered below ambient dew point). However, this vapour can only become flammable and explosive under certain well-known conditions. The flammability range denotes the range of concentrations of LNG vapour in air that forms a flammable mixture that can be ignited and burn. For methane, the dominant component of LNG vapour, the flammability range is approximately between 5 and 15 percent by volume. When the vapour concentration exceeds this upper flammability limit, it cannot burn because too little oxygen is present and when concentration is below the lower flammability limit, it cannot burn because too little methane is present. Two examples of situations where the LNG vapour concentration is outside the flammable range are within a closed tank where the LNG vapour concentration is close to 100% and leakage of small quantities of LNG vapour in well ventilated areas where the LNG vapour will rapidly mix with air and dissipate to less than 5% concentration. In either of these cases, the LNG vapour will not burn.

When LNG is spilled, it will cool down the surroundings as it vaporizes and mixes with diluting air. The behaviour will be different if the spill is on land or on water. When spilled on land, the vaporization of LNG will initially be rapid but slows down as the ground cools and it can take long time for the LNG pool to evaporate. When spilled on water on the other hand, heat will be transmitted through the water and the LNG pool will float and boil on the water, rapidly vaporizing, until the LNG pool is evaporated. The LNG vapour will normally spread rapidly, and it may travel some distance before it is diluted below the flammable limit.

There are two ways for a gas vapour within the flammability range to ignite, either spontaneously or from contact with a source of ignition such as flames, sparks or hot surfaces. The autoignition temperature is the lowest temperature at which flammable gasses will ignite spontaneously. At this temperature, the gas will ignite spontaneously after several minutes of heat exposure. Higher temperatures will cause ignition after shorter exposure times and with temperatures high above the autoignition temperature, ignition can be virtually instantaneous. For a mixture of methane vapour with air at atmospheric pressure of about 10% (in the middle of the flammability range), the autoignition temperature is above 540 °C. Thus, the vapour from LNG spilled on ground or on water will normally dissipate into the atmosphere without igniting if it does not encounter an ignition source in the form of a flame, a spark or a source of heat of more than 540 °C. The autoignition temperature associated with LNG (primarily methane) is found to be higher than what is associated with most other liquid fuels.

2.1.1 Main types of LNG hazards

The basic properties of LNG and LNG vapour can be summarized to identify the main types of LNG hazards:

1. Pool fires. If LNG spills occur near an ignition source, a mix of the evaporating gas and air will burn above the LNG pool. Such pool fires are intense and burn far more rapidly and hotly than e.g. oil and gasoline fires. Furthermore, they cannot easily be extinguished and all the LNG must normally be consumed before they go out. Due to the high temperatures, the thermal radiation from a pool fire may injure unprotected people and damage property a considerable distance away from the fire itself. For example, in the event of a collision followed by a pool fire at the side of the ship, the thermal radiation from the fire might be lethal within a radius that covers both vessels involved in the collision.
2. Vapour clouds. If not immediately ignited, the evaporating natural gas may form a vapour cloud that can drift some distance from the spill site. LNG that is released from a temperature-controlled container begins to warm up and hence return to its gaseous state. Initially colder and heavier than the surrounding air, a vapour cloud is created above the released liquid. It mixes with the surrounding air and begins to disperse. The cloud will ignite if it encounters an ignition source while its concentration is within the flammability range. An LNG vapour cloud fire are expected to gradually burn its way back to the spill source and continue to burn as a pool fire.
3. Cryogenic temperatures. If LNG is released, direct contact with the cryogenic liquid will freeze the point of contact and damage tissues of humans, animals and aquatic fauna. Embrittlement leading to structural failure and equipment damage may also occur when materials not designed for such low temperatures come into contact with LNG.
4. Asphyxiation. Although not toxic, a non-ignited LNG vapour could asphyxiation because it is displacing breathable air.
5. Rollover. When LNG supplies of multiple densities are loaded into a tank, they might not mix at first, but instead form various layers within the tank. Subsequently, these layers may spontaneously rollover to stabilize the liquid in the tank. As the lower layer of LNG is heated by normal heat leak, it changes density and might eventually become lighter than the upper layer. This might cause a liquid rollover to occur with a sudden vaporization of LNG that might result in overpressure. However, this is a design condition in recognized LNG construction standards, and the LNG tanks are believed to withstand the pressure from possible rollover incidents.
6. Rapid Phase Transition (RPT). LNG, being lighter than water, floats and vaporizes when released on water. If large enough quantities of LNG are released on water at a fast enough rate, a rapid phase transition (RTP) may occur. In this case, heat is transferred from the water to the LNG causing the LNG to instantaneously convert from a liquid to a gaseous phase. This rapid transition between phases causes a large amount of energy to be released in the form of a physical explosion, although without any combustion. Such a rapid phase transition might have the potential to shatter windows and glass nearby and is only assumed to constitute a minor hazard to people and buildings nearby.
7. Explosion. In its liquid state, LNG is not explosive, and LNG vapour will only explode if ignited in a mixing with air within the flammable range and within an enclosed or semi-enclosed space.

Due to the physical properties of LNG, there are also some types of hazards that are not particularly associated with LNG.

1. Pollution. LNG spills will cause minimal pollution or damage to the marine environment beyond local damages due to contact with the cold liquid or possible damages due to a possible fire. LNG is neither toxic nor persistent. In a LNG spill scenario, the released LNG will vaporize and either disperse into the atmosphere or, in some special circumstances, ignite and burn until there are no LNG left.

2. BLEVE. Boiling Liquid Expanding Vapour Explosions (BLEVE) are only associated with pressurized liquids. An LNG tank is not designed for pressure and can probably not pressurize to a level that would cause a serious BLEVE event.

2.2 LNG tanker safety regulations

Safety is an important issue for LNG carriers, and numerous safety regulations exist in order to ensure the LNG ships are safe. LNG carriers need to comply with a number of different rules that are common to all ship types, as well as a set of regulations particularly developed for ships carrying liquefied gas. In the following, a brief overview of the most important safety regulations applicable to LNG vessels and LNG crew will be given.

In addition to strict requirements on the LNG vessels itself, safety issues are seriously considered during site selection and design of LNG terminals. Issues that are normally considered are, control of traffic near ports, local topology and weather conditions, safe mooring possibility, tug capability, safe distances and surrounding industry and population and training of terminal staff. These considerations contribute to enhance the safety of LNG shipping in its most critical phase, i.e. sailing in restricted waters or around terminal and port areas.

2.2.1 General LNG safeguards

General safety and security features for LNG pertain to the following main elements

- Primary containment
- Secondary containment
- Safeguard systems
- Separation distance

The primary containment should provide safe storage and isolation of LNG. Due to its cryogenic temperatures, the material selected for tanks that comes into contact with LNG is critical. Carbon steel, for example, loses its ductility and becomes brittle at very low temperatures, and the use of high nickel content steels, aluminium and stainless steel is necessary, although costly, to prevent embrittlement and material failures. A typical storage tank is double-walled, like a tank within a tank, with insulation between the walls of the tanks. The inner tank will be in contact with the LNG and is made of materials suitable at cryogenic temperatures. The outer tank does not necessarily provide any extra protection in case of LNG leakage from the inner tank, but it holds the insulation in place. The most common cargo insulation materials include polyurethane, polyvinyl, chloride foam, polystyrene and perlite.

The secondary containment provides protection beyond the primary containment, and should be able to contain any LNG leakage in the event of tank failure. Thus, any released LNG should be isolated and controlled by the secondary containment. For land based LNG storage tanks, the secondary containment can either be in the form of a dike or dam impoundment surrounding the single containment tanks (primary containment) or a double containment tank where both the inner and outer tank are capable of independently containing the LNG. For LNG ships, the secondary barrier can take different forms depending on the type of construction of the storage tanks. For membrane ships, it may be a complete secondary containment equivalent to the primary barrier. For LNG carriers with spherical tanks, which are independent, the secondary barrier can be a splash barrier with a drip pan at the bottom from which accumulated liquid evaporates.

Various safeguard systems should be in place in all LNG facilities. These systems include various monitoring systems to detect LNG releases, fire, smoke, low temperatures and to monitor LNG levels and vapour pressures. These can again trigger different emergency shutdown systems (ESD) or automated fire fighting systems. These systems should ensure that the likelihood of releases is minimal and that the released volume is small if a release should occur. One safeguard system specific to LNG carriers is the double hull construction. This construction provides enhanced protection for the integrity of the cargo in the event of collision or grounding incidents. In addition, there are ship-handling safety features such as sophisticated radar and positioning systems, global maritime distress systems, approach velocity meters and automatic mooring line monitoring.

Separation distances beyond the impoundment area defined by the secondary containment are important for protecting surrounding areas in the unlikely event of an LNG release or a fire. The separation distance should include thermal radiation protection zones and flammable vapour dispersion zones around the LNG facility. The thermal protection zone should be large enough so that the heat from an LNG fire does not exceed a specified limit for people and property. The flammable vapour dispersion zone should be large enough to encompass the flammable part of a vapour cloud. For land based LNG facilities in the U.S., there are standards for how to calculate these distances for each specific LNG facility [6].

For maritime LNG transport, there are different safety zones for ships in transit and ships in port. In the U.S., port safety zones are established by the United States Coast Guard (USCG) and port captain based on the specific risk factors at a given terminal. There are two main purposes of safety zones for LNG ships. A) To minimize the risk of collision when the ship is underway and B) to protect surrounding property and personnel from hazards related to ignition when at berth. In some ports, the USCG requires a tug escort or a guard boat when the LNG carrier is underway to a receiving terminal.

In addition to these general LNG safeguards, there are more specific requirements for controlling the risk associated with maritime transport. Some safety regulations apply for all types of ships whereas additional safety requirements apply to ships carrying liquefied gas such as LNG in particular.

2.2.2 Maritime regulations for all ship types

There are a number of international regulations applicable to ships engaged in international trade that also LNG carriers have to comply with in addition to class rules and possible national rules of the flag state. Perhaps the most important one when it comes to safety is the International convention for the Safety of Life at Sea (SOLAS) [9]. This regulation contains basic construction and management requirements for all types of ships. Examples of areas covered by SOLAS are subdivision and stability, machinery and electrical installations, fire protection, detection and extinction systems, life-saving appliances and surveys and inspections. Class rules apply for structural strength. There is also a special code for ships carrying liquefied gas included in the SOLAS regulations, the IGC code [10], and this code will be described briefly in the following subchapter of this annex.

SOLAS also contains a number of other codes related to safety and security that applies to shipping in general. Examples of these are the Fire Safety Systems Code (FSS Code) [11], the International Management Code for the Safe Operations of Ships and for Pollution Prevention (ISM Code) [12] and the International Ship and Port Facility security Code (ISPS Code) [13]. These codes imply requirements aiming at enhancing the safety on LNG shipping activities as well as shipping in general.

Other IMO regulations pertaining to safety are contained in the International convention on Load Lines [14] which addresses the limits to which a ship may be loaded, the International Convention for the prevention of Collisions at Sea (COLREG) [15] addressing issues related to steering, lights and signals and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW Convention) [16] which addresses issues related to the training of crew. The International Convention for the Prevention of Pollution from Ships (MARPOL) [17] addresses issues related to marine and air pollution from ships. These regulations are applicable to all ships and thus also to LNG carriers.

2.2.3 Regulations specific to ships carrying liquefied gas in bulk

The IGC code [10] prescribes a set of requirements pertaining to safety related to the design, construction, equipment and operation of ships involved in carriage of liquefied gases in bulk. Some of the contents of this code will be outlined in the following. The IACS unified requirements for gas tankers were partly derived from the IGC code. [18].

The code i.a. specifies the ship survival capability and the location of cargo tanks. According to the type of cargo, a minimum distance of the cargo tanks from the ship's shell plating is stipulated in order to protect the cargo in case of contact, collision or grounding events. Thus the code prescribes requirements for ships carrying different types of liquefied gas, and defines four different standards of ships, as described in Table 2. LNG carriers are required to be ships of type 2G and all LNG carriers should be designed with double hull and double bottom.

Table 2: Categories of ship standards according to the IGC Code

Ship type	Intended cargo	Location of cargo tanks – minimal distance inboard	
		From the side shell plating	From the bottom shell plating
3G	A type 3G ship is a gas carrier intended to carry products which require moderate preventive measures to prelude the escape of such cargo.	Nowhere less than 0.76 meters.	B/15 or 2 meters from the moulded line at centreline and nowhere less than 0.76 meters
2PG	A type 2PG ship is a gas carrier ≤ 150 meters in length intended to transport products which require significant preventive measures to prelude the escape of such cargo, and where the products are carried in independent type C tanks.	Nowhere less than 0.76 meters.	B/15 or 2 meters from the moulded line at centreline and nowhere less than 0.76 meters
2G	A type 2G ship is a gas carrier intended to transport products which require significant preventive measures to prelude escape of such cargo.	Nowhere less than 0.76 meters.	B/15 or 2 meters from the moulded line at centreline and nowhere less than 0.76 meters
1G	A type 1G ship is a gas carrier intended to transport products which require maximum preventive measures to prelude escape of such cargo.	B/5 or 11.5 meters, and nowhere less than 0.76 meters.	B/15 or 2 meters from the moulded line at centreline and nowhere less than 0.76 meters

The IGC code requires segregation of cargo tanks and cargo vapour piping systems from other areas of the ship such as machinery spaces, accommodation spaces and control stations, and prescribes standards for such segregation. Furthermore, standards for cargo control rooms and cargo pump-rooms are provided as well as standards for access to cargo spaces and airlocks. There are also requirements for leakage detection systems and for the loading and unloading arrangements.

Different types of cargo containment systems for LNG are permitted by the IGC code, and the two main types of LNG containment systems in use in the world tanker fleet are membrane tanks and independent tanks. Membrane tanks are tanks which consist of a thin layer or membrane, supported through insulation by the adjacent hull structure. The membrane should be designed in such a way that thermal expansion or contraction does not cause undue stress to the membrane. The independent tanks are self-supporting in that they do not form a part of the ship's hull. The IGC code defines three categories of independent tanks: Type A, B and C. Type C tanks are pressure tanks and will not be required for LNG vessels since LNG are transported at ambient pressure. Regardless of what containment system is used, the tanks should be design taking factors such as internal and external pressure, dynamic loads due to the motions of the ship, thermal loads and sloshing loads into account, and structural analyses should be carried out.

A separate secondary barrier is normally required for LNG containment systems to act as a temporary containment of any leakage of LNG through the primary barrier. For membrane tanks and independent type A tanks, a complete secondary barrier is required. For independent type B tanks, a partial secondary barrier is required, whereas no secondary barrier is required for independent type C tanks. The secondary barrier should prevent lowering of the temperature of the ship structure in case of leakage of the primary barrier and should be capable of containing any leakage for a period of 15 days. Additional requirements regarding insulation and materials used for the cargo containment systems as well as construction and testing, piping and valving etc. are included in the IGC code.

The IGC code also requires certain safety equipments to be carried onboard LNG carriers. These include ship handling systems such as positioning systems, approach velocity meters, and automatic mooring line monitoring and cargo handling systems such as emergency shutdown systems (ESD) and emergency release system (ERS). In addition, systems for vapour and fire detection, fire extinguishing (dry chemical powder) and temperature control are required. Finally, the code contains operational requirements related to i.a. cargo transfer methods, filling limits for tanks and the use of cargo boil-offs as fuel as well as requirements on surveys and certification.

Equivalents to the various requirements in the code are accepted if it can be proven, e.g. by trials, to be as effective as what is required by the code. This applies to fittings, materials, appliances, apparatuses, equipments, arrangements, procedures etc, but it is noted that no operational options or procedures can be accepted as an alternative to requirements related to fittings, materials, appliances, apparatuses or equipments.

In addition to the numerous regulations, codes, recommendations and guidelines regarding LNG carriers issued by IMO, there are a number of other international recommendations and guidelines for safe LNG shipping, e.g. standards of best practice issued by SIGTTO (The Society of International Gas Tanker & Terminal Operators). It is out of scope to describe them all, but it is noted that extensive regulations and guidelines related to safety of LNG carriers exist. This extensive set of rules and guidelines is undoubtedly contributing to the high safety standard and the good safety record that has been experienced for the fleet of LNG carriers.

2.2.4 Training requirements of LNG crew

In addition to strict regulations on the ship itself, there are also extensive international regulations specifying the necessary training and experience of crew that operate LNG carriers. These include general training in basic seamanship which are applicable to all kind of maritime crew as well as specialized LNG-specific training for crew working on LNG carriers. The international rules on training requirements are contained in regulations such as the STCW 95 [16] and the ISM code [12]. In addition, there might be flag state or company specific training requirements that go beyond these international regulations, but such additional requirements will not be discussed herein. The competence level of LNG crew has generally been regarded as quite high compared to that of other ship types. A study presented in [19] demonstrates that the performance score of crew onboard gas and chemical tankers are the best among cargo carrying ships, second only to that of passenger vessels.

STCW 95 contains minimum training requirements for crew engaged in international maritime trade. In particular, chapter V of the STCW code contains *standards regarding special training requirements for personnel on certain types of ships*, among them liquefied gas carriers. One requirement for masters, officers and ratings assigned specific duties and responsibilities related to cargo or cargo equipment on all types of tankers, e.g. LNG tankers, is that they shall have completed an approved *tanker familiarization course*. Such a course should as a minimum cover the following topics:

- Characteristics of cargoes
- Toxicity
- Hazards
- Hazard control
- Safety equipment and protection of personnel
- Pollution prevention

This course shall provide the theoretical and practical knowledge of subjects required in further specialized tanker training. Specialized training for liquefied gas tankers should as a minimum include the following syllabus:

- Regulations and codes of practice
- Advanced fire fighting techniques and tactics
- Basic chemistry and physics related to the safe carriage of liquefied gases in bulk
- Health hazards relevant to the carriage of liquefied gas
- Principles of cargo containment systems
- Pollution
- Cargo-handling systems
- Ship operating procedures including loading and discharging preparation and procedures
- Safety practices and equipment
- Emergency procedures
- General principles of cargo operations

In addition to these training requirements, masters, chief engineering officers, chief mates, second engineering officers and any persons with immediate responsibilities for loading, discharging and care in transit of handling of cargo in a LNG tanker are required to have at least 3 months sea service on a liquefied gas tanker.

Due to the extensive training requirements and experience level of their personnel, the maritime LNG industry claims that the crew sailing the LNG fleet are among the best in the world. This is confirmed by the study presented in [19]. However, a shortage of experienced LNG crew is foreseen in the near future, especially with the expected growth of the LNG fleet. Thus acquiring sufficient crew with the required level of experience, training and knowledge of LNG are believed to be one of the major safety-related challenges to the maritime LNG industry in the years to come [8].

2.3 World fleet of LNG carriers

The focus for this risk analysis is ocean going LNG carriers. The current world fleet of LNG carriers is comparable small in relation to other ship types, but it has been increasing steadily in recent years. It is expected to increase even more in the coming years. As of August 2005, the LNG fleet contains 183 ships, with another 130 vessels in the order books. The total size of the current fleet is almost 22 million cubic meters, giving an average size of almost 120,000 cubic meters for the present fleet of LNG carriers. However, the largest segments of the LNG fleet are ships with sizes 120,000 cubic meters and more. The total capacity of the 130 vessels in the order books is just over 20 million cubic meters, corresponding to an average size of 156,000 cubic meters per vessel. Figure 3 shows the size distribution of the LNG fleet as of 2003, derived from Lloyds World Fleet Statistics.

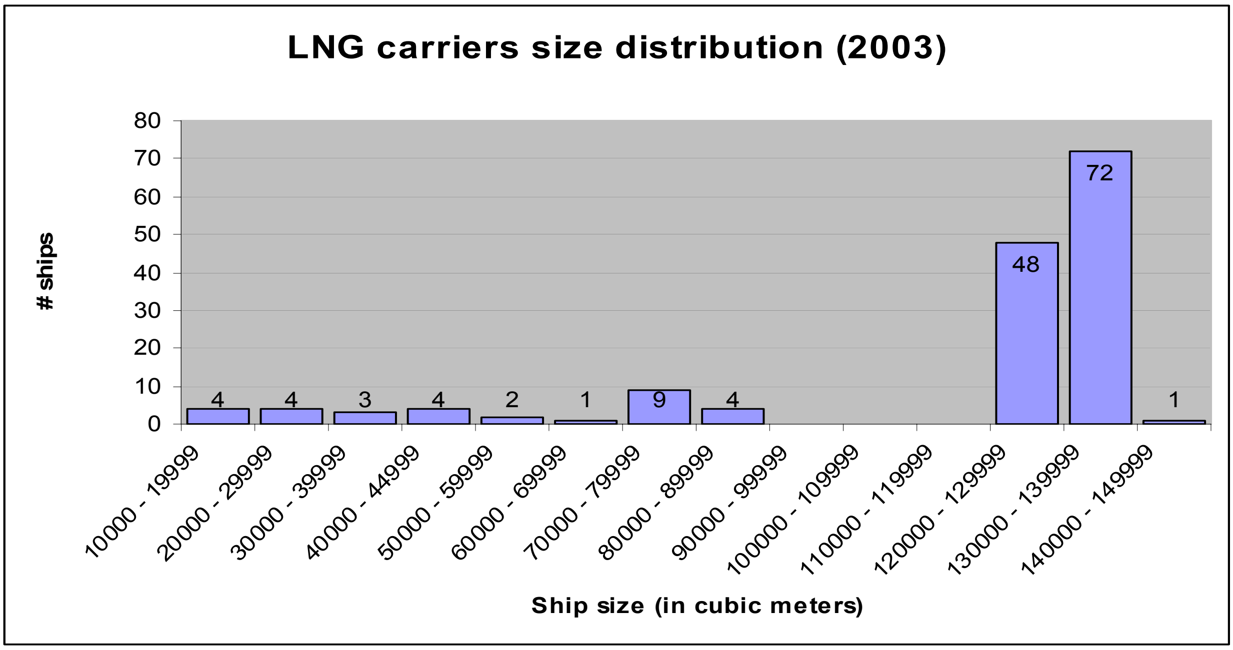

Figure 3: LNG carriers, size distribution (2003)

LNG super-tankers with capacities of 200,000 – 250,000 cubic meters are foreseen in the near future. Thus, the forthcoming developments in the LNG fleet are expected to result in more as well as bigger LNG carriers involved in the worldwide trade. The development of the LNG carriers fleet since its beginning with two vessels in 1964 is illustrated in Figure 4, based on data from the Fairplay database. A forecast of the expected growth in the LNG fleet for the rest of the decade is also included [8]. During the more than 40 years of LNG shipping since 1964, the total number of LNG carrier shipyears are approximately 2,838 (including 2005). 1,857 of these are from 1990 and later.

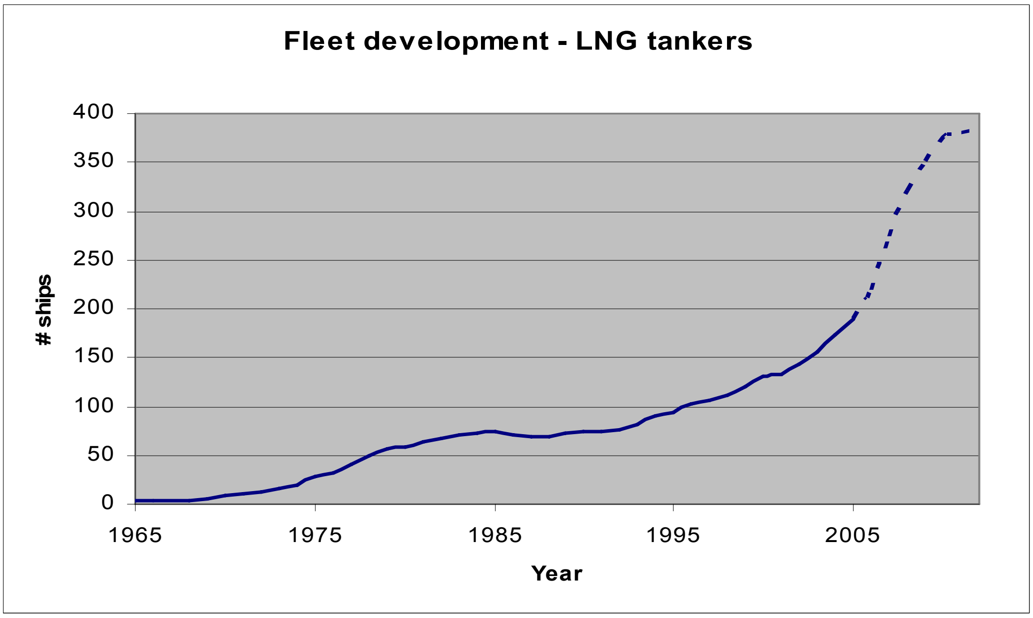

Figure 4: LNG fleet developments, 1965 – 2005 and forecast 2005 - 2010

The increasing interest in LNG shipping is expected to result in an increase in both the number of LNG vessels as well as their size and cargo carrying capacity. Thus, it will be increasingly important to properly control the risk associated with such shipments. In addition, innovative solutions for design, construction and operation of LNG vessels are foreseen, and it is important to have an understanding of the risks of both conventional, standard LNG designs as well as new, innovative design solutions. Hence, this risk analysis of LNG carriers aims at assessing the risk level associated with current standard LNG carriers in order to provide a baseline risk level for comparison and evaluation of novel design alternatives.

The current fleet of LNG carriers are dominated by two types of vessel designs, i.e. the membrane tank designs and the spherical tank designs. Other types of LNG carriers also exist, e.g. the self supporting prismatic design (SPB type), but these only make up a small part of the LNG fleet. The distribution of the different tanker types among the LNG fleet is as follows: Out of 183 LNG carriers, 91 are membrane type tankers, 83 are spherical type tankers and 9 are of other types of containment systems (as of August 2005). This corresponds to about 50% membrane ships, 45% spherical tankers and 5% of other types of ships.

Both the main types are double hull vessels, but with different cargo containment systems. 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 ships 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 ships 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. The current fleet of LNG carriers contains approximately the same share of spherical and membrane LNG tankers, although membrane tankers are dominant among LNG newbuildings.

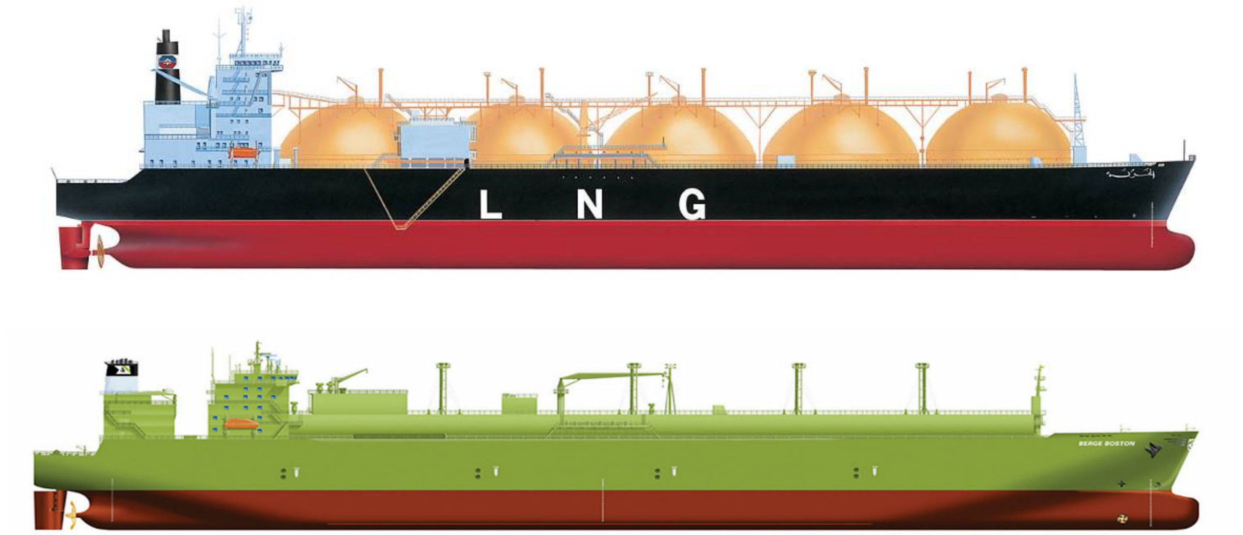

Figure 5: Main types of LNG carriers: Moss spherical tankers (top) and membrane tankers (bottom)

LNG vessels are generally well design and well maintained, and the world fleet of LNG tankers have a good safety records since international LNG shipping began in 1959. No major LNG spills have occurred at sea or in port even though LNG tankers have been involved in both grounding and collision incidents.

2.3.1 Major LNG trades

The main producers and exporters of LNG are in the North-Africa/Middle East region, in Southeast Asia and Australia as well as Nigeria and Alaska. The main consumers and importers of LNG are in the USA, Japan and South Korea, Southern Europe including Turkey and India. Hence, the major LNG trading routes go as indicated by Figure 6.

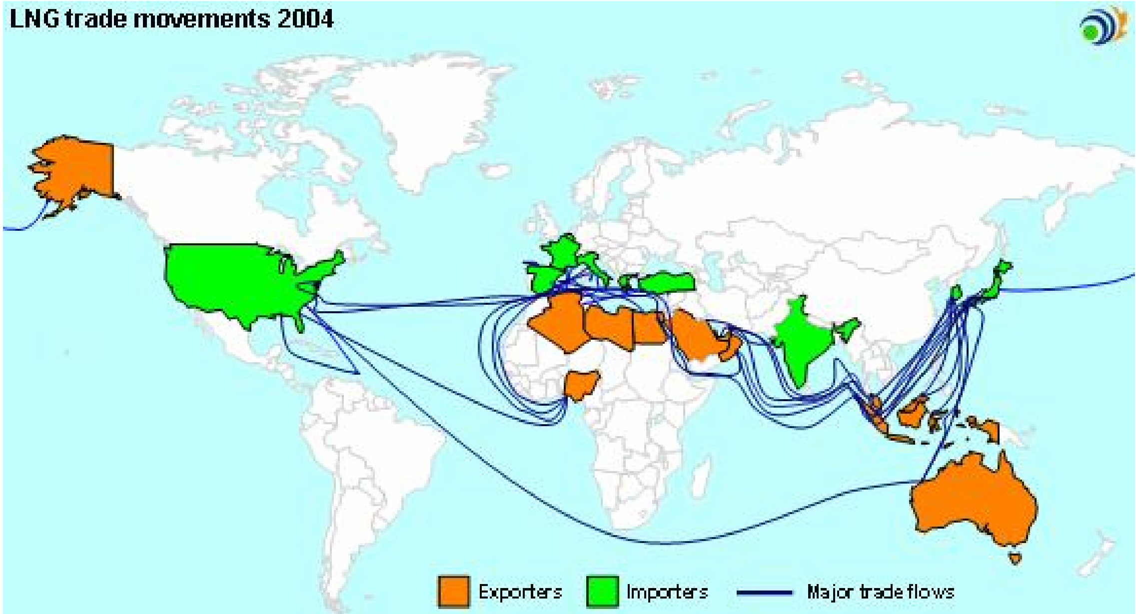

Figure 6: Major LNG trades between main LNG exporters and LNG importers. (Picture from http://www.lngoneworld.com/)

One thing that may be observed from studying the major LNG trades in Figure 6 is that, apart from the Alaskan trade, none of the major trades go through particularly icy environments. Thus, additional hazards from LNG shipping in icy waters have not been an important issue for most of the trades to date. However, this situation is expected to change in the near future, especially with the foreseen rise of LNG activities out of i.a. Russia and Norway in arctic and sub-arctic areas [20], [21].

At any rate, LNG shipping in icy waters and the particular hazards associated with such activities are not within the main focus of this study, which is the transatlantic LNG trade. However, some hazards related to ice will be briefly considered as special cases in this study.

Another important observation from studying the major LNG trades is that an LNG tanker will normally sail in ballast condition about 50% of the time. I.e. they will sail from the exporter to the importer loaded with LNG and then return along the same route in ballast. LNG membrane carriers are not allowed to operate with partially filled tanks, and for the purpose of this study, two sailing conditions are assumed, i.e. fully loaded with cargo and in ballast, with a distribution of 50% probability of each.

3 Accident Scenarios

For the purpose of this study, an accident is interpreted according to the definition in the IMO FSA guidelines [1]: An unintended event involving fatality, injury, ship loss or damage, other property loss or damage or environmental damage. Hence, an event does not necessarily have to involve fatalities in order to be regarded as an accident.

3.1 Experience with LNG tankers

The first LNG cargo that was shipped by sea in an LNG tanker was transported from Louisiana, USA to Great Britain by the Methane Pioneer in 1959 [22]. This demonstrated that it was possible to safely transport large quantities of LNG by sea. The first purpose built LNG tanker was the Methane Princess, which transported the first commercial cargo from Algeria to Great Britain in 1964, and since then the marine transportation of LNG has gradually increased. Thus, more than 40 years of experience with LNG tankers has accumulated over the years, and this experience can serve as a good indication of credible accident scenarios.

It should be realised however, that the fleet of LNG tankers has undergone major developments during this time, and that the current fleet contains both more ships as well as bigger ships than previous years. Developments in safety regulations and standards for design, construction and equipment have also influenced the types of accident scenarios that are relevant. In addition, new trading patterns and routes for LNG shipments have emerged during the years as well as new owners, operators and crew with little experience with LNG. This means that some accidents that have happened in the past are not necessarily describing credible accident scenarios in the present situation, and that new accident scenarios that have not materialized in the past might be important. At any rate, past accident experience of LNG shipping should not be regarded as more than merely good indications of accidents that might be relevant in present and future LNG shipping activities and other possible scenarios should also be investigated.

3.1.1 LNG experimental trials and simulations

A number of spill tests have been conducted since the 1970s that have contributed to the knowledge of how spilled LNG would behave in the event of an accident. Various spill tests on land have been sponsored by i.a. American Gas Association (AGA), U.S. Department of Energy (DoE), Japan Gas Association (JGA) and BG/Gaz de France, investigating issues such as vapour dispersion, fire radiation and cloud explosion. Spill tests on water have been sponsored by i.a. the United States Coast Guard (USCG), DoE, BG/Gaz de France and Shell. The largest land pool size in these tests has been 35 meters in diameter, and the largest liquid pool spread on water has been 30 meters.

Current knowledge about LNG spill characteristics are substantiated by and established based on a number of different tests and models. However, it is questionable whether the results from testing of relatively small scale LNG releases are applicable to very large releases. Furthermore, no models currently exist for accurately predicting LNG spills from double hull tankers, although some models exist that can roughly estimate the magnitude of effects for incidents involving release of large amounts of LNG on water ([23], [25]).

3.1.2 Operational experience – Previous accidents with LNG tankers

A literature survey on the experience during the history of LNG shipping reveals information of 182 incidents with or without LNG spillage involving LNG carriers of more than 6,000 GRT (up to and including 2005). These are listed in Table 13 in appendix A.1. The information about these accidents has been obtained from different sources, none of which contains information about all accidents and some of the sources giving slightly different information for one and the same accident. The various sources, which are also listed in Table 13, are: Houston Law Center [27], IZAR [28], Colton Company [29], DNV [30], LRFP [31] (from 1978 – 2004), QUEST [32] and MHIDAS [33]. It should also be noted that ships occasionally change names, and that different names have sometimes been referred to for the same accident from various sources.

Very few fatalities have been reported as a result of LNG carriers in operation in the past. According to available information, as listed in appendix A.1, there has been one incident where a terminal worker died and one incident where a fatality among the crew on a bulk carrier that collided with a LNG carrier occurred. This would indicate a potential loss of lives (PLL) of 7.05 x 10^{-4} per shipyear. In addition to this, there have been some fatalities associated with LNG carriers not in normal operation, i.e. the death of one shipbuilder during construction and one incident with 6 fatalities during ship trials[1].

Of the 182 accidents listed in appendix A.1, 24 will be out of scope of this study for various reasons:

- 7 incidents in yards during construction which is out of scope
- 7 incidents in yards or dry-dock during repair or maintenance which is out of scope
- 1 incident with piracy which is out of scope
- 3 incidents occurred to ships while in tow which is considered out of scope
- 3 incidents occurred during trials which is out of scope
- 3 incidents occurred to ships that were laid up and is out of scope

In addition to these, there were two incidents involving LNG carriers that occurred when the ship was assumed to be in LPG service. It may therefore be argued that also these incidents should be regarded as irrelevant to the current study. However, the types of incidents these vessels were involved in, grounding, collision and contact, is not dependent on the type of cargo, and since these vessels are part of the LNG fleet, the accidents are believed to be relevant.

Some of the accident involves the very first commercial LNG carriers built in the 1960s, and these ships are of a different design than most LNG carriers currently under operation. Thus, these ships are not directly representative for the current fleet of LNG carriers. Nevertheless, they will still be considered in this study.

Thus, previous experience amounts to 158 known incidents involving LNG carriers. For the purpose of simplicity, all the vessels are divided into three generic ship categories according to the type of containment system: Membrane tankers[2], spherical tankers and other LNG tankers, e.g. prismatic tanks. It should also be noted that the list is not necessarily a complete list of all incidents that has occurred in the past, but it is still believed to give a good indication of the risk picture. (E.g., a number of problems related to leakage of the secondary barrier of CS1 type membrane systems have recently been reported, but these are not a part of the statistical material used herein). The statistics below can be derived from the available material.

Of the 158 incidents considered further, 58 involved a membrane tanker, 80 a spherical tanker, 18 other types of LNG tankers and 2 involved an unknown ship. Thus, without considering the severity of the incident or the exposure of the different types of ships, the available material suggests that an initiating event is more likely onboard a spherical tanker than on other types of LNG tankers. This is illustrated in Figure 7 (left chart). The current fleet of LNG tankers is dominated by the two types of LNG containment systems referred to as membrane and spherical, which contains approximately the same number of ships for each of the types.

However, a significant part of the available accident statistics covers incidents which happened in the early years of LNG shipping, and may not be representative for the current situation. E.g. according to the statistics, “other” type of LNG carriers, which only amounts to 5% of the LNG fleet, are involved in 11% of the incidents, and this seems relatively high considering the relatively few vessels of this type. However, upon closer investigation it is found that these incidents are mostly associated with the accident

[1] One incident in 1989 that claimed 27 lives with a nameless chemical tanker loading LNG has also been reported in one source (#136 in Table 13, appendix A.1), but it has not been possible to verify this information. Hence, no confidence is put on this information and no regard is given to this incident in this study.

[2] It has not been distinguished between the different types of membrane systems.

statistics in the early years of LNG shipping, when these types of ships made up a larger part of the LNG fleet. More specifically, 16 of the 18 incidents involving these types of ships occurred prior to 1985. Considering only incidents occurring from 1985 and later, one arrives at the following distribution: 61% membrane, 33% spherical and 4% other types (right chart in Figure 7). Compared to the statistics for the whole period of LNG shipping, is can be seen that membrane type LNG ships are dominating the accident statistics after 1985.

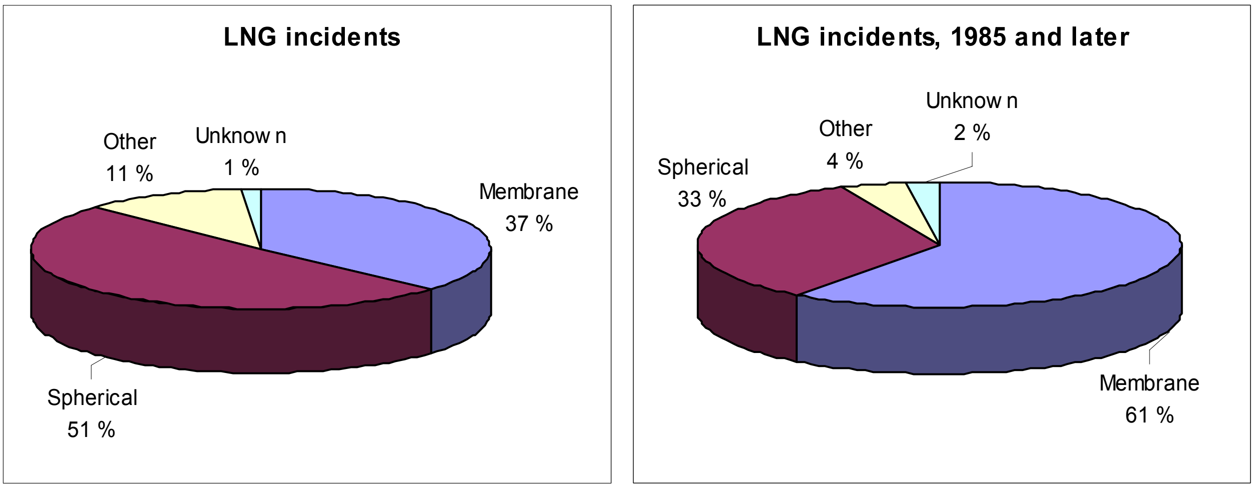

Figure 7: Breakdown of LNG incidents on ship type.

Thus, without going into more details, the available material indicates that incidents have happen more often on spherical type LNG ships than on membrane type ships during the history of LNG shipping. However, the statistics also indicate that accidents have happened more frequently on membrane type ships during the last 20 years. The available material is too sparse and the uncertainties related to e.g. possible underreporting of incidents are too large to draw any definite conclusions, but it is noted that incidents occur on all types of LNG carriers, and for the purpose of this high-level study, the probability of an incident can be assumed to be in the same order of magnitude for membrane and spherical LNG carriers.

The 158 relevant incidents reported in appendix A.1 can be grouped into a few generic accident types. The following accident categories are assumed appropriate for previous accident experience:

1. Collision (striking or being struck by another vessel)
2. Grounding (touching bottom or stranding)
3. Contact (with an object, another vessel, etc…)
4. Fire or explosion
5. Equipment or machinery failure (power generation, propulsion, steering etc…)
6. Heavy weather
7. Incidents while loading/unloading of cargo (leakage, overfilling, rollover, etc…)
8. Failure of cargo containment system (loss of cargo containment integrity, leakage of primary barrier, sloshing, liquid nitrogen leakage, cargo-related equipment failure etc…)

It is noted that it is sometimes difficult to determine exactly which accident category is most appropriate, and the categorisation of the accidents is undeniably subjective. As a general rule, the incident will be categorized according to the first event, but some exceptions exist. Some examples of incidents that could have been placed in different categories are given below:

- Some accidents have been initiated by a strike of lightning causing fire while loading. This accident can defensible be categorized as incidents while loading, incidents due to bad weather or a fire incident, and the choice might seem arbitrary. However, since the main hazard in these types of incidents is the fire, these will be categorized as fire events.

- An accident where a short circuit ignited LNG vapour while unloading might have been categorized as incidents while loading, equipment failure or fire. However, this incident will be categorized as fire, due to fire being the main hazard.
- Some incidents are reported as engine breakdown following by contact, grounding or collision. This might be categorized either as machinery failure or contact, grounding or collision. However, this will be categorized as contact/grounding/collision since this corresponds to the accident scenario which will be further investigated. Equipment or machinery failures that do not lead to any subsequent accidents will be labelled as equipment or machinery failure.
- Failures in cargo pumps, gas compressor pumps and other equipment related to the cargo containment system might have been categorized as equipment and machinery failures, but since these types of equipment is related to the cargo containment system and thus specific to the carriage of LNG, such failures will be labelled as failure of cargo containment system for the purpose of this study.
- One incident reported “compressor damage”. Without further details, it cannot be known whether this is related to the cargo, the engines or other things. However, for the purpose of this study, if no other details are reported, this is taken as an equipment or machinery failure.
- Failures in cargo pumps are categorized as incidents related to unloading of cargo since this is the only times when these pumps are used.
- Reports of violent sloshing and subsequent damages in heavy weather might have been categorized as either heavy weather or failure of cargo containment system. Since these problems are related to the cargo containment system of LNG, such incidents will be labelled as failure of cargo containment system.

The following distribution of accident categories was found in the historical data (an exposure of 2,838 shipyears has been used in order to estimate the accident frequency):

Table 3: Breakdown of historic accident data on accident categories

Accident category	**Number of accidents**	**Accidents frequency (per shipyear)**
Collision	19	6.7×10^{-3}
Grounding	8	2.8×10^{-3}
Contact	8	2.8×10^{-3}
Fire	10	3.5×10^{-3}
Equipment or machinery failure	55	1.9×10^{-2}
Heavy weather	9	3.2×10^{-3}
Incidents while loading/unloading of cargo	22	7.8×10^{-3}
Failure of cargo containment system	27	9.5×10^{-3}
Total	*158*	5.6×10^{-2}

These numbers represent the available accident data for the whole history of LNG shipping, and it might be interesting to see how the picture has changes over time. Thus, the available data is broken down into four periods of time, from 1964 – 1975, from 1976 – 1985, from 1986 – 1995 and from 1996 – 2005. The distribution of the different accident categories over these periods of time are presented in Table 4. It has also been distinguished between accidents that are specific to LNG carriers and accidents that are general to all types of vessels. Accidents such as collision and fire are regarded as general shipping accidents, since it occurs on all types of ships. The consequences might be very different for LNG ships compared to other types of ships if major releases of LNG occur, but apart from that, these accidents are not specific to LNG vessels.

Two of the eight accident categories selected above are specific to LNG shipping, i.e. incidents while loading/unloading of cargo and failure of the cargo containment system. Hence, the development of these types of accident categories over time will also be studied. This information is also contained in Table 4.

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

Accident category	64 – 75	76 – 85	86 – 95	96 – 05	64 – 05
Collision	1	10	4	4	19
Grounding	1	6		1	8
Contact		4		4	8
Fire	2	5		3	10
Equipment or machinery failure		39	7	9	55
Heavy weather		6	3		9
General ship accidents	**4**	**70**	**14**	**21**	**109**
Incidents while loading/unloading of cargo	4	13	3	2	22
Failure of cargo containment system	7	15	5		27
LNG specific accidents	**11**	**28**	**8**	**2**	**49**
Total	*15*	*98*	*22*	*23*	*158*

Apart from an apparent rise in accidents during 1976 – 1985, the total number of reported accidents involving LNG carriers is found to be quite similar for the different periods of time. Realizing that the LNG fleet has grown since 1964, this indicates that the safety level has increased or at least has stayed about the same. Possibly, the relatively high number of accidents occurring from 1976 to 1985 may be due to underreporting of accidents during later periods and does not necessarily mean that the actual number of accidents was very much higher in this period (E.g. information about merely four incidents occurring during the years 1991 – 1995 seems very low). However, this was not further investigated, and it is not clear why so many accidents were reported in the period 1976 – 1985, the majority of which was related to equipment and machinery failure. At any rate, the statistics are too sparse to draw any definite conclusions, but one general trend can be observed: The number of LNG specific accidents seems to have decreased since 1976 – 85.

In order to gain a better understanding of the accident frequency, the number of accidents can be measured against the exposure in order to arrive at the accident frequency per shipyear. This is done for the different periods of time in Table 5 and Figure 8 below. From these numbers and graphs it can easily be seen that the frequency of LNG specific accidents has declined since 1964. Furthermore, the frequency of general ship accidents has declined since 1976 – 1985. One possible explanation for this might be that there has been an evolution in the safety standards of LNG shipping that have resulted in enhanced safety when it comes to LNG specific hazards. At any rate, the average accident frequencies over the whole time span is deemed to give an appropriate, high-level indication of the current risk level of LNG carriers.

Table 5: Historic accident data and exposure over different periods of time						
Time period		**64 – 75**	**76 – 85**	**86 – 95**	**96 – 05**	**64 – 05**
Exposure (accumulated # shipyears)		***116***	***585***	***770***	***1367***	***2838***
General ship accidents	# accidents	4	70	14	21	109
	Accidents/shipyear	3.4×10^{-2}	1.2×10^{-1}	1.8×10^{-2}	1.5×10^{-2}	3.8×10^{-2}
LNG specific accidents	# accidents	11	28	8	2	49
	Accidents/shipyear	9.5×10^{-2}	4.8×10^{-2}	1.0×10^{-2}	1.5×10^{-3}	1.7×10^{-2}
All accidents	# Accidents	15	98	22	23	158
	Accidents/shipyear	1.3×10^{-1}	1.7×10^{-1}	2.9×10^{-2}	1.7×10^{-2}	5.6×10^{-2}

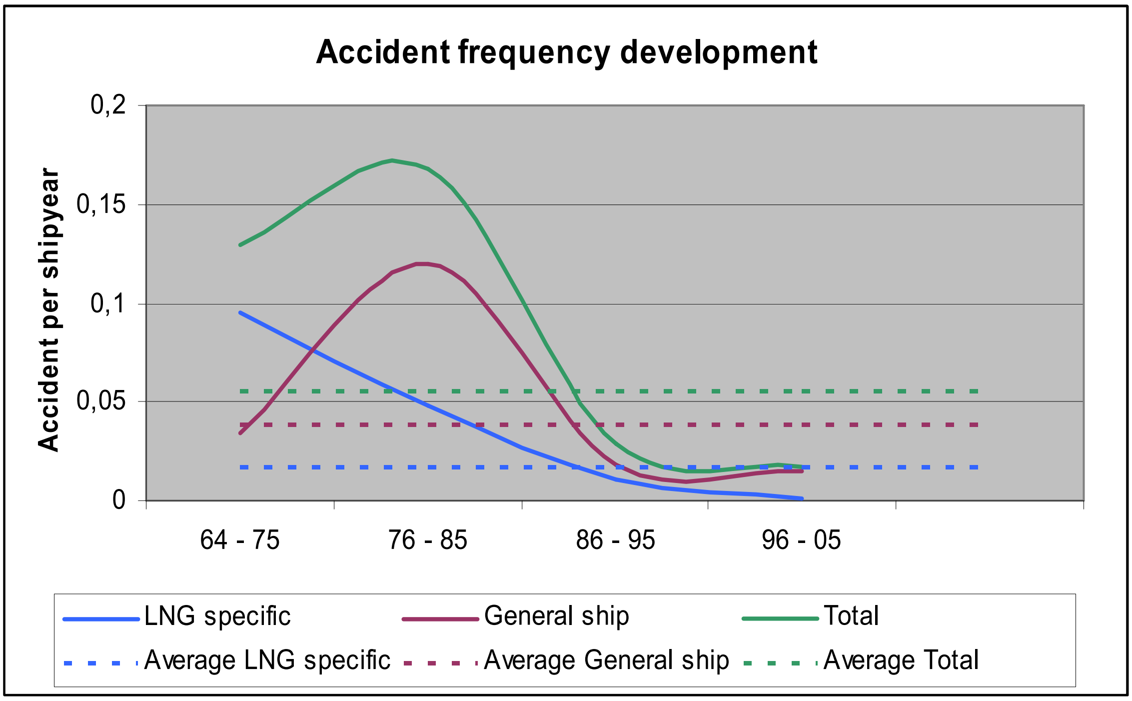

Figure 8: Development of accident frequency over time

3.2 *Results from HAZID*

A HAZID of LNG carriers was carried out prior to this risk analysis. The various operational phases of LNG tankers were considered in a structured way in order to identify all possible and relevant hazards. Then, for each hazard, initial ranking in terms of estimated frequency and severity of consequence were completed. The results from this task were reported in a HAZID report [2].

One of the results from the HAZID is a risk register listing what was believed to be the most relevant hazards regarding LNG carriers. This risk register contains a total of 120 hazards from the various operational phases of a LNG carrier. Some of these hazards are duplicated in the risk register in order to take into account that they can occur in several operational phases, meaning that the number of different hazards in the register is actually somewhat lower than 120.

Based on the subjective estimates of frequencies and consequences for the various hazards by the HAZID participants, the accumulative risk from all the hazards can be summed in terms of "equivalent number of fatalities per shipyear" (ref. tables 6 and 7 in the HAZID report [2]). By doing so, one arrives at the total risk of 2.7×10^{-1} equivalent fatalities per shipyear. However, this includes all hazards including the hazards arising from operation in icy conditions. Very few LNG vessels operate in icy regions, and hence these hazards should not be included when considered the average risk of the fleet. Other hazards are also included that were defined out of scope, e.g. occupational hazards and hazards related to terrorism. Ignoring these contributions as well, the risk sum from the relevant hazards is 1.1×10^{-1} equivalent fatalities per shipyear according to the HAZID.

The various hazards in the risk register of the HAZID report are associated with different risk components, such as human safety, environmental and economic related risks. Of these, only the human safety component is within the scope of this study. Thus, in order to extract the human safety risk level according to the HAZID, hazards without contributions to the human safety risk should not be included in the risk summation. Counting only the relevant hazards that contribute to the human safety risk, ignoring ice, occupational hazards and terrorism, the total risk becomes 5.2×10^{-2} fatalities per shipyear. To concretize, this fatality rate corresponds to an average of one fatality every 20 years for a given LNG carriers or, for a fleet of approximately 180 vessels, an average of 9 fatalities per year. Clearly, the historic safety record of the LNG fleet thus far is better than what this value suggest. It should be kept in mind, however, that this is not a result of any risk analysis, but is based on the initial estimates from the HAZID team (which generally overestimate the risk).

Based on the initial ranking of the hazards in terms of frequency and severity of consequence, all hazards are assigned a risk index. Hence, prioritizing of the various hazards in terms of risk was made possible. The twelve highest ranked hazards according to the HAZID are repeated in Table 6. Two of the hazards in this list, i.e. hazards 2 and 12, are occupational hazards or security hazards, both of which are out of scope of this study. These hazards are marked by the shaded rows in the table. Thus, ten relevant hazards are suggested as most important from the HAZID report.

Table 6: Top-ranked hazards from the HAZID report			
Priority	**Hazard**	**Operational phase**	**Risk index from HAZID studies**
1	Faults in navigation equipment	Navigation in coastal waters (without tug)	7.0
2	Crew falls or slips onboard	General hazards	7.0
3	Shortage of crew when LNG trade is increasing	Training	6.8
4	Rudder failure	Navigation in coastal waters (without tug)	6.8
5	Rudder failure	Manoeuvring	6.8
6	Severe weather causing vessel to ground/collide	Transit in open sea	6.6
7	Steering and propulsion failure	Manoeuvring	6.6
8	Severe weather causing vessel to ground/collide	Manoeuvring	6.6
9	Faults in navigation equipment	Manoeuvring	6.6
10	Steering and propulsion failure	Navigation in coastal waters (without tug)	6.6
11	Collision with other ships or facilities	Arriving in port	6.6
12	Terrorist attacks/intentional accidents	General hazards	6.5

The prioritized list of hazards is used to propose accident scenarios to be taken forward in the step 2 of the FSA, i.e. this risk analysis. The accident scenarios suggested by the HAZID report are listed in Table 7. Again, some of these scenarios are regarded as out of scope of this study, i.e. the occupational hazard scenario, the terrorist attack scenario and the scenario in icy waters. However, the icy waters scenario will be considered as a special case.

Comparing the suggested accident scenarios from the HAZID report with the eight accident categories used in the previous chapter of this annex, it can be seen that these are in general agreement with each other. The *collision*, *grounding* and *fire* scenarios would be more or less identical. The e*quipment and machinery failure* accident category from the previous chapter of this annex is not really describing an accident scenario, but may be the cause or initiating event of various other scenarios such as *collision*, *grounding* etc. The *heavy weather* accident category would to a certain extent correspond to the *intact stability failure* scenario suggested by the HAZID report, since loss of intact stability is normally associated with heavy weather. (Loss of intact stability due to failure in loading/ballasting procedures is not believed to be a realistic scenario when it comes to LNG tankers). However, it should be noted that none of the *heavy weather* incidents reported in appendix A.1 caused loss of intact stability. However, *heavy weather* can be assumed to be the initiating event of an *intact stability failure* scenario. *Gas leakage* in the HAZID report would correspond to, or at least be a subset of, the *failure of cargo containment system* category in this annex. Finally, *incidents while loading/unloading of cargo* corresponds to *LNG spill during loading/unloading* and *escalating incidents from quayside* in the HAZID report.

Thus, the main difference between the two set of accident categories/scenarios is that the HAZID report do not suggest considering contact scenarios apart from contact with ice. None of the sources identifies other scenarios such as e.g. loss of structural strength as an important issue for LNG carriers.

Table 7: Suggested accident scenarios from the HAZID report and their main causes

Scenario No.	Description	Main cause
1	Collision	Navigation error, human failure, procedural faults, steering equipment failure, machinery failure, bad weather conditions,
2	Grounding	Navigation error, human failure, procedural faults, steering equipment failure, machinery failure, bad weather conditions,
3	Fire onboard	Failure in fire detection system, equipment malfunction, gas leakage, work conducted without a safe job analysis (SJA), procedural faults,
4	Intact stability failure	Failure of loading/ballasting procedures, abnormal wave conditions, structural faults, tank leakage,
5	Occupational accidents	Work conducted without SJA, human failure, wrong procedures, wrong use of procedures, abnormal weather conditions,
6	Gas leakage	Damage to tank structure, valve faults, damage to piping, operational error of gas system, engine faults, overloading,
7	LNG spills during loading/unloading	Procedural faults, equipment failure, excessive forces, mooring system damage/fault, ballast system damage/fault, lack of stability, roll-over, lack of crew competence, collision with passing ship,
8	Terrorist attacks	External factors
9	Escalating incidents from quayside	Procedural faults, equipment failure, mooring system damage/fault, lack of crew competence
10	Contact damage - ice related	High speed into ice, fatigue in ice operation, lack of ice management,

3.3 Selected accident scenarios for further studies

Based on the review of previous incidents involving LNG tankers and on the results from the HAZID, the following generic accident scenarios are selected for further studies in this risk analysis:

General maritime accident scenarios:

1. Collision
2. Grounding
3. Contact
4. Fire or explosion
5. Heavy weather/Loss of intact stability

LNG specific accident scenarios:

6. Incidents while loading or unloading of cargo
7. Failure/leakage of cargo containment system

This set of generic accident scenarios corresponds well with both the accident categories used to categorize previous accident experience and the scenarios suggested by the HAZID report.

The main difference from the accident categories earlier in this annex is that equipment and machinery failure is not included as a separate scenario. Such failures will be important as initiating or escalating events in other accident scenarios. For example, loss of steering or propulsion might lead to collision, grounding or contact accidents, and failure in fire protection systems might contribute to the consequences in a fire scenarios. However, equipment and machinery failure that do not lead to any subsequent accident will not be further considered in this risk analysis, and no generic accident scenario for equipment and machinery failure is deemed necessary.

The main difference from the scenarios suggested by the HAZID report is that scenarios that are out of scope will not be taken further, i.e. the occupational accidents scenario, the terrorist attack scenario and the ice-related scenarios. However, the operation of LNG carriers in icy conditions will be considered as a special case.

4 Frequency Assessment

4.1 Accident frequency estimated from experience

The available accident statistics as reviewed in the previous chapter gives an indication of the accident frequency of the different generic accident scenarios selected for further study. The accident frequencies for the relevant scenarios are reproduced in Table 8.

Table 8: Accident frequency according to experience

Generic accident scenario	**Number of incidents**	**Accident frequency** (per shipyear)
Collision	19	6.7×10^{-3}
Grounding	8	2.8×10^{-3}
Contact	8	2.8×10^{-3}
Fire or explosion	10	3.5×10^{-3}
Heavy weather/Loss of intact stability	9	3.2×10^{-3}
Incidents while loading/unloading of cargo	22	7.8×10^{-3}
Failure/leakage of cargo containment system	27	9.5×10^{-3}

These accident frequencies can be taken as the frequency of an initiating event causing the various accident scenarios. Especially, for the heavy weather/Loss of intact stability scenario it should be kept in mind that the frequency is not indicating the frequency of intact stability failure, but rather an initiating event that is heavy weather damage that might have the potential to develop into loss of stability.

A similar study has previously been carried out and reported in [37] where frequencies are estimated for some of these accident scenarios. For comparison, the relevant results from [37] are reproduced in Table 9. Compared to the frequency estimates in Table 8, it can be seen that the estimates are generally in fine agreement. However, the estimates in Table 8 are somewhat higher for all the scenarios, most notably for the grounding scenario, and this might be due to a more comprehensive study of available accident statistics. At any rate, this agreement serves to substantiate the estimates arrived at in this study.

Table 9: Accident frequency from previous similar study [37]

Accident type	**Relevant accident scenario**	**Accident frequency** (Per shipyear)
Collision	Collision	3.9×10^{-3}
Contact	Contact	2.6×10^{-3}
Fire/Explosion	Fire or explosion	3.3×10^{-3}
Wrecked/Stranded	Grounding	6.6×10^{-4}

In order to assess whether these estimates seems reasonable or not, they can be compared to frequency estimates of similar incidents for other ship types that has previously been reported. In Table 10, the frequencies of collision, contact and fire and explosion incidents are compared to previous estimates for single hull oil tankers [38], double hull oil tankers [39], oil/chemical tankers [40], chemical tankers [41], LPG tankers [42] and bulk carriers [43].

Table 10: Accident frequencies for other ship types (per shipyear)							
Accident type	**SH Oil tanker**	**DH Oil tanker**	**Oil/ Chemical tanker**	**Chemical tanker**	**LPG tanker**	**Bulk carrier**	**LNG carrier**
Collision	9.9×10^{-3}	8.6×10^{-3}	4.3×10^{-2}	9.4×10^{-3}	2.2×10^{-2}	1.9×10^{-2}	6.7×10^{-3}
Contact	4.9×10^{-3}	3.1×10^{-3}	1.2×10^{-2}	4.6×10^{-3}	3.0×10^{-3}	1.1×10^{-2}	2.8×10^{-3}
Fire/ Explosion	3.7×10^{-3}	1.1×10^{-3}	1.1×10^{-2}	4.5×10^{-3}	4.3×10^{-3}	2.9×10^{-3}	3.5×10^{-3}

As can be seen from this table, the accident frequencies are in the same order of magnitude for the different accident types, and the estimates for LNG carriers seems reasonable also when comparing with accident frequencies associated with other ship types. In general, the accident frequencies for LNG carriers are found to be somewhat lower than for the other ship types, but this was expected due to e.g. the high focus on safety of these ships and the generally high competence of LNG crew.

Having established frequencies of initiating events for each accident scenario, it might be argued that there will be no need for detailed fault tree analysis in this high-level risk analysis. This corresponds to the following assumptions:

- The available accident data are statistically significant
- The uncertainty in the information is small
- The present situation is comparable to the period of time over which the accident statistics have been collected.

For the purpose of this overall risk analysis, these seem like valid assumptions, and it is hence suggested to use the frequencies in Table 8 above as the frequencies of events initiating the various accident scenarios. Thus, fault tree analysis will not be carried out as part of this analysis.

5 Consequence Assessment

The expected consequences in each of the identified scenarios will be estimated by the use of event trees. First, a set of event trees will be constructed for each of the accident scenarios and then the event trees will be quantified using a variety of different techniques. This will be outlined in the following. As frequency for the first event in the event trees, the estimates based on accident experience presented in section 4.1 will be used. The event trees can be seen in appendix A.4 of this annex.

5.1 Construction of event trees

At a high level, the total risk associated with the operation of LNG carriers is assumed to be the sum of the risk contributions from the seven selected accident scenarios. The risk contributions from all other scenarios are assumed to be negligible in comparison. Thus, the overall risk model can be illustrated as in Figure 9 below. The risk contribution from each of the accidents scenarios will be estimated based on more detailed risk models and event trees.

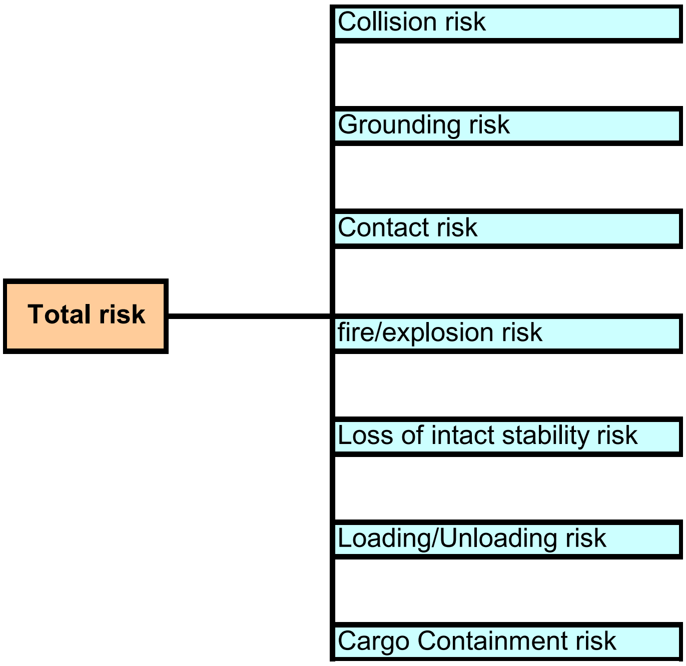

Figure 9: Overall risk model, LNG carriers

In general, an accident may occur while the LNG carrier is loaded or in the ballast condition. Naturally, the risk contributions from these two cases will be very different, and the risk contributions from ships fully loaded are expected to dominate. Nevertheless, an LNG carrier will typically spend 50% of its time in ballast, so both types of scenarios will be considered in this study. However, this distinction does not exist for the last two accident scenarios that are LNG cargo specific.

5.1.1 Collision scenario

A typical collision scenario with an LNG carrier might develop in the way described in the following. First, a collision occurs. The LNG vessel might be struck by another vessel or it might be the striking ship. If the LNG vessel is the striking ship, the likelihood of further escalation of the incident for the LNG vessel can be regarded as small as it will receive the collision impact in the bow. Furthermore, the collision might occur when the LNG carrier is in ballast or when it is fully loaded, and this will influence the further escalation of the event.

When the LNG carrier is the struck ship, the collision might or might not cause damage that penetrates the outer hull and the inner hull. If the collision damage penetrates the inner hull, it might cause leakage of cargo. Leakage of cargo might again result in materialization of an LNG hazard such as pool fire, drifting vapour cloud, Rapid Phase Transition, etc. Cryogenic temperatures of LNG or heat generated from a pool fire might deteriorate the strength of the ship and may eventually lead to sinking. Penetration of the inner hull might also cause loss of stability and hence cause the ship to sink in the ballast condition, although this is rather unlikely. If LNG hazards materialize or the ship sinks, failure of evacuation may lead to a number of fatalities among the crew. Third party risk to public on shore or onboard other vessels are not within the scope of this study and will not be included in the risk model. Thus, the following risk model for the collision scenario will be adopted (Figure 10):

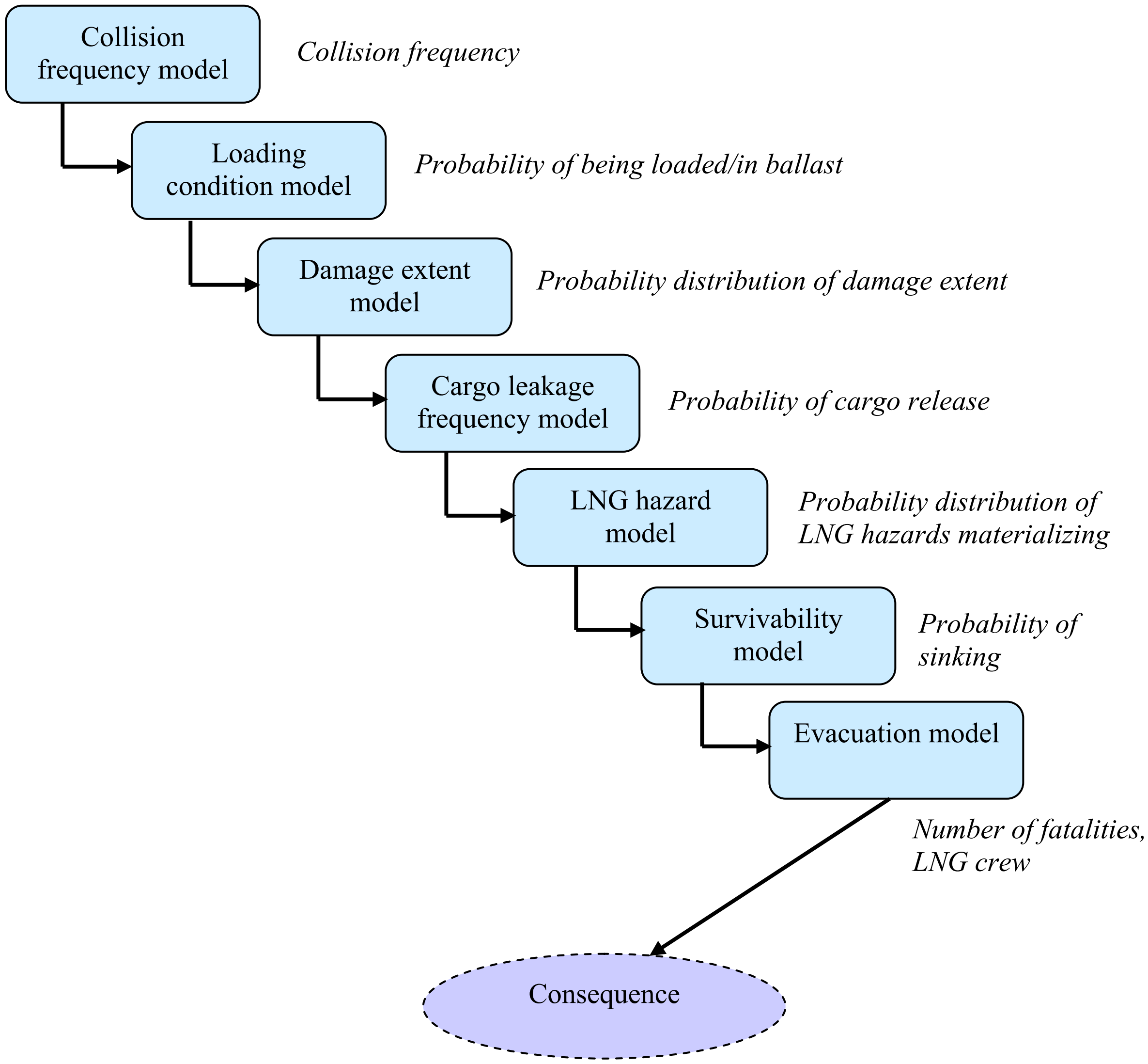

Figure 10: Risk model for collision of LNG carrier.

This risk model can be represented by an event tree. This event tree can be found in appendix A.4 of this annex.

5.1.2 Grounding scenario

The grounding scenario will in many ways be similar to the collision scenario. First, a grounding event might occur when the vessel is either loaded with LNG or in the ballast condition. The grounding will result in a certain extent of damage to the ship bottom, and this damage might or might not cause leakage of cargo and/or loss of stability. If LNG is released, one or more of several LNG hazards might materialize. Again, the LNG carrier might sink due to the grounding damage or due to deteriorating strength caused by the leakage of LNG. Finally, if crew are not able to evacuate in time, there might be fatalities due to either the LNG hazards or the sinking of the ship.

The risk model for the grounding scenario will be as illustrated in Figure 11.

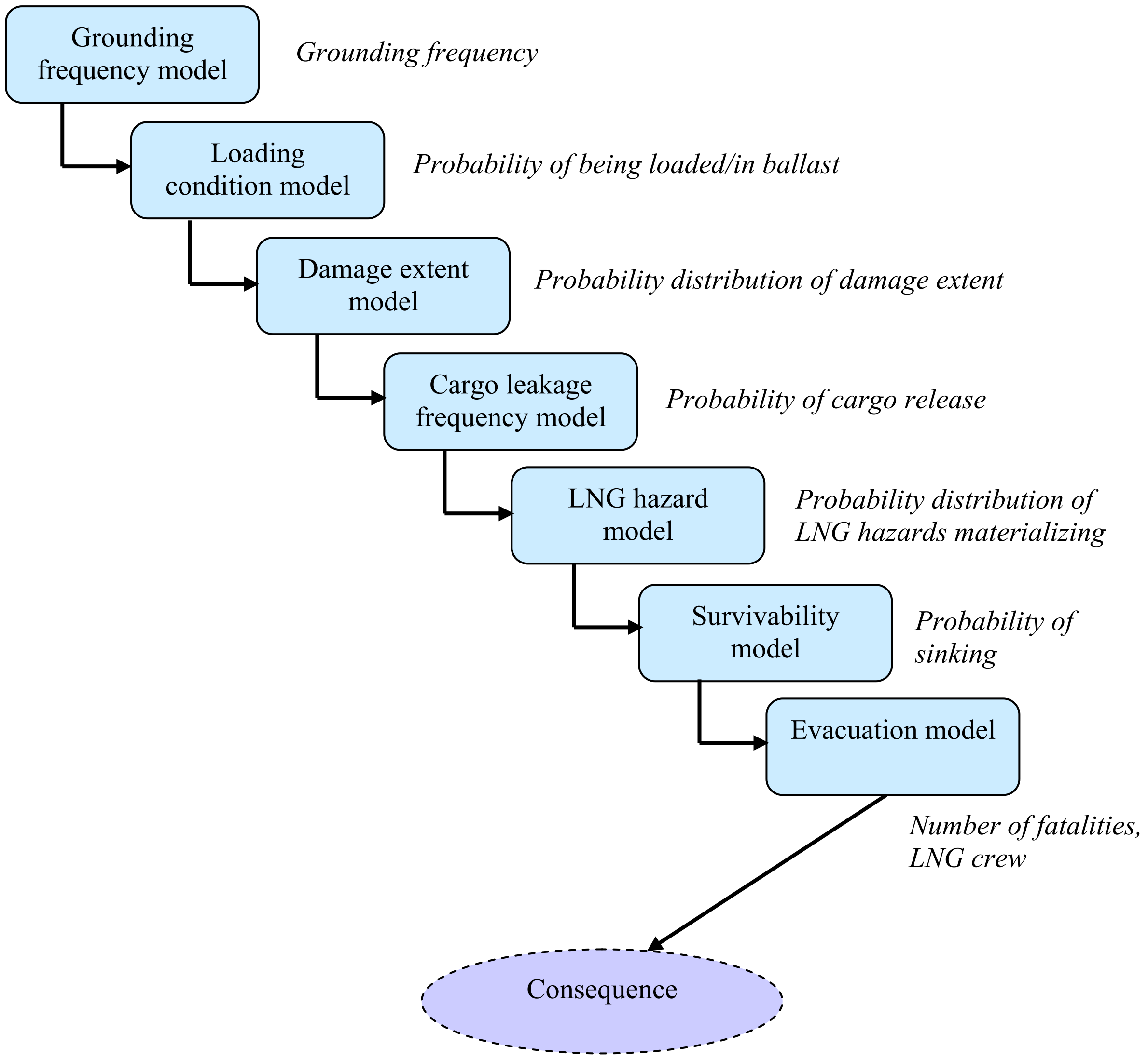

Figure 11: Risk model for grounding of LNG carrier.

This risk model can be presented as an event tree, as seen in appendix A.4 of this annex.

5.1.3 Contact scenario

The contact accident scenario will be very similar to the grounding and the collision accident scenarios outlined in the previous sections. Contact damage might result in similar subsequent events as collision and grounding damages. The contact incident risk model is illustrated in Figure 12.

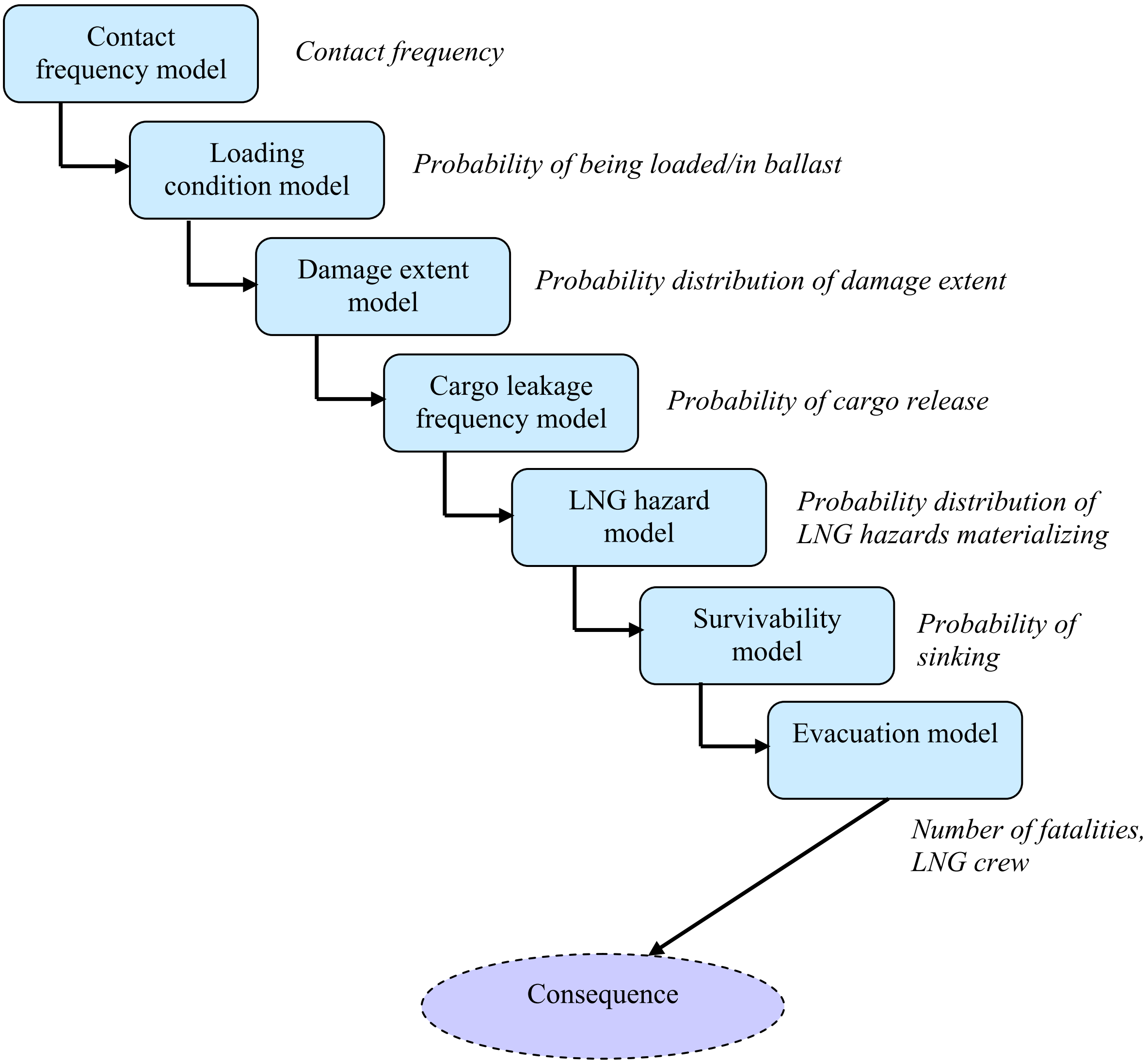

Figure 12: Risk model for contact incidents of LNG carrier.

The risk contribution from the contact scenario can also be represented as an event tree, which is presented in appendix A.4 of this annex.

5.1.4 Fire or explosion scenario

The fire or explosion scenario describes an incident where a fire or an explosion is the initiating event. Thus, accidents where other events such as collision lead to LNG spillage and subsequently fire of LNG vapour are not considered here. For the purpose of this study, it is distinguished between three types of fire scenarios, namely 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, no LNG specific hazards are assumed and the scenario will resemble similar fire incidents on other cargo ships, e.g. oil tankers. Fires in the cargo area will be specific to LNG carriers, and according to expert judgement, the only place in the cargo area where it is likely to assume that a fire will start is in the compressor room. For a compressor room fire, the following scenario is assumed: The fire protection systems might fail in preventing or extinguishing the fire/explosion and the fire/explosion might lead to breach in the cargo containment system and hence leakage of LNG. If there is leakage of LNG, an LNG hazard such as a pool fire might materialize, and there will be a probability that the ship will not survive. Finally, in the event of an escalating fire, the crew need to evacuate and failure to do so in time will cause a number of fatalities.

The fire and explosion risk model adopted in this study is illustrated in Figure 13. The risk contribution from this scenario can also be represented as an event tree, which is presented in appendix A.4 of this annex.

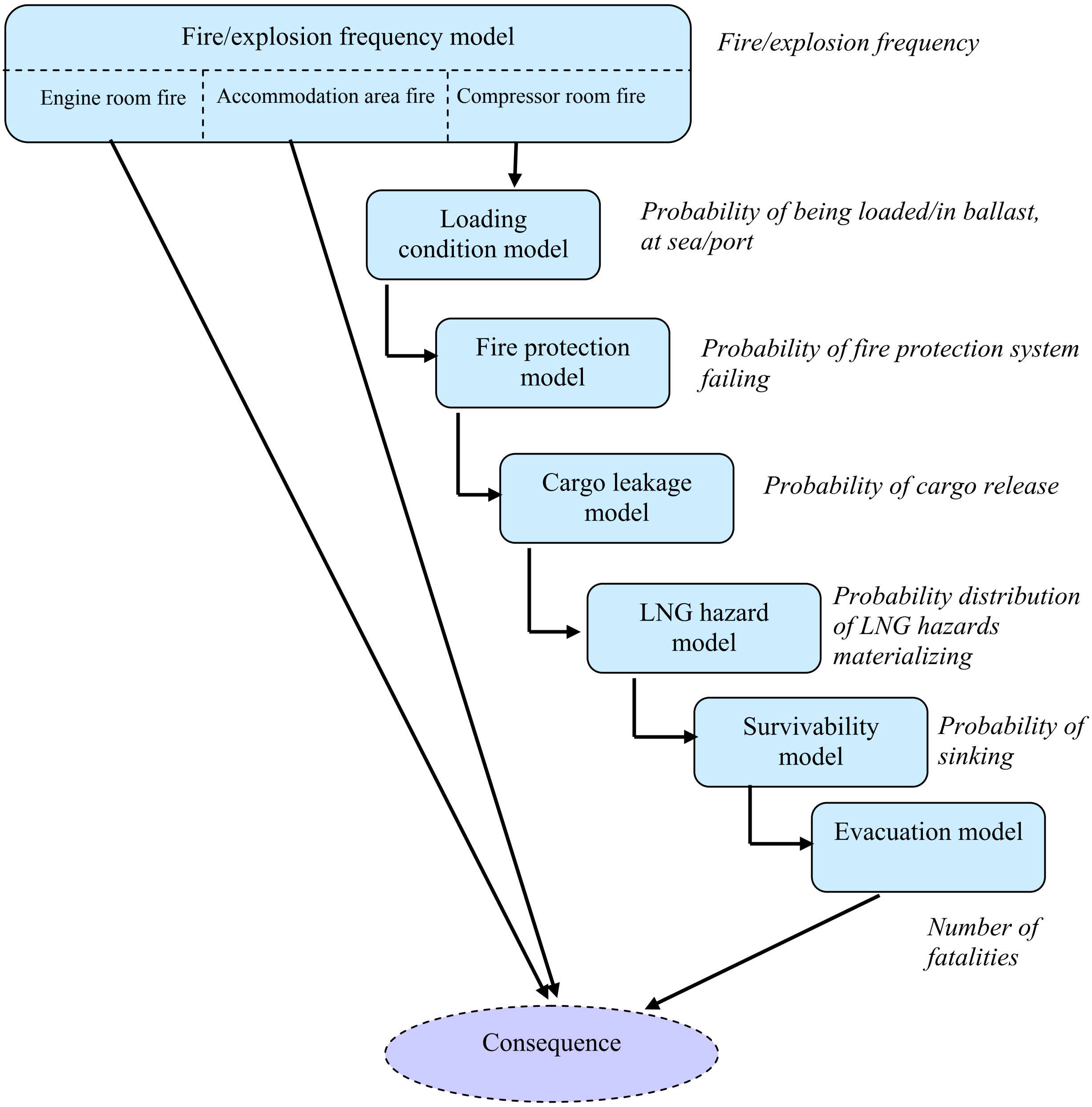

Figure 13: Risk model for fire and explosion of LNG carrier.

5.1.5 Heavy weather/Loss of intact stability scenario

Intact stability is maintained when a vessel's centre of gravity is located below the geometric metacentre. So long as the sea is calm, a small initial positive GM (metacentric height) would satisfy the basic intact stability requirements for any vessel and normally prevents capsizing. However, the world's oceans can be very hostile and minimum freeboards have had to be established to restrict the ingress of water together with minimum GM values to ensure that positive stability is maintained throughout the range of rolling in a seaway. Also incorrect loading/unloading procedures can lead to situations where free surface effects can occur, leading to the rolling of the ship. The buoyancy and stability characteristics of these ships in intact condition can be checked against the provisions given in the IMO resolution A.749(18).

Due to the particularities of the stability of LNG carriers, loss of stability in intact condition can only be cause of concern in case of:

- Abnormal wave conditions, especially with a freak wave crest located amidships.
- Failure in the loading/ballasting procedures, normally controlled and monitored by complex integrated cargo/ballast control systems, which command the often large number of ballast tanks (more than 20) and the cargo tanks (4 or 5).
- Extensive ice accumulation on deck, especially in the bow and other horizontal surfaces.
- Sloshing loads of the LNG cargo when a tank is partially filled, a matter of concerns especially for prismatic tanks of unusual length.
- Ballast water exchange (BWE)
- Combination of some of the factors above.

Of these factors, the one related to ice formation on deck is out of scope of the present study because it deals with risks that are present only in icy waters and therefore irrelevant for the main part of the current LNG fleet. The sloshing scenario is included in the failure of cargo containment system category and will not be treated here. However, it is assumed that the probability of loss of intact stability due to sloshing loads is small, and current regulations do not allow LNG carriers to operate with partially filled tanks. (It is noted that there will still be free liquid surface in the tanks even when fully loaded, i.e. loaded to more than 95% capacity).

Loss of intact stability might also be a concern during ballast water exchange if the correct sequence of loading/unloading of specific tanks is not adequately performed or if operation has to be suspended before completed due to adverse weather conditions [44]. Until now, no accidents have been reported due to ballast water exchange at sea, and considering the generally high competence level of LNG crew, it is assumed that the probability of loss of intact stability because of ballast water exchange is very low. For the purpose of this study, it is assumed that the risk contribution from such a scenario is negligible.

Due to the fact that the freeboard of LNG vessels presents values of nearly 18 m, in both cargo and ballast condition, the probability of green water damage of the bow or any deck structure of a cargo tank and subsequent water ingress due to freak waves is highly reduced. The freak wave would have a severe impact on the LNG stability if the ship is abeam to the wave allowing the rolling of the ship that can, in ultimate, lead to ship capsize. However, LNG vessels have highly trained crews which lead to conclude that such an event is very unlike. It is assumed that only the encounter with a freak wave while at the same time having loss of propulsion power could lead to the loss of intact stability.

Freak waves occur mainly on moderate and high latitude waters, where one can observe strong wind activity. They were registered on waters of North Atlantic, North Pacific and Antarctic Ocean, and also in the neighbourhood of Europe (Bay of Biscay, Celtic Sea, North Sea and Norwegian Sea). These waves can have singular heights above 20 m and their appearance is a random event [45]. Such a wave can look like an almost vertical water "wall" (both during occurrence of gales, and during completely windless weather, when only swell are present) or a “negative" wave on the water surface. The last one is a very deep and steep valley on the water surface. Ships coming to the edge of such a valley begin to accelerate flowing down, before the bow of the ship plunges in a steep wall of water on the opposite side of the valley causing extensive damages of the bow part. Rolling through board masses of waters contribute to serious damages of the superstructure and the bridge [46]. The displacement power under-water bow part is huge and huge bending moments act on the hull, possibly exceeding the resistance of the construction of the hull. In many storms, the number of wave records containing an abnormal wave, as defined by an abnormality index larger than 2, represented a percentage of 0% to 3.6% of the total time series in each storm [47], [48]. The average of these two values can be used and therefore one may assume that the probability of a freak wave, given the existence of a storm sea state, is: $P(fw \mid storm) = 0.018$.

The probability of encountering such a freak wave would also be conditioned on being in a storm sea state, and on being at the exact location of the freak wave. The probability of being in a storm sea state will be highly dependent on the geographical area, but in a global perspective, it would not be assumed to be very high. Even in the event of a freak wave, the probability of being at the exact location of the wave is presumed to be very low. The likelihood of this happening simultaneous to experiencing loss of propulsion power is assumed to be extremely remote, and it describes an exceptional scenario from which the risk contribution will be negligible. Hence, this issue will not be further pursued in this study.

The lolling effect is considered a safety issue for tankers having exceptionally wide cargo tanks (i.e. having cargo tank breadths greater than 60% of the vessels maximum beam). This effect occurs mainly in liquid transfer operations such as cargo loading/unloading, ballasting and deballasting, ballast water exchange and tank cleaning operations. Like in the case of other tank ships, LNG carriers can prevent incidents of lolling (the uncontrolled heeling of tankers due to loss of initial intact stability) during simultaneous ballast and cargo operations by requiring tankers designs that provide adequate intact stability. Due to MARPOL regulation in port, the initial metacentric height GM must be no less than 0.15 m and in loading/unloading operations the initial metacentric height and the righting lever curve are to be corrected for the effect of the free surface of liquid in tanks. Also the master of the ship should be supplied with a Loading and Stability Information booklet. This booklet should contain details of typical service and ballast conditions, provisions for evaluating other conditions of loading and a summary of the ship's survival capabilities. In addition, the booklet should contain sufficient information to enable the master to load and operate the ship in a safe and seaworthy manner. For LNG carriers, a lolling event is deemed very unlikely due to i.a. redundancy of loading/unloading systems, Cargo/Ballast Simulators and highly skilful and trained crew. This is corroborated by the inexistence of loss of the intact stability of LNG's in loading/unloading operations thus far. In conclusion, the risk contribution from lolling events is regarded as negligible.

Based on the arguments above, one may conclude that the probability of a loss of intact stability due to heavy weather or due to operational procedures is very small, and the risk contribution from such scenarios will hence be ignored in this study.

5.1.6 Incidents while loading or unloading of cargo scenario

Incidents when loading and unloading of cargo whilst in port are in general of small scale where possible injuries or fatalities are caused to a limited number of the crew. Fatal accidents may only happen when crew members are being exposed directly to LNG and suffer severe frost injuries due to the cold liquid (-162 degrees).

There are strict procedures in place for this type of operation and few incidents have taken place for this incident type. In line with the heavy focus on safety both at the terminals and onboard the risks of having fatal accidents, or any incidents at all, during loading and unloading are further reduced. This fact is clearly seen in Table 3. The CCS and transfer systems are designed to cater for the risk of overfilling and other aspects that may result in leakage/spills of either LNG as liquid or as gas.

The risk model for loading/unloading incidents of an LNG carrier is illustrated in Figure 14. The corresponding event tree is provided in appendix A.4 of this annex.

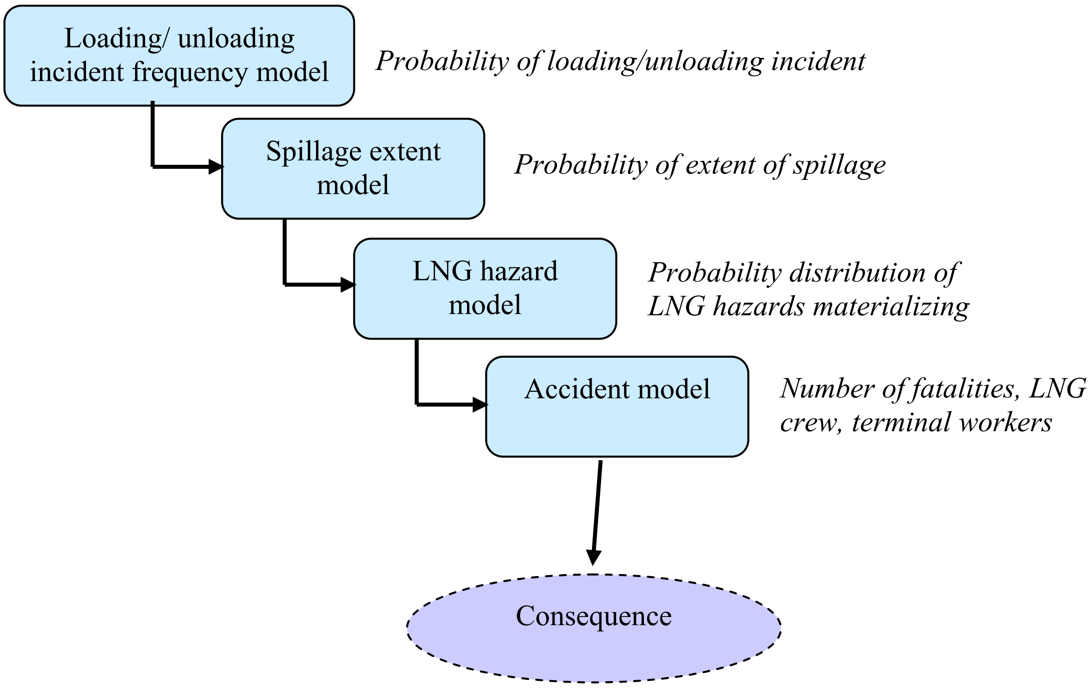

Figure 14: Risk model for loading/unloading incidents of LNG carrier.

5.1.7 Failure/leakage of cargo containment system

The cargo containment system (CCS) onboard LNG vessels have a good safety record as no fatal accidents have happened due to failure of the CCS itself. There is no distinction in the accident data between the Moss-type and the membrane-type CCS. The two main incidents that may take place in this scenario are leakage of gas and leakage of LNG (liquid).

Gas leakage from tank could result from a combined failure of the inner and outer structure and (nitrogen) pressure system. Then gas would be released to hold space between inner hull and tank. This will have no fatal effect on crew members. The CCS has detection systems that should detect leakages and there are strict procedures in place for this scenario. All systems onboard are redundant and regularly maintained. In general, if leaks from the CCS are detected, the vessel shall within 15 days sail to the nearest port in order to unload.

There are incidents where leakage of gas from membrane type tanks have been recorded, but these incidents are taken care of by the inter-barrier nitrogen system and the effects of these incidents are negligible in terms of fatalities. LNG leakage from the tanks may also be a result of either fatigue cracks in tanks or tank sloshing. LNG release in Moss-type vessels will be from tanks to hold space between inner hull and tank, which then will lead to a secondary big leak to ballast tanks. In membrane-type vessels there will be an LNG release directly to ballast tanks.

No accidents related to LNG leaking directly into the inner hull or ballast tanks have been reported and therefore the risk contribution from this incident is assumed small. Fatigue cracks in inner hull and ballast water leaks in to insulation system surrounding tanks is an issue with membrane systems as it will reduce the insulation effect of tanks as water freeze to ice and destroy the insulation. Also, if there is insufficient drainage of the ballast water between the inner hull and the insulation system, an overpressure sufficient to lift the membranes and thus damage the system may build up. Such cracks and leakages will need to be repaired sooner or later but it is deemed unlikely that this will develop into a serious accident. It is noted that membrane systems leaks, and progressively more so over time. However, this is handled by operational procedures, i.e. by purging the interbarrier spaces with N_2 and monitoring the gas content.

The additional scenarios where the CCS may be considered to fail and the cargo will leak are effects of collision or grounding and these aspects are covered in the respective scenarios. In conclusion, leakage of

LNG from the CCS itself will be discovered and repaired before leading to fatal accidents and therefore the risk contribution is negligible. Hence, no event tree for this scenario will be developed.

5.2 Quantification of event trees

In order to quantify the event trees and assign probabilities for the various escalating events, and thereby to quantify the probabilities 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 three, the method that was found to be most practical and the information sources that were assumed most relevant was utilized. These will be explained in the following for each of the identified accident scenario.

5.2.1 Collision scenario

The collision frequency model gives the collision frequency in terms of collisions per shipyear. For the purpose of this study, accident statistics is deemed sufficient to establish this, and this suggests a collision frequency of 6.7×10^{-3} per shipyear. The collision frequency model also contains the probability of being struck or being the striking ship in a collision event. For the purpose of this study, it is assumed that LNG vessels are struck in 50% of the collision accidents they are involved in, and hence a probability of 0.5 is adopted. For striking ships, the probability of receiving critical damage is assumed to be negligible, so these scenarios will not contribute to the collision risk.

Due to the nature of the LNG trade, an LNG carrier is assumed to go in ballast about 50% of the time. Hence, a probability of 0.5 is adopted for the loading condition model.

The damage extent model contains two parts. First, there is the probability of receiving the damage outside of the cargo area. Using a typical LNG vessel as reference, this corresponds to receiving the damage in approximately the following area: The foremost 2/15 of the ship and the aft 1/5 of the ship. The probability of receiving the damage in these areas conditioned on being struck by another vessel can be estimated from the collision damage location distribution presented in [51]. The statistics suggest that P(foremost 2/15) = 0.2 and P(aft 1/5) = 0.15. Thus, the probability of receiving the damage outside of the cargo area will be 0.35.

The next part of the damage extent model determines whether the damage received will be critical or not with regards to damage stability. This again contains two parts. First, there is the probability of receiving a damage that extends through the outer hull. Most collisions occur at low speed and do not result in any significant damage. For LNG carriers, many minor collisions will be with tug boats with low risk of penetrating the outer hull, and about one third of the collision accidents surveyed in this study are collisions with tugs (see appendix A.1). It is assumed that ⅓ of the collision are with tugboats that will not penetrate the outer hull. Obviously, for a damage to be critical it must first crack a hole in the outer hull and cause water ingress. A couple of previous studies have estimated the probability of water ingress given collision for two other ship types, i.e. P = 0.38 for passenger ships [49] and P = 0.35 for bulk carriers [50]. These probabilities are in general agreement, and it is assumed that they are also applicable to LNG carriers. Thus, the resulting probability of water ingress given collision will be 0.24.

Even if collision damage penetrates the outer hull, it will not necessarily be critical to the integrity of the ship. This will be determined by damage statistics collected by the HARDER project and presented in [51][3]. According to the IGC Code [10], a critical damage to the side should be more than $\frac{1}{3}L^{2/3}$ or 14.5

[3] It should be noted that the HARDER data is not covering LNG carriers in particular, and that the majority of the statistics are collected from oil tankers and bulk carriers. It may be assumed that LNG carriers are somewhat better in withstanding collision damage, and in this case, the estimates obtained from using HARDER data might be slightly conservative for LNG carriers. Especially for spherical tankers, where the cargo tanks do not extend all the way to the inner hull over the full length of the ship, HARDER data might give conservative results. Nevertheless, the HARDER statistics are believed to be the best available source of information, and it is not believed that possible differences in strength will be very significant. Thus, the HARDER data will be utilized as outlined herein, although it is noted that this might result in conservative results where the HARDER data have been exploited.

meter in length and penetrate more than B/5 or 11.5 meter in the transverse direction. For the reference vessel chosen for this study, this would correspond to a damage extending 14.5 meters in the longitudinal direction and 8.5 meters in the transverse direction or approximately L/20 and B/5. From the damage statistics, the following can be read:

- Damage length: $P(l > L/20) = 0.6$
- Damage penetration: $P(b > B/5) = 0.35$

However, it is realized that any damage in the cargo area that extends through the double hull and penetrates the cargo tanks will be critical in terms of damage stability for a vessel in loaded condition. Hence, any damage deeper than the double hull will be regarded as critical. For our reference vessel, the double hull has a depth of 2.3 meters. In addition to this, there will be a layer of insulation with a thickness of about 0.5 meter and this total thickness corresponds to about B/15 for the reference vessel. Thus, a collision damage penetrating more than B/15 in the cargo area will be regarded as critical. According to the damage statistics, the probability of receiving damages with this depth condition on collision is about 0.6. For vessels in ballast condition, it is assumed that critical damages in cargo area are both longer than L/20 and deeper than B/15, corresponding to a probability of 0.36.

Thus, the probabilities of receiving a critical damage conditioned on being struck by collision, which will be used in the event tree, are:

- Outside the cargo area: 0.24 x 0.6 x 0.35 = 0.05
- In cargo area
  - In loaded condition: 0.24 x 0.6 = 0.14
  - In ballast condition: 0.24 x 0.6 x 0.6 = 0.086

The cargo leakage frequency model assumed in this study is quite simple. Leakage of cargo is assumed if and only if the following three conditions are met: a) the collision occurs in the loaded condition b) the collision damage is received in the cargo area and c) the damage is critical according to the discussion above. Hence, the cargo leakage frequency model is determined from the damage extent model, and will take either values 0 or 1. The assumption that no substantial leakage of LNG will occur in ballast condition might not be entirely true as some LNG will normally be kept in the tanks in order to keep them refrigerated. However, the potential amount of LNG spills will be significantly reduced, and for the purpose of this study, no substantial leakage of LNG will be assumed in ballast condition.

If there are leakage of LNG, LNG specific hazards might materialize. This is modelled by the LNG hazard model. Asphyxiation and cryogenic damages to crew will only happen if the crew are on deck in the cargo area at the time of collision, and this is deemed very unlikely. Thus, these hazards will be regarded as negligible. However, two hazards will most likely materialize in all cases of substantial leakage, i.e. cryogenic damage to hull and an initial Rapid Phase Transition. The probabilities for these hazards materializing are set to 1 in case of a substantial leakage of LNG. However, the RPT will not be critical to the ship or the crew, and does not represent a hazard in itself. The possibility of consequential consequences due to the cryogenic damages of the hull will be further discussed in the following.

Following the rapid phase transition, one of three possible scenarios will take place. In the first, there will be no ignition of the LNG vapour, and it will simply disperse into the air until the natural gas concentration is below the lower flammable limit. In the second scenario, the LNG vapour will be ignited during the collision, e.g. by sparks from the colliding steel, and a pool fire will start on the water surface. In the third scenario, a vapour cloud will be formed that starts to drift away from the collision area and subsequently gets ignited. This will lead to the vapour burning back to the LNG pool, causing a pool fire that will continue for the duration of the LNG spill. According to expert judgement, the first scenario will happen in 80% of the cases, whereas the probability of the two latter cases will be about 0.1 each[4].

[4] It should be noted that other experts might have different opinions, and some will claim that the probability of instantly igniting the LNG vapour is very high due to sparks from the colliding steel. However, the concentration of LNG vapour will initially be very high, and probably above the flammability limit so that ignition will not happen even though sparks are present. At any rate, it should be noted that the estimates used are uncertain.

Hence, the values that will be used in the LNG hazard model will be 0 or 1 for cryogenic damage to the hull corresponding to collisions without or with spillage of LNG. Furthermore, the probability of a drifting cloud that is ignited will be 0.1 and the probability of a pool fire will be 1 in case of a drifting cloud that is ignited and 0.11 in the case of no drifting cloud that is ignited. These values are used in the event tree.

The probability of surviving/sinking in a collision scenario will depend on the extent of collision damage received and on whether or not leakage of cargo has resulted in damage to the hull due to cryogenic temperatures or heat. For the purpose of this study, it is assumed that the probability of surviving is 0 if a critical damage is received or if LNG leakage occurs. It is assumed that leakage of LNG in a collision event will cause cryogenic damage to the hull that will eventually lead to sinking of the ship. The probability of surviving is 1 if there has been no critical damage and therefore no leakage of LNG. These values will be used in the event tree.

It should be emphasized that the actual scenario development in the case of LNG leakage is highly uncertain, and expert opinions differ considerably. In this study it has been assumed that any significant leakage of LNG will result in cryogenic damages to the hull that will consequentially lead to sinking of the vessel. However, it should be stressed that this assumption is rather conservative, leading to somewhat conservative estimates, and that it is conceivable that only minor cryogenic damages that the ship is able to survive could result from the leakage. It is acknowledged that substantial uncertainties are associated with this issue, and the effect of the cryogenic damages to the hull on the damage stability should be further investigated in order to gain a deeper understanding of how a likely scenario will develop. This is out of scope of the current study, but is recommended for further work.

The evacuation model will determine the probability of fatalities as well as the number of fatalities among the crew onboard the LNG carrier. Both the probability of fatalities and expected number of fatalities will depend on what hazards have materialized. This study considers two possible causes of death among the crew in a collision scenario, i.e. radiation from the pool fire and failure to evacuate before the ship sinks. In some scenarios, both hazards will be present, i.e. in a scenario where there is a pool fire and the ship sinks.

Consequence estimates of LNG accidents are difficult to arrive at, and no statistics are available. It has also not been within the scope of the current study to carry out detailed simulations or calculations to estimate the consequences. For the purpose of this high level study, expert judgement from a Delphi session has been used for the expected consequences of a collision with an LNG carrier. It should be noted that expert judgement should always be used with care [53], but the estimates obtained from the Delphi session are believed to be the best estimates currently available. The Delphi session is described in more details in appendix A.3, and the following results from the Delphi session will be used in the collision event tree:

- Probability of fatalities if pool fire: 0.525
- Probability of fatalities if sinking: 0.978
- Expected number of fatalities due to pool fire: 3.11
- Expected number of fatalities due to sinking: 12.9
- Probability of fatalities if pool fire and sinking: 0.989
- Expected number of fatalities if fire and sinking: 16

Based on the results from the expert judgement, more fatalities will result from the sinking of the vessel and failure to evacuate in time than from the pool fire itself.

5.2.2 Grounding scenario

The grounding frequency model contains the probability of a grounding incident per shipyear. This is found from accident statistics to be 2.8×10^{-3} per shipyear.

The loading condition model is the same as for the collision scenario, i.e. equal probability of being loaded or being in ballast condition of 0.5.

The damage extent model contains two parts. First, there is the probability of receiving the damage outside of the cargo area, and again damage location distributions collected by the HARDER project, this time for grounding damages, can be used together with the measures of the reference vessel to estimate this probability. According to the statistics, The probability of receiving the damage in the foremost 2/15 of the ship is P(foremost 2/15) = 0.2, and the probability of receiving the damage in the aft 1/5 of the ship is about P(aft 1/5) = 0.1. Thus, the probability of receiving the damage outside of the cargo area is estimated to 0.3.

The second part of the damage extent model determines whether the grounding damage is critical or not in terms of damage stability. First, the damage needs to crack the outer hull, and the probability for this is estimated to be 0.76 for passenger ships [49]. For the purpose of this study, the same value will be used for LNG carriers.

Then the damage must be extensive enough to be critical and this will again be determined by damage statistics collected by the HARDER project [51]. According to the IGC code [10], the measures of critical bottom damage are dependent on the damage location. For about the foremost third of the vessel, a critical damage should be more than $\frac{1}{3}L^{\frac{2}{3}}$ or 14.5 meters in length, more than B/6 or 10 meters in the transverse direction and more than B/15 or 2 meters deep. For any other part of the ship, a critical damage would be damages larger than $\frac{1}{3}L^{\frac{2}{3}}$ or 5 meters in length, B/6 or 5 meters in the transverse direction and more than B/15 or 2 meters deep. For the reference vessel chosen for this study, the following damages would be critical:

- Forward 1/3 of the ship: 14.5 meters or L/20 longitudinal extent
  7 meters or B/6 transverse extent
  2 meters from the bottom shell
- Other parts of the ship: 5 meters or L/55 longitudinal extent
  5 meters or B/8 transverse extent
  2 meters from the bottom shell

The damage distributions collected by the HARDER project contain statistics for the damage location, the longitudinal extent of damage and the penetration depth as measured from the bottom shell, but data on the transversal extent of grounding damages are not available. However, for the purpose of this study, it is assumed that any damage is critical that meets both the longitudinal and penetration depth limits for critical damage. Furthermore, it is assumed that the damage length and damage penetration depth is independent of the damage location.

The available damage distributions give the following probability estimates:

- Damage location: P(x in front of 0.3L) = 0.4
- Damage location: P(x other part of ship) = 0.6
- Damage length: P(l > L/20) = 0.7
- Damage length: P(l > L/55) = 0.85
- Penetration depth: P(d > 2 meters) = 0.12

These estimates give the following probabilities for receiving critical damage given water ingress:

- Probability of critical damage in front of 0.3L = 0.4 x 0.7 x 0.12 = 3.4 x 10^{-2}
- Probability of critical damage rest of ship = 0.6 x 0.85 x 0.12 = 6.1 x 10^{-2}

In total, this gives the probability of receiving critical damage in a grounding event given water ingress of 9.5 x 10^{-2}.

However, it is realized that any damage that leads to puncture of the cargo tanks and hence leakage of LNG will be critical. The reference vessel has a double bottom of 2.9 meters, and in addition to that there is the cargo tank insulation. Hence, it is assumed that a grounding damage should at least be deeper than

3.4 meters to be critical[5]. According to the damage statistics, the probability of grounding damage to be deeper than this is about 0.1. This probability is very close to 9.5×10^{-2} as found above, and for the purpose of this study, an approximate value of 0.1 is assumed for the probability of receiving a critical damage in case of grounding with water ingress in both ballast and loaded condition and for damages both within and outside of the cargo area. Thus, the total probability of receiving critical damage conditioned on grounding is 0.76 x 0.1 = 0.076. This value will be used in the event tree.

Substantial leakage of cargo is assumed if and only if the following three conditions are met: a) the LNG carrier is in loaded condition, b) the grounding damage is received in the cargo area and c) the damage is critical. Hence, the cargo leakage frequency model is determined from the damage extent model and will take the value of either 0 or 1 depending on whether the conditions are met or not.

If cargo is released in a grounding incident, a number of LNG specific hazards might materialize. This is described by the LNG hazard model. The difference from the LNG hazard model for collision scenarios is that in a grounding scenario, the leakage of LNG will be through the bottom, but otherwise, the generic hazards will be the same. It is not likely that there will be any fatalities due to asphyxiation or cryogenic injuries among the crew. However, cryogenic damages to the hull will be expected if there are any substantial releases of LNG. Hence, this probability will be either 0 or 1 dependent on the LNG leakage model.

Grounding incident that leads to leakage of LNG, will produce LNG vapour, and this vapour might either disperse into the atmosphere until it reaches the lower flammability level without being ignited, be ignited at the site of the spill and burn as a pool fire or form a cloud that drift downwind and are ignited by an ignition source away from the spill site. In the latter case, the vapour will typically burn back to the spill site and continue to burn as a pool fire. The probability distributions for these events are assumed similar as the collision scenario, i.e. 0.8, 0.1 and 0.1 respectively. These values will be used in the event tree.

The survivability model in a grounding scenario will be simple and only dependent on the extent of the grounding damage and on whether LNG is spilled or not. For the purpose of this study, it is assumed that the probability of surviving is 0 if a critical damage is received or if LNG leakage occurs. It is assumed that leakage of LNG will cause cryogenic damage to the hull that will eventually lead to sinking of the ship[6]. The probability of surviving is 1 if there has been no critical damage and therefore no leakage of LNG. These values will be used in the event tree.

For the purpose of this study, the evacuation model for the grounding scenario will be identical to the one used in the collision scenario, i.e. results obtained from the Delphi session outlined in appendix A.3.

5.2.3 Contact scenario

The contact scenario will be treated very similar to the grounding scenario, and the probability of a contact event was found to be equal the probability of a grounding event from the accident statistics. Also, no damage distribution functions for contact damages are reported by the HARDER project. For the purpose of this high level study, the risk contribution from the contact scenario will be assumed identical to the risk contribution from the grounding scenario, except for one detail: According to estimates presented in [49], the probability of flooding given a contact incident is assumed to be 0.38 and not 0.76 which was assumed for grounding. Thus, the risk contribution from the contact scenario will be exactly half of the contribution from the grounding scenario. All other probabilities in the event tree are assumed to be identical to the grounding scenario. The resulting event tree for contact scenarios is presented in appendix A.4.

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[5] It is noted that this is an optimistic assumption, mainly for two reasons: First, a double bottom of 2.9 meters is not the norm, and shallower double bottoms are frequently used. In addition, a grounding damage does not necessarily need to extend deeper than the insulation layer in order to be critical, and it might be sufficient to extend through the double bottom in some cases. Hence, assuming a critical damage depth of 3.4 meters is optimistic.

[6] Again, this is a conservative assumption that might contribute to overestimate the risk (see the discussion for the collision scenario in the previous section of this report).

5.2.4 Fire or explosion scenario

Accident statistics indicate that the probability of a fire or explosion is 3.5×10^{-3} per shipyear. However, the statistics used for this estimate also contains vent riser fires which are not considered to constitute any significant hazard to the crew or the ship. Upon further examination of the statistical material, it appears that 50% of the reported fires are vent riser fires. These will not be regarded in this study, and hence the probability of a fire in the machinery spaces, accommodation areas or compressor room, as identified as the main contributors in chapter 5.1.4, is estimated to be 1.8×10^{-3}.

No good statistics are available for estimating the distribution of LNG carrier fires that start in the machinery spaces, accommodation areas or compressor room respectively. However, it can be assumed that the situation will resemble that of oil tankers, and for the purpose of this study, results from a review of aframax tanker incidents will be used [54]. In this study, 118 fire and explosion incidents are investigated, of which 79 fires and 39 explosions. According to this study, fires on aframax tankers were distributed in the following way: Machinery spaces 70%, accommodation area 14% and cargo area 16% (a somewhat different distribution were estimated for explosion scenarios). However, it is seen that an unproportional high ratio of the cargo area fires occurred under repair, i.e. 83%. Such accidents are out of scope of the current study and the fire distribution should be adjusted accordingly. Reducing the ratio of cargo area fires by 83%, results in less than 3% of the fires starting here. For the purpose of the current study, 3% of the fires are assumed to start in the cargo area or, more specifically, in the compressor room above the cargo tanks. It may be argued that the cargo area is very different for an LNG tanker and an oil tanker, and this suggests that probabilities arrived at from such comparison are not very accurate. However, fire statistics for LNG carriers are too scarce to be of any use, and statistics from oil tankers are believed to be the best available source of information. The resulting distribution of fires is:

- 81% in the machinery spaces
- 16% in the accommodation area
- 3% in the compressor room

In the two first cases, the probability of such a fire to spread to the cargo area and lead to ignition of LNG vapour is regarded as negligible. Thus, such fires are not unique to LNG carriers, and statistics from other tankers can be used in order to estimate its consequences. Referring to the study presented in [54], a total of 44 fatalities were found for the 118 fire and explosion incidents that were investigated, indicating a fatality rate of 0.37 fatalities per fire or explosion. This fatality rate will be assumed for fires in machinery spaces and accommodation area, and for the purpose of the current study, one fatality is assumed with a probability of 0.37.

For the fires in the compressor rooms, a more detailed risk model will be adopted. First, it is realized that the ship will be in ballast and in loaded condition in 50% of the time. Furthermore, it is assumed that the ship will be at port in a loading or unloading situation in 10% of the time and at sea for the remainder of the time. These values will be used in the loading condition model and are inserted in the event tree.

The risk model contains a fire protection model that considers the probability of fire fighting systems being effective in preventing or putting out the fire. It is assumed that if the fire fighting system is successful, no further escalation of events will take place. However, there might be fatalities related to the initial outbreak of fire, and for the purpose of this study, the average of 1 fatality in 37% of the fires will be used. This will be the average in both cases where the fire protection system works and where it does not work but where the fire does not cause leakage of LNG.

Only if the fire protection systems fail, will the outbreak of fire lead to a serious accident. There are strict requirements on fire fighting systems and these are normally considered to be quite reliable. In a study on High Speed Crafts (HSC) performed by MCA [55], a failure to control the fire of 1% was used. In a recent study on passenger ships, it was estimated that between 70% and 75% of all fires were not escalating [56]. It can be assumed that this corresponds to the success rate of the fire fighting systems (both manual and automatic systems). For the purpose of this study on LNG carriers, it is assumed that the fire fighting systems have a similar success rate to that of HSC and passenger ships and the average will be used, i.e. 85% chance of controlling the fire and 15% chance of escalating fire. These values are inserted in the event tree.

In the event of a fire or explosion that is not extinguished by the fire protection system, there is a possibility that the event will cause a breach in the cargo tanks and hence cause leakage of LNG. The compressor room is located on the top of the cargo tanks, and it is assumed that leakage of LNG will only be possible if the tanks are fully loaded. Hence, the probability of LNG leakage will be set to zero in the ballast condition. Furthermore, it is believed to be very unlikely that a fire or explosion will be powerful enough to create a breach in the cargo tanks, and the probability of LNG leakage will be low even in loaded condition. There are no statistics available from which it is possible to extract estimates for this probability. Experts consulted during this study agree that the probability is low, and an estimate of around 3% seems reasonable. However, for the purpose of this study, a deliberately conservative estimate of 10% will be used, but it is noted that this is believed to be somewhat high. At any rate, this probability will not have any notable influence on the overall results. A probability of leakage conditioned on a fire that the fire protection system fails to control of 0.1 will be used in the event tree.

The only LNG hazard considered in this scenario is pool fires, and in the event of LNG leakage, a pool fire seems very likely. This is especially so since in most cases there is already a fire in the compressor room, and this will be able to ignite vapour from the LNG spill. The only cases where there will be LNG leakage and no pool fire is when there is an explosion in the compressor room that causes breach of the LNG tanks but no fire. However, for the purpose of this study, this possibility will be ignored and the probability of pool fire is set to either 1 or 0, for cases with and without leakage respectively. Furthermore, in accordance with the assumptions in the collision and grounding scenarios, it is assumed that the probability of surviving will be 1 if there are no LNG leakage and 0 if there is LNG leakage. Clearly, this assumption is conservative, and it should be noted that it might lead to overestimation of the risk (see discussion for consequential cryogenic damages for collision and grounding events). Nevertheless, The values described above are imported into the event tree.

As the final component in the fire and explosion risk model, the evacuation model will determine the expected number of fatalities in various circumstances of compressor room fires. These cases can briefly be divided into the following three categories: a) where there is a fire or explosion, but no leakage of LNG, b) where there are LNG leakage and a pool fire at port and c) where there are LNG leakage and a pool fire at sea. Previous estimates can be adopted for these cases under the following assumptions. In case a), it is assumed that compressor room fires without LNG spillage will resemble engine room fires, and an average probability of 0.37 for 1 fatality will be used. For case b) and c), the estimates extracted from the Delphi session held in conjunction with the collision and grounding scenarios will be utilized, and it is assumed that the probability of fatalities will be 0.989 in both these cases. For case c), the average number of fatalities will be the same as for the collision scenario, i.e. 16, but for incidents happening while at port a somewhat lower estimate will be assumed. For the purpose of this study, it is assumed that the number of fatalities will be reduced to half for accidents happening at port compared to the ones occurring at sea, resulting in an average number of expected fatalities of 8. These estimates are used in the event tree.

5.2.5 Heavy weather/Loss of intact stability scenario

It was concluded that loss of stability due to heavy weather conditions or operational procedures is very low and therefore the risk contribution is regarded as negligible.

5.2.6 Incidents while loading or unloading of cargo scenario

There are 183 LNG ships trading the oceans, as of August 2005, which each in average conduct 12 roundtrips a year and thus spend app. 24 days loading/unloading cargo a year. It is limited statistics available for the spillage rate during loading/unloading, but based on the results from the HAZID of LNG tankers conducted in Step1 of this FSA, the hazard "LNG spill on deck or to sea" was given a risk score of 3.4 + 1.6 = 5.0.[7]

A frequency score of 3 reflects that this hazard is likely to occur once per year in a fleet of 1000 ships, i.e. likely to occur in the total life of several similar ships. A frequency score of 4 reflects that this hazard is likely to occur once per year in a fleet of 100 ships, i.e. about ¼ probability to occur in the total life of a ship's life. A consequence score of 1 reflects that this hazard causes single or minor injuries. A consequence score of 2 reflects that this hazard causes multiple or severe injuries.

In this respect, it could be conservatively estimated that amongst the 183 ships sailing today, a spillage incident may take place once a year in average. Thus the spillage frequency per ship is estimated to 1/183, which is 0.0055 (5.5×10^{-3}). This number is in reasonable agreement with the 7.8×10^{-3} (0.0078) that is given in Table 3 for incidents during loading/unloading. Incidents are a rough description that may also contain other hazards than spillages. According to the accident review performed in this study, 22 loading/unloading events have been reported, but only 9 of these reported any leakage of LNG. This corresponds to a frequency of 3.2×10^{-3} per shipyear for such incidents resulting in leakage. In this respect, it is considered that 0.0032 is the spillage frequency on average per ship year and no risk reduction will be utilised for the fact that loading/unloading only takes place over 2 days during a roundtrip.

The spillages in questions are considered to be small scale spillages, which only can cause harm (asphyxiation and frost injuries) to crew members and cause structural damage to areas being directly exposed to the LNG. It is not considered that the following hazards could materialise:

- Drifting vapour cloud ignition
- Pool fire
- Enclosed space explosion
- Rapid Phase Transition

In order for crew members to be injured by any spillage taking place, the crew members need to be near the point of spillage. The crew members are only close to any valves transferring the LNG liquid when starting up and closing down the transfer operation. In the meantime, the transfer is remotely controlled and the presence of crew members to valves is limited. In this respect, it is not considered that hoses and pipes will cause LNG spillage as these are designed to cater for any situation that may arise within such an operation. Provided a ship spends 24 hrs in average to load the tanks, it is estimated that the crew may be exposed to any LNG spillages taking place for an app. of 2 hrs (1 hrs hook-up and 1 hrs decoupling). Thus the spillage extent model provides a risk contribution of "no exposure" of 22/24 and for "exposure" of 2/24.

Spillages occurring when crew is present are conservatively assumed to harm the crew member in terms of frost injuries in all incidents, i.e. 100% of the incidents. Provided the crew member is harmed it is assumed that this injury is fatal for 1 person, whilst other persons are escaping with burn wounds.

Based on the above assumptions and data available for the LNG vessels, the risk contribution from this scenario is calculated to 2.64×10^{-4} fatalities per shipyear.

5.2.7 Failure/leakage of cargo containment system

It was concluded that operational leakage of LNG from the CCS itself will most likely be discovered and repaired before leading to fatal accidents and therefore the risk contribution is negligible. To repair a tank means offhire and this might have notable economic consequences, but it is not a safety issue.

[7] This HAZID session had a member from a renowned Norwegian LNG ship operator.

6 Risk Summation

Based on the risk modelling outlined in the previous sections, the contributions from the various scenarios to the total potential loss of lives (PLL) from LNG shipping operations can be extracted. This is presented in Table 11.

Table 11: Potential loss of lives from LNG carrier operations (per shipyear)

Accident scenario	**PLL (Crew)**
Collision	4.00×10^{-3}
Grounding	2.93×10^{-3}
Contact	1.46×10^{-3}
Fire or explosion	6.72×10^{-4}
Heavy weather/Loss of intact stability	≈ 0
Incidents while loading/unloading of cargo	2.64×10^{-4}
Failure/leakage of cargo containment system	≈ 0
Total PLL	$\mathbf{9.32 \times 10^{-3}}$

The results from the study can also be used to estimate the individual risk and to produce FN-curves that illustrate the societal risk picture. This will be done for both crew and passengers.

6.1 Individual risk for crew

Intuitively, individual risks for 3rd parties or passengers are not an issue in this context, and only the individual risk for the LNG crew will be considered. It is assumed that all members of the crew are equally exposed to the risk.

Assuming a crew of 30 on a typical LNG carrier, a fatality rate of 9.32×10^{-3} per shipyear would seem to correspond to an individual risk of 3.11×10^{-4} per year. However, more than one complete crew is needed for continuous operation of an LNG carrier. With a 50-50 rotation scheme, two complete crews are needed, and in the case of a one-on/two-off scheme, there will be three crews. This would correspond to an individual risk for crew of 1.55×10^{-4} per year and 1.04×10^{-4} per year respectively. A 50-50 rotation scheme is assumed to be most widespread and hence, the individual risk for LNG crew members is taken to be 1.55×10^{-4} per year for ship accidents. Compared to the individual risk acceptance criteria suggested in chapter 1.2.1 it is seen that the individual risk level is within the ALARP area. The historic individual risk for crewmembers of LNG carriers is reported in [57] as 1.2×10^{-4} per year where it was used for setting target safety values for CNG carriers. Comparing this value with the individual risk as estimated in this study, it is seen that the numbers are in reasonable agreement. However, it is noted that the risk analysis covered ship accidents and contributions from occupational hazards were excluded from the study. Historic occupational fatality rates have been reported as 4.9×10^{-4} per year, and even if this contribution is added to the results from the risk analysis, the individual fatality risk for crew falls within the ALARP region, i.e. a total individual risk of 6.5×10^{-4} per year.

6.2 FN-curves for LNG crew

The results from the risk analysis can be used to produce the FN-curve for the overall risk to crew in Figure 15. Compared to the established risk acceptance criteria, it is clearly seen that also the societal risk lies within the ALARP region.

An FN-curve that shows the contribution from each of the main accident scenarios, i.e. collision, grounding, contact, fire and explosion and loading/unloading events, may also be produced. This is shown in Figure 16, and it is easily seen that the risk level is dominated by the collision, grounding and contact scenarios. However, the fire/explosion and loading/unloading scenarios are the dominating contributors to low consequence risk in the order of one fatality.

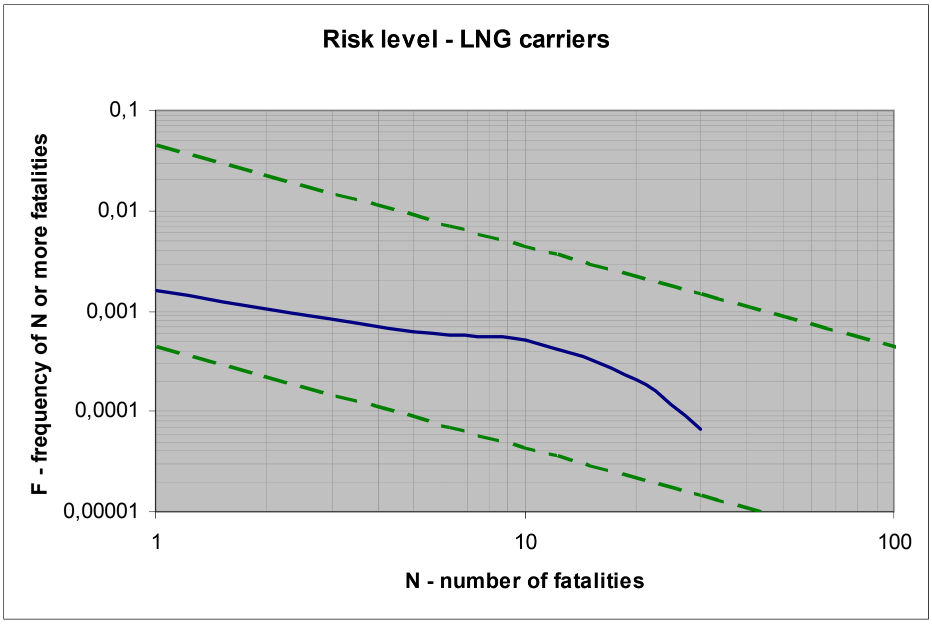

Figure 15: FN-curve for total risk to crew.

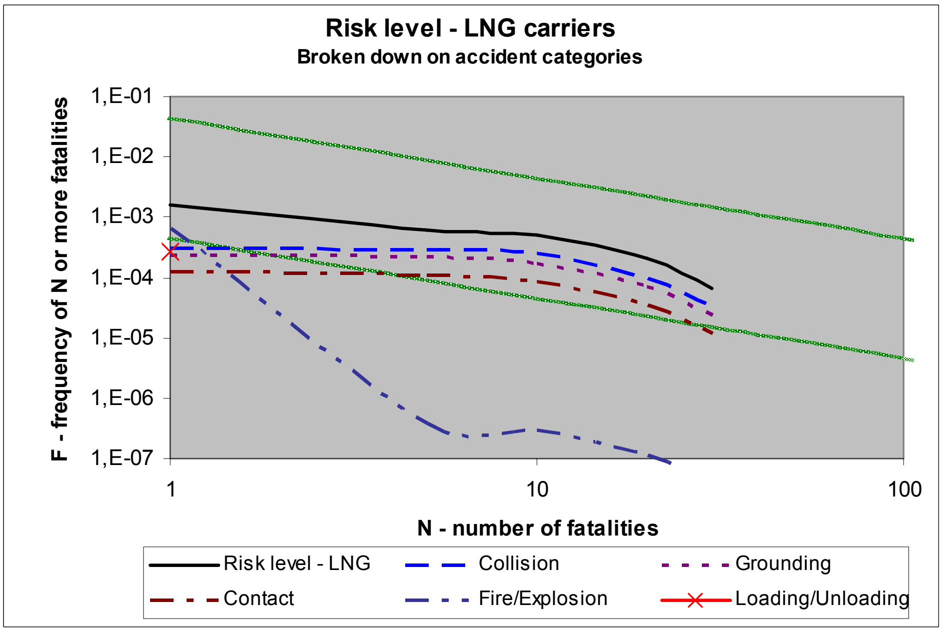

Figure 16: FN-curve for risk to crew, broken down on accident categories.

7 Preliminary Conclusions and Recommendations

This annex has presented a risk assessment that forms the second step of a high level, generic FSA on the current fleet of LNG carriers. The conclusions and recommendations from this study are twofold: First some areas of improvements are suggested where further studies can be focused in order bridge the gaps in available statistics and fundamental knowledge about hazards and risks related to LNG shipping. Then, high risk areas are identified, where it is recommended that future efforts in risk reduction are focused.

7.1 Review of uncertainties

Even though the risk assessment presented in this annex is believed to be based on the best available estimates, it 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.

Due to the unavoidable and inherent subjectivity of this study, the results must be considered to be uncertain. However, for a high level analysis such as this one, the results are still believed to be meaningful, and it is believed that the estimates of the overall risk of LNG carrier operations are the best estimates available to date. It is realised that there will always be uncertainties connected to such a generic studies, and it is unavoidable to incorporate a number of assumptions. These assumptions will introduce biases into the study, but every effort has been made to make the assumptions in this study explicit. If new knowledge in any area of the study is obtained, these assumptions might easily be modified and the results might be updated.

Some of the assumptions made in this study are conservative whereas others might be optimistic. It is not feasible to quantify the effect of the assumptions, and the sum of the various assumptions might skew the overall results in either way. However, it is believed that the net effect of all assumptions on overall estimates are more likely to be conservative than optimistic. In Table 12, some of the assumptions that might influence the results are stated.

In some areas of the study, uncertainties have been particularly salient, and it is suggested that further studies within these areas should be carried out. The results of this risk assessment should hence be updated accordingly. The areas associated with the highest uncertainties are in most cases related to the consequences of a major LNG accident and are represented towards the right-hand side of the event trees. In the following, some areas where new knowledge would result in significant improvements of the results of this risk assessment are highlighted. It is noted that the presented risk analysis is modular by design, and one or more modules can easily be replaced or updated if new knowledge becomes available.

Table 12: Conservative and optimistic assumptions made in the current study		
Assumption	**Effect**	**Relevant scenarios**
HARDER data has been used for collision and grounding damages	Conservative	Collision, grounding and contact
Consequential cryogenic damages due to LNG release assumed to sink the ship	Conservative	Collision, grounding, contact and fire and explosion
Probability of crack in tanks in case of compressor room fire = 0.1	Conservative	Fire and explosion
Fire frequency compared to oil tankers	Conservative	Fire and explosion
Fire fighting system assumed similar as for HSC and passenger ships	Conservative	Fire and explosion
No leakage of LNG in ballast condition	Optimistic	Collision, grounding, contact and fire and explosion
Critical damage penetration in grounding scenarios is 3.4 meters	Optimistic	Grounding
No cryogenic damages to crew	Optimistic	Collision, grounding and contact
High probability (0.8) of no pool fire in the event of LNG leakage	Optimistic	Collision, grounding and contact

What has been referred to as the *LNG Hazard model* in this study must be regarded with a certain degree of uncertainty. Luckily, no major event involving leakage of LNG from an LNG vessel has occurred so far, and the course of events that has been assumed in such a case is therefore somewhat speculative. Some studies exist where certain credible accident scenarios have been described, but the results of these are also considered as uncertain. Furthermore, no probability distributions or quantification of probabilities for various scenarios have been established. It is therefore acknowledged that further studies on these issues will have the potential to significantly enhance the current understanding and quantification of such risks. Such studies could be in the form of experiments, calculations or simulations.

The *damage extent models* used in this study is based on statistics collected by the HARDER project. It can be argued that these statistics, or at least part of the statistical foundation, is not entirely relevant to LNG carriers. This is because some of the material is rather old and because it includes different types of vessels. If new and updated damage statistics were to be made available, particularly statistics which are more relevant to LNG carriers, this should be incorporated into the current study and the results should be updated. In particular, the *cargo leakage model* is a direct result of the *damage extent model*, so this would also be updated. However, for the time being, the damage statistics presented by the HARDER project are believed to constitute the best available predictions for use in the *damage extent model*.

There are also believed to be notable uncertainties related to the *survivability model*. It is e.g. assumed that leakage of LNG will cause cryogenic damage and disintegration of the hull and cause loss of stability and sinking. However, no such event has ever taken place and the actual course of events is uncertain. In particular, the timeframe associated with such a situation is highly uncertain and estimates of the time it will take before integrity is lost or the time to sink have not been available. Further studies within these areas, e.g. in the form of experiments, calculations or simulations, would have the potential to contribute significantly to the reliability of the results from the current study.

The *survivability model* and the *LNG hazard model* will also influence the *evacuation model*. In particular, the time to sink and the types of hazards that are present will influence directly the expected number of fatalities. In addition, the LNG hazard ranges that have been implicitly assumed are uncertain.

Improved knowledge about these issues and how these influence the evacuation process would have the potential to reduce the uncertainties associated with the *evacuation model*.

All in all, there are a number of uncertainties associated with this study, and improvements in almost all areas would be favourable. It is also emphasized that in general, a generic, global 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 all the uncertainties, the results from the current study are believed to be meaningful and robust on a high level for the world fleet of LNG carriers.

7.2 Identified high risk areas and preliminary recommendations

The overall risk associated with LNG carriers was found to be in the ALARP area. Thus, all risks should be made ALARP and cost effective risk reduction measures should be sought in all areas.

However, three areas or generic accident scenarios where identified which together are responsible for about 90% of the total risk. These scenarios are collision, grounding and contact, and they are related in that they describe a situation where the LNG vessel is damaged because of an impact from an external source such as another vessel or floating object, the sea floor or submerged objects, the quay or shore etc.

By studying the risk models associated with these scenarios, four sub-models in particular stands 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.

In particular, and related to collision, grounding and contact, it is recommended that further efforts in step 3 of this FSA focuses on measures related to:

- Navigational safety. Improvements in navigational safety would reduce the frequency of collisions, groundings and contact events. However, when it comes to collisions, it is realized that the most critical scenario is being hit by another vessel. Thus, enhanced navigational safety on the whole fleet, not only for LNG vessels should be considered.
- Manoeuvrability. Improved manoeuvrability, e.g. related to steering and propulsion reliability would have the potential to reduce the frequency of accidents. Extended use of tugs might reduce the frequency of contact and grounding events near the terminals.
- Collision avoidance. Examples of collision avoidance options are extended use of safety zones around LNG carriers and warning boats in busy waters to clear the way for the LNG carrier.
- Cargo protection. Measures to prevent spillage in the event of an impact would have the potential to reduce the risk. Enhancing the cargo containment system’s ability to maintain its integrity when receiving damage, could e.g. be achieved by improved structural strength or ability to deform or absorb impact energy without cracking.
- Damage stability. Reducing the probability of sinking in the event of an accident would decrease the risk. Possible measures could be related to protecting the hull from cryogenic damages from spilled LNG or generally enhanced survival capabilities in damaged condition
- Evacuation arrangements. The consequence, and thereby the risk, could be reduced if improvements in the evacuation performance could be achieved. Possible improvements could be related to evacuation procedures, escape route layout or life saving appliances.

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Appendix to Annex I

A.1 Operational experience – Previous accidents involving LNG tankers

The following table contains a list of known past incidents involving LNG carriers. Both minor incidents and serious accidents are included, but incidents involving small LNG carriers, i.e. less than 6,000 GRT are left out. The source of information for the various incidents is given in the rightmost column. The shaded rows correspond to incidents that are considered out of scope. The incidents are categorized according to the following crude accident categories, as described in the main annex:

- Collision: Col
- Grounding: Grd
- Contact: Cnt
- Fire or explosion: FE
- Equipment or machinery: EM
- Heavy Weather: HW
- Loading/Unloading: L/U
- Cargo containment system: CCS

Table 13: Historic LNG carrier accidents with and without spillage of cargo

#	Year	Ship name (Year built)	Type of cargo containment - *Membrane* - *Spherical* - *Other*	Activity	Injuries /fatalities	LNG spill	Incident category	Incident description	Source
1.	1964	Methane Progress (b. 1964)	Other (Prismatic tanks)	Loading	No	No	FE	• Lightning struck forward vent riser while loading at Arzew, Algeria. Fire quickly extinguished using nitrogen purge line. Although loading had been stopped due to bad weather, gas generated by the loading was still being vented.	QUEST

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
2.	1965	Methane Progress (b. 1964)	Other (Prismatic tanks)	In port	No	No	FE	• Lightning struck forward vent riser shortly after the ship left the port of Arzew, Algeria. Fire quickly extinguished using nitrogen purge connection. Gas was being vented because it was not being used as fuel gas at that time.	QUEST
3.	1965	Cinderella (Jules Verne) (b. 1965)	Other (Vertical cylinders)	Loading	No	Yes	L/U	• Overfilling. Tank cover and deck fractures. • Small release of LNG caused by cargo being overfilled while loading at Arzew, Algeria. Tank cover plating and deck plating fractured due to low temperature embrittlement.	Houston Law Center, IZAR, Colton, QUEST
4.	1965	Methane Princess (b. 1964)	Other (Prismatic tanks)	Disconnecting after discharge	No	Yes	L/U	• Valve leakage. Deck fractures. • Leaking valve allowed small amount of LNG to be released from the ship's cargo manifold when the cargo transfer arms were disconnected. Deck plating fractured due to low temperature embrittlement.	Houston Law Center, IZAR, Colton, QUEST
5.	1966	Methane Progress (b. 1964)	Other (Prismatic tanks)		No	Yes	CCS	• Cargo leakage reported. No details.	QUEST
6.	1969	Polar Alaska (Methane Polar) (b. 1969)	Membrane	Transportation	No	Yes	CCS	• Violent sloshing of LNG in refrigerated tank en route to Alaska caused cable tray to break loose. This in turn slashed thin membrane cargo tank wall releasing contents. No fire or explosion reported. • Sloshing of the LNG heel in No. 1 tank caused part of the supports for the cargo pump electric cable tray to break loose, resulting in several perforations of the primary barrier (invar membrane). LNG leaked into the interbarrier space. No LNG released from the secondary	DNV Report, MHIDAS, QUEST

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	Year	Ship name (Year built)	Type of cargo containment - *Membrane* - *Spherical* - *Other*	Activity	Injuries /fatalities	LNG spill	Incident category	Incident description	Source
								barrier.	
7.	1970	Arctic Tokyo (b. 1969)	Membrane	Transportation	No	No	CCS	• A few hours out of Japan heavy seas caused sloshing of cargo tanks in LNG ship steaming from Japan to Alaska. A thin membrane wall bent in four places and a half inch crack formed in a weld seam. • Sloshing of the LNG heel in No. 1 tank during bad weather caused local deformation of the primary barrier (invar membrane) and supporting insulation boxes. LNG leaked into the interbarrier space at one location. No LNG released from the secondary barrier.	MHIDAS, QUEST
8.	1971	Methane Princess (b. 1964)	Other (Prismatic tanks)		No	No	CCS	• Cracks in the inner hull allowed ballast water to enter cargo hold and contact cargo insulation.	QUEST
9.	1971	Descartes (b. 1971)	Membrane		No	Yes	CCS	• Gas leak from tank, faulty connection between tank dome and membrane wall. Crew reportedly tried to conceal leak from authorities. Mechanical failure. • A minor fault in the connection between the primary barrier and the tank dome allowed gas into the interbarrier space.	DNV Report, QUEST
10.	1971	Methane Progress (b. 1964)	Other (Prismatic tanks)		No	No	CCS	• Deck cracked by liquid nitrogen release from pressure relief valve.	QUEST
11.	1971	Esso Brega (LNG Palmaria) (b. 1969)	Other (Esso)	Unloading LNG into storage tank	No	Yes	L/U	• Rollover. Tank developed a sudden increase in pressure. LNG vapour discharged from the tank safety valves and vents. Tank roof slightly damaged. No ignition. • LNG held on ship for month before discharge. Boil off produced warmer denser material. Filling line was t base of 50000 m3 tank. Eighteen hours after filling rollover produced pressure surge to 1.42	Houston Law Center, IZAR, Colton,

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	Year	Ship name (Year built)	Type of cargo containment - *Membrane* - *Spherical* - *Other*	Activity	Injuries /fatalities	LNG spill	Incident category	Incident description	Source
								times nominal maximum design pressure. LNG released from vent and relieved over three hours.	DNV Report
12.	1971	Methane Progress (b. 1964)	Other (Prismatic tanks)		No	No	L/U	• Deck cracked when liquid nitrogen storage tank was overfilled.	QUEST
13.	1972	Methane Progress (b. 1964)	Other (Prismatic tanks)		No	No	CCS	• Cracks in the inner hull allowed ballast water to enter cargo hold and contact cargo tank insulation.	QUEST
14.	1974	Methane Progress (b. 1964)	Other (Prismatic tanks)	In port	No	No	Grd	• Touched bottom at Arzew. • Ran aground at Arzew, Algeria. Damaged rudder. No LNG released.	Houston Law Center, Colton, QUEST
15.	1974	Methane Progress / Methane Princess (?) (b. 1964)	Other (Prismatic tanks)	Tied up at jetty	No	No	Col	• The coaster Tower Princess struck the Methane Progress as it was tied up at the LNG jetty at Canvey Island, UK, tearing a 3 feet gash in its stern. No LNG was spilled and no fire. • Rammed by the Tower Princess (a coastal freighter) while moored at Canvey Island LNG Terminal. Created a 3-foot gash in the outer hull. No LNG released.	MHIDAS, QUEST
16.	1974	Geomitra (b. 1975)	Membrane	Under construction	No	No		• Fire in #5 cargo tank insulation during construction in France.	QUEST

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
17.	1976	? (At Guayaquil, Ecuador)	?	Unloading	> 50 people injured	Yes	L/U	• A short circuit on unloading tanker ignited LNG vapour. A series of explosions destroyed five natural gas tanks and wrecked "Shell Oil Co" jetty over three hours before fire fighters helped by light rain managed to keep fire under control.	DNV report, MHIDAS
18.	1977	LNG Challenger (b. 1974)	Spherical	At anchor	No	No	Col	• Struck by tank ship Lincolnshire while lying at anchor (or moored?) off the coast of Bahrain. Minor damage to starboard rear quarter. No cargo released. Believed to be in LPG service when this occurred.	QUEST
19.	1977	LNG Delta (b. 1978)	Membrane	Loading at terminal	1 killed	Yes	L/U	• Aluminium valve failure on contact with cryogenic temperatures. Wrong aluminium alloy on replacement valve. LNG released but no vapour ignition.	Houston Law Center, IZAR, Colton
20.	1977	LNG Aquarius (b. 1977)	Spherical	Discharging	No	No	FE	• Lightning struck two vent risers simultaneously while cargo was being discharged at Tobata, Japan. Fires quickly extinguished. Venting believed to be due to leaking relief valves on cargo tanks.	QUEST
21.	1977	LNG Aquarius (b. 1977)	Spherical	Loading	No	Yes	L/U	• Tank overfilled. • LNG released from vent riser when cargo tank was overfilled at P. T. Badak LNG liquefaction plant in Indonesia. LNG flowed over the tank cover plating, but no brittle fracturing occurred.	Houston Law Center, IZAR, Colton, QUEST
22.	1978	LNG Capricorn (b. 1978)	Spherical	Under construction	No	No		• Fire in # 5 cargo tank insulation and its butyl covering during construction in Massachusetts, USA	QUEST
23.	1978	LNG Aries	Spherical	At terminal	No	No	HW	• Torn away from dock at Canvey Island by storm-force winds and	QUEST,

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	Year	Ship name (Year built)	Type of cargo containment - *Membrane* - *Spherical* - *Other*	Activity	Injuries /fatalities	LNG spill	Incident category	Incident description	Source
		(b. 1977)						flood tide. The ship was not connected to the cargo transfer arms. • Port anchor and cable slipped and buoyed in position 15 degrees.	LRFP
24.	1978	Khannur (b. 1977)	Spherical	Transportation	No	No	Col	• Collision with cargo ship Hong Hwa in the Straits of Singapore. Minor damage. No LNG released	QUEST
25.	1978	LNG Challenger (b. 1974)	Spherical	Near harbour	No	No	Cnt	• Struck by floating crane Magnus IX near Bahrain harbour. Minor damage to hull. No cargo released. Believed to be in LPG service when this occurred.	QUEST
26.	1978	Polar Alaska (b. 1969)	Membrane	At pier	No	No	Cnt	• Made hard contact with Phillips loading pier at Kenai, Alaska. No details of damages reported. Subsequently sailed.	LRFP
27.	1978	Methane Progress (b. 1964)	Other (Prismatic tanks)		No		CCS	• Sustained damage to No 3 cargo tank. Details unknown.	LRFP
28.	1978	Gadila (Bekalang) (b. 1973)	Membrane		No	No	EM	• Sustained propeller damage. Continued trading.	LRFP
29.	1978	El Paso Southern (LNG Delta) (b. 1978)	Membrane	Trials	No	No		• Stranded in James River after leaving shipyard for trials. Refloated after two hours and proceeded to sea.	LRFP
30.	1978	LNG Gemini (b. 1978)	Spherical	At terminal	No	No	CCS	• Reported to have contamination of cargo tanks, pipelines and pumps whilst at Nagoya terminal.	LRFP
31.	1978	Hilli	Spherical		No	No	EM	• Propeller damage discovered at Das Island	LRFP

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
		(b. 1977)							
32.	1979	Methane Progress (b. 1964)	Other (Prismatic tanks)		No	No	FE	• Fire in insulation between #3 cargo hold and the transverse cofferdam.	QUEST
33.	1979	Mostefa Ben Boulaid (b. 1976)	Membrane	Unloading	No	Yes	L/U	• Valve leakage. Deck fractures. • Small release of LNG from the hinge-pin of a check valve while discharging cargo at Cove Point, Maryland. Deck plating fractured due to low temperature embrittlement.	Houston Law Center, IZAR, Colton, QUEST
34.	1979	Pollenger (LNG Challenger) (Hoegh Galleon) (b. 1974)	Spherical	Unloading	No	Yes	L/U	• Valve leakage. Tank cover plate fractures. • Fractures in tank cover and deck • Loaded with LNG when some cargo leaked onto steel plate tank cover during discharging • Small discharge of LNG from a valve gland while discharging cargo at Distrigas Terminal, Everett, Ma. USA. Tank cover plating fractured due to low temperature embrittlement.	Houston Law Center, IZAR, Colton, DNV report, QUEST
35.	1979	El Paso Paul Kayser (b. 1975)	Membrane	At sea	No	No	Grd	• Stranded. Severe damage to bottom, ballast tanks, motors water damaged, bottom of containment system set up. • Stranded in straits of Gibraltar. Was subsequently re-floated and towed to harbour to discharge cargo. Vessel was dry-docked when survey revealed extensive damage. • Ran aground at 14 knots while manoeuvring to avoid another vessel in the Strait of Gibraltar. Bottom damaged extensively. No LNG released. Vessel refloated, towed to shelter and cargo transferred to	Houston Law Center, Colton, DNV report, QUEST

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
								sister ship, the El Paso Sonatrach.	
36.	1979	Isabella (b. 1975)	Membrane	Transportation	No	No	FE	• Explosion in engine room.	LRFP
37.	1979	El Paso Howard Boyd (Matthew) (b. 1979)	Membrane	Transportation	No	No	Grd	• Stranded in the York Spit Channel due to rudder failure. Failure of hydraulic pump that controls rudder.	LRFP
38.	1979	El Paso Consolidated (b. 1977)	Membrane		No		CCS	• Damage to No 1 tank. Surveys of No 1 tank was carried out from stagings when localized areas of buckling affecting the tank crown, side bulkheads and forward and aft transverse bulkheads were noted.	LRFP
39.	1979	El Paso Southern (LNG Delta) (b. 1978)	Membrane		No	No	EM	• Starboard anchor broken.	LRFP
40.	1979	Pollenger (LNG Challenger) (b. 1974)	Spherical	Shifting anchorage	No	No	EM	• Lost starboard anchor and chain while shifting anchorage at Gibraltar.	LRFP
41.	1979	Ben Franklin (b. 1973)	Membrane	Laid up	No	No		• Broke shackle of mooring chain in near gale whilst laid up. Reconnected to buoy with tug assistance..	LRFP
42.	1979	LNG Capricorn	Spherical		No	No	Col	• In collision with motor tub boat Lancang 11. Bulbous bow damaged.	LRFP

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
		(b. 1978)							
43.	1979	LNG Aquarius (b. 1977)	Spherical		No	No	EM	• Mechanical failure due to flooding of forward pumproom at BP terminal. Fire pump, fuel oil transfer pump, two electrical distribution panels and some electric wiring affected.	LRFP
44.	1979	LNG Capricorn (b. 1978)	Spherical	On voyage	No		CCS	• Cargo compressor explosion while on voyage.	LRFP
45.	1979	Hilli (b. 1975)	Spherical		No	No	CCS	• Damage to insulation of cargo tanks.	LRFP
46.	1979	El Paso Columbia (b. 1979)	Other (Prismatic tanks)	In tow	No	No		• Stranded in Mississippi whilst in tow. Subsequently refloated. This ship was withdrawn before it was used in LNG service.	LRFP
47.	1979	El Paso Savannah (b. 1979)	Other (Prismatic tanks)	On trials	No	No		• Developed cracks in polyurethane foam insulation between hull and cargo while on trials in Mexican gulf. Cracks discovered after gas was pumped out following the trials and extended around all five aluminium cargo tanks. The length of one fissure was 30 inches. This ship was withdrawn before it was used in LNG service.	LRFP
48.	1980	LNG Libra (b. 1979)	Spherical	At sea	No	No	EM	• Shaft moved against rudder. Tail shaft fractured. • Propeller tail shaft fractured while enroute from Indonesia to Japan, leaving the ship without propulsion. Ship towed to the Phillippines; cargo transferred to sister ship LNG Leo, then towed to Singapore for repairs.	Houston Law Center, Colton, QUEST
49.	1980	LNG Taurus (b. 1979)	Spherical	In port	No	No	Grd	• Stranded. Ballast tanks all flooded and listing. Extensive bottom damage.	Houston Law

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
								• Ran aground in heavy weather at Mutsure Anchorage off Tobata, Japan. Bottom damaged extensively. No LNG released. Vessel refloated, proceeded under own power to a berth at Kitakyushu LNG Terminal and cargo discharged. • Stranded at Mutsure anchorage in heavy weather. Refloated with tug assistance and taken to Nagasaki for repairs. Starboard Nos 3, 4 and 9 ballast tanks flooded with carry-over to No 9 port ballast tank. Listing 4 degrees.	Center, Colton, QUEST, LRFP
50.	1980	Arctic Tokyo (b. 1969)	Membrane	On voyage	No		CCS	• Tank damage whilst on voyage between Nikiski and Yokohama.	LRFP
51.	1980	Geomitra (Bilis) (b. 1975)	Membrane		No	No	EM	• Damage sustained to port diesel generator engine.	LRFP
52.	1980	El Paso Howard Boyd (Matthew) (b. 1979)	Membrane	Adrift from dock	No	No	Grd	• Stranded at Hampton Roads after breaking adrift from dock.	LRFP
53.	1980	Mourad Didouche (b. 1980)	Membrane		No	No	Col	• In collision with tug Seybouse in heavy weather. Lost starboard 50-man lifeboat and various fractures on port lifeboat. Propeller blade fractured. Windglass breaks damaged. Aft docking winches brakes overheated and seized. Mooring winch drum fractured.	LRFP
54.	1980	LNG Aquarius	Spherical		No	No	EM	• Sustained damage to No 2 auxiliary turbine.	LRFP

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
		(b. 1977)							
55.	1980	LNG Leo (b. 1978)	Spherical	Discharging	No		L/U	• One mooring rope parted and ship moved in strong winds, contacting pier while discharging LNG. Shore gangway broken. Two liquid and one vapour return chicksan arms extended from normal position. Ship sustains minor damage and pier fenders are damaged.	LRFP
56.	1980	LNG Leo (b. 1978)	Spherical		No	No	EM	• Compressor damage.	LRFP
57.	1980	LNG Leo (b. 1978)	Spherical		No	No	Col	• In collision with unidentified tug at Sakai. Damage to one port shell plate in way of No 10 ballast tank.	LRFP
58.	1980	LNG Libra (b. 1979)	Spherical	At sea	No	No	EM	• Forward pumproom flooded at sea due to defects in emergency fire pump motor and forward transfer pump motor.	LRFP
59.	1980	LNG Capricorn (b. 1978)	Spherical		No	No	EM	• Contamination of main boilers.	LRFP
60.	1980	LNG Aries (b. 1977)	Spherical		No	No	EM	• Rudder and auxiliary turbine damage damage.	LRFP
61.	1980	LNG Taurus (b. 1979)	Spherical		No	No	EM	• Sustained damage to main and auxiliary turbines.	LRFP
62.	1981	El Paso Columbia (b. 1979)	Other (Prismatic tanks)	In tow	No	No		• Ran aground off the coast of Nova Scotia (near Cape Sable Island) while being towed to Halifax for lay-up. Extensive bottom damage. Engine room and one cargo hold flooded. This ship was never used in LNG service due to problems with the tank insulation system that are unrelated to this incident.	QUEST

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
63.	1981	Larbi Ben M'Hidi (b. 1977)	Membrane		No	No	Col	• In collision with tanker Ionian Commander off Arzew.	LRFP
64.	1981	Bachir Chihani (b. 1979)	Membrane		No	No	CCS	• Damage to secondary barrier No 3 cargo tank discovered. Actual time and place of casualty unknown. Insulating panels and cement layer on tank heavily soaked with seawater. Cement loosened and damaged.	LRFP
65.	1981	LNG Aquarius (b. 1977)	Spherical		No		HW	• Heavy weather damage off Nagoya. Reported deck cracks around No 5 dome.	LRFP
66.	1981	LNG Aries (b. 1977)	Spherical		No	No	Col	• In collision with tug B. Lancing I. Bulbous bow damage.	LRFP
67.	1981	LNG Leo (b. 1978)	Spherical		No	No	EM	• Turbine damage. Misalignment of main low pressure turbine. Rudder bearing damage and tail shaft damage discovered.	LRFP
68.	1981	LNG Leo (b. 1978)	Spherical		No	No	Grd	• Touched bottom at Tobata.	LRFP
69.	1981	LNG Gemini (b. 1978)	Spherical		No	No	EM	• Sustained rudder damage.	LRFP
70.	1981	LNG Gemini (b. 1978)	Spherical		No	No	EM	• Reported damage to main and auxiliary turbines.	LRFP
71.	1981	LNG Gemini	Spherical	Discharging	No	No	L/U	• Stator windings of one cargo pump motor burnt out while discharging at Bontang.	LRFP

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#	Year	Ship name (Year built)	Type of cargo containment - *Membrane* - *Spherical* - *Other*	Activity	Injuries /fatalities	LNG spill	Incident category	Incident description	Source
		(b. 1978)							
72.	1981	LNG Capricorn (b. 1978)	Spherical	At sea	No	No	EM	• Turbo generator damage. Sustained vibration and journal bearing damages.	LRFP
73.	1981	LNG Capricorn (b. 1978)	Spherical	At terminal	No	No	FE	• Explosion in air intake duct of port main boiler at Arun terminal.	LRFP
74.	1981	LNG Taurus (b. 1979)	Spherical		No	Yes	CCS	• Fractures in main deck and internals discovered.	LRFP
75.	1981	LNG Virgo (b. 1979)	Spherical	On voyage	No	No	EM	• Boiler damage whilst on voyage.	LRFP
76.	1981	LNG Libra (b. 1979)	Spherical	On voyage	No		HW	• Damage to weather deck and rudder in way of cargo domes whilst on voyage from Tobata to Botang in heavy weather. Various weather deck and stiffening fractures in way of all 5 cargo tank domes.	LRFP
77.	1981	Lake Charles (LNG Edo) (b. 1980)	Spherical		No	No	Grd	• Sustained stranding damage. Time and place unknown.	LRFP
78.	? Prior to 1982	Descartes (b. 1971)	Membrane	At sea	No	No	EM	• Lost rudder at sea. Towed to port.	QUEST
79.	?	El Paso	Membrane		No	Yes	CCS	• Minor release of LNG from a flange. Deck plating fractured due to	QUEST

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#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
	Prior to 1982	Consolidated (b. 1977)						low temperature embrittlement.	
80.	? Prior to 1982	Larbi Ben M'Hidi (b. 1977)	Membrane	Transfer arm disconnection	No	Yes	L/U	• Vapour released during transfer arm disconnection	QUEST
81.	? Prior to 1982	Jules Verne (Cinderella) (b. 1965)	Other (Vertical cylinders)		No	No	FE	• Lightning struck vent riser. Fire quickly extinguished.	QUEST
82.	1982	Genota (Bubuk) (b. 1975)	Membrane		No	No	EM	• Main boiler damage off Yokohama.	LRFP
83.	1982	Tenaga Satu (b. 1979)	Membrane	On voyage	No	No	EM	• Machinery damage whilst on voyage from Dunkirk to Marseilles. Malfunction of cargo and stripping pumps during gas trials. Nitrogen line in No 1 tank has sustained damage.	LRFP
84.	1982	LNG Aquarius (b. 1977)	Spherical		No	No	EM	• Survey requested in respect of bottom damage. Reported damage to rudder carrier bearing. Sustained damage to main and No 1 auxiliary turbines.	
85.	1982	LNG Aquarius (b. 1977)	Spherical		No	Yes	CCS	• Fractured upper deck and internal members.	LRFP
86.	1982	LNG	Spherical		No		CCS	• Sustained cracks in way of tank domes. Modifications being carried	LRFP

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		Gemini (b. 1978)						out in order to avoid recurrence of cracking.	
87.	1982	LNG Gemini (b. 1978)	Spherical		No	No	EM	• Sustained bow thrusters damage.	LRFP
88.	1982	LNG Gemini (b. 1978)	Spherical	On voyage	No	No	Cnt	• Struck submerged object whilst on voyage from Arun terminal to Osaka. On blade slightly bent at tip.	LRFP
89.	1982	LNG Capricorn (b. 1978)	Spherical		No	No	EM	• Turbines/boilers damage. Sustained damage to rudder carrier bearing discovered.	LRFP
90.	1982	LNG Aries (b. 1977)	Spherical		No	No	EM	• Damage to rudder carrier bearing discovered. Misalignment of main engine low pressure turbine to gear box. Defective stiffening in way of cargo tank domes to weather deck welded connections. Date and cause unknown.	LRFP
91.	1982	LNG Libra (b. 1979)	Spherical		No	No	EM	• Rudder carrier bearing damage discovered.	LRFP
92.	1982	Lake Charles (LNG Edo) (b. 1980)	Spherical		No	No	EM	• Gas turbine compressor damage.	LRFP
93.	1983	LNG Capricorn (b. 1978)	Spherical		No		HW	• Sustained heavy weather damage.	LRFP

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#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
94.	1983	Gari (Bekulan) (b. 1973)	Membrane		No	No	Col	• In collision with tug Kenyana and tug Kentibas. No details of any damage.	LRFP
95.	1983	Tenaga Empat (b. 1981)	Membrane	On voyage	No	No	EM	• Sustained propeller stern bearing failure whilst on voyage from Stavanger to La Ciotat.	LRFP
96.	1983	Tenaga Satu (b. 1982)	Membrane		No		CCS	• Sustained cargo pump defects and resultant cargo tank damage.	LRFP
97.	1983	Norman Lady (b. 1973)	Spherical		No	Yes	EM	• Leakage of outer stern tube seal, discovered while anchored at Khor Fakkan.	LRFP
98.	1983	Norman Lady (b. 1973(	Spherical	Weighing anchor	No	No	EM	• Lost anchor and anchor shackle whilst weighing anchor prior to mooring at Das Island. Joining shackle found with split pin bolt missing.	LRFP
99.	1983	LNG Aquarius (b. 1977)	Spherical		No	No	EM	• Bow thruster damage.	LRFP
100.	1983	LNG Aries (b. 1977)	Spherical	On voyage	No	No	HW	• Sustained heavy weather damages whilst on voyage from Himeji to Arun. Various damages sustained to deck fittings on flush forecastle deck.	LRFP
101.	1983	LNG Aries (b. 1977)	Spherical		No		EM	• Sustained damage to high-duty gas compressor. Cause and date of casualty unknown.	LRFP
102.	1983	LNG Taurus	Spherical		No	No	EM	• Sustained rudder carrier bearing damage. Sustained boiler damage.	LRFP

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#	Year	Ship name (Year built)	Type of cargo containment - *Membrane* - *Spherical* - *Other*	Activity	Injuries /fatalities	LNG spill	Incident category	Incident description	Source
		(b. 1979)							
103.	1983	LNG Taurus (b. 1979)	Spherical	Unloading	No		L/U	• Sustained main cargo pump damage.	LRFP
104.	1983	LNG Virgo (b. 1979)	Spherical		No	No	EM	• Sustained tailshaft damages. Cause and date of casualty unknown. Rudder carrier double roller bearing damage. Defective stiffening discovered in way of cargo tank dome.	LRFP
105.	1983	LNG Libra (b. 1979)	Spherical	Discharging	No		L/U	• Sustained discharge pump damage.	LRFP
106.	1984	LNG Aquarius (b. 1977)	Spherical	Under repair	No	No		• Fire involving insulation on upper part of spherical tank #3 during repairs at Nagasaki, Japan.	QUEST
107.	1984	Esso Brega (LNG Palmaria) (b. 1969)	Other (Esso)	Laid up	No	No		• Broke moorings whilst laid up at Spezia during heavy weather. Later berthed with tug assistance. Reportedly no damages sustained.	LRFP
108.	1984	SNAM Palmaria (LNG Palmaria) (b. 1969)	Other (Esso)		No	No	Col	• In collision with tug Benghazi at Marsa El Brega. No details of damage reported.	LRFP
109.	1984	Tenaga Satu (b. 1982)	Membrane		No	No	Cnt	• Sustained various contact damages. Damage sustained in way of engine room starboard side, Nos 1 and 2 ballast tanks starboard side forward, No 4 ballast tank portside amidships.	LRFP

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#	Year	Ship name (Year built)	Type of cargo containment - *Membrane* - *Spherical* - *Other*	Activity	Injuries /fatalities	LNG spill	Incident category	Incident description	Source
110.	1984	Tenaga Satu (b. 1982)	Membrane		No	No	EM	• Rudder pintle bush defect. Rudder gudgeon bush lifted 5 inches and retaining bolts missing. Drydocking necessary. Various machinery damages.	LRFP
111.	1984	Tenaga Satu (b. 1982)	Membrane	Berthing	No	No	Col	• Damaged by collision with tug Kapit whilst berthing at Bintulu. Damage sustained to starboard side aft in way of engine room aft end.	LRFP
112.	1984	Tenaga Dua (b. 1981)	Membrane		No	No	EM	• Boiler damage discovered at Stavanger. Sailed for La Ciotat. Port boiler floor tube external surface pitting discovered at La Ciotat. Freshwater monowall boiler, all floor tubes found with surface pitting up to 3 mm in depth in various places.	LRFP
113.	1984	Ramdane Abane (b. 1981)	Membrane		No	Yes	CCS	• No 5 tank leaking. No 5 tank membrane leaking together with several suction manifolds cracked.	LRFP
114.	1984	LNG Aquarius (b. 1977)	Spherical	Under repair	No	No		• Caught fire in No 3 hold, alleged due to hot slag whilst repairs being effected.	LRFP
115.	1984	LNG Aquarius (b. 1977)	Spherical	Departing	No	No	EM	• Sustained main boiler feed water pump damage whilst departing Brunei.	LRFP
116.	1984	LNG Aries (b. 1977)	Spherical	Unloading	No	No	L/U	• Sustained No 4 cargo pump damage discovered.	LRFP
117.	1984	LNG Libra (b. 1979)	Spherical	Unloading	No	No	L/U	• Cargo pumps failed.	LRFP
118.	1984	LNG	Spherical	On voyage	No	Yes	CCS	• Sustained No 1 cargo space leakage whilst on voyage from Tobota for	LRFP

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		Gemini (b. 1978)						Bontang.	
119.	1984	LNG Gemini (b. 1978)	Spherical	On voyage	No		HW	• Sustained heavy weather damage whilst on voyage from Osaka to Botang. Ballast tank damage. Ballast tank found cracked in way of weld.	LRFP
120.	1984	LNG Virgo (b. 1979)	Spherical		No		CCS	• Main deck cracked in way of No 5 tank dome centreline aft box girder due to overpressure of inert gas in void spaces.	LRFP
121.	1984	LNG Aquarius (b. 1977)	Spherical	Unloading	No		L/U	• Main cargo feed pump damage.	LRFP
122.	1984	LNG Aries (b. 1977)	Spherical		No		EM	• Sustained rudder damage.	LRFP
123.	1984	LNG Capricorn (b. 1978)	Spherical		No		EM	• Damage to rudder pintle and carrier bearing.	LRFP
124.	1985	Ramdane Abane (b. 1982)	Membrane		No	No	Col	• Collision while loaded. Port bow affected. No LNG released. • Damaged by collision with MV Triglav. Sustained damage to port bow.	QUEST, LRFP
125.	1985	Gadinia (Bebatik) (b. 1972)	Membrane	In port	No	No	EM	• Steering gear failure. No details of damage reported.	Houston Law Center, Colton
126.	1985	Isabella	Membrane	Unloading	No	Yes	L/U	• Cargo valve failure. Cargo overflow. Deck Fractures.	Houston

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		(b. 1975)						• LNG released as a result of overfilling a tank. Deck fracture due to low temperature embrittlement. • Damaged by explosion due to breaking of a valve in tank whilst discharging.	Law Center, IZAR, Colton, QUEST, LRFP
127.	1985	Annabella (b. 1975)	Membrane		No	Yes	CCS	• Reported as "pressurized cargo tank". Presumably, some LNG released from the tank or piping. No other details. • No 1 cargo tank damaged.	QUEST, LRFP
128.	1985	Tenaga Empat (b. 1981)	Membrane		No	No	CCS	• Damages to cofferdam void spaces.	LRFP
129.	1985	Tenaga Satu (b. 1982)	Membrane	Unloading	No	No	L/U	• Sustained cargo pump failure.	LRFP
130.	1986	Tenaga Lima (b. 1981)	Membrane	Departing	No	No	EM	• Sustained machinery trouble whilst departing Port Said. Intermediate shaft bearing overheated.	LRFP
131.	1986	Hilli (b. 1975)	Spherical	Off port	No	No	Col	• Damaged by collision with oil/chemical/molasses tank Global Mercury off Port Kelang. Damages to port side shell plates and port wing ballast tank. Adjacent internal members crushed and distorted.	LRFP
132.	1986	LNG Virgo (b. 1979)	Spherical	On voyage	No	No	Col	• Slightly damaged by collision with MFV Koshin Maru.	LRFP
133.	1987	Pollenger (LNG	Spherical	On voyage	No	No	EM	• Sustained main condenser circulating pump failure whilst on voyage from New York to Sakaido.	LRFP

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		Challenger) (b. 1974)							
134.	1989	Tellier (b. 1973)	Membrane	Loading	No? (same as # 136?)	Yes	HW	• Broke moorings. Hull and deck fractures. • Wind blew ship from its berth at Skikda, Algeria. Cargo transfer arms sheared. Piping on ship heavily damaged. No LNG released; cargo transfer had been stopped. No PERC system[8]. According to some verbal accounts of this incident, LNG was released from the cargo transfer arms. • Broke moorings whilst loading at Skikda in heavy weather on 15.2.89. Hull and deck damaged.	Houston Law Center, IZAR, Colton, QUEST, LRFP
135.	1989	Larbi Ben M'Hidi (b. 1977)	Membrane				HW	• Listed by Lloyds as "heavy weather". No other details known. • Mooring ropes parted at Mers El Kebir in heavy weather. Tug assistance requested. Minor damage sustained.	QUEST, LRFP
136.	1989	?	?	Loading	27 fatalities?	Yes	HW	• A chemical tanker broke away from its moorings and sank in heavy gales. During loading of 17,000 tonnes of liquefied natural gas (LNG), the vessel broke free in heavy weather damaging 4 loading arms. A small leakage of the product occurred. The vessel dragged its anchors in the early hours, and was battered by force 10 winds and smashed to the break water. Out of a crew of 29 only two survived the incident.	DNV report
137.	1990	Bachir Chihani (b. 1979)	Membrane	At sea	No	No	CCS	• Sustained structural cracks allegedly caused by stressing and fatigue in inner hull. • Cracks in the inner hull allowed ballast water into the space behind the	Houston Law Center,

[8] A PERC system is a safety device that will allow the loading arms to disconnect automatically when the arm's envelope limit alarm 2nd step is reached. This can be caused by excess drifting of the ship beyond the allowable area.

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								cargo hold insulation.	Colton, QUEST
138.	1990	Arzew (Galeomma) (b. 1978)	Membrane	In tow	No	No		• Damaged by collision with tug whilst in tow.	LRFP
139.	1990	Ramdane Abane (b. 1981)	Membrane		No		CCS	• Sustained structural cracks.	LRFP
140.	1990	Larbi Ben M'Hidi (b. 1977)	Membrane		No		CCS	• Sustained structural cracks.	LRFP
141.	1990	Louisiana (LNG Abuja) (b. 1980)	Spherical	Discharging	No		L/U	• Sustained damage to No 9 cargo pump whilst discharging cargo at Lake Charles, La.	LRFP
142.	1990	Louisiana (LNG Abuja) (b. 1980)	Spherical	At sea	No	No	EM	• Sustained No 1 turbo-generator damage in Gibraltar area.	
143.	1991	Laieta (b. 1970)	Other (Esso)		No	No	EM	• Port turbo-alternator damage sustained at Barcelona.	LRFP
144.	1991	Louisiana (LNG	Spherical	Laid up	No	No		• Mooring parted whilst laid up at Penn Terminal, Philadelphia in heavy weather.	LRFP

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		Abuja) (b. 1980)							
145.	1992	LNG Port Harcourt (b. 1977)	Membrane		No	No	EM	• Main low-pressure turbine damage.	LRFP
146.	1992	Lake Charles (LNG Edo) (b. 1980)	Spherical		No		EM	• Propeller damage sustained due to contact with buoy at Pyong Taek.	LRFP
147.	1993	Hassi R'Mel (b. 1971)	Membrane	In dry-dock	No	No		• Caught fire in accommodation area whilst in dry-dock at Marseilles. Received assistance from fire brigade.	LRFP
148.	1993	Hassi R'Mel (b. 1971)	Membrane	Under repair	No	No		• Caught fire in engine room whilst under repair in Hamburg.	LRFP
149.	1993	Hoegh Gandria (b. 1977)	Spherical	Anchorage			Col	• In collision with container vessel Ever Oasis at Singapore anchorage.	LRFP
150.	1994	Annabella (b. 1975)	Membrane	Under repair	No	No		• Struck dock whilst under repair at Marseilles after lines broke in heavy weather. Hull indented over 10 meters.	LRFP
151.	1995	Mourad Didouche (b. 1980)	Membrane	In yard	No	No		• Lifting cable broke while turbine being lifted out of engine room, causing turbine to fall from great height at Marseilles shipyard.	LRFP
152.	1996	LNG Finima	Membrane	Anchored	No	No		• Piracy. Boarded by pirates while anchored. Stole paint and broached a lifeboat. Pirates fled after being discovered.	LRFP

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		(B. 1983)							
153.	1996	Bachir Chihani (b. 1979)	Membrane	In port	No	No	EM	• Reported due to carry out repairs at Marseilles to engines and two tanks.	LRFP
154.	1996	Mostefa Ben Boulaid (b. 1976)	Membrane	At quay, discharging	No	No	FE	• Electrical fire in main engine room alongside Distrigas terminal. Crew extinguished fire. Cargo discharged at reduced rate. • Had electrical fire in main engine-room while tied up alongside Distrigas LNG terminal, Boston, 05 Feb 1996. Lost power. Fire extinguished by crew. Cargo discharge continuing. Power restored and sailed 09 Feb • Electrical fire in main engine room while docked at the LNG terminal in Everett, Ma, USA. Fire extinguished by crew. LNG cargo subsequently transferred to the terminal without incident.	DNR report, LRFP, QUEST
155.	1996	LNG Portovenere (b. 1996)	Membrane	Sea trials (Empty)	6 dead	No		• Had fire break out in engine room about 13 nautical miles off Genoa. Fire quickly brought under control and extinguished. Damage minor. In tow. • Engine room fire during sea trials near Genoa, Italy. CO2 fire extinguishing system discharged before engine room was evacuated. Five technicians and one ABS surveyor died.	LRFP, QUEST
156.	1997	Northwest Swift (b. 1989)	Spherical	At sea	No	No	Col	• Collision with fishing vessel. Damage to port side and bulwark. No water ingress. • Collided with fishing vessel about 400 km from Japan. Some damage to hull, but no ingress of water and no loss of LNG.	IZAR, DNV report, QUEST
157.	1997	LNG Capricorn	Spherical	In port	No	No	Cnt	• Sustained damage to shell plating on contact with mooring dolphin at a Hamasaki pier. No spillage or damage to cargo system.	IZAR, DNV

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		(b. 1978)						• Struck a mooring dolphin at a pier near the Senboku LNG terminal in Japan. Some damage to hull, but no ingress of water end no loss of NG.	report, LRFP, QUEST
158.	1998	Mostefa Ben Boulaid (b. 1976)	Membrane	In port	No	No	EM	• Reported at Boston with generator problems.	LRFP
159.	1998	LNG Bonny (B. 1981)	Membrane	At sea	No	No	EM	• Had complete power failure and drifting 90 miles off Miyakoshima. Tug on scene, repair crew aboard vessel, repairs completed and resumed voyage. • Electric power failure while enroute from Indonesia to Korea. Salvors repaired generator.	LRFP, QUEST
160.	1999	Methane Polar (b. 1969)	Membrane	In port Empty	No	No	Cnt	• Had engine breakdown and struck the Petrotrin jetty at Point Fortin, while being brought in empty for loading. No damage reported. • Engine failure during approach to Atlantic LNG jetty. Struck and damaged Petrotrin pier. No injuries or loss of cargo.	IZAR, LRFP, DNV report, QUEST
161.	1999	Matthew (b. 1979)	Membrane	At sea	No	No	EM	• Had tailshaft problem and overheated bearing and arrived Boston in tow.	LRFP
162.	2000	Hanjin Pyeong Taek (b. 1995)	Membrane	At sea	No	No	Col	• Collision with bulk carrier Corali near Busan. Damage occurred to shell plating.	IZAR, LRFP
163.	2000	LNG Jamal (b. 2000)	Spherical	At wharf	No	No		• Insulating materials & vinyl sheeting burnt out during welding operations on No 3 tank cover at wharf in Mitsubishi Dockyard. Fire controlled same day.	LRFP

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
164.	2000	Hoegh Galleon (Pollenger) (b. 1974)	Spherical	In yard	1 ship builder dead	No		• An outbreak of fire caused damage to part of the tank insulation. 1 ship builder died. • Fire in cargo tank insulation during repair/maintenance work in Singapore. One worker killed.	IZAR, LRFP, QUEST
165.	2001	Ramdane Abane (b. 1982)	Membrane	At sea	No	No	EM	• Engine break down. Towed away from the coast by tug Ria de Vigo. Engine restarted and proceeded same day.	IZAR, LRFP
166.	2001	Methane Polar (b. 1969)	Membrane	At sea In ballast	No Three injuries and one fatality of bulk carrier crew	No	Col	• Collision with bulker. Minor hull damage. • In collision with bulk carrier Eastwind off Algeria. Sustained holing to bow. Subsequently arrived Piraeus for repairs.	IZAR, Colton, LRFP
167.	2001	Khannur (b. 1977)	Spherical	Unloading	No	Yes	L/U	• Product leak through a vent. Cracks in tank dome. Over-pressurisation of cargo in No 4 tank.	IZAR, Colton, LRFP
168.	2002	Norman Lady (b. 1973)	Spherical	At sea	No	No	Col	• Collision with a U.S. Navy nuclear-powered attack submarine, the U.S.S. Oklahoma City. In ballast condition. Ship suffered a leakage of seawater into the double bottom dry tank area.	Houston Law Center, IZAR, Colton, LRFP

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
169.	2002	Mostefa Ben Boulaid (b. 1976)	Membrane	Unloading	No	Yes	L/U	• A spillage resulted in a cracked deck. Thought to be human error as the alarm that should alert personnel had been isolated. No one was hurt. • Overfilling. Cracks on deck	IZAR, Colton
170.	2003	Methane Princess (b. 2003)	Membrane	Under construction	No	No		• Had fire on board while under construction at Daewoo Shipbuilding. Fire under control five hours later after burning part of the cargo tanks. Damage fairly minor.	LRFP
171.	2003	Century (b. 1974)	Spherical	At sea	No	No	EM	• Sustained main engine damage offshore Algeria. Under tow by two tugs to Syros Shipyards.	LRFP
172.	2003	Hoegh Galleon (Pollenger) (b. 1974)	Spherical	At sea	No	No	EM	• Gearbox problems. Being towed to Ferrol. Major repairs.	Colton, LRFP
173.	2003	Hilli (b. 1975)	Spherical	At Anchorage	No	No	EM	• Boiler tube failure	LRFP
174.	2003	Gimi (b. 1976)	Spherical	Approaching pier	No	No	Grd	• Softly touched bottom approaching pier at Lake Charles. Preliminary survey indicated no damage.	LRFP
175.	2003	Fuwairit (b. 2003)	Membrane	In yard Under construction	No	No		• Grounded during passage of typhoon “Maemi” while at Samsung Heavy Industries shipyard in Korea	LRFP

Table 13: Historic LNG carrier accidents with and without spillage of cargo									
#	**Year**	**Ship name (Year built)**	**Type of cargo containment** - *Membrane* - *Spherical* - *Other*	**Activity**	**Injuries /fatalities**	**LNG spill**	**Incident category**	**Incident description**	**Source**
176.	2003	Galicia Spirit (b. 2004)	Membrane	In yard Under construction	No	No		• Grounded at Pallangpo breakwater after mooring ropes released during typhoon "Maemi" while at Daewoo shipyard. Sustained damage to bottom and starboard shell plating.	LRFP
177.	2003	LNG Berge Arzew (b. 2004)	Membrane	In yard Under construction	No	No		• Mooring ropes broke due typhoon "Maemi" and drifted away from berth at DaeWoo yard, Busan, touching bottom. Towed to shipyard. Bottom plating damage. Permanent repairs completed end Jan 2004.	LRFP
178.	2004	British Trader (b. 2002)	Membrane	At sea	No	No	FE	• Minor electrical fire onboard, damaged one transformer, contained and underway	LRFP
179.	2004	Methane Arctic (b. 1969)	Membrane	Discharging	No	No	FE	• Had minor fire break out after being struck by lightning at Barcelona. Fire extinguished after an hour by vessel's own means. Damage slight.	LRFP
180.	2004	Tenaga Lima (b. 1981)	Membrane	At sea	No	No	Cnt	• Made contact with a submerged rock due to a strong southerly current. The starboard side shell plating in way of No 1 membrane tank was reportedly heavily damaged but did not require temporary repairs at Mokpo. Sailed for Yokohama for permanent repairs.	LRFP
181.	2005	Hispania Spirit (b. 2002)	Membrane	Berthing operations	No	No	Cnt	• Contact. Hull damage. Sustained hull damage during berthing operations, resulting in oil spill quickly isolated, contained and minimised.	LRFP
182.	2005	Laieta (b. 1970)	Other (Esso)	In ballast	No	No	EM	• Reported engine breakdown while in ballast. Vessel taken in tow for Barcelona. Salvage services rendered under LOF 2000.	LRFP

Some remarks to some of these accidents are in order:

Accident # 5: No more information about this accident is known. QUEST quotes “Frozen fire” by L. N. Davis as reference for this information [34].

Accident # 15: Different sources give different vessels for this accident. The MHIDAS database gives Methane Progress as the vessel involved in this accident, while the QUEST reference states that it was the Methane Princess.

Accident # 17: The name of the LNG vessel involved in this accident is not known. Information on this accident was only found in the DNV report and not mentioned in any of the other known sources, apart from the MHIDAS database.

Accident # 19: Confusing information from various sources regarding this accident. According to the Colton reference, a valve failure incident occurred on the LNG Delta at sea in 1977. No mention of any fatalities. The IZAR reference states that there is a valve failure incident with the ship LNG Delta, formerly named Arzew, in 1977. No mention of any fatalities. The Houston Law Center reference states that there was an accident on shore at Arzew, Algeria, where 1 worker froze to death. The description of this accident, i.e. a valve failure on contact with cryogenic temperatures, is identical to the description of the LNG Delta accident. According to LRFP, the same ship has not been named LNG Delta and Arzew. Thus, the information in the IZAR reference is partly wrong. Also, the information from Colton that the ship was at sea would also be wrong. According to another source [32], what happened was that a terminal worker on the LNG export terminal at Arzew was frozen to death during a ship-loading operation. A large-diameter valve ruptured, causing the worker to be sprayed by LNG. The death was caused by the low temperature of the LNG liquid, and the spilled LNG did not ignite.

Accident # 78: The year of this incident is not known. Information about this incident appeared in Hazardous Cargo Bulletin article published in 1982 [35], so accident must have been prior to 1982.

Accident # 79: The year of this incident is not known. Information about this incident appeared in Hazardous Cargo Bulletin article published in 1982 [35], so accident must have been prior to 1982.

Accident # 80: The year of this incident is not known. Information about this incident appeared in Hazardous Cargo Bulletin article published in 1982 [35], so accident must have been prior to 1982.

Accident # 81: The year of this incident is not known. Information about this incident appeared in conference article published in 1982 [36], so accident must have been prior to 1982.

Accident # 134: It is unclear whether different information from various sources refers to the same accident. An accident involving the LNG carrier Tellier in 1989 is reported in several of the available sources. Most details of this accident found in QUEST, which contained the information in the last bullet in the table above for this accident. Obviously, the Tellier was blown away from its berth at Skikda, Algeria, causing significant damages to the ship. In the DNV report, an accident with an unnamed ship is reported where a chemical tanker with LNG broke away from its moorings and sank in heavy gales at Skikda, Algeria in 1989 (Accident # 48). Apart from the sinking, this accident description is very similar to the accident of Tellier the same year and at the same location. Thus, this can possibly refer to the accident involving Tellier. However, the DNV report continues to state that the accident had 27 fatalities, whereas no fatalities were mentioned in any of the other sources. The reference for the information in the DNV report is given as various Hazardous Cargo Bulletin issues, and the exact source of this information has not been tracked down. It is thus unclear whether the accident referred to in the DNV report is the same as the one involving Tellier, although this seems possible. It should be noted also that none of the sources has been verified in terms of accuracy of information.

Accident # 135: No further information about this accident is available, and the reference given for this information in the QUEST source is private communications. According to the information that is available, there is no contradiction between the information about this event and the accident involving 27 fatalities reported in the DNV report (Accident # 48). Thus, the accident reported in the DNV report might also possibly refer to this accident involving the Larbi Ben M'Hidi.

Accident # 136: The information of this accident which supposedly resulted in 27 fatalities has not been found in other sources than the DNV report. The source of this information could not be found due to ambiguous reference in the DNV report. The reference that was provided only stated Hazardous Cargo Bulletin (various) without providing information about volume, issue or year. Thus, further information about this incident has not been found, and it is e.g. not known which LNG vessel this incident supposedly involved. Neither has it been possible to verify the information about this incident. Possibly, this is the same incident as either Accident # 134 or Accident # 135 which are similar accidents occurring the same year. It might also be a separate incident, and finally, the information about this accident may be wrong altogether. It is deemed highly unlikely that a chemical tanker would be loaded with LNG as chemical tankers are normally not designed to handle cryogenic temperatures. Thus the information seems contradictory, and no trust is put in the accuracy of this information. Notwithstanding, the accident is kept in the table of known accidents although no regard is given to this information in the actual risk assessment carried out in the current study.

A.2 Economic value of LNG shipping

This discussion on the economic value of LNG shipping or more precisely, of a typical LNG carrier, is used in chapter 1.2 of the main report in order to derive risk acceptance criteria pertaining to LNG carriers.

The economic value of an LNG carrier is taken as the result of the annual revenuer. Fernleys LNG Weekly gives the spot rates for LNG carriers in the period from January 2005 to May 2007, Figure 17.

The average spot rate in this period is USD 53,000. On average, 360 days a year is assumed, taking occasional docking time into account, e.g. once every 2 – 5 years depending on the vessel. Thus, the day rates amount to an annual income of about USD 19.1 million per year.

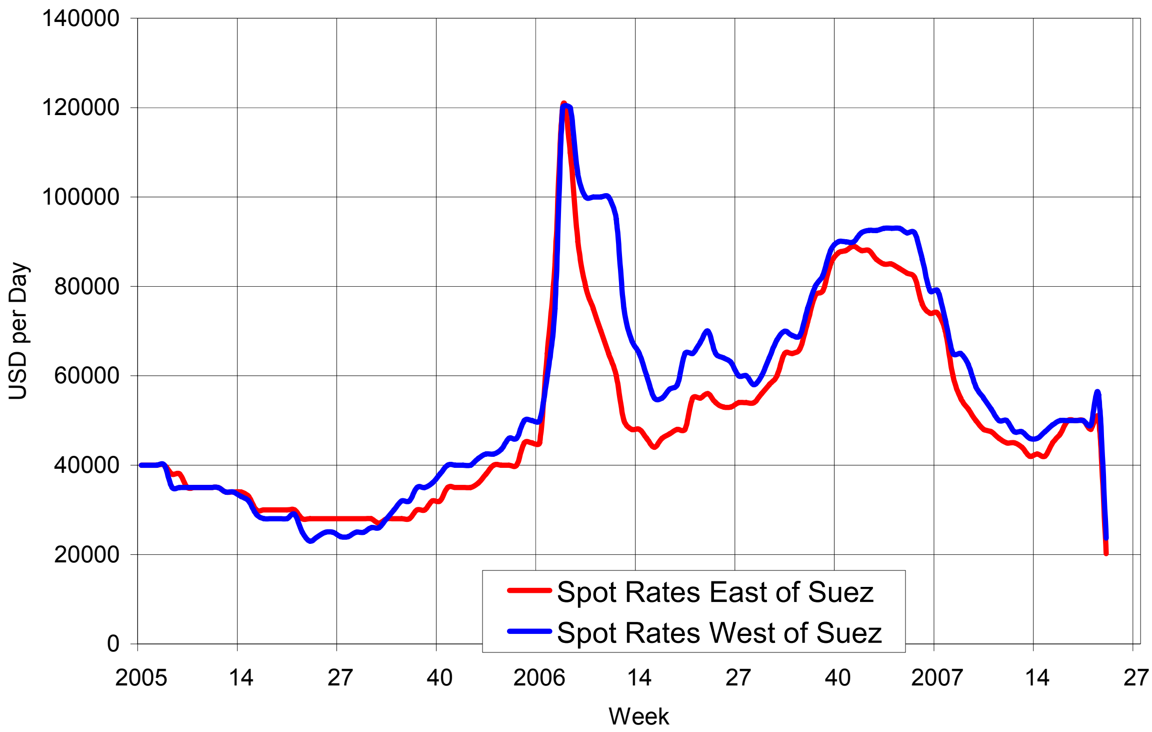

Figure 17: LNG Spot Charter Rates - 138-145.000 cbm Modern Vessel

References Appendix A.2

Fernleys LNG weekly 21

A.3 Consequence estimation for collision and grounding scenarios – Delphi session

In order to estimate a consequence distribution for the various collision and grounding accident scenarios, a group of DNV experts were invited to a DELPHI session. The group consisted of four experts which all had experience with LNG operations and risk analyses[9]. The experts were given the following questionnaire (Figure 18):

Delphi session:
Consequence estimation for collision and grounding events of LNG carriers

Scenario 1:

Assume that:

- A collision or grounding event has occurred that has resulted in accidental release of LNG
- The LNG carrier has a crew of 30
- A pool fire has started at the spill site

What is the probability that there will be:

0 fatalities among the crew:	P =
1 fatality among the crew:	P =
5 fatalities among the crew:	P =
10 fatalities among the crew:	P =
20 fatalities among the crew:	P =
30 fatalities (whole crew) among the crew:	P =

Scenario 2:

Assume that:

- A collision or grounding event has occurred that has resulted in sinking of a LNG carrier
- The LNG carrier has a crew of 30

What is the probability that there will be (due to not being able to evacuate in time before the ship sinks):

0 fatalities among the crew:	P =
1 fatality among the crew:	P =
5 fatalities among the crew:	P =
10 fatalities among the crew:	P =
20 fatalities among the crew:	P =
30 fatalities (whole crew) among the crew:	P =

Figure 18: Questionnaire for consequence estimates

The results from the four experts are presented in Table 14.

[9] The four experts were: Marianne Hauso, Håkon Graven, Peter Hoffmann and Wilhelm Christian Magelssen

Table 14: Results from Delphi session – consequence estimates					
Scenario 1	**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Average**
P(0)	0,1	0,7	0,6	0,5	0,475
P(1)	0,25	0,1	0,3	0,35	0,25
P(5)	0,3	0,1	0,08	0,08	0,14
P(10)	0,2	0,05	0,01	0,04	0,075
P(20)	0,1	0,025	0,01	0,02	0,03875
P(30)	0,05	0,025	0	0,01	0,02125
Sum = 1	1	1	1	1	1
Scenario 2	**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Average**
P(0)	0	0	0,01	0,08	0,0225
P(1)	0	0,05	0,05	0,05	0,0375
P(5)	0,1	0,2	0,14	0,15	0,1475
P(10)	0,4	0,5	0,5	0,5	0,475
P(20)	0,3	0,2	0,2	0,15	0,2125
P(30)	0,2	0,05	0,1	0,07	0,105
Sum = 1	1	1	1	1	1

Based on these results, the following probabilities can be extracted:

- Probability of fatalities if pool fire: 0.525
- Probability of fatalities if sinking: 0.978
- Probability of fatalities if pool fire and sinking: 0.989
- Expected number of fatalities due to pool fire: 3.11
- Expected number of fatalities due to sinking: 12.9
- Expected number of fatalities if fire and sinking: 16

These estimates will be included in the event tree for the collision and grounding scenarios.

A.4 Event trees

The event trees for the various accident scenarios that have been developed within this study are presented in this appendix. The initial overall risk model containing seven different accident scenarios is illustrated in Figure 9. However, upon further investigation, it was found that two of these did not contribute notably to the total risk; hence the overall risk model is reduced to the one in Figure 19.

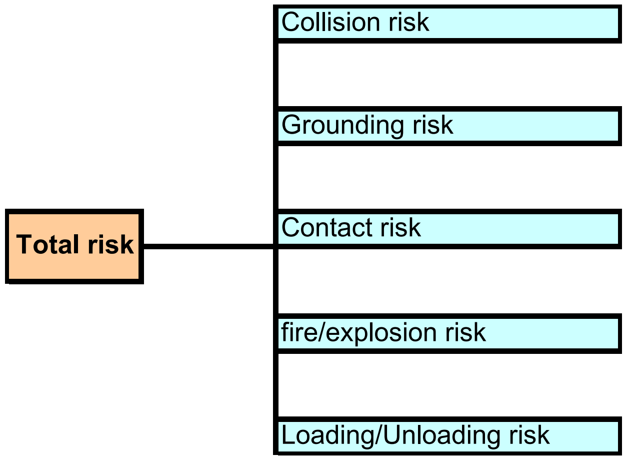

Figure 19: Modified overall risk model, LNG carriers

In the following, five event trees will be presented, i.e. for these scenarios:

- Collision
- Grounding
- Contact
- Fire and explosion
- Loading and unloading incidents

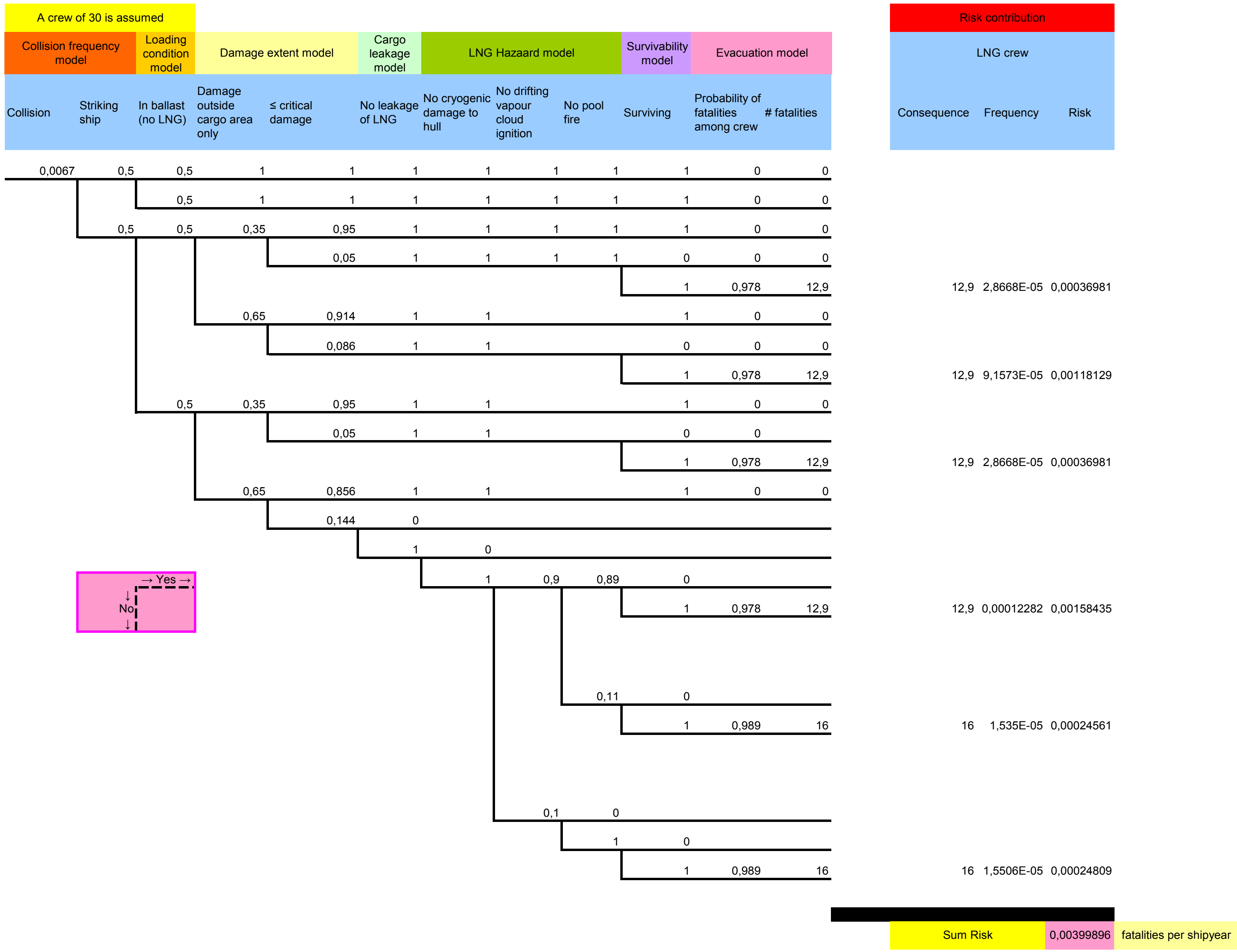

Figure 20: Event tree for collision scenario

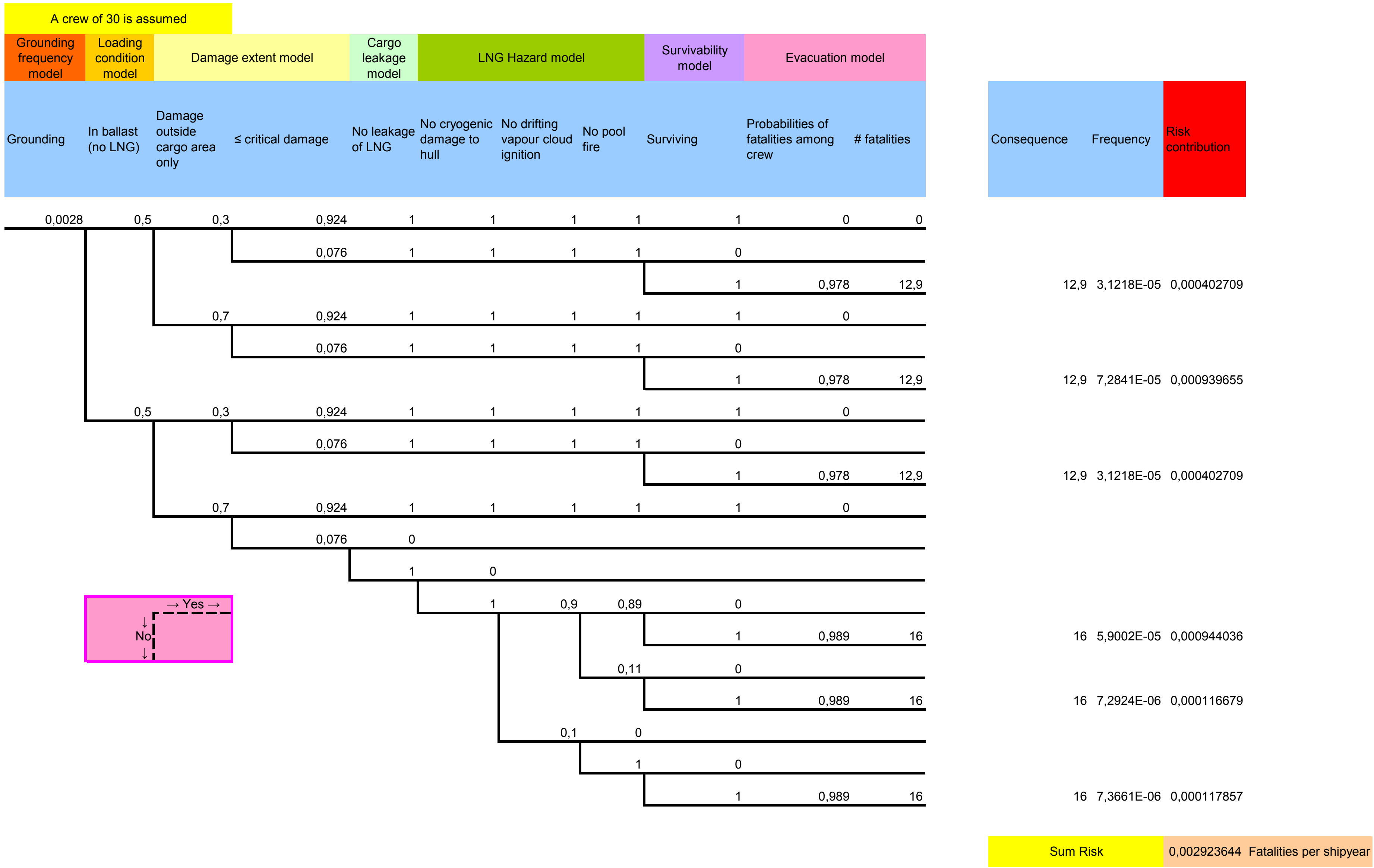

Figure 21: Event tree for grounding scenario

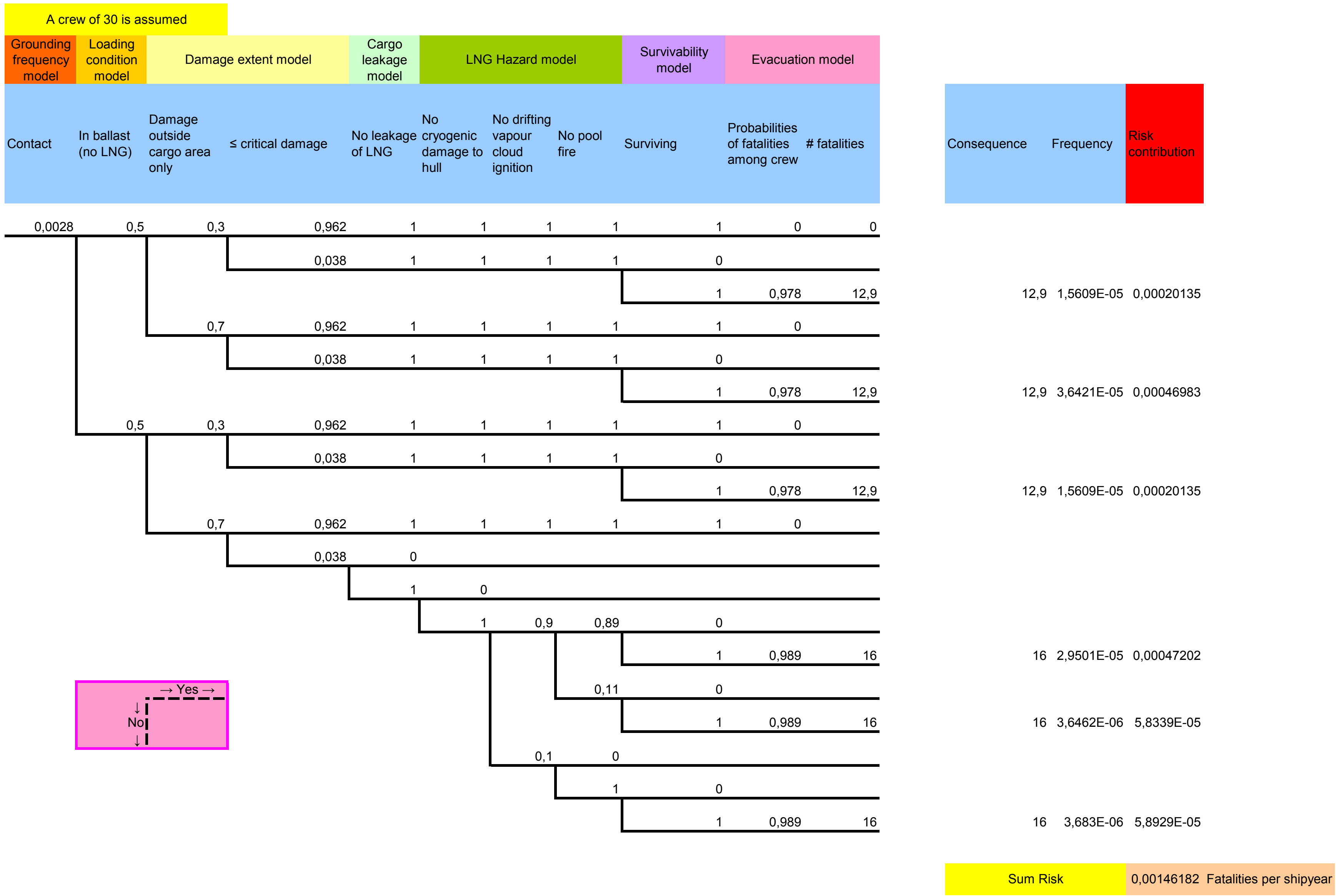

Figure 22: Event tree for contact scenario

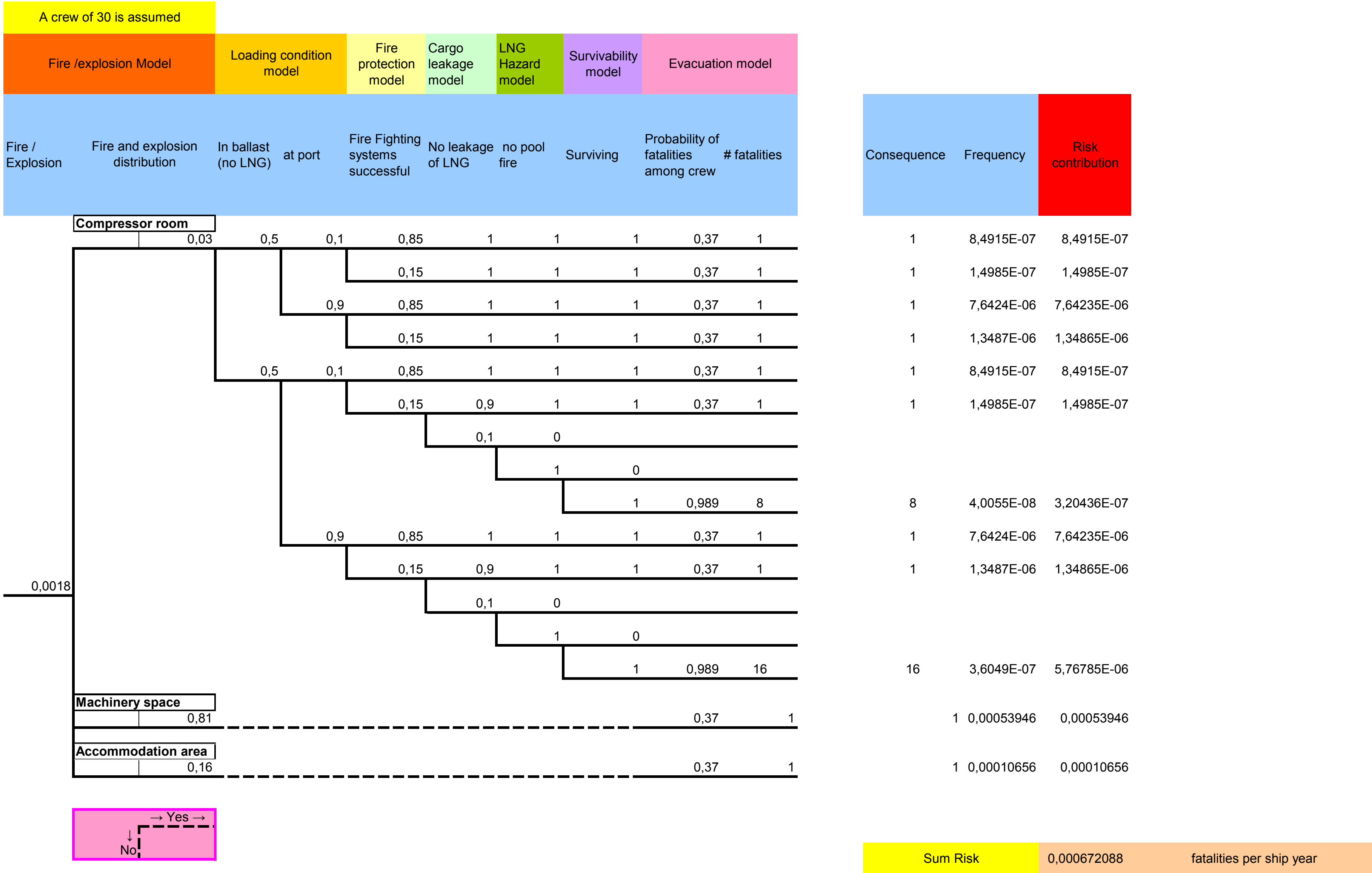

Figure 23: Event tree for fire and explosion scenario

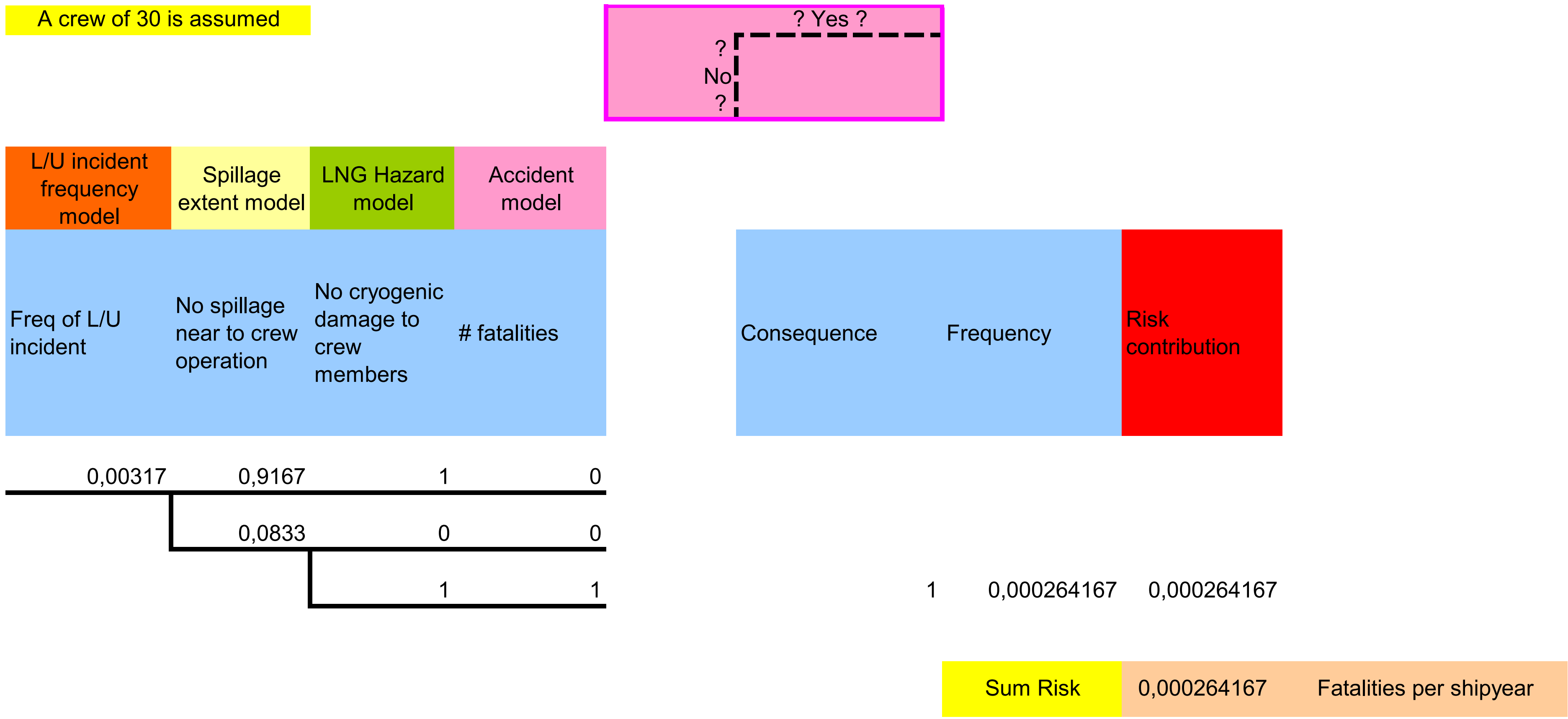

Figure 24: Event tree for loading/unloading incident scenario

Annex II: Risk Control Options and Cost Benefit Analysis

9 Introduction

According to the conclusions arrived at in the risk analysis, groundings, collisions and contacts are responsible for about 90% of the total risk pertaining to LNG carrier operations, and such accidents are most likely to cause a major casualty. It is important to mention the Yuyo Maru / Pacific Ares collision in Tokyo Bay in 1974 which, while involving naptha and not LNG, produced a horrifying loss of life on board the two ships.

Thus, while it is true that LNG has an almost clean liability claims record, claims do actually occur on LNG ships. UK Club's Major Claims Analysis records 32 claims in the past 18 years, with a total payout of $17.5 million. The majority of these claims are in fact personal injury and dock damage claims [59].

Casualties will always occur, and occur to the best run ships and the best way to prevent such casualties may be to try and prevent all incidents on the basis that any incident can turn out to be a major one. In this respect, given that LNG ships are exceptionally carefully designed, built and maintained, the weakest links in the chain are as usual human error – by the crew and also by pilots. The UK Club's Analysis of Major Claims shows clearly that collision and grounding claims, the main category of claims likely to give rise to a major LNG incident, are caused primarily by error on the part of deck officers. This should not be a surprise to anyone. What may be, however, is that no less than 5 % of major claims by frequency are caused by pilot error, and that no less than 14% of collisions have errors by pilots as the predominant cause.

According to the conclusions from the risk assessment, it was recommended to focus on measures related to the following issues when exploring possible risk control options:

- Navigational safety. Improvements in navigational safety would reduce the frequency of collisions, groundings and contact events. However, when it comes to collisions, it is realized that the most critical scenario is being hit by another vessel. Thus, enhanced navigational safety on the whole fleet, not only for LNG vessels should be considered.
- Manoeuvrability. Improved manoeuvrability, e.g. related to steering and propulsion reliability would have the potential to reduce the frequency of accidents. Extended use of tugs might reduce the frequency of contact and grounding events near the terminals.
- Collision avoidance. Examples of collision avoidance options are extended use of safety zones around LNG carriers and warning boats in busy waters to clear the way for the LNG carrier.
- Cargo protection. Measures to prevent spillage in the event of an impact would have the potential to reduce the risk. Enhancing the cargo containment system's ability to maintain its integrity when receiving damage, could e.g. be achieved by improved structural strength or ability to deform or absorb impact energy without cracking.
- Damage stability. Reducing the probability of sinking in the event of an accident would decrease the risk. Possible measures could be related to protecting the hull from cryogenic damages from spilled LNG or generally enhanced survival capabilities in damaged condition
- Evacuation arrangements. The consequence, and thereby the risk, could be reduced if improvements in the evacuation performance could be achieved. Possible improvements could be related to evacuation procedures, escape route layout or LSA.

This list has been used as a starting point for the work carried out within this task and reported herein.

9.1 Objective and scope of work

This task focused on the third and fourth steps – Risk Control Options and Cost Benefit Analysis – in a high-level, generic FSA study on conventional ocean going LNG carriers involved in international trade.

Step 3: Risk Control Options

The purpose of step 3 is to propose new effective and practical RCOs comprising the following four principal stages:

- Focusing on risk areas needing control;
- Identifying potential risk control measures (RCOs);
- Evaluating the effectiveness of the RCOs in reducing risk

10 risk control options were identified and described, and later assessed for their effectiveness in reducing risk. Both "general approaches" which controls risk by controlling the likelihood of accidents and "distributed approaches" which provides control of escalation of accidents have been considered.

During the Risk Analysis the main risk generators were identified, i.e. collision, grounding and contact accidents. Therefore, measures related to the following should be considered:

- Manoeuvrability
- Collision and grounding avoidance
- Cargo protection

In addition, Risk Control Options aimed at reducing the risk of fire or explosion, incident/accident while loading and unloading of cargo and failure leakage of cargo containment system are taken into count.

Step 4: Cost Benefit Analysis

The purpose of this step is to identify and compare benefits and costs associated with the implementation of each RCO identified and defined in step 3.

Comparisons of cost effectiveness for RCOs have been made by calculating two indices which express cost effectiveness in relation to safety of life: Gross Cost of Averting a Fatality (GCAF) and Net Cost of Averting a Fatality (NCAF) as described in chapter 10. The costs will be expressed in terms of life cycle costs and will include costs related to initial investment, operating, training, inspection, certification decommission, etc.

The cost benefit assessment has consisted of the following stages, with considerations of the risk levels assessed in step 2:

- Arrange the RCOs, defined in step 3, in a way to facilitate understanding of the resulting costs and benefits
- Estimate the pertinent costs, risk reductions and economic benefits for all selected RCOs
- Estimate and compare the cost effectiveness of each option, in terms of the cost per unit risk reduction by dividing the net cost by the risk reduction achieved as a result of implementing the option
- Rank the RCOs from a cost-benefit perspective in order to facilitate the decision-making recommendations in step 5.

9.2 Limitations

This task is restricted to study the cost effectiveness associated with measures onboard the LNG vessels only. Risk Control Options focusing on the LNG exporting or receiving terminals are out of scope.

The results from the risk analysis are currently the best estimate on the actual risk level for the various accident categories, and there are uncertainties associated with these results. The assessment is based on introduction of one RCO at the time only. Introduction of one RCO will lead to higher NCAF/GCAFs for other RCOs addressing the same hazards. However, this dependency of the different RCOs has not been accounted for in this study.

The economical benefits of introducing a measure are mainly accounted for in terms of reduced accident costs. The assessments are based on various assumptions and the values used in the calculations should be regarded as somewhat uncertain. However, efforts have been made to explicitly state all relevant assumptions for the sake of transparency.

10 Methodology for Cost Benefit Assessment

10.1 Assessment criteria

Cost effectiveness are assessed in terms of Gross Cost of Averting a Fatality (GCAF) and Net Cost of Averting a Fatality (NCAF). Their definitions are:

$$GrossCAF = \frac{\Delta C}{\Delta R} \quad (10.1)$$

$$NetCAF = \frac{\Delta C - \Delta B}{\Delta R} \quad (10.2)$$

Where:

ΔC is the cost per ship of implementing the Risk Control Option.

ΔB is the economic benefit per ship resulting from the implementation of the Risk Control Option.

ΔR is the risk reduction per ship, in terms of the number of fatalities averted, implied by the Risk Control Option.

In accordance with current practice within IMO and the proposals presented in MSC 72/16 ([74]), the following criteria have been adopted for this cost-effectiveness assessment: *A risk control measure will be recommended for implementation if it has notable potential for risk reduction and GCAF ≤ USD 3 million or NCAF ≤ USD 3 million*. For risk control options where the estimated GCAR/NCAF is close to USD 3 million, further scrutiny might be required.

10.2 Risk reduction calculations

For estimating the possible risk reduction of implementing the measures, the Event Trees developed in step 2 of the FSA were used. In addition, general fault trees of tankers developed in another European Research project (POP&C) have been used to supplement the event trees and to evaluate the effects of risk reducing measures [81].

An example: "Redundant propulsion system" implies upgrading the probabilities in the event trees of propulsion system failure that could lead to e.g. collision, grounding or contact. By doing this, the risk reduction represented in decreased expected fatality frequencies may be estimated.

The risk reduction has been expressed in terms of lives saved per vessel lifetime, and has served as input to the GCAF and NCAF calculations.

10.3 Cost and benefit calculations

The cost and benefit of the RCOs will typically be spread over the lifetime of the vessel. Some RCOs might involve annual costs while others may involve costs at other intervals. In order to be able to compare the costs and benefits and calculate the NCAF and GCAF, Net Present Value (NPV) calculations have been performed using the formulae given below:

$$NPV = A + \frac{X_1}{(1 + r)} + \frac{X_2}{(1 + r)^2} + ... + \frac{X_T}{(1 + r)^T} = A + \sum_{t=1}^{T} \frac{X_t}{(1 + r)^t} \qquad (10.3)$$

Where:

X_t = cost (or benefit) of RCO in year t.

A = amount spent initially for implementation of RCO.

r = depreciation rate.

T = lifetime of risk control option, i.e. remaining operational lifetime of the vessel

The direct costs of the measures have been divided into two parts: Initial costs and running costs over the lifetime of the vessel. The initial costs include all costs of implementing the measure, e.g. acquiring and installing equipment, writing of procedures and training of crew. Thereafter there might be additional costs at regular intervals in order to maintain the effect of the measure, e.g. equipment service and refreshment courses. The additional cost might for example be annual, bi-annual or fifth–annual.

The implementation of a RCO might have other benefits than reducing number of fatalities. Other benefits might be reduced maintenance cost, reduced expected annual accident cost and less time off-hire. The reduced expected accident cost for each RCO has been found by assessing the potential risk reduction for each case. The potential risk reduction is then used to find the expected reduction in annual accident cost.

11 Review of Current Measures to Prevent Release of LNG

11.1 Regulatory framework

LNG carriers carry a cryogenic liquid. Accordingly, specialized materials, constructions methods, and operating procedures are needed to safely handle LNG. The general rules and regulations that govern ships at sea do not address the particular concerns of LNG and therefore, specific rules and regulations have been developed in order to ensure the safety of LNG tankers. There are several IMO publications and conventions regarding design, construction, and operation of LNG tankers. Some of the most important are:

Regulations:

- International Code for Ships Carrying Liquefied Gases in Bulk (IGC Code), 1993
- 1994/1996 Amendments to the IGC (replaced the Gas Carrier Code)
- International Convention for Safety of Life at Sea (SOLAS Consolidated edition 2004 and last amendments).
- International Convention for Prevention of Pollution from Ships (MARPOL) 1973/78 Consolidated 1991 and later amendments, including 1997 Annex VI "Prevention of Air Pollution from Ships".
- Convention on the International Regulations for Preventing Collisions at Sea 1972, consolidated edition 2002
- International Convention on Load lines 1966 and Protocol of 1988, consolidated edition 2002
- International Convention on Tonnage Measurement of Ships 1969, as amended by IMO Resolutions A493/494(XII).
- Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (Gas Carrier Code), 1983
- International Convention on Standards of Training, Certification and Watch keeping (STCW) for Seafarers, 1978
- International Management Code for the Safe Operation of Ships and for Pollution Prevention (ISM Code) – adopted by IMO Resolution A.741 (18) in 1994

Guidelines:

- A330 (IX) “Safe access to and working in ballast spaces”
- IMO Resolution A272 (VIII) and A330 (IX) Safe Access to and Working in Large Cargo Tanks and Ballast Spaces.
- IMO Resolution A601 (XV) “Provision and display of manoeuvring information onboard ships”
- IMO Resolution A708 (XVII) “Navigation bridge visibility and functions and SOLAS Chapter V Regulation 22” LNG Carrier Specification Module A General Specification
- IMO Resolution A719 (XVII) “Prevention of air pollution on ships “
- IMO Resolution A751(18) Interim Standards for Ship Manoeuvrability.
- IMO Resolution A.830 (XIX) “Code on alarms and indicators”

- IMO Resolution A 868 (XX) “Guidelines for the control and management of ship’s ballast water to minimise the transfer of harmful aquatic organisms and pathogen (except Ballast Water Management Plan)”
- IMO Resolution MSC 57(67) for access arrangements to tanker bows.
- IMO Resolution MSC 137 (76) “Standards for ship manoeuvrability”
- IMO latest performance standards for all navigation equipment
- IMO MSC Circular 982 “Principles relating to bridge design (SOLAS Chapter V Regulation 15)”
- IMO MSC Circular 1053 “Explanatory notes to the standards for ship manoeuvrability”
- IMO MSC Circular 1091, June 2003 “Issues to be considered when 20 introducing new technology on board ships”
- IMO MSC Circular 1097, June 2003 “Guidance relating to the implementation of SOLAS Chapter XI-2 and the ISPS Code”
- ILO Guide to Safety and Health in Dock Work 1976, amended in 1979
- ILO Codes of Practice: Safety and health in dock work 1979
- The recommendations of the OCIMF Tanker Structures Co-operative Forum
- OCIMF Recommendations on Equipment for the Towing of Disabled Tankers 1981 (see SOLAS/IMO Res A.535).
- OCIMF Mooring Equipment guidelines 1997
- OCIMF Guidelines and Recommendations for the Safe Mooring of Large Ships at Piers and Sea Islands 1994
- OCIMF Recommendations for Ships’ Fittings for Use with Tugs 2002
- OCIMF Ship-to-Ship Transfer Guide (Liquefied Gases), 1980.
- OCIMF HSE at Newbuilding and repair shipyards and during factory acceptance testing, 2003
- OCIMF / SIGTTO Recommendations for Manifolds for Refrigerated Liquefied Natural Gas Carriers (LNG) 1994
- ICS / OCIMF / SIGTTO Ship-to-Ship Transfer Guide (Liquefied Gases) 1995
- ICS Guide to Helicopter/Ship Operations
- SIGTTO Recommendations and Guidelines for Linked Ship/Shore Emergency Shutdown of Liquefied Gas Cargo Transfer 1987
- SIGTTO Guidelines for the Alleviation of Excessive Surge Pressures on ESD 1987
- SIGTTO Recommendations for the Installation of Cargo Strainers on LNG Carriers and for Emergency Shut Down System
- SIGTTO Recommendations for Manifolds for Refrigerated Liquefied Natural Gas Carriers
- SIGTTO Port Information for LNG Export and Import Terminals
- IEC Publication 60092 “Electrical installations in ships”
- IEC Publication 60533 “Electrical and electronic installations on ships - electromagnetic compatibility”

- ISO 484-1:1981 “Shipbuilding - Ship screw propellers - Manufacturing tolerances - Part 1: Propellers of diameter greater than 2.5m”
- ISO 2923:1996 plus Cor 1:1997 “Acoustics - Measurement of noise onboard vessels”
- ISO 4406:1999 “Hydraulic fluid power - Fluids - Method for coding the level of contamination by solid particles”
- ISO 6954:2000 “Mechanical vibration - Guidelines for the measuring, reporting and evaluation.
- ISO 8468 Ship’s bridge layout and associated equipment.
- ISO 8573-1:2001 “Compressed Air – Part 1: Contaminants and purity classes”
- ISO 8861:1988 “Engine room ventilation in diesel engine ships”
- ISO 10816-1:1995 “Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts, Part 1: General guidelines” LNG Carrier Specification Module A General Specification
- ISO 17894 “Computer Applications - General principles for the development and use of programmable electronic systems in marine applications”
- ISO/IEC 15288 “System lifecycle processes”
- VDI 2056 “Criteria for assessment of mechanical vibrations in machines”
- VDI 2063-1985 “Measurement and evaluation of mechanical vibration of reciprocating piston engines and compressors”
- SNAME Technical & Research Bulletin 3-39 “Guide for shop and installation tests”
- SNAME Technical & Research Bulletin 3-47 “Guide for sea trials”
- SNAME Technical & Research Bulletin 5-2 “Gas trials guide for LNG Vessels”
- BS 1807-1981 “Surface finish requirements for reduction gears”

The single most important of these international requirements for LNG carrier design is the IGC Code. This provides the basic requirements that flag states and classification societies may supplement with more detailed requirements.

11.2 LNG design characteristics to prevent releases

LNGs should survive the normal effects of flooding following assumed hull damage caused by some external forces. In addition, to safeguard the ship and the environment, a double hull is provided to protect the cargo tank area in the case of grounding, collision and contact events.

In the following, some of the LNG carriers design characteristic that help to prevent significant releases of LNG in case of accidents are described.

Location of cargo tanks: The IGC Code requires cargo tanks to be protected at least a specified minimum distance inboard from the ship’s shell plating. For a LNG carrier this distance will be not less than B/15 or 2m whichever is less measured from the moulded line of the bottom shell plating at centreline and nowhere less than 760mm from the shell plating.

Segregation of the Cargo Area: The IGC Code requires that hold spaces should be segregated from machinery and boiler spaces, accommodations spaces, service spaces, control stations, chain lockers, drinking water tanks and stores.

Accessibility to spaces: In order to facilitate inspection of various structures and equipment in gas carriers, the IGC Code requires arrangements that allow visual inspection of at least one side of the inner hull structure and insulation located in hold spaces. Adequate access to cargo tanks to allow internal inspection is also required.

Leak Detection for Gas Carrier Hold Spaces: The IGC Code requires hold spaces and insulation areas where cargo leakage could occur to be equipped with gas detection and low temperature alarms.

Cargo Containment Design Requirements: The IGC Code mandates cargo containment designs that address a design vapour pressure for the containment system that considers the cargo vapour pressure and the maximum allowable relief valve setting.

Structural Analysis Requirements: The IGC Code mandates that structural analyses be performed for each type of cargo containment design to address the specific loads of concern for that type of cargo containment design. The IGC Code also defines the allowable stresses for independent cargo tanks.

Secondary Barrier Provisions: LNG carriers built to the IGC Code require a secondary cargo barrier to contain an envisaged leakage of liquid cargo. Membrane and Type A independent tanks require a full secondary barrier. Independent Type B tanks only require a partial secondary barrier.

Low Temperature Provisions: In addition to the requirements to handle envisaged leakage, the IGC Code requires a combination of proper material selection, adequate insulation, and use of heating systems to ensure that hull structures are not exposed to temperatures below their design temperature.

Construction and Testing Requirements for Cargo Containers: The IGC Code includes construction and testing requirements that address welding, workmanship, quality assurance, hydro pneumatic or hydrostatic pressure testing, leak testing, and non-destructive testing of welds.

Pressure Vessel and Piping System Requirements: The IGC Code contains provisions for general design requirements to ensure that the piping is appropriately designed and fabricated.

Emergency Shutdown Valves and Shutdown Systems: The IGC Code requires remotely controlled emergency shutdown valves on the ship for stopping liquid and vapour transfers between the ship and shore. Cargo pumps and compressors must be arranged to shut down automatically if the emergency shutdown system closes the emergency shutdown valves.

Cargo Pressure/Temperature Control: The IGC Code requires pressure control for the cargo system in order to keep the cargo tank pressure under the tank design pressure or the maximum allowable relief valve setting (MARVS).

Pressure Relief Systems: the IGC Code requires at least two pressure relief valves of appropriate capacity. The valves have to be provided with vent piping that minimizes the potential for accumulation of LNG vapour on deck or ingress of vapour into areas where it might create a dangerous condition.

Vacuum Protection Systems: The IGC Code requires that any LNG cargo tank not designed for the maximum pressure differential that could be developed by (1) pumping out a tank without vapour return, (2) operating a refrigeration system, or (3) sending boil-off vapour to machinery spaces, be provided with a vacuum protection system.

Vessel Fire Protection Systems: Per the IGC Code, LNG carriers require a firewater main system and hydrants/hose stations with the ability to supply at least two jets of water to any part of the deck in the cargo area and parts of the cargo containment and tank covers above the deck.

Cargo Tank Instrumentation: In order to allow LNG carrier crew to monitor cargo tank conditions, the IGC Code requires a variety of instrumentations.

Vessel Gas Detection Systems: In addition to gas detection discussed previously, the IGC Code requires a permanently installed gas detection system with audible and visual alarms for different areas of the vessel.

Gas Detection and Safety Shutdown Systems for Terminal Operations: LNG unloading systems and docks are equipped with LNG vapour detection, fire detection, and associated safety shutdown systems that shut down pumping operations and close valves to isolate the transfer lines.

Emergency Release Couplings: Current designs for LNG terminals have emergency release couplings that are fitted between the ship's cargo manifold and the receiving station. These couplings are designed to release if vessel movement exceeds predetermined limits.

12 Identified Risk Control Options

In order to identify new risk control options, various experts were invited to participate in brainstorming sessions. In all, three expert workshops were held in order to come up with and prioritize possible risk control options for LNG carriers within this study. The descriptions of the major hazards and corresponding risk control options from the hazard identification and the results from the risk analysis were summarised and presented to the experts and served as a starting point. A further description of the RCO workshops and results from these can be found in appendix A.5 of this annex.

The outcome of the RCO workshops was a list of 9 prioritized risk control options that were selected for further evaluation in terms of cost effectiveness assessment:

RCOs to reduce the collision, grounding and contact:

- Required maintenance plan for critical items.
- Increase double hull width, increase double bottom depth or increase hull strength.
- Redundant propulsion system - two shaft lines.
- Improved navigational safety.
- Restriction on crew schedule to avoid fatigue of crew.
- Increased use of simulator training.

RCOs to reduce fire or explosion:

- Required maintenance plan for critical items.
- Restriction on crew schedule to avoid fatigue of crew.
- Periodic Thermal image scanning of engine room.

RCOs to reduce incident while loading and unloading of cargo:

- Redundant radar sounding for filling level check.

RCOs to reduce failure leakage of cargo containment system:

- Strain gauges (for measuring stresses onboard).
- Redundant radar sounding for checking filling level.

These risk control options will be described in more details in the following.

12.1 Detailed description of selected RCOs

12.1.1 RCO 1: Required maintenance plan for critical items

When viewing the vessel life cycle cost breakdown, only about 25% of the costs may be directly related to acquisition. That means 75% of the total cost is operation and support and is made up of personnel, maintenance and modernization. According to [77] the largest of these (37%) are personnel costs, followed by maintenance (21%) and modernization (13%). From this breakdown one may see the economical importance that maintenance represents in the vessel life cycle.

There are basically two maintenance approaches: corrective maintenance (CM), also known as run-to-failure, where a piece of equipment is not maintained until it fails, and preventive maintenance (PM), which is performed in order to avoid a failure. The latter approach has traditionally been adopted by most ship owners. However, the criticality of some systems onboard leads to special attention to be taken in regard to their maintenance. By introducing Risk Based Maintenance [83] (and risk based inspection), the criticality class identification is replaced with two fields, namely probability and consequence associated with failure. Introduction of this approach together with improvements of inspection and maintenance planning are expected to improve the safety and reduce the risk of unavailability of the systems.

Required maintenance plans for four separate systems will be evaluated, i.e. for the propulsion, navigational, steering and cargo handling system. The cost effectiveness assessment of these alternatives will be described in appendix A.2 of this annex.

12.1.2 RCO 2: Strain gauges (for measuring stresses onboard)

In a simplistic form strain gauges can be seen as devices used to measure deformation (strain) of a structure. Strain gauges allow hull monitoring from the bridge in order to evaluate the structural behaviour during several operation phases. It is then possible, with a high level of accuracy, to monitor the hull structure in critical areas which are known to potentially have fatigue or stress concentration during operation.

Typically the strain gauges applications can be related to wave load estimations in specific sea states and assessment of hulls structural response during these operation loads. This assessment is particularly important under severe weather conditions where extreme sea states can occur. Also, they can provide warnings of overloading by the ability that these systems have to evaluate, in real time, the current load, reducing substantially the risks of structural damage. Due to the constant increase of ship dimensions crews have more difficulties in estimating stress overloading during loading/unloading operations. Furthermore, constant and cyclic loads lead to the fatigue phenomena. A hull monitoring system with static strain measurement capability can be used to monitor changes in static stress distribution in the hull during cargo loading. Therefore, the results of hull monitoring provide valuable information not only about the vessel but also in how to optimise the design of new ships in the same class. Recent systems allow also the evaluation of weight increase due to ice conditions and tank sloshing, particularly in LNG vessels.

In LNG vessels, due to their load capacities and dimensions, are vessels under high variations of stress as consequence of bending and torsional moments during loading/unloading operations. These high stress concentrations are particularly high in the main deck since this is the area with larger distance to the neutral axis of the structure, and particularly amidships where the bending moments are higher. In order to assess the torsional moments, it is normally required that two strain gauges be placed in both sides of the vessel in order to assess the associated displacements.

Although there were identified several risks in which strain gauges could be used as potential warning system to help make decisions, this study will evaluate it in term of reduction of failure or leakage of cargo containment system. Situations where failure of the containment may occur due to fatigue reasons, where cracks develop due to the cyclic stress impact or due to sloshing effect are addressed. Sloshing-induced impact loads can cause a critical damage on tank structure, particularly in membrane insulation systems but also to the hull structure, the pump tower and supports. The strain gauges can be used to assess and monitor the situation allowing, in some cases, to avert consequential events.

The strain gauges are installed in the containment system and the measurement data are displayed, logged and further analysed on the bridge in order to assist the navigation, controlling by these means the membrane strain behaviour. By decreasing the frequency of encounter between the vessel and waves, through changing the ship's velocity or/and route, leading to a decrease in the excitation frequency in the tanks and therefore to a decrease of the sloshing effect and damage on tank structure

In appendix A.2 a detailed cost-benefit analysis of implementation of strain gauges in the containment system is presented.

12.1.3 RCO 3: Increase double hull width, double bottom depth or hull strength

LNG carriers are intrinsically safe ships as they are built with a double hull structure. This arrangement may avoid major consequences in the case of a collision or grounding event.

The IGC Code requires cargo tanks to be protected at least a minimum distance inboard from the ship's shell plating. In the case of a LNG vessel, this distance shall be not less than B/15 or 2 m, whichever is less, for the bottom, and 760 mm for the side. In general, due to design and production constraints, these dimensions, i.e.: double side width and double bottom depth are beyond the required ones.

As a potential option, an evaluation on the effects of an increase of the double hull dimensions and ship strength for collision and grounding aspects has been carried out on a typical vessel, to assess the suitability of measures of this type.

The contemplated cases analysed have been:

- 20% increment of the double hull width.
- 20% increment of the double bottom depth.
- increase the hull strength (maintaining the double side and double bottom original dimensions)

The details of this cost effectiveness evaluation are contained in appendix A.2.

12.1.4 RCO 4: Redundant propulsion system - two shaft lines

According to statistics on tanker accidents between 1976 and 1994, around 30% of all total losses were caused by machinery failure [82]. Many of them could have been avoided if the ships had had redundant propulsion and/or steering systems.

The redundant propulsion and steering system must ensure that, irrespective of the ship's loading condition, when a failure in a propulsion or steering system occurs:

- The manoeuvrability of the ship can be maintained.
- A minimum speed can be maintained to keep the ship under control.
- The ship can maintain operation with a redundant propulsion or steering system so that a vessel can ride out the storm or slowly make for harbour.
- The propulsion and steering functions are quickly re-established.

Redundant propulsion and steering systems can greatly reduce the risk of vessel disability and subsequent loss of life or cargo and damage to the environment. The benefits of installing redundant propulsion and steering systems are clear from an operational point of view:

- Greater reliability.
- Improved safety levels.
- Higher vessel availability.

For the purpose of this cost effectiveness assessment, redundant propulsion systems will be achieved by installation of independent engines and two shaft lines. This would also imply different hull forms compared to ships with single propellers. The cost effectiveness of this risk control option is evaluated in appendix A.2.

12.1.5 RCO 5: Improved navigational safety

Improved navigational safety can be achieved in a number of different ways, and therefore this risk control option has to be more clearly defined. A previous study on navigational safety on large passenger ships has evaluated the cost effectiveness of twelve prospective risk control options, and identified 4 cost effective risk control options with a "considerable potential for reducing the frequency of collision and grounding" [62]. These are:

a. ECDIS (Electronic Chart Display and Information System)
b. Track control system
c. AIS (Automatic Identification System) integration with radar
d. Improved bridge design

The risk control options related to navigational safety in the list above might be promising alternatives for LNG carriers as well, and the cost effectiveness of implementing these for LNG carriers will be evaluated in this study. Hence, the risk control option *improved navigational safety* is defined as implementation of one or more of these alternatives. These will be briefly described in the following, and a more comprehensive description can be found in e.g. the FSA report for passenger ships [61] or NAV 51/10 [62].

ECDIS is a navigational aid that can be an alternative to nautical paper charts and publications to plan and display the ship's route as well as to plot and monitor ship positions throughout the voyage. It is capable to determining a vessel's position in real time. The use of this aid would reduce the navigation officer's workload compared to using paper charts. Although not mandatory, the use of ECDIS onboard current vessels is quite common and the proposed risk control option is to make ECDIS mandatory for LNG carriers. Results from a recent study of ECDIS for ship types other than large passenger vessels has been submitted to the IMO Maritime Safety Committee's 81st session, and this study will be referred to whenever appropriate [63], [64].

Track control systems are continuously comparing the vessel's actual course with that originally planned. The intended route will be planned before departure and entered in the track control system, and real time information from navigational equipment will be utilized in order to ensure that the planned route is followed. In case of deviations, e.g. due to environmental forces, the vessel is automatically corrected to follow the intended track. The track control system is a powerful tool that will liberate more time for the operating officer to monitor traffic conditions, although the navigator still has to ensure that the plotted track is actually followed. It is possible to integrate the track control system with the ECDIS proposed in the previous risk control option.

An Automatic Identification System (AIS) is designed to send and receive information in relation to a vessel's identity, course and cargo. Current regulations require such information to be presented in an AIS display and the minimum requirements are three lines of data consisting basic information of a selected target. Additional information can be obtained by scrolling, and it is time consuming and distractive for the navigator to search for such information. The AIS can also be integrated with the radar's Automatic Radar Plotting Aid (ARPA) function so that the additional data is available in the radar display. This is believed to improve the radar performance and navigation in different ways:

- Easier access of AIS information
- Detection of targets which are in radar shadow areas
- Identification of ship names for radar targets
- Accounting for the ship's rate of turn, hence predicting more accurately the target's path
- Extend the radar's range in some cases
- Clarify the target's intentions

Benefits from the AIS-ARPA integration will include enhanced situation and traffic condition awareness and improved ability to make early decisions based on real-time data for avoidance of potential collisions.

SOLAS contains minimum requirements regarding mandatory equipment and gives limited requirements related to bridge layout. Improved bridge design means an upgrade from standard/minimum SOLAS bridge design in order to achieve improved performance of all navigation related tasks as well as enhanced cooperation between the bridge team members. The aim is to enhance the navigational safety by reducing the probability of failure in bridge operations by any cause. For the purpose of this cost effectiveness assessment, the voluntary DNV class notation for nautical safety, NAUT-AW is referred to [65]. This voluntary class notation regulates i.a.

- Design of the workspace and the bridge layout
- Navigational equipment
- Human-machine interface

12.1.6 RCO 6: Restriction on crew schedule to avoid fatigue of crew

Fatigue can be defined in many ways. However, it is generally described as a state of feeling tired, weary, or sleepy that results from prolonged mental or physical work, extended periods of anxiety, exposure to harsh environments, or loss of sleep. The result of fatigue is impaired performance and diminished alertness [78]. There have been many ship incidences where fatigue has been a suspected contributing factor or cause. Fatigue has been discounted as a potential cause of human error, and a common myth has existed that fatigue could be prevented by characteristics of personality, intelligence, education, training, skill, compensation, motivation, physical size, strength, attractiveness, or professionalism.

Much legislation already exists in particular related to the mandating rest periods for watchkeeping personnel. The major international regulation that specifically takes fatigue of crewmembers into account, the I*nternational Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW 95),* was adopted in 1995. This requires a minimum of 10 hours rest in every 24 hours (which may be reduced to 6 hours every 24 hours for a period of not more than two days). These regulations require that such rest periods be enforced on watchkeeping personnel. Additional guidelines from (e.g. Resolution A.772 (18) disseminated as MSC/Circ. 1014) have been developed to provide ways of recognising fatigue and standardized formats to record daily hours of work and rest.

Two recent studies show the importance of fatigue of seafarers. One indicated 25% of all seafarers experienced fatigue on at least half of their trips and that 24% of seafarers saw others working in a fatigued state on at least half of their trips [78]. The UK Marine Accident Investigation Board (MAIB) recently noted that in an analysis of 65 incidents over a 10 year period, one-third of the groundings involved a fatigued officer alone on the bridge at night, two-thirds of the vessels involved in collisions were not keeping a proper lookout, and one third of all the accidents that occurred at night involved a sole watch keeper on the bridge [79].

Although particular legislation exists regarding working and resting periods onboard, there is some lack of definition regarding port operations of loading and unloading. Potential problems are related to cases where crews work long hours when at port leading to fatigue at a later time when the ship has left port. This fatigue issue is mainly related to vessels which are engaged in frequent port operations, and this may eventually be more relevant in the future with the development of smaller LNG vessels for short sea shipping.

Thus, this control option is an extension of the STCW/ILO regulations regarding rest periods to the time spent in port in order to obtain reduction of crews fatigue and hence in the probability of collisions, groundings and contact. In appendix A.2 a detailed cost-benefit analysis of this risk control option is presented.

12.1.7 RCO 7: Increased use of simulator training

This risk control option aims at increasing the bridge team's ability to handle difficult manoeuvring tasks and crisis situations by increased use of simulator training. The effect of such training would be better navigational safety and a reduced risk of collision, grounding and contact events.

The simulator training could be specially designed for particular port environments, underwater topography and particular bridge layouts on specific vessels and would give the participants exercises in handling challenging situations from different positions of the bridge team. Important parts in such exercises might be passage planning, situation awareness and operation during malfunction of critical technical equipment.

The risk control option suggested herein goes beyond the basic training requirements defined by IMO's International Convention on Standards of Training, Certification and Watch keeping for Seafarers (STCW) [60]. For the purpose of this study, increased use of simulator training is assumed to require sending all crewmembers of the bridge team on a 5-day simulator training course every 5 years.

In a previous FSA on navigational safety of passenger ships [61], similar risk control options were investigated for passenger ships. The results from this study have been submitted to IMO [62] and received positive feedback. Hence, this study will be referred to and estimates in the current study will be based on these previous results whenever appropriate.

12.1.8 RCO 8: Periodic thermal image scanning of engine room

Independent studies on different ship types indicate that engine room fires are the most frequent fires occurring onboard ships [67], [68], [69]. Furthermore, leakage of oil onto hot surfaces is the main reason for engine room fires [70]. It is believed that this is also the case for LNG carriers with diesel engines, for which accident statistics are scarce.

It is emphasised that many LNG carriers are operating with steam turbine engines instead of diesel engines which are most common on other ship types, and the risk picture is very different for these different machinery types. Engine room fires due to hot surfaces are believed to be a bigger problem for ships with diesel engines than for ships with steam turbines. Thus, this particular risk control option is believed to be most relevant for LNG carriers with diesel engines and the analysis will only be applicable to those vessels. It is noted that new LNG carriers are likely to be built with regasification units and diesel engines instead of steam turbines, and for these new vessels, the analysis will be relevant.

This risk control option aims at reducing the engine room fire frequency by periodically performing thermal image scanning of the engine rooms in order to identify and remove possible hot surfaces. For the purpose of this study it is suggested that thermal image scanning of the engine rooms are performed once every year, and that appropriate corrective measures are carried out according to the findings in the survey. E.g. any surfaces above 220 °C are to be insulated or otherwise protected in order to avoid ignition of flammable fluids. Currently, there are no mandatory requirements regarding this, but infrared thermoscanning is a part of the voluntary DNV class for additional fire protection (F-AMC) [71].

12.1.9 RCO 9: Redundant radar sounding for checking filling level

One of the risks faced by LNG ships' hull underwriters is the potential for cryogenic damage to the ship once LNG is released onto the ship's structure. This spillage can be due to overfilling, malfunction of a valve or human failure among other causes.

The levels of storage tanks on board must be continuously monitored since overfilling or product discharge on deck could have consequences for human life and for property. Especially the loading and unloading procedures have to be carefully supervised and monitored to keep everything under control.

To check level indicators for cargo tanks, the IGC Code (Rule 13) requires that each cargo tank should be fitted with at least one liquid level gauging device, designed to operate at pressures not less than the MARVS of the cargo tank and at temperatures within the cargo operating temperature range. If only one liquid level gauge is fitted it should be arranged so that any necessary maintenance or repairs can be carried out while the cargo tank is in service. Usually this gauging device is a radar sounding device.

If a redundant radar sounding is provided for each LNG tank the risk of overfilling during cargo transfer may be reduced. By carrying a second gauging device, spillage during loading procedures can be avoided in cases where the compulsory gauging device fails, and this will reduce the risk of overfilling.

13 Cost effectiveness of selected RCOs

According to this study, the following cost effectiveness estimates are arrived at for each of the investigated risk control options. The cost effectiveness is presented in terms of both the Gross Cost of Averting a Fatality (GCAF) and the Net Cost of Averting a Fatality (NCAF). The numbers are given in 10^6 USD/fatalities.

As a basis for the cost benefit calculations, the following important assumptions are made:

- Total number of crew members 30
- Assumed lifetime of the LNG vessel 40
- Depreciation rate 5%

Table 15: GCAF and NCAF values associated with each risk control option.

Risk Control Options Description	Gross CAF (10^6 USD/fatality)	Net CAF (10^6 USD/fatality)
RCO 1.- Risk based maintenance. *a. Propulsion system* *b. Steering systems* *c. Navigational system* *d. Cargo handling system*	a. 57.2 b. 7.4 c. 2.21 d. 159	a. <0 b. <0 c. <0 d. 118
RCO2: Strain gauges.	394.1	351.2
RCO 3: Increase double hull width, double bottom depth or hull strength. a. Increase double hull width. b. Increase double bottom width. c. Increase hull strength.	a. 74.3 b. 59.5 c. 60.0	a. 70.8 b. 54.2 c. 55.1
RCO 4: Redundant propulsion system - two shaft lines.	60.8	54.2
RCO 5: Improved navigational safety. a. ECDIS. b. Track control system. c. AIS integrated with radar. d. Improved bridge design.	a. 3.1 b. 0.4 c. 0.06 d. 2.3	a. < 0 b. < 0 c. < 0 d. < 0
RCO 6: Restriction on crew schedule to avoid fatigue of crew.	159	153
RCO 7: Increased use of simulator training.	12	5.8
RCO 8: Periodic Thermal image scanning of engine room.	28	20
RCO 9: Redundant radar sounding for filling level check.	236	231.9

All numbers are based on introduction of one RCO only. Introduction of more than one RCO will lead to higher NCAF/GCAFs for other RCOs addressing the same risks.

High GCAF/NCAF values indicate that the considered RCO is not a cost effective measure. A negative NCAF indicates that the RCO is economically beneficial in itself, i.e. the costs of implementing the RCO is less than the economical benefit of implementing it. According to current practice within IMO and selected criteria for this study, a risk control option will be regarded as cost-effective if it is associated with GCAF ≤ USD 3 million or NCAF ≤ USD 3 million. Cost effective measures that can be demonstrated to have a high potential for risk reduction will consequently be recommended for implementation.

The results of the cost-effectiveness assessments show that:

- *RCO 1 (c) – "Risk Based Maintenance" (navigational systems) and RCO 5 (a, b, c, and d) – "Improved navigational safety" have negative NCAF, implying a positive economical effect from implementation and also their GCAF values are below or very close to the limit of USD 3 million per averted fatality. Hence, these RCOS could be recommended also based on safety considerations alone.*
- *RCO 1(a, b) – "Risk Based Maintenance" have a negative NCAF, implying a positive economical implementation, although the potential for risk reduction is small.*
- *RCO 1 d) – "Risk Based Maintenance (Cargo handling system)", RCO 2 – "Strain Gauges", RCO 3 - "Increase double hull width, double bottom depth or hull strength", RCO 4 - "Redundant propulsion system – two shaft lines", RCO 6 – "Restriction on crew schedule to reduce fatigue", RCO 7 - "Increased use of simulator training", RCO 8 - "Periodic thermal image scanning of engine room" and RCO 9 - "Redundant radar sounding for filling level check" have GCAF ranges from 12 to very high values, the NCAF ranges from 5.8 to 351. Hence these RCOs are not cost effective according to this assessment.*

14 Concluding remarks

Prior to initiating the work on this FSA on LNG carriers, the general opinion about the fleet of LNG carriers was that these vessels are associated with a high safety level. LNG tankers were thought of as well designed, constructed, maintained and operated vessels with much attention to safety. Indeed, the safety record of the LNG carrier fleet is among the best in the world.

These perceptions have been substantiated by this FSA study where it was found that a) the safety level lies in the ALARP region and b) most investigated RCOs were found to be not-cost effective. In spite of much effort put into identifying new risk control options related to various hazards LNG carrier are exposed to, only risk control options related to navigational safety have been found to be cost effective. Presumably, this can be explained by the generally high focus on safety within the LNG industry, and the corresponding high safety level of LNG tankers and with the relatively low costs associated with implementing navigational measures.

These findings, that navigational measures represent cost effective means to reduce the risk, are in agreement with similar studies on other shiptypes. I.e. recent studies have demonstrated that navigational risk control options are cost effective for large passenger ships as well as some other types of cargo vessels. It is also in agreement with the risk analysis carried out within this FSA which identified collision and grounding scenarios as the most important risk contributors.

Acknowledging the physical properties of LNG and the possible severe consequences of a major spill accident following a collision and grounding and the difficulty of assuring that the LNG tanks will be able to withstand high energy collision and grounding impacts, preventing such accidents to occur in the first place seems intuitively to be the best strategy for mitigating the risk. Enhanced navigational safety is one obvious alternative for such preventive measures, and as such it should not be surprising that RCOs related to navigation turned out to be the most cost effective.

Notwithstanding the high safety level associated with LNG carriers, the identification of several cost-effective risk control options – all related to navigational safety – demonstrate that the risk associated with LNG carriers are not ALARP. In order to bring the risk level down to ALARP it is therefore recommended that these RCOs should be made a requirement for the LNG tanker fleet.

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Appendix to Annex II

A.5 Risk Control Options: Expert Workshops

In order to select possible new risk control options for further evaluation, three expert workshops were arranged. The main tasks in these workshops were to identify new risk control options and to prioritize them in terms of expected cost effectiveness. Each workshop contained two parts. The first was a brainstorming session where all new risk control options the experts could come up with were recorded. In the second part, the experts were asked to rank and rate all identified risk control options in terms of perceived cost effectiveness according to their subjective opinion. The ranking from all the experts where then analysed by the project team, and the ten most promising options according to expert opinion were selected for further cost effectiveness analysis.

A.5.1 General information and workshop participants

Three meetings took place with different participants:

The first meeting was held in Madrid on the 6th and 7th of March 2006 with the following participants:

Avelino Martínez Cimadevila	Navantia	Ship yard
Miguel Hernández Aznar	Navantia	Ship yard
Santiago González Tejero	Navantia	Ship yard
Pedro Antão	IST	Research centre
Francisco Del Castillo de Comas	Navantia	Ship yard
Victoria Martínez	Navantia	Ship yard
Erik Vanem	DNV	Classification society

In order to validate the results from the initial meeting, a second meeting was held in Oslo on the 21st of March 2006 with the following participants:

Gunnar Rød	DNV	Classification society
Sverre Valsgård	DNV	Classification society
Bjørn Lian	DNV	Classification society
Trygve Tobiesen	DNV	Classification society
Arve Lepsøe	DNV	Classification society
Erik Vanem	DNV	Classification society

In order to evaluate the impact of the implementation of the selected risk control options in different scenarios, a third internal meeting was held in Lisbon on the 2nd of June, with the following participants:

Yordan Garbatov	IST	Research centre
Ângelo Teixeira	IST	Research centre
Tiago Santos	IST	Research centre
Pedro Antão	IST	Research centre

Together these participants form a representative specter of the maritime industry dealing with LNG vessels, and they represent a comprehensive expertise on safety aspects of LNG carriers.

A.5.2 Preliminary results from the first workshop

The list of risk control options that were identified during the first meeting is summarized in table 2 together with the average rating from the participating experts. The ratings are based on the experts' subjective opinions, where 1 is the lowest and 5 is the highest score in terms of perceived cost effectiveness. All risk control options with a score higher than 3.5 were initially selected for further investigation and brought forward to the second workshop for further discussion.

Table 16: Ranking of Risk Control Options at first workshop

Proposed Risk Control Options	**Average score**
Retractable thrusters or pod near centre of gravity of the vessel.	4,8
Risk based maintenance –required maintenance plan for critical items.	4,5
Strain gauges (for measuring stresses onboard	4,2
Increase double hull width/ hull strength, and/or double bottom depth.	4
High lift rudder/fish –tale rudder/compensated rudder. (Improve manoeuvrability requirements)	4
Redundant radar sounding for checking filling level.	3,8
Redundant propulsion system / two shaft lines.	3,8
Improved navigational safety. (ECDIS?, extra watch-out on bridge, etc...).	3,8
Sonar equipment (to avoid collision, contact and powered grounding).	3,8
Restrictions on crew schedule (to avoid fatigue of crew).	3,8
Require electronic chart systems on all vessels	3,6
Increased use of simulator training	3,6
Increase vessel design life - reliability based design.	3,6
For membrane carriers: Install double filters in the intake piping systems (to prevent metal particles entering the tank and damaging the invar membrane inside the tank).	3,5
Black box on the bridge.	3,4
New hydrographic surveys in many parts of the world.	3,4
Segregate opposing traffic, create lanes in congested areas.	3,2
Multiple echo sounders.	3,2
Post squat tables in wheelhouse.	3,2
Increase requirements for coating in ballast tank.	3,2
Redundant ventilation system in compressor rooms.	3
Proper pilot training in certain areas.	3
Deformable tanks.	2,8
Fitting of crankcase explosion prevention devices, i.e. inerting the crankcase with N_2. (For new vessels with diesel engines burning oil).	2,8
Flexible joints between distribution pipes on board the vessel.	2,6
Additional class notation for vessels operating in icy waters, strengthening the bow/hull.	2,4
Install pressure gauge to prevent pressure pumps to be started when tanks are empty than can result in under-pressure and collapse of the tanks.	2,4

Make salvage operations cheaper	2,4
Thermal imaging in engine room	2,4
Fender/safety belt around the vessel to absorb collision energy.	2,2
Increase the number of cargo tanks (same volume, but smaller tanks)	2,2
Softening the bulbous bows (on all vessels) to make this collapse instead of the struck vessel	2
Gas combustion unit	2

A.5.3 Outcome of the second workshop and final list of RCOs

The aim of the second meeting was threefold: a) possible to identify new risk control options not considered in the first workshop, b) to evaluate and validate the selection of risk control options carried forward from the first workshop and c) to revise the list of risk control to be subject to detailed cost effectiveness analyses. Thus, the outcome of the second workshop would be the final list of risk control options to be evaluated in this study.

A few other issues were also discussed without making it to the prioritized list of risk control options, i.e. stirring equipment to avoid rollover (more critical for stationary tanks than for vessel engaged in normal trade) and increased use of water mist systems for fire protection. At any rate, the following amendments to the list of risk control options were made in the second workshop:

Measures proposed at the first workshop:

1. Retractable thrusters or pod near centre of gravity of the vessel
2. Risk based maintenance – required maintenance plan for critical items
3. Strain gauges (for measuring stresses onboard)
4. Increase double hull width, hull strength and/or double bottom depth
5. High lift rudder/fish-tale rudder/compensated rudder (improve manoeuvrability requirements)
6. redundant radar sounding for checking filling level
7. Redundant propulsion system/two shaft lines
8. Improved navigational safety (ECDIS, extra watch-out on bridge etc.)
9. Sonar equipment (to avoid collision, contact and powered grounding)
10. Restrictions on crew schedule (to avoid fatigue of crew)
11. Require electronic chart systems on all vessels
12. Increased use of simulator training
13. Increase vessel design life – reliability based design

Revised list after the second workshop

1. Risk based maintenance – required maintenance plan for critical items
2. Strain gauges (for measuring stresses onboard)
3. Increase double hull width, hull strength and/or double bottom depth
4. Redundant propulsion system/two shaft lines
5. Improved navigational safety (ECDIS, improved bridge design etc.)
6. Restrictions on crew schedule (to avoid fatigue of crew).
7. Increased use of simulator training (also better crew training/common terminology)
8. Periodic thermal image scanning of engine rooms (e.g. at class renewal)
9. redundant radar sounding for checking filling level

Thus, the final list of nine risk control options contains the risk control options that were selected for further evaluation and cost-effectiveness assessment.

A.5.4 Outcome of the third workshop

The main aim of the third workshop was to evaluate the impact of the implementation of the selected risk control options in different scenarios. The results of this workshop are presented in Table 3.

Table 17: Expert opinion evolution of IST RCO's

Risk Control Options (RCO)	**Scenario**	**Risk Reduction with implementation of RCO (%)**			
		Expert 1	**Expert 2**	**Expert 3**	**Average**
Risk Based Maintenance –a-	Fire / explosion	20	15	10	15
	Drift grounding	20	18	23	20
Risk Based Maintenance –b-	Collision	5	2	7	5
	Drift grounding	25	25	40	30
	Contact	15	15	15	15
Risk Based Maintenance –c-	Collision	10	15	21	15
	Powered Grounding	5	15	12	10
	Contact	10	10	24	15
Risk Based Maintenance –d-	L/U incident	20	5	5	10
Strain Gages	Containment failure	50	15	25	30
Restriction on crew schedule (in port) to avoid fatigue of crew	Collision	10	20	15	15
	Grounding	15	25	20	20
	Contact	35	30	25	30

A.5.5 Short CV's of workshop participants

Participants in the first workshop:

Francisco del Castillo

Francisco del Castillo is a M.S. Naval Architect, graduated from Madrid Polytechnic University. He is also Master in Shipping Business and Maritime Law by ICADE Comillas University of Madrid. He has been working for Astilleros Españoles, IZAR and now for Navantia in merchant and military vessels as a ship designer since 1997. Mr. del Castillo has over 8 years of engineering and management experience in the field of naval and commercial ship design and construction. He has been mainly involved in passenger and LNG ship projects, especially involved in general design and safety aspects. He has also been very active in the R&D area participating in several international projects regarding Safer Ship Design.

Avelino Martinez Cimadevila

Avelino Martínez has a broad experience in the field of structural design and analysis. He has an M.S. in Naval Architecture from the Polytechnic University of Madrid (1978). Since then, he has been actively involved in the design and analysis of various merchant and naval vessels. He is currently Structural Project Manager for OPV´s in Navantia Technical Direction in Madrid, responsible for structural design and analysis. Mr Martínez has been an active member of v Euroyards Technical Groups and he has deep experience working with the several Classification Societies.

Miguel Hernández Aznar

Miguel Hernández is an officer of the Merchant Marine, graduated from University of La Coruña. He has been working for several shipping companies and Astilleros Españoles, IZAR and is now working for Navantia as Head of International Programs Section R&D Department. Mr. Hernández has over 24 years of experience in the field of shipping business as well as in construction. Also he is Master in shipping business for Maersk and Master in Business for IZAR.

Santiago González Tejero

Santiago González is a M.S. Naval Architect, graduated from Madrid Polytechnic University. He has been working for Astilleros Españoles, IZAR and now for Navantia in merchant and military vessels as a ship structure and hull form designer since 1997.

Pedro Antão

Pedro Antão is an engineer in Naval Architecture and Marine Engineering from IST, Lisbon, and MSc in Reliability Engineering and Safety Management from the University of Heriot-Watt, Edinburgh. Pedro Antão has worked at IST Unit of Marine Technology and Engineering in research projects related to Maritime Accidents, Human Factors and Human Reliability, Risk Analysis and Safety since 1999.

Erik Vanem

Erik Vanem has a Cand. Scient degree (Master of Science equivalent) in Physics from the University of Oslo. He has two years onboard experience from a seismic vessel, working with onboard seismic processing. He has been working with maritime risk analysis/FSA within DNV Research for about three years. His experience includes FSA studies and risk assessment of passenger ships, bulk carriers and oil tankers. Topics such as fire and evacuation, damage stability, collision and grounding scenarios, navigation and environmental risk have been studied.

Victoria Martínez

Victoria Martínez is a Naval Architect, graduated from Madrid Polytechnic University. She is also Master in Shipping Business and Maritime Law by ICADE Comillas Pontificia University of Madrid. She is currently working for Navantia in R&D projects since 2005.

Additional participants in the second workshop:

Gunnar Rød

Gunnar Rød graduated from NTH, Trondheim in 1974 with a Master of Science degree. He has been employed at DNV since 1974 and is currently the ship type responsible for gas carriers.

Sverre Valsgård

Sverre Valsgård holds a Master of Science degree (1969) and a doctoral degree (1979) from NTH, Trondheim. He has been working for DNV since 1972 where he is currently working at the Maritime Technology and Production centre. He has a broad experience within e.g. structural analysis, LNG tank design criteria, collision damage evaluations, probabilistic methods and rule development. He has several years experience with working with LNG carriers.

Bjørn Lian

Bjørn Lian is an engineer from Oslo Technical Maritime School where he graduated in 1980 with a major in naval architecture. He currently holds the position of principal surveyor in the field of fire safety at DNV. Previous working experience includes working for Leif Høegh & Co and the Royal Norwegian Navy.

Trygve Tobiesen

Trygve Tobiesen holds a Master of Science degree from NTH, Trondhaim, where he graduated in 1964. He has worked with gas tankers at DNV head office as a specialist for more than 35 years and is currently employed as principle surveyor at the department for cargo handling, piping systems and gas carriers.

Arve Lepsøe

Arve Lepsøe is an engineer from Tønsberg Maritime Høyskole (1992) and a Master of Science from NTH, Trondheim with a major in nautical science (1997). His previous working experience includes working as a navigator on Norwegian Navy vessels and as deck officer on several chemical tankers in international trade. He is currently working as senior nautical surveyor in the department for control systems and nautical safety at DNV (since 1998).

Additional participants in the third workshop:

Yordan Garbatov

Yordan Garbatov is an Assistant Professor at the Naval Architecture and Marine Engineering Department at IST. He graduated as a Naval Architect from the University of Varna in 1986 and concluded his PhD at IST in the area of Fatigue Reliability and Reliability-Based Maintenance Planning. He has nearly 80 papers published in national and international conferences and journals.

Ângelo Teixeira

He graduated as a Naval Architect from IST and MSc from the Glasgow University. Currently is concluding his PhD. He works in the area of structural reliability and industrial safety. He has 43 papers published in national and international conferences and journals.

Tiago Santos

He graduated as a Naval Architect from IST and MSc from the Glasgow University. Currently is concluding his PhD. He works in the area of intact and damage stability. He has 23 papers published in national and international conferences and journals.

Other experts consulted:

Carlos Oliveira

Carlos Oliveira is presently Maritime Operations Director in the Port of Sines (LNG terminal). He is also an experienced master of commercial vessel with long experience at sea.

Helder Almeida

Helder Almeida is presently Port Facility Security Office in the Port of Lisbon. He is also officer of commercial vessels.

Helder Almeida

Carlos Almeida is presently a Port State Control Officer. He is also Captain of commercial vessels.

A.6 Cost, Benefits and Risk Reduction assessment of selected RCO

A.6.1 RCO 1: Risk based maintenance

In this risk control option four critical systems have been selected for the purpose of evaluating the cost effectiveness of introducing risk based maintenance (RBM) and risk based inspection (RBI). Traditionally, shipboard machinery and system maintenance relies on planned maintenance (based on prescribed time schedule), and to varying degrees on predictive maintenance (using condition-monitoring techniques). With the proposed RCO schemes risk assessment techniques are introduced to provide a rational decision-making process to optimize maintenance tasks, and hence costs, while at the same time achieving optimal reliability for the system in all its operating modes.

Risk Based Maintenance for the following systems will be considered:

- RCO 1a: Propulsion System
- RCO 1b: Steering System
- RCO 1c: Navigational System
- RCO 1d: Cargo Handling System

It is very difficult to quantify the cost associated with introduction of these maintenance schemes. However, from the comparison of the different maintenance schemes it becomes clear that the risk based maintenance implies additional analysis through the application of analytical tools (FMECA, RCM task selection flow diagrams, risk based decision making tools, etc.) and additional monitoring of the critical items identified by the analysis. Therefore it was assumed that the costs associated with the implementation of this RCO will be the necessary analysis of the system and the increase of the monitoring onboard.

RCO 1a: Propulsion system

The propulsion system of a typical LNG vessel is constituted basically by a steam turbine, and a reliquefaction plant for the cargo boil-off. The steam turbine is a complex system composed by valves, seal rings, casing, inlets, bearings, nozzles, etc. This machine is essentially a high-speed machine, whereas a propeller is more efficient at lower speeds. The installation of a speed reducer is required to optimize the propulsion system. Due to the complexity and importance of this system, detailed risk analysis and monitoring is required with the application of RBM. Typically the costs associated with the mentioned studies and monitoring are usually high.

The input to the cost estimates are given in the table below:

Table 18: Input to Cost estimate for RCO 1a	
Required Input	Input Value
Initial investment	USD 500,000
Annual Cost	USD 5,000

The estimation costs, given above, were provided by risk analysis consultant companies. On performing this analysis it was considered the upper bound in terms of the costs in order to obtain a conservative result. This corresponds to a NPV = USD 0.585 million for a 40 year ship lifecycle and a depreciation rate of 5%.

The direct implications of the unavailability of the propulsion system, during sailing, could be the possibility of drift grounding. Also the fire/explosion events can occur due to lack of adequate maintenance.

According to the risk analysis presented in the previous annex, the annual frequency of fire/explosion in the engine room was estimated to 1.46 x 10^{-3} per shipyear. In relation to the drift grounding, the data concerning LNG accidents presented in the previous annex show that none was derived from propulsion failures. The annual frequency of drift grounding due to unavailability of any of the systems was estimated to 8.40 x 10^{-4} per shipyear.

One of the problems related to RBM is that there are still very few publications where applications are studied, particularly within the transport sector. Thus, due to the lack of adequate data, the risk reduction values were found based on expert opinion. For the purpose of this study the following assumptions were made:

- 15% of fire/explosions in the engine room could be avoided
- 20% of all drift groundings due to unavailability of the propulsion system could be avoided

The results are summarized in Table 19.

Table 19: Risk Reduction

Required Input	Scenario	Initial frequency	Fatalities per Ship Year initial	% reduction	Frequency reduction	Fatalities per ship Year final	N. Lives Saved
RCO 1a	Fire/explosion	1.46 x 10^{-3}	5.39 x 10^{-4}	15 %	2.19x 10^{-4}	4.58x 10^{-4}	8.09x 10^{-5}
RCO 1a	Grounding (Drift)	8.40 x 10^{-4}	8.77 x 10^{-4}	20 %	1.68x 10^{-4}	7.02x 10^{-4}	1.76x 10^{-4}

This corresponds to an annual fire/explosion frequency reduction of 2.19 x 10^{-4} incidents, corresponding to 8.09 x 10^{-5} fatalities per ship year or 0.0032 fatalities per ship over a lifetime of 40 years. For the purpose of the study an estimated cost of an engine room fire/explosion in a LNG is USD 4 million and additional USD 2.4 million as a result of the unavailability of the ship, i.e. a total cost of USD 6.4 million. With a probability of having a fire/explosion accident of 1.46 x 10^{-3} and a reduction of 15%, the Annual Benefit will be USD 1,402.

For drift grounding, the calculations will be similar with an annual frequency reduction of 1.68 x 10^{-4} incidents, corresponding to 1.76 x 10^{-4} fatalities per ship year or 0.007 fatalities per ship for a ship lifetime of 40 years. The economic benefit will be reduced probability of total loss, reduced damage repair costs and reduced downtime due to damage repairs. For total losses, it is assumed that the average cost associated with this equals the new building cost of an LNG carrier, i.e. USD 170 million according to the previous annex. For total losses occurring in the loaded condition, the additional cost of cargo loss is also considered, i.e. USD 17.5 million. The cost of an impact damage that is not resulting in total loss is assumed to consist of repair costs and downtime. For the purpose of this study, and in accordance with statistics from Navantia shipyards, average repair costs are assumed to amount to USD 1.5 million per accident, and average downtime due to the repairs are 30 days. Assuming a daily rate of USD 60,000 in accordance with what was assumed in the risk analysis, the average downtime costs per accident is hence estimated to be USD 1.8 million.

Associating the reduction probabilities with the assumed costs for total loss, cargo loss and repairs of hull damages outlined above, the average economic benefit resulting of this risk control option can be calculated. The probability of a drift grounding that result in total loss (sinking) is 6.38 x 10^{-5}, cargo loss 3.19 x 10^{-5} and hull damages 7.76 x 10^{-4} per ship year respectively.

Table 20: Average economic benefit (per ship year).

Scenario	Type of cost associated	Probability	% reduction	Reduction probability	Cost associated (USD million)	Economic benefit (USD)
Drift grounding	Total loss	6.38 x 10^{-5}	20%	1.27 x 10^{-5}	170	2.169
	Cargo loss	3.19 x 10^{-5}	20%	6.38 x 10^{-6}	17.5	112
	Damage outer hull	7.76 x 10^{-4}	20%	1.55 x 10^{-4}	3.3	512
Total						2.793

The Annual Benefit will be USD 2.793. This corresponds to 0.048 million within the 40 year ship lifecycle. Combining the two scenarios the total benefit per ship during lifetime is estimated to be NPV = USD 0.072 million.

On the benefit side it was considered not only the risk reduction but also that the implementation of the maintenance schemes will increase the availability of the system under consideration. Early detection of a fault through RBM may result in a repair cost X, whereas if it would escalated to more damaging failure mode it would have a cost Y where Y>>X. Obviously this depends on the particular failure mode. Navantia provided a range of costs for occasional repairs as a consequence of possible failure modes within the system. It was considered that one occasional repair, on the ship lifecycle, can be avoided with the implementation of RBM. The benefits of such prevention will equal the costs of repairing and reduced downtime. Most of the failure modes within the propulsion system cannot be repair at sea and have to be done on shipyard. Furthermore, in most vessels the propulsion system is composed by non-redundant components.

From shipyard data an estimative of the inherent costs of occasional repair and days necessary to perform the task were given. For the propulsion system an estimative range from 250.000 USD - 500.000 USD and 10 - 25 days, depending on the complexity of the failure and the availability of spare components, was estimated. For this assessment the lower bound of the estimative were used, obtaining a benefit of 0.85 million USD, assuming a daily rate of USD 60,000. The estimates of cost, risk reduction and economic benefit are summarized below:

Δ C	USD 0.585 million
Δ R	0.0102 fatalities per ship
Δ B	USD 0.92 million

This corresponds to the following cost effectiveness estimates:

GCAF	57.2 million	USD / fatalities
NCAF	<0	(32.6 million USD / fatalities)

It can thus be seen that NCAF < 0 correspond to a cost effective risk control options, although GCAF > USD 3 million suggests that the potential for risk reduction is somewhat limited. It also can be concluded that the initial assumption of a single repair saved during the ship lifetime, is sufficient to obtain a negative NCAF.

RCO 1b: Steering system

The steering system, which is composed of several main components (steering gear, rudder, hydraulics or electric engines, etc), is an essential system in normal ship operation. The failure of this system during normal ship operation can lead to possible drift groundings, collisions or contacts. As in the case of the propulsion system most of the failure modes that can occur during sailing can not be repaired onboard.

This system is not as complex as the propulsion and therefore the costs associated with the risk based maintenance studies will be lower. The input to the cost estimates are given in the table below:

Table 21: Input to Cost estimate for RCO 1b

Required Input	Input Value
Initial investment	USD 200,000
Annual Cost	USD 2,000

This corresponds to NPV = USD 0.234 million for a 40 year ship lifecycle and a depreciation rate of 5%.

According to the risk analysis presented in the previous annex:

- The annual frequency of Collision was estimated to 6.7 x 10^{-3} per shipyear.
- The annual frequency of Drift grounding was estimated to 8.4 x 10^{-4} per shipyear.

- The annual frequency of Contact was estimated to 2.8 x 10^{-3} per shipyear.

The expected risk reduction from implementation of this risk control option is difficult to assess, and the following estimates are based on expert opinion:

- 5% of all above collisions could be avoided.
- 30% of all above drift groundings could be avoided.
- 10% of all above contacts could be avoided.

The results are summarized in Table 22.

Table 22: Risk Reduction

Required Input	Scenario	Initial frequency	Fatalities per Ship Year initial	% reduction	Frequency reduction	Fatalities per ship Year final	N. Lives Saved
RCO – 1b	Collision	6.70 x 10^{-3}	6.01 x 10^{-3}	5 %	3.35x 10^{-4}	5.71x 10^{-3}	3.00x 10^{-4}
RCO – 1b	Drift Grounding	8.40 x 10^{-4}	8.77 x 10^{-4}	30 %	2.52x 10^{-4}	6.14x 10^{-4}	2.63x 10^{-4}
RCO – 1b	Contact	2.80 x 10^{-3}	1.46 x 10^{-3}	15 %	4.20x 10^{-4}	1.24x 10^{-3}	2.19x 10^{-4}
	Total:	**1.03 x 10^{-2}**	**8.34 x 10^{-3}**	**13%**	**1.01 x 10^{-3}**	**7.56 x 10^{-3}**	**7.83 x 10^{-4}**

This corresponds to an annual frequency reduction of 1.01 x 10^{-3} incidents and 7.83 x 10^{-4} fatalities per ship year, or 0.0313 fatalities per ship throughout its lifetime.

The following accident costs are associated with these scenarios:

Total loss:	USD	170 million
+ Total loss – loaded condition	USD	17.5 million
Outer hull damages:	USD	3.3 million

According to the risk analysis carried out in the previous task the following probabilities can be calculated:

- The probability of a collision and contact that results in total loss (sinking) is 3.09 x 10^{-4} and 1.06 x 10^{-4} per ship year respectively.
- The probability of total loss in loaded condition, and hence of cargo loss is 3.09 x 10^{-4} * 0.5 = 1.55 x 10^{-4} per ship year for the collision scenario and 5.32 x 10^{-5} for the contact scenario.
- The probability of a damage in the cargo area extending through the outer hull where assessed to be 6.39 x 10^{-3} and 2.69 x 10^{-3} per ship year for collision and contact scenario respectively.
- For drift grounding scenarios the probabilities would be: total loss = 6.38 x 10^{-5} per ship year, cargo loss = 3.19 x 10^{-5} per ship year and damage in the cargo area extending through the outer hull = 7.76 x 10^{-4} per ship year.

Associating the probability reductions with the assumed costs for total loss, cargo loss and repairs of hull damages outlined above, the average economic benefit achievable from this risk control option can be estimated.

Table 23: Average economic benefit (per ship year).						
Scenario	Type of cost associated	Probability	% reduction	Reduction probability	Cost associated (USD million)	Economic benefit (USD)
Collision	Total loss	3.09×10^{-4}	5%	1.55×10^{-5}	170	2627
	Cargo loss	1.55×10^{-4}	5%	7.75×10^{-6}	17.5	136
	Damage outer hull	6.39×10^{-3}	5%	3.19×10^{-4}	3.3	1054
	Total					3817
Grounding	Total loss	6.38×10^{-5}	30%	1.91×10^{-5}	170	3254
	Cargo loss	3.19×10^{-5}	30%	9.57×10^{-6}	17.5	167
	Damage outer hull	7.76×10^{-4}	30%	2.32×10^{-4}	3.3	768
	Total					4189
Contact	Total loss	1.06×10^{-4}	15%	1.91×10^{-5}	170	2703
	Cargo loss	5.32×10^{-5}	15%	7.98×10^{-6}	17.5	140
	Damage outer hull	2.69×10^{-3}	15%	4.04×10^{-4}	3.3	1331
	Total					4174
Total collision, grounding and contact						**12,180**

The total annual benefit is estimated to USD 12,180. The Benefit per ship during its lifetime is calculated to be NPV = USD 0.209 million.

It is assumed that implementation of this RCO will imply that one occasional repair can be avoided during the ship lifecycle. Data provided by Navantia for this specific system indicate a range of costs of 15,600 – 292,500 USD and 8 – 15 days of repair. Hence, an average benefit of 495,600 USD is assumed. The estimates of cost, risk reduction and economic benefit are summarized below:

Δ C	USD 0.234 million
Δ R	0.0313 fatalities per ship
Δ B	USD 0.704 million

With these values the respective NCAF and GCAF values may be calculated:

GCAF	7.4 million	USD / fatalities
NCAF	< 0	(15 million USD/ fatalities)

From these results one may conclude that particular RCO for the steering system is cost effective since NCAF is negative. However, the GCAF exceeds USD 3 million, and the potential for risk reduction is somewhat limited.

RCO 1c: Navigational system

The input to the cost estimates are given in the table below:

Table 24: Input to Cost estimate for RCO 1c	
Required Input	Input Value
Initial investment	USD 100,000
Annual Cost	USD 1,000

From this it is possible to estiamte the NPV for the costs of implementation to NPV = USD 0.117 million for a 40 year ship lifecycle and a depreciation rate of 5%.

According to the risk analysis presented in the previous annex:

- The annual frequency of Collision was estimated to 6.7 x 10^{-3} per shipyear.
- The annual frequency of Powered Grounding was estimated to 1.96 x 10^{-3} per shipyear.
- The annual frequency of Contact was estimated to 2.8 x 10^{-3} per shipyear.

The expected risk reduction from implementation of this risk control option is based on expert opinion:

- 15% of all above collisions could be avoided.
- 10% of all above powered groundings could be avoided.
- 15% of all above contacts could be avoided.

The risk reduction is summarized in Table 25.

Table 25: Risk Reduction

Required Input	Scenario	Initial frequency	Fatalities per Ship Year initial	% reduction	Frequency reduction	Fatalities per ship Year final	N. Lives Saved
RCO – 1c	Collision	6.70 x 10^{-3}	6.01 x 10^{-3}	15 %	1.00x 10^{-3}	5.1x 10^{-3}	9.02x 10^{-4}
RCO – 1c	Powered Grounding	1.96 x 10^{-3}	2.05 x 10^{-3}	10 %	1.96x 10^{-4}	1.8x 10^{-3}	2.05x 10^{-4}
RCO – 1c	Contact	2.80 x 10^{-3}	1.46 x 10^{-3}	15 %	4.20x 10^{-4}	1.24x 10^{-3}	2.19x 10^{-4}
	Total:	**1.1 x 10^{-2}**	**9.52 x 10^{-3}**	**13%**	**1.62 x 10^{-3}**	**8.19 x 10^{-3}**	**1.33 x 10^{-3}**

This corresponds to an annual total frequency reduction of 1.62 x 10^{-3} incidents, resulting in 1.33 x 10^{-3} fatalities per ship year, or 0.053 fatalities per ship.

The following accident costs are associated with these scenarios:

Total loss:	USD	170 million
+ Total loss – loaded condition	USD	17.5 million
Outer hull damages:	USD	3.3 million

According to the risk analysis:

- The probability of a collision and contact that results in total loss is 3.09 x 10^{-4} and 1.06 x 10^{-4} per ship year respectively.
- The probability in total loss in loaded condition, and hence of cargo loss is 1.55 x 10^{-4} per ship year for the collision scenario and 5.32 x 10^{-5} for the contact scenario.
- The probability of a damage in the cargo area extending through the outer hull where assessed to be 6.39 x 10^{-3} and 2.69 x 10^{-3} per ship year for collision and contact scenario respectively.
- For powered groundings, the probabilities are: total loss: 1.5 x 10^{-4} per ship year, cargo loss: 7.5 x 10^{-5} per ship year and damage in the cargo area extending through the outer hull: 1.3 x 10^{-3} per ship year.

Associating the reduction probabilities with the assumed costs for total loss, cargo loss and repairs of hull damages outlined above, the average economic benefit resulting of this risk control option may be estimated.

Table 26: Average economic benefit (per ship year).						
Scenario	Type of cost associated	Probability	% reduction	Reduction probability	Cost associated (USD million)	Economic benefit (USD)
Collision	Total loss	3.09×10^{-4}	15%	4.64×10^{-5}	170	7880
	Cargo loss	1.55×10^{-4}	15%	2.32×10^{-5}	17.5	407
	Damage outer hull	6.39×10^{-3}	15%	9.58×10^{-4}	3.3	3163
	Total					11449
Grounding	Total loss	1.5×10^{-4}	10%	1.5×10^{-5}	170	2550
	Cargo loss	7.5×10^{-5}	10%	7.5×10^{-6}	17.5	131
	Damage outer hull	1.8×10^{-3}	10%	1.8×10^{-4}	3.3	594
	Total					3275
Contact	Total loss	1.06×10^{-4}	15%	1.59×10^{-5}	170	2703
	Cargo loss	5.32×10^{-5}	15%	7.98×10^{-6}	17.5	140
	Damage outer hull	2.69×10^{-3}	15%	4.04×10^{-4}	3.3	1331
	Total					4174
Total collision, grounding and contact						**18,899**

From the above table an estimated annual benefit will be USD 18,899. The benefit per ship during its lifetime is calculated to be NPV = USD 0.324 million. No additional economic benefits were considered for this particular RCO. The estimates of cost, risk reduction and economic benefit are summarized below:

Δ C	USD 0.117 million
Δ R	0.053 fatalities per ship
Δ B	USD 0.324 million

With these values the respective NCAF and GCAF values may be calculated:

GCAF	2.21 million	USD / fatalities
NCAF	< 0	(÷ 3.9 million USD/ fatalities)

From these results one may conclude that this risk control options is cost effective since the both GCAF and NCAF are less than USD 3 million.

RCO 1d: Cargo handling system

With the objective of performing efficient loading/unloading operations different cargo machinery equipment is installed onboard LNG carriers. The cargo handling system is designed with consideration of conformity to the port facilities to normal and safe operation. Basically the cargo handling machinery used is cargo pumps, fuel gas compressors, vaporizers, gas blower/compressor, inert gas generator, etc. Also additional instrumentation for cargo monitoring is installed namely level gauge, pressure gauge, gas detectors and temperature gauges. Some of this equipment is accommodated in separated compartments as the case of the compressors room. The cargo system is connected to port loading/unloading arms and to pipeline systems that take the LNG to full-containment storage tanks.

The input to the cost estimates are given in the table below:

Table 27: Input to Cost estimate for RCO 1d	
Required Input	Input Value
Initial investment	USD 100,000
Annual Cost	USD 4,000

I.e., NPV = USD 0.168 million for a 40 year ship lifecycle and a depreciation rate of 5%.

Failure of the cargo system, despite the fact that there is redundancy of most of the equipment, can lead to loading/unloading incidents or downtime. According to the risk analysis presented in the previous annex:

- The annual frequency of loading/unloading accidents was estimated to 3.17 x 10^{-3} per shipyear

For the purpose of the study the following assumptions were made:

- 10% of all loading/unloading incidents may be avoided by implementing this RCO.

The risk reduction is summarized in Table 28.

Table 28: Risk Reduction

Required Input	Scenario	Initial frequency	Fatalities per Ship Year initial	% reduction	Frequency reduction	Fatalities per ship Year final	N. Lives Saved
RCO – 1d	L/U Incident	7.8 x 10^{-3}	2.64 x 10^{-4}	10 %	7.8x 10^{-4}	2.38x 10^{-4}	2.64x 10^{-5}

An annual frequency reduction of 7.8 x 10^{-4} incidents, or 2.64 x 10^{-5} fatalities per ship year, corresponds to 0.0011 fatalities per ship throughout its lifetime. The cost of a loading/unloading incident is 0.8 million, i.e. the annual benefit will be 624 USD. This results in NPV = USD 0.011 million.

According to Navantia Data the occasional repair cost of the cargo handling system ranges from 32.500 – 45.500 USD. Thus, NPV= USD 0.0435 million will be assumed. The estimates of cost, risk reduction and economic benefit are summarized below:

Δ C	USD 0.168 million
Δ R	0.0011 fatalities per ship
Δ B	USD 0.0435 million

With these values, the NCAF and GCAF values presented below are obtained:

GCAF	159 million	USD / fatalities
NCAF	118 million	USD/ fatalities

From these results one may conclude that this risk control options is not cost effective since both GCAF and NCAF have significantly higher values than USD 3 million.

A.6.2 RCO 2: Strain gauges.

In order to assess the cost of strain gauges system with an integrated system for fatigue and sloshing monitoring in LNG vessels, a supplier was contacted[1]. According to the supplier the sloshing monitoring system price ranges approximately 200,000-250,000 €/ship or about USD 250,000-313,000. This estimative includes installation, equipment, software and commissioning. Also, according to the supplier additional ongoing costs for maintenance or repair would be marginal.

The input to the cost estimates are given in the table below:

Table 29: Input to Cost estimate for RCO 2

Required Input	Input Value	Reference
Initial investment	USD 250.000	Supplier

A NPV for the costs of implementation = USD 0.25 million will be assumed.

According to the historic accident data presented in the previous annex, the annual frequency for failure/leakage of the containment system was 9.5 x 10^{-3} per ship year. However, not all the cases are related to fatigue and sloshing events resulting in structural damage. Taking into account the identified accidents the annual frequency of fatigue and sloshing incidents that resulted into containment failure was estimated to 5.3 x 10^{-3} per ship year.

[1] www.hullmos.com

Another important aspect is related to the initial number of fatalities per ship year. According to the risk analysis, the risk contribution from failure/leakage of the containment system was negligible. In order to correctly assess this control option an estimative of this value must be performed. Considering the above frequency and assuming a 1% probability that one fatality will occur, a correspondent 5.3 x 10^{-5} fatalities per ship year is estimated. The expected risk reduction from implementation of this risk control option is difficult to assess, and expert opinion was used:

- In 30% of all above incidents escalation to large structural damages could have been avoided by the implementation of strain gauges in the tanks.

This corresponds to an annual total risk reduction of 3.70 x 10^{-3} incidents, resulting in 3.70 x 10^{-5} fatalities per ship year. Results are summarized in Table 30.

Table 30: Risk Reduction							
Required Input	Scenario	Initial Frequency	Fatalities per ship year initial	% reduction	Frequency reduction	Fatalities per ship year final	N. Lives Saved
RCO –2	Containment failure	5.3x 10^{-3}	5.29 x 10^{-5}	30 %	1.59 x 10^{-3}	3.70 x 10^{-5}	1.58 x 10^{-5}

According to shipyard data on repair due to damages related to fatigue and sloshing in tanks, economic benefit from averting an incident is assumed to be USD 1 million. Thus, the annual benefit for the owner will be USD 1,590, resulting in a NPV of USD 0.0272 million per ship lifetime. These estimates of cost, risk reduction and economic benefit are put together in the following.

Δ C	USD 0.25 million
Δ R	6.32 x 10^{-4} fatalities per ship
Δ B	USD 0.0272 million

With these values, the NCAF and GCAF values presented below are obtained:

GCAF	394.1 million	USD / fatalities
NCAF	351.2 million	USD / fatalities

From these results one may conclude that this risk control options is not effective since the obtained GCAF and NCAF values are much higher than the USD 3 million.

A.6.3 RCO 3: Increased double hull width, double bottom depth or hull strength.

For the purpose of this study, an evaluation on the effects of an increase of the double hull dimensions and ship strength for collision, grounding and contact aspects has been carried out on a typical LNG vessel, to assess the cost effectiveness of measures of this type.

In this study the cargo holds have been kept fixed so the total cargo volume of the LNG carriers remains constant (138,000 m^3). What have been varied are the main dimensions of the vessel, particularly breadth and depth. As consequence of the main dimensions modifications, the gross tonnage of the vessel will be higher than the conventional and also the bunker consumptions. However the effect of these modifications has been not taken into account. The benefit for the owner, less serious damages, should be reduced in a certain quantity as consequence of these bigger dimensions.

For the purpose of this study, the economic benefit from the implementation of this RCO on LNG carriers will be reduced probability of total loss, reduced damage repair costs and reduced downtime due to damage repairs. For total losses, it is assumed that the average cost associated with this equals the new building cost of a typical LNG carrier, i.e. USD 170 million. For total losses occurring in the loaded condition, the additional cost of cargo loss is also considered, i.e. USD 17.5 million. The cost of an impact damage that is not resulting in total loss is assumed to consist of repair costs and downtime. For the purpose of this study, and in accordance with statistics from Navantia shipyards, average repair costs are assumed to amount to USD 1.5 million per accident, and average downtime due to the repairs are 30 days. Assuming a daily rate of USD 60,000 in accordance with what was assumed in the risk analysis, the average downtime costs per accident (not total loss) is hence estimated to be USD 1.8 million. Thus, the following costs are associated with these accident scenarios:

Total loss:	USD	170 million
+ Total loss – loaded condition	USD	17.5 million
Other hull damages:	USD	3.3 million

These estimates will be used in the assessment of this risk control option. The contemplated cases analysed are:

- RCO 3a: 20% increment of the double hull width, and outer side scantlings
- RCO 3b: 20% increment of the double bottom depth, and bottom scantlings
- RCO 3c: increase of the vessel strength (maintaining the double side and double bottom original dimensions)

These RCO will not really avert incidents, but will reduce the number of actual incidents that receives critical damages, i.e. reduce number of total losses and instead make them less serious damages.

RCO 3a: Increased double hull width

The inputs to the cost estimates for increasing the double side width are given in the table below:

Table 31: Input to Cost estimate for RCO 3a		
Required Input	Input Value	Reference
Initial investment	USD 1,500,000	Yards Calculation
Annual Cost		

The initial value represents the investment to increase 20% the double side width. Annual maintenance costs are considered the same in both options although generally speaking the vessel with a wider double side will be easier to maintain. The total cost associated with implementation of RCO 3a has a net present value NPV= USD 1.5 million.

According to the risk analysis presented in the previous annex:

- The annual frequency of Collision and Contact was estimated to 6.7×10^{-3} and 2.8×10^{-3} per shipyear respectively.
- The annual frequency of Collision and Contact only in the LNG cargo area was estimated to 2.18×10^{-3} and 1.96×10^{-3} per shipyear respectively.
- The annual frequency of Collision and Contact only in the cargo area that results in total loss (sinking) is 2.50×10^{-4} and 7.45×10^{-5} per ship year respectively.
- The probability of total loss in loaded condition, and hence of cargo loss is 1.25×10^{-4} per ship year for the collision scenario and 3.72×10^{-5} for the contact scenario.
- Finally, the probability of a damage in the cargo area extending through the outer hull where assessed to be 1.93×10^{-3} and 1.88×10^{-3} per ship year for collision and contact scenario respectively.

According to the risk analysis, the collision damage extent model contains two parts: the probability of receiving the damage outside of the cargo area and the probability of receiving critical collision damage in terms of damage stability. First, the damage needs to crack the outer hull, and the probability for this is estimated to be 0.24. It was highlighted that any damage in the cargo area that extends through the double hull and penetrates the cargo tanks will be critical for a vessel in loaded condition. Hence, any damage deeper than the double hull will be regarded as critical. For our reference vessel, the double hull has a depth of 2.3 meters. In addition to this, there will be a layer of insulation with a thickness of about 0.5 meter and this total thickness corresponds to about B/15. According to the damage statistics, the probability of receiving damages with this depth condition on collision is about 0.6. For vessels in ballast condition, it is assumed that critical damages in cargo area are both longer than L/20 and deeper than

B/15, corresponding to a probability of 0.36. Thus, the probabilities of receiving a critical damage conditioned on being struck by collision, which was used in the event tree, in the cargo area are:

- In loaded condition: 0.14
- In ballast condition: 0.086

If the vessel double hull is increased from 2.3 meters to 2.75 meters, in this case the penetration of a collision or contact damage should at least be 3.25 meters to be critical (B/13). According to the damage statistics, the probability of grounding damage to be between B/15 and B/13 meters is about 0.04 (see figure below), so the probability of grounding damage to be deeper than 3.25 meters is about 0.56. Thus, the total probability of receiving critical damage conditioned on being struck by collision in the cargo area is:

- In loaded condition: 0.13
- In ballast condition: 0.080

Hence, for the purpose of this study, it is assumed that the probability of receiving critical side damage in the cargo area by a collision is reduced about 8% in absolute terms or 1% in relative terms considering 100% of damage cases in the cargo area. This new value will be used in the collision event tree. For contact events, it is assumed that the probability of receiving a critical damage in the cargo area is reduced also about 8% in absolute terms or 0.3% in relative terms.

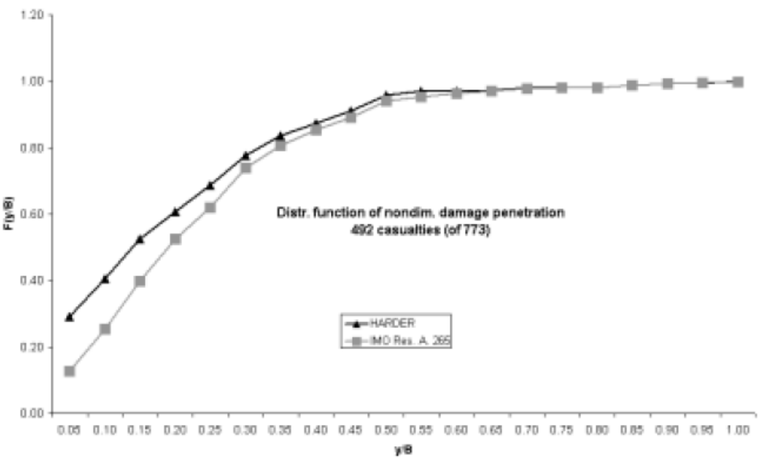

Figure 25: Cumulative distribution function of non-dimensional damage penetration (773 records)

With the implementation of RCO 3a the probabilities of having a critical damage in the cargo area in collision and contact scenarios are reduced by around 1%. The potential loss of lives (PLL), taking into account both collision and contact events, is reduced from 7.47 x 10^{-3} to 6.98 x 10^{-3} per ship year. I.e., an annual total reduction of 5.05 x 10^{-4} fatalities per ship year and 0.0202 fatalities averted per ship over a lifetime of 40 years.

Table 32: Risk Reduction						
Required Input	Scenario	Initial Frequency	PLL per Ship Year initial	% reduction of critical damage (*)	PLL per Ship Year final	N. Lives Saved
RCO 3a	Collision	6.70 x 10^{-3}	6.01 x 10^{-3}	1 %	5.60 x 10^{-3}	4.21 x 10^{-4}
RCO 3a	Contact	2.80 x 10^{-3}	1.46 x 10^{-3}	1 %	1.38 x 10^{-3}	8.47 x 10^{-5}
	Total:	**9.50 x 10^{-3}**	**7.47 x 10^{-3}**		**6.98. x 10^{-3}**	**5.05 x 10^{-4}**

Note s: (*) % in relative terms considering all collision or contact incident damage in the cargo area.

Associating the attained reduction probabilities with the assumed costs for total loss, cargo loss and repairs of hull damages, the average economic benefit resulting of this risk control option can be estimated to be USD 4,050 per shipyear (see table below). Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of NPV = USD 69,500.

Table 33: Average economic benefit (per ship year)						
Scenario	Type of cost associated	Probability	% relative probability variation (*)	Variation probability	Cost associated (USD million)	Economic benefit (USD)
Collision	Vessel loss	(11%) 2.50×10^{-4}	- 1 %	- 2.00×10^{-5}	170	3,400
	Cargo loss	(6%) 1.25×10^{-4}	- 0.5 %	- 1.00×10^{-5}	17.5	175
	Damage outer hull	(89%) 1.93×10^{-3}	+ 1%	+ 2.00×10^{-5}	3.3	- 66
	Total					3,509
Contact	Total loss	(4%) 7.45×10^{-5}	- 0.3 %	- 5.96×10^{-6}	170	508
	Cargo loss	(2%) 3.72×10^{-5}	- 0.15 %	- 2.98×10^{-6}	17.5	52
	Damage outer hull	(96%) 1.88×10^{-3}	+ 0.3 %	+ 5.96×10^{-6}	3.3	-19
	Total					541
Total collision and contact						**4,050**

Note s: (*) % in relative terms considering all collision or contact incident damage in the cargo area.

Putting these estimates of cost, risk reduction and economic benefit together, one obtains:

Δ C	USD 1.5 million
Δ R	0.0202 fatalities per ship
Δ B	USD 0.07 million

This corresponds to the NCAF and GCAF values presented below for this risk control option:

GCAF	74.3 million	USD / fatalities
NCAF	70.8 million	USD / fatalities

Hence, it can be seen that to increase the double hull width 20% is not a cost effective risk control option according to the cost-effectiveness criteria.

RCO 3b: Increased double bottom depth

The input to the cost estimates of increasing the double bottom depth are given in the table below:

Table 34: Input to Cost estimate for RCO 3b		
Required Input	Input Value	Reference
Initial investment	USD 1,000,000	Yards Calculation
Annual Cost		

The initial value represents the inversion to increase the double bottom depth by 20%. Annual maintenance costs are considered the same in both options although generally speaking the vessel with a bigger double bottom depth will be easier to maintain. The total cost associated with implementation of RCO 3b has a net present value NPV = USD 1 million.

The following probabilities were derived in the risk analysis:

- The annual frequency of grounding was estimated to 2.8×10^{-3} per shipyear.
- The annual frequency of grounding damage only in the LNG cargo area was estimated to 1.96×10^{-3} per shipyear.
- The annual frequency of grounding damage only in the cargo area that results in total loss (sinking) is 1.49×10^{-4} per ship year.
- The probability in total loss in loaded condition, and hence of cargo loss is about 7.45×10^{-5} per shipyear for the grounding scenario.

- Finally, the probability of a damage in the cargo area extending through the outer hull where assessed to be 1.81 x 10^{-3} per ship year for grounding scenario.

According to the risk analysis, the damage extent model contains two parts: the probability of receiving the damage outside of the cargo area and the probability of receiving a critical grounding damage. First, the damage needs to crack the outer hull, and the probability for this is estimated to be 0.76. Then the damage must be extensive enough to be critical and this will again be determined by damage statistics collected by the HARDER project.

The reference vessel has a double bottom of 2.9 meters, and in addition to that there is the cargo tank insulation. Hence, it is assumed that a grounding damage should at least be deeper than 3.4 meters to be critical. According to the damage statistics, the probability of grounding damage to be deeper than this is about 0.1. Thus, the total probability of receiving critical damage conditioned on grounding is 0.76 x 0.1 = 0.076. This value was be used in the grounding event tree.

If the vessel double bottom is increased from 2.9 meters to 3.50 meters, the grounding damage should at least be deeper than 4.10 meters to be critical. According to the damage statistics, the probability of grounding damage to be between 3.5 and 4.1 meters is about 0.02 (see figure below), so the probability of grounding damage to be deeper than 4.1 meters is about 0.08. Thus, the total probability of receiving critical damage conditioned on grounding is 0.76 x 0.08 = 0.061 after the implementation of this RCO. Hence, for the purpose of this study, it is assumed that the probability of receiving a critical bottom damage in the cargo area is reduced about 20% in relative terms for the implementation of this RCOs (1.5% considering 100% of grounding incident causing damage in the cargo area). This new value will be used in the grounding event tree.

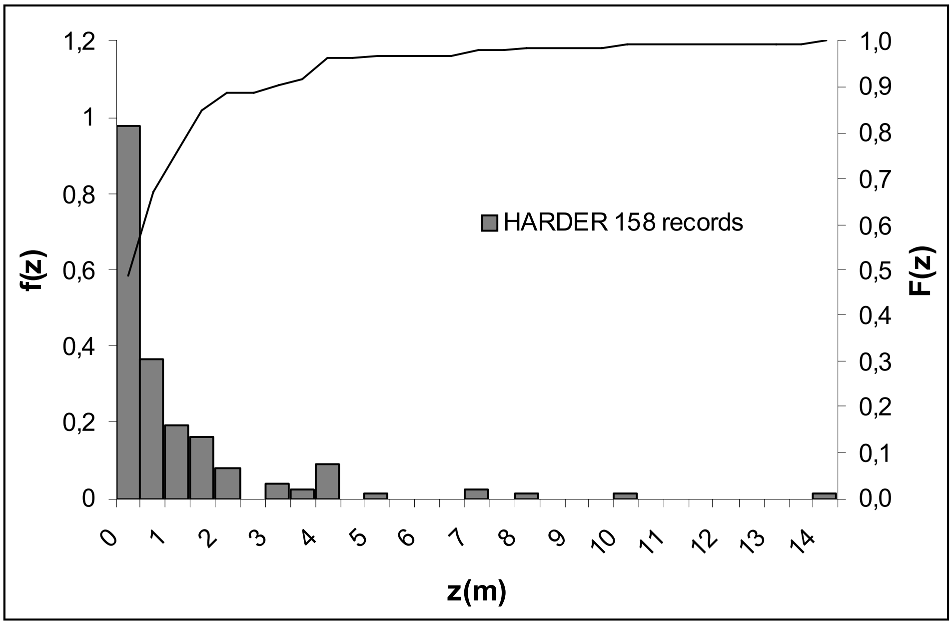

Figure 26: Grounding - histogram and distribution function versus penetration depth.

The implementation of RCO (3b) may reduce the probability of having a critical damage in the cargo area in grounding scenarios by around 20% in absolute terms or by 1.5% in relative terms. So the potential loss of lives (PLL) taking into account grounding events is reduced from 2.92 x 10^{-3} to 2.50 x 10^{-3} per ship year. That means an annual total reduction of 4.20 x 10^{-4} fatalities per ship year and 0.0168 fatalities averted over a lifetime of 40 years.

Table 35: Risk Reduction						
Required Input	Scenario	Annual Frequency per ship year	Fatalities per Ship Year	% reduction of critical damage (*)	Fatalities per Ship Year after RCO implementation	N. Lives Saved
RCO 3b	Grounding	2.80×10^{-3}	2.92×10^{-3}	1.5%	2.50×10^{-3}	4.20×10^{-4}

Note s: (*) % in relative terms considering all grounding incidents in the cargo area.

Associating the reduction in probabilities with the assumed costs for total loss, cargo loss and repairs of hull damages outlined above, the average economic benefit achievable from this risk control option can be estimated to USD 5,228 per shipyear. Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of NPV = USD 89,708.

Table 36: Average economic benefit (per ship year).						
Scenario	Type of cost associated	Probability	% relative probability variation (*)	Reduction probability	Cost associated (USD million)	Economic benefit (USD)
Grounding	Total loss	(7.6%) 1.49×10^{-4}	- 1.5%	$- 2.98 \times 10^{-5}$	170	5,066
	Cargo loss	(3.8%) 7.45×10^{-5}	-0.75%	$- 1.49 \times 10^{-5}$	17.5	260
	Damage outer hull	(92.4%)1.81×10^{-3}	+1.5%	$+ 2.98 \times 10^{-5}$	3.3	98
Total grounding						**5,228**

Note s: (*) % in relative terms considering all grounding in the cargo area.

These estimates of cost, risk reduction and economic benefit are put together in the following:

Δ C	USD 1.0 million
Δ R	0.0168 fatalities per ship
Δ B	USD 0.09 million

These values correspond to the following NCAF and GCAF values:

GCAF	59.5 million	USD / fatalities
NCAF	54.2 million	USD / fatalities

Hence, it can be seen that to increase the double bottom depth by 20% is not a cost effective risk control option according to the cost-effectiveness criteria.

RCO 3c: Increased hull strength

The input to the cost estimates are given in the table below:

Table 37: Input to Cost estimate for RCO 3c		
Required Input	Input Value	Reference
Initial investment	USD 3,000,000	Yards Calculation
Annual Cost		

The initial value represents the inversion to increase 20% the hull strength in the cargo area. The hull strength increments will be attained with a heavier hull structure leading to an increment in the displacement of about 3%. For this study annual bunker costs are considered the same in both options although generally speaking the vessel with an increased strength will consume slightly more bunker. The total cost associated with implementation of RCO 3c has a net present value NPV = USD 3 million.

According to the risk analysis presented in the previous annex:

- The annual frequency of collision was estimated to 6.7×10^{-3} per shipyear.
- The annual frequency of grounding was estimated to 2.8×10^{-3} per shipyear.

- The annual frequency of contact was estimated to 2.8 x 10^{-3} per shipyear.

The expected risk reduction from implementation of this risk control option is calculated from the event trees developed in the risk analysis. For the purpose of this study, assuming that the effect of a 20% hull strength increment is equivalent to increase the double hull width of the vessel by 20%, the following has been considered: 1% probability reduction of critical damage in collision and contact scenarios and 2% probability reduction of critical damage in grounding scenarios.

According to the risk analysis, the potential loss of lives (PLL) in collision, grounding and contact events is 1.04 x 10^{-2} per ship year. The estimated reduction of the critical damage in the collision, grounding and contact scenarios correspond to an updated PLL of 9.13 x 10^{-3} per ship year. This corresponds to an annual total reduction of 1.26 x 10^{-3} PLL per ship year obtained from the event trees developed during the risk analysis and 0.050 fatalities per ship over a lifetime of 40 years.

Table 38: Risk Reduction

Required Input	Scenario	Annual Frequency per ship year	Fatalities per Ship Year initial	% reduction of critical damage (*)	Fatalities per Ship Year final	N. Lives Saved
RCO – 3c	Collision	6.70 x 10^{-3}	6.01 x 10^{-3}	1%	5.58 x 10^{-3}	4.30 x 10^{-4}
RCO – 3c	Grounding	2.80 x 10^{-3}	2.92 x 10^{-3}	2%	2.37 x 10^{-3}	5.50 x 10^{-4}
RCO – 3c	Contact	2.80 x 10^{-3}	1.46 x 10^{-3}	1%	1.18 x 10^{-3}	2.78 x 10^{-4}
Total:		**1.23 x 10^{-2}**	**1.04 x 10^{-2}**		**9.13 x 10^{-3}**	**1.26 x 10^{-3}**

Note s: (*) % in relative terms considering all incidents in the cargo area by scenario (collision, grounding and contact).

According to the risk analysis the following probabilities can be calculated:

- The probability of a collision grounding and contact in the cargo area is 2.18 x 10^{-3}, 1.96 x 10^{-3} and 1.96 x 10^{-3} per ship year respectively.
- The probability of a collision grounding and contact in the cargo area that results in total loss is 2.50 x 10^{-4}, 1.49 x 10^{-4} and 7.45 x 10^{-5} per ship year respectively.
- The probability in total loss in loaded condition, and hence of cargo loss is 1.25 x 10^{-4} per ship year for the collision scenario, 7.45 x 10^{-5} for the grounding scenario and 3.72 x 10^{-5} for the contact scenario.
- Finally, the probability of a damage in the cargo area extending through the outer hull where assessed to be 1.93 x 10^{-3}, 1.81 x 10^{-3} and 1.88 x 10^{-3} per ship year for collision and contact scenario respectively.

Associating the reduction probabilities with the assumed costs for total loss, cargo loss and repairs of hull damages outlined above, the average economic benefit resulting of this risk control option can be calculated to USD 14,141 per shipyear. Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of NPV = USD 242,651.

Table 39: Average economic benefit (per ship year).						
Scenario	Type of cost associated	Probability	% relative probability variation (*)	Reduction probability	Cost associated (USD million)	Economic benefit (USD)
Collision	Total loss	(11%) 2.50 x 10^{-4}	- 1 %	- 2.18 x 10^{-5}	170	3706
	Cargo loss	(6%) 1.25 x 10^{-4}	- 0.5 %	- 1.09 x 10^{-5}	17.5	191
	Damage outer hull	(89%) 1.93 x 10^{-3}	+ 1%	+ 2.18 x 10^{-5}	3.3	-72
	Total					3825
Grounding	Total loss	(7.6%) 1.49 x 10^{-4}	- 2 %	- 3.92 x 10^{-5}	170	6664
	Cargo loss	(3.8%) 7.45 x 10^{-5}	-1%	- 1.96 x 10^{-5}	17.5	343
	Damage outer hull	(92.4%)1.81 x 10^{-3}	+2%	+ 3.92 x 10^{-5}	3.3	-129
	Total					6878
Contact	Total loss	(4%) 7.45 x 10^{-5}	- 1 %	- 1.96 x 10^{-5}	170	3332
	Cargo loss	(2%) 3.72 x 10^{-5}	- 0.5 %	- 9.80 x 10^{-6}	17.5	172
	Damage outer hull	(96%) 1.88 x 10^{-3}	+ 1%	+ 1.96 x 10^{-5}	3.3	-65
	Total					3439
Total collision, grounding and contact						**14,141**

Notes: (*) % in relative terms considering all incidents in the cargo area by scenario (collision, grounding and contact).

These estimates of cost, risk reduction and economic benefit are put together in the following:

Δ C	USD 3.0 million
Δ R	0.050 fatalities per ship
Δ B	USD 0.24. million

These values correspond to the following NCAF and GCAF values:

GCAF	60.0 million	USD / fatalities
NCAF	55.1 million	USD / fatalities

It can be seen that the GCAF and NCAF values are above the limit of USD 3 million. It can therefore be concluded that none of the three RCOs are cost effective risk control options.

A.6.4 RCO 4: Redundant propulsion system - two shaft lines

The input to the cost estimates are given in the table below:

Table 40: Input to Cost estimate for RCO 4		
Required Input	Input Value	Reference
Initial investment	USD 2,500,000	Yards Calculation
Annual Cost	USD 25,000	

The initial value represents difference in building cost for the new propulsion system (2 diesel engines instead of a steam turbine, 2 shaft lines instead of one, new hull forms). Annual maintenance costs are small and represent extra maintenance work during the expected lifetime of the system. The total cost associated with implementation of RCO 4 has a net present value of USD 2.93 million.

The expected risk reduction from implementation of this risk control option can be somewhat more difficult to assess. However, for the purpose of this study, the generic fault trees developed in the POP&C project [81] will be used:

- 5% collision probability reduction.

- 26% grounding probability reduction or what it is the same 86.4% drift grounding probability reduction. (Note: Based on accident data, it is assumed that about 30% of the grounding risk stems from drift grounding, and a risk reduction of 86.4% will only be effective in these events. At any rate, a risk reduction of 86.4% for 30% of all grounding events will be assumed in the current study)
- 10% contact probability reduction.

According to the risk analysis presented in the previous annex:

- The annual frequency of collision was estimated to 6.7 x 10-3 per shipyear.
- The annual frequency of grounding was estimated to 2.8 x 10-3 and so the annual frequency of drift grounding will be 8.40 x 10^{-4} per shipyear.
- The annual frequency of contact was estimated to 2.8 x 10-3 per shipyear.

According to the risk analysis, the potential loss of lives (PLL) taking into account collision, drift grounding and contact events is 8.34 x 10^{-3} per ship year. Thus a collision, drift grounding and contact risk reduction of 5 %, 86.4 % and 10 % respectively, correspond to an update PLL of 7.14 x 10^{-3} per ship year. This corresponds to an annual total reduction of 1.2 x 10^{-3} fatalities per ship year and, over a lifetime of 40 years, 0.0482 fatalities per ship.

Table 41: Risk Reduction

Required Input	Scenario	Initial Frequency	Fatalities per Ship Year initial	% reduction	Fatalities per ship Year final	N. Lives Saved
RCO 4	Collision	6.70 x 10^{-3}	6.01 x 10^{-3}	5%	5.70 x 10^{-3}	3.00 x 10^{-4}
RCO 4	Drift Grounding	8.40 x 10^{-4}	8.77 x 10^{-4}	86.4%	1.19 x 10^{-4}	7.58 x 10^{-4}
RCO 4	Contact	2.80 x 10^{-3}	1.46 x 10^{-3}	10%	1.32 x 10^{-3}	1.46 x 10^{-4}
Total:		**1.03 x 10^{-2}**	**8.34 x 10^{-3}**	**33,8%**	**7.14 x 10^{-3}**	**1.20 x 10^{-3}**

For the purpose of this study, the economic benefit will be reduced probability of total loss, reduced damage repair costs and reduced downtime due to damage repairs. For total losses, it is assumed that the average cost associated with this equals the new building cost of an LNG carrier, i.e. USD 170 million. For total losses occurring in the loaded condition, the additional cost of cargo loss is also considered, i.e. USD 17.5 million. The cost of an impact damage that is not resulting in total loss is assumed to consist of repair costs and downtime. For the purpose of this study, and in accordance with statistics from Navantia shipyards, average repair costs are assumed to amount to USD 1.5 million per accident, and average downtime due to the repairs are 30 days. Assuming a daily rate of USD 60,000, the average downtime costs per accident (not total loss) are estimated to be USD 1.8 million. Thus, the following total costs are associated with these scenarios:

Total loss:	USD	170 million
+ Total loss – loaded condition	USD	17.5 million
Other hull damages:	USD	3.3 million

According to the risk analysis and with the assumed costs associated with total loss, cargo loss and repairs of hull damages outlined above, the average economic benefit resulting of this risk control option is USD 18,664 per shipyear. Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of NPV = USD 320,276.

Table 42: Average economic benefit (per ship year).						
Scenario	Type of cost associated	Probability	% reduction	Reduction probability	Cost associated (USD million)	Economic benefit (USD)
Collision	Total loss	3.09×10^{-4}	5%	$1{,}55 \times 10^{-5}$	170	2627
	Cargo loss	1.55×10^{-4}	5%	$7{,}75 \times 10^{-6}$	17.5	136
	Damage outer hull	6.39×10^{-3}	5%	$3{,}19 \times 10^{-4}$	3.3	1054
	Total					3,817
Grounding (Drift)	Total loss	6.38 x 10-5	86.4%	$5{,}51 \times 10^{-5}$	170	9371
	Cargo loss	3.19 x 10-5	86.4%	$2{,}76 \times 10^{-5}$	17.5	482
	Damage outer hull	7.76 x 10-4	86.4%	$6{,}70 \times 10^{-4}$	3.3	2212
	Total					12,065
Contact	Total loss	1.06×10^{-4}	10%	$1{,}06 \times 10^{-5}$	170	1802
	Cargo loss	5.32×10^{-5}	10%	$5{,}32 \times 10^{-6}$	17.5	93
	Damage outer hull	2.69×10^{-3}	10%	$2{,}69 \times 10^{-4}$	3.3	887
	Total					2782
Total collision, grounding and contact						**18,664**

Putting these estimates of cost, risk reduction and economic benefit together, one obtains:

Δ C	USD 2.93 million
Δ R	0.0482 fatalities per ship
Δ B	USD 0.32 million

This corresponds to the following NCAF and GCAF values:

GCAF	60.8 million	USD / fatalities
NCAF	54.2 million	USD / fatalities

The GCAF and NCAF values are above the limit of USD 3 million and it can be concluded that this RCO is not cost effective.

A.6.5 RCO 5: Improved navigational safety

For the purpose of this study, four alternative risk control options aiming at improving the navigational safety will be evaluated, i.e. requiring ECDIS, Track control system, AIS integration with radar and improved bridge design. These risk control options will be evaluated separately in terms of cost effectiveness in the following.

The different risk control options related to navigational safety will have different risk reducing effects on various scenarios such as collision and grounding. Hence, different cost effectiveness can be achieved. However, when it comes to the economic benefits, these will have some similarities. For the purpose of this study, the economic benefit from enhanced navigational safety on LNG carriers will be reduced probability of total loss, reduced damage repair costs and reduced downtime due to damage repairs. For total losses, it is assumed that the average cost associated with this equals the new building cost of an LNG carrier, i.e. USD 170 million. For total losses occurring in the loaded condition, the additional cost of cargo loss is also considered, i.e. USD 17.5 million. The cost of an impact damage that is not resulting in total loss is assumed to consist of repair costs and downtime. For the purpose of this study, and in accordance with statistics from Navantia shipyards, average repair costs are assumed to amount to USD 1.5 million per accident, and average downtime due to the repairs are 30 days. Assuming a daily rate of USD 60,000, the average downtime costs per accident (not total loss) is hence estimated to be USD 1.8 million.

Thus, the following total costs are associated with these scenarios:

Total loss:	USD	170 million
+ Total loss – loaded condition	USD	17.5 million
Other hull damages:	USD	3.3 million

These estimates will be used in the assessment of the risk control options related to navigational safety.

RCO 5a: ECDIS

The cost of implementing ECDIS (including back up arrangements and maintenance cost) on a passenger vessel was estimated in the FSA on navigational safety of large passenger ships, and these cost elements are assumed similar for LNG carriers as well. However, the large passenger ship study did not consider the additional costs of training the officers in the use of ECDIS, whereas this cost was partly included in a more recent ECDIS study on other ship types. Both previous studies assumed that ECDIS will not incur any additional costs due to chart updates compared to conventional charts, and this is assumed also in the current study.

There are no specific references to ECDIS in the STCW convention but it is stated that mariners should be competent to carry out the duties they are expected to perform. For ships using ECDIS as the primary means of navigation, the watchkeeping officers and master should therefore be properly trained in the operation and use of such systems before using them operationally at sea. This may be achieved by e.g. attending IMO model course 1.27 or similar courses. Even though there are room for interpretations related to the extent of ECDIS training that is required by current regulations, for the purpose of this study, it is assumed that an ECDIS course is required for bridge personnel for ships where ECDIS is the primary means of navigation. Hence, these additional costs are taken into consideration in the following.

The total costs associated with this risk control option are hence: Initial acquisition and installation cost for the ECDIS and back up arrangements, maintenance cost and training cost. The training cost should also include costs related to travel, lodging, board and overtime pay in connection with the course. Several ECDIS courses are currently offered, and the fees for classroom courses vary from USD 550 to almost USD 1500 for courses of 3 to 5 days duration[1]. Computer based on-board training on ECDIS is also offered which might be a cheaper option. However, for the purpose of this cost effectiveness assessment, it is assumed that necessary training will be achieved at four-day courses and an average course fee of USD 1000 is assumed. It is further assumed that a total of 8 officers per vessel need to attend this course and that there will be no requirement for repetition courses. The estimates for travel costs, board and lodging and overtime pay used in the "increased use of simulator training" will be assumed also for ECDIS courses, but adjusted to a four-day course instead of a five-day course.

ECDIS training is currently a part of most curricula in the education of new navigational officers, and it is assumed that future newly qualified mariners will not need this additional training courses. Thus, training costs are assumed to be limited to sending 8 officers on a four-day training course when ECDIS is implemented on the vessel, i.e. it is an initial cost and no future costs are assumed in relation to training of officers. All cost elements associated with this risk control option is summarized in the following:

Initial acquisition and installation cost			USD	32,000
Initial cost for back up arrangements:			USD	20,000
Training cost, per officer				
Course fee	USD	1,000		
+ Travel cost	USD	1,500		
+ Board and lodging	USD	600		
+ Overtime pay	USD	800		

[1] Based on information about courses offered at SMSC in Norway (http://www.smsc.no/), Seagull AS in Norway (http://www.seagull.no), IDESS in the Philippines (http://www.idess.com/), Lairdside Maritime Centre in UK (http://www.lairdside-maritime.com/) and Warsash Maritime Centre in UK (http://www.warsashcentre.co.uk/).

x Number of officers to attend course		8	USD	31,200
Maintenance costs - annual	USD	500		
NPV – Maintenance costs			USD	9,100

Hence, the total cost associated with implementation of this risk control option has a net present value of NPV = USD 92,300. This cost will be assumed in the current cost effectiveness assessment.

The risk reduction of requiring LNG carriers to navigate using ECDIS can be difficult to assess, but a previous study reported to IMO in NAV 81/INF.9 has estimated this for three other ship types, i.e. an oil tanker of 80,000 DWT, a product tanker of 4,000 DWT and a bulk carrier of 75,000 DWT, using a Bayesian network model. According to this study, a power grounding risk reduction of 36% would be achieved for all three ship types from introducing ECDIS. For the purpose of this study, it is assumed that a risk reduction of 36% for power grounding scenarios will also be achieved by requiring ECDIS on LNG carriers. It is further assumed that ECDIS will have no notable effect on other accident scenarios such as collision, contact etc. Based on accident data, it is assumed that about 70% of the grounding risk stems from powered grounding, and a risk reduction of 36% will only be effective in these events. Drift groundings will generally not be prevented by enhanced navigational safety. At any rate, a risk reduction of 36% for 70% of all grounding events will be assumed in the current study.

According to the risk analysis, the potential loss of lives in grounding events is 2.93×10^{-3} per shipyear, i.e. 2.05×10^{-3} per shipyear for power grounding. Thus, a power grounding risk reduction of 36% corresponds to a reduced fatality rate by 7.38×10^{-4} per shipyear and Δ risk = 2.95×10^{-2} per ship for a vessel lifetime of 40 years. The probability of a powered grounding that results in total loss is 1.5×10^{-4} per shipyear. The probability of total loss in loaded condition, and hence of cargo loss is 7.5×10^{-5} per shipyear. The probability of a damages extending through the outer hull only from these scenarios were assessed to be 1.3×10^{-3}per shipyear. Thus, a risk reduction of 36%, corresponding to implementation of the risk control option, would result in the following average reduction in the following probabilities:

Total loss:	5.4×10^{-5}	Per shipyear
- Total loss – loaded condition	2.7×10^{-5}	Per shipyear
Outer hull damage:	4.8×10^{-4}	Per shipyear

With the assumed costs associated with total loss, cargo loss and repairs of hull damages outlined above, this probability reduction corresponds to an average economic benefit associated with this risk control option of USD 11,200 per shipyear. Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of NPV = USD 203,000.

Putting these estimates of cost, risk reduction and economic benefit together, one arrives at the following cost effectiveness associated with these risk control options:

GCAF	3.1 million	USD/ fatalities
NCAF	< 0	(-3.8 million USD/ fatalities)

Hence, it can be seen that ECDIS is a cost effective risk control option according to the cost-effectiveness criteria. The fact that ECDIS is associated with a negative NCAF value indicates that implementation of this risk control option is economical beneficial in itself, even without considering the risk reduction potential. Also, the GCAF value is very close to the limit of USD 3 million per averted fatality which indicates that implementation of ECDIS could be recommended also based on safety considerations alone. It is also noted that one of the assumptions made in this study was that ECDIS would only reduce the risk related to grounding events. However, the risk in other scenarios such as collision might also be reduced, and if such effects were to be accounted for as well, even lower GCAF and NCAF values could be expected. Thus, the conclusion that ECDIS is a cost effective risk control option for LNG carriers is believed to be robust. This is also in agreement with previous studies that have recommended ECDIS on other shiptypes such as large passenger vessels and various other cargo vessels.

RCO 5b: Track Control System

The cost of implementing track control systems was estimated in the previous FSA on navigational safety on large passenger ships, and these cost estimates will be assumed appropriate also for the current study.

I.e. an initial investment of USD 4,000 and an annual maintenance cost of USD 200 per year are assumed. This amounts to a net present value of USD 7,600 USD for a vessel with a lifetime of 40 years.

According to the study on navigational safety of large passenger ships, track control systems were assessed to have the same risk reducing effect as ECDIS. It is assumed that also for LNG carriers, the effect of implementing track control system is similar to that of implementation of ECDIS. However, previous implementation of ECDIS is a prerequisite for track control systems, so the risk potential will already have been reduced with 36% according to the discussion above. An additional risk reduction of 36% from implementing track control on the residual risk thus corresponds to a risk reduction of 23% compared to the pre-ECDIS risk level. Hence, for the purpose of this study, 23% probability reduction for powered grounding events will be assumed.

According to the risk assessment of LNG carriers, the potential loss of lives in grounding events is 2.93×10^{-3} per shipyear, and 2.05×10^{-3} per shipyear for power grounding. Thus, a power grounding risk reduction of 23% corresponds to a reduced fatality rate by 4.72×10^{-4} per shipyear and Δ risk = 1.89×10^{-2} per ship for a vessel lifetime of 40 years. Thus, the reduction in grounding frequency due to implementation of track control corresponds to the following risk reduction:

Δ risk	4.72×10^{-4}	Per shipyear
Δ risk	1.89×10^{-2}	Per ship

A reduction of 23% of the probability for powered grounding also corresponds to a reduction of total loss probabilities and probabilities of receiving other hull damages due to grounding. The following reduction in damage probabilities will result from implementation of track control systems:

Total loss:	3.4×10^{-5}	Per shipyear
- Total loss – loaded condition	1.7×10^{-5}	Per shipyear
Outer hull damage:	3.1×10^{-4}	Per shipyear

With the assumed costs associated with total loss, cargo loss and repairs of hull damages outlined above, this probability reductions corresponds to an average economic benefit associated this risk control option of USD 7,100 per shipyear. Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of NPV = USD 129,700.

Putting these estimates of cost, risk reduction and economic benefit together, one arrives at the following cost effectiveness associated with these risk control options:

GCAF	0.4 million	USD/ fatalities
NCAF	< 0	(-6.5 million USD/ fatalities)

Thus, according to this study, the implementation of a track control system together with ECDIS is a cost effective risk control option. The negative NCAF value indicates that implementation of this risk control option is economical beneficial in itself, even without considering the risk reduction potential. Also, the GCAF value is well below to the limit of USD 3 million per averted fatality which implies that implementation of track control would be recommended also based on safety considerations alone. The GCAF and NCAF values are found to be well below the criteria of USD 3 million. Hence, the conclusion that track control system is a cost effective risk control option for LNG carriers is believed to be robust.

RCO 5c: AIS integration with radar

The cost of integrating AIS with the ARPA radar was estimated in the FSA on cruise navigation, and it is assumed that the same initial and annual costs applies to the implementation of this risk control option onboard LNG vessels: initial equipment and upgrading cost of USD 2,000 and an annual maintenance cost of USD 100. This amounts to a net present value of the costs associated with this risk control option of NPV = USD 3,800 for a vessel with a 40-year lifetime.

Furthermore, according to the FSA on cruise navigation, this risk control option will have a risk reducing effect of 26% on collision scenarios. This estimate will also be assumed in the current study, i.e. the risk contribution from the collision scenarios will be reduced by 26% due to integrating AIS with radar. According to the risk assessment in step 2 of this FSA, the potential loss of lives in collision scenarios are

4.4×10^{-3} for crew and 1.6×10^{-3} for passengers per shipyear, i.e. a total potential loss of lives of 6.0×10^{-3} per shipyear. A risk reduction of 26% in these scenarios thus corresponds to a reduced fatality rate by 1.56×10^{-3} per shipyear and Δ risk = 6.25×10^{-2} per ship for a vessel lifetime of 40 years. Thus, the reduction in collision frequency due to integration of AIS with radar corresponds to the following risk reduction:

Δ risk	1.56×10^{-3}	Per shipyear
Δ risk	6.25×10^{-2}	Per ship

A reduction of 26% of the probability for collision also corresponds to a reduction of total loss probabilities and probabilities of receiving other hull damages due to collision. The following reduction in damage probabilities will result from implementation of track control systems:

Total loss:	8.0×10^{-5}	Per shipyear
- Total loss – loaded condition	4.8×10^{-5}	Per shipyear
Outer hull damage:	1.1×10^{-3}	Per shipyear

With the assumed costs associated with total loss, cargo loss and repairs of hull damages outlined above, this probability reduction corresponds to an average economic benefit associated with this risk control option of USD 18,000 per shipyear. Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of NPV = USD 328,200.

Putting these estimates of cost, risk reduction and economic benefit together, one arrives at the following cost effectiveness associated with these risk control options:

GCAF	0.06 million	USD/ fatalities
NCAF	< 0	(-5.2 million USD/ fatalities)

It can be seen from this assessment that the GCAF value is well below the limit of USD 3 million per fatality, and that the NCAF value is negative. This means that AIS integration with radar is assessed to be cost effective. It is also seen that the values are well below the criteriaand this conclusion is believed to be robust also when the uncertainties and various assumptions are taken into account.

RCO 5d: Improved bridge design

Improved bridge design is a rather ambiguous description of a risk control option that will be considered for enhancing navigational safety. This may be achieved in a number of different ways, but for the purpose of this study, it is assumed that improved bridge design means requirements similar to workstation requirements contained in the DNV class notation NAUT-AW. Furthermore, it is assumed that the current fleet of LNG carriers on average has similar standard on the bridge design as the fleet of cruise vessels. Hence, the study on large passenger ships will be referred to and used as base for estimating costs and reductions in accident frequencies for LNG vessels.

According to the FSA study on cruise navigation, it was assumed that upgrading an average cruise vessel bridge design to NAUT-AW or similar would result in an initial cost of USD 80,000 as well as increased annual maintenance costs of USD 2,000. For the purpose of this study, these costs are assumed also for upgrading an average LNG vessel bridge design. I.e. the net present value of the costs associated with this risk control option is estimated to be NPV = 116,300 USD.

According to the FSA on cruise navigation, the risk associated with collision and grounding can be reduced by 7% and 5% respectively by improving the bridge design. However, DNV experts on nautical safety believes that these estimates are too low, and in a technical note investigating the effect of additional nautical class notations on nautical related accidents it is concluded that *there is a significant, statistical different between mean nautical accident rates of ships with and without additional nautical class notation* [66]. Statistics indicates that the accident frequency for collision, contact and grounding may be reduced by as much as almost 50% - with the most notable reductions being on the collision and contact frequencies – by implementing the requirements in these additional class notations. Bridge design is an important part of these requirements.

For the purpose of this study on LNG carriers, the assumed percentual reduction in collision and grounding frequencies will be based on the estimated in the FSA on cruise navigation. However, in accordance with discussions with DNV experts on nautical safety, improved bridge design be assumed twice what was estimated in the cruise FSA, i.e. it is assumed that the risk associated with collision and grounding can be reduced by 14% and 10% respectively by improving bridge design on LNG tankers. This is still assumed to represent conservative estimates. In addition it is assumed that improved bridge design will have a risk reduction effect also in contact scenarios, and for the purpose of this study, the same risk reduction as for collision scenarios will be assumed, i.e. a risk reduction of 14%. Assuming these risk reductions combined with the risk assessment from step 2 of this FSA, the risk reduction of this risk control option is assessed to:

Δ risk	1.25×10^{-3}	Per shipyear
Δ risk	5.00×10^{-2}	Per ship

A reduction of 14%, 10% and 14% of the probability for collision, grounding and contact accidents also corresponds to a reduction of total loss probabilities and probabilities of receiving other hull damages due to these scenarios. The following reduction in damage probabilities from these scenarios will result from implementation of improved bridge design:

Total loss:	7.3×10^{-5}	Per shipyear
- Total loss – loaded condition	4.1×10^{-5}	Per shipyear
Outer hull damage:	8.5×10^{-4}	Per shipyear

With the assumed costs associated with total loss, cargo loss and repairs of hull damages outlined above, this probability reductions corresponds to an average economic benefit associated this risk control option of USD 15,900 per shipyear. Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of NPV = USD 289,500.

Putting these estimates of cost, risk reduction and economic benefit together, one arrives at the following cost effectiveness associated with these risk control options:

GCAF	2.3 million	USD/ fatalities
NCAF	< 0	(-3.5 million USD/ fatalities)

Thus, improved bridge design is a risk control option that is associated with a GCAF value less than USD 3 million and a negative NCAF value, and as such it is regarded as cost effective according to this study. The conclusion is believed to be robust and improved bridge design is carried forward as a cost effective risk control option that is recommended for implementation.

A.6.6 RCO 6: Restriction on crew schedule to avoid fatigue of crew

The extension of the STCW/ILO regulations to port operations and would have the potential to reduce crew fatigue. However it should be noted that the impact could be dependent of many variables such as vessel flag, number of crew members, route, etc.

According to several experts contacted, which included a port facility security officer, a port state control officer and a LNG port terminal officer, all masters of commercial vessels, the STCW guidelines are presently followed by most of LNG crews, even during port operations. Due to the high standards of crew training and safety management systems associated with this vessel type and the low number of port operations performed by them, this risk control option would only have impact on a small percentage of the present fleet, i.e. nearly 4.5% of the present fleet according to expert opinion.

In many operations of port state control the fatigue of the crew is evident resulting in the normal detention of the ship until there is a safety guaranty that normal operations can be carried out. An estimation of 8 hours of detention will be used in order to assess the cost associated to this control option. The sailing and port time for LNG carriers are estimated as 90% and 10% respectively. This corresponds to 329 and 36 days respectively. Considering a 24 hour normal loading/unloading, an 8 hour increase of port time in 4.5% of the fleet per port operation, results in an average increase of 20 min/per ship/per port operation. This is an increase of 1.375% on the port time which in the round year results in a sum of additional 0.495 days in port. This value corresponds to additional downtime, which has estimated to 60.000

USD/day, corresponding to a cost of 29.700 USD. The input to the cost estimates are given in the table below:

Table 43: Input to Cost estimate for RCO 6		
Required Input	Input Value	Reference
Initial investment	0	
Annual Cost	USD 29.700	Estimate

The NPV for the costs associated with this RCO is USD 0.509 million.

According to the risk analysis:

- The annual frequency of Collision was estimated to 6.7 x 10^{-3} per shipyear
- The annual frequency of Powered Grounding was estimated to 2.8 x 10^{-3} per shipyear
- The annual frequency of Contact was estimated to 2.8 x 10^{-3} per shipyear.

The expected risk reduction from implementation of this risk control option is difficult to assess. Considering statistics of fatigue contribution to these accidents and eliciting expert opinion, the following estimates may be obtained:

- 15% of all above collisions could be avoided for 4.5% of the fleet = 0.7%
- 20% of all above groundings could be avoided for 4.5% of the fleet = 0.9%
- 30% of all above contacts could be avoided for 4.5% of the fleet = 1.4%

Table 44 summarizes the achieved risk reduction.

Table 44: Risk Reduction							
Required Input	Scenario	Initial Frequency	Fatalities per Shipyear initial	% reduction	Frequency reduction	Fatalities per shipyear final	N. Lives Saved
RCO - 6	Collision	6.70 x 10^{-3}	6.01 x 10^{-3}	0.7 %	4.20 x 10^{-5}	5.97 x 10^{-3}	4.21 x 10^{-5}
RCO - 6	Powered Grounding	1.96 x 10^{-3}	2.05 x 10^{-3}	0.9 %	1.76 x 10^{-5}	2.03 x 10^{-3}	1.85 x 10^{-5}
RCO - 6	Contact	2.80 x 10^{-3}	1.46 x 10^{-3}	1.4 %	3.92 x 10^{-5}	1.44 x 10^{-3}	2.04 x 10^{-5}
Total:			**9.52 x 10^{-3}**	**22%**		**7.77 x 10^{-3}**	**8.10 x 10^{-5}**

This corresponds to 8.10 x 10^{-5} lives saved per shipyear or 3.2 x 10^{-3} fatalities per ship throughout its lifetime.

Associating the reduction in probabilities with the assumed costs for total loss, cargo loss and repairs of hull damages, the average economic benefit resulting of this risk control option can be estimated. From the table below, the estimated annual benefit will be USD 26,348 x 0.045 = USD 1200. The benefit per ship during lifetime to is calculated to be NPV = USD 20,300.

To summarize:

Δ C	USD 0.509 million
Δ R	3.2 x 10^{-3} fatalities per ship
Δ B	USD 20,300

The corresponding NCAF and GCAF values are presented below.

GCAF	159 million	USD / fatalities
NCAF	153 million	USD / fatalities

From these results one may conclude that this would not be a cost effective risk control option according to the cost-effectiveness criteria.

A.6.7 RCO 7: Increased use of simulator training

The costs related to this risk control option are the costs of sending the bridge team members of the crew to simulator training courses and consist of course fee, travel cost, accommodation and board and overtime pay. For the purpose of this study, it is assumed that a typical LNG carrier will operate with four officers onboard at any time. Furthermore, a 50-50 rotation scheme is assumed, meaning that a total of 8 officers are needed for continuous operation of the vessel. The proposed risk control option implies sending these 8 officers on simulator training courses every five years.

The course fee for such a five-day simulator training course will vary considerably according to where the course is held. For example, course fees for comparable courses at SMSC in Trondheim[1] are almost USD 4,000, whereas 5-days courses at IDESS in the Philippines[2] cost less than USD 1,000. However, for the purpose of this study, an average course fee of USD 3,000 will be assumed. This is in line with the estimates used in the FSA study on navigational safety for passenger ships. For the purpose of this study, the estimates on travel expenses and board and lodging used for passenger ships will also be adopted from the passenger ship study. In addition, one additional cost element will be included, i.e. overtime pay for officers attending the training course. It is assumed that these courses will have to be attended out of regular working schedule, and one week's pay is assumed. Assuming an average yearly salary of about USD 50,000, the extra pay for attending a week-long course is estimated to be USD 1,000. The average cost estimates, incurring every five years for each officer, are summarized below:

- Course fee: USD 3,000
- Travel costs: USD 1,500
- Accommodation and board USD 800
- Overtime pay USD 1,000

Assuming no other cost elements, the total cost, for 8 officers, amounts to USD 50,400 every five years. For a vessel with a lifetime of 40 years, this corresponds to a net present value of NPV = USD 207,000.

This risk control option will enhance the navigational safety of LNG vessels and it is assumed that risk reductions related to collision, grounding and contact scenarios can be achieved. It is recognized that risks related to drift grounding will not be addressed by this risk control option, and for the purpose of this study, acknowledging that most groundings are powered groundings, it is assumed that 70% of all grounding events are powered grounding. According to the risk analysis of LNG carriers, the potential loss of lives from these scenarios is 7.9×10^{-3} among crew and 1.59×10^{-3} among passengers, totalling 9.5×10^{-3} per shipyear. This will be assumed as the potential for risk reduction for this risk control option.

It is quite difficult to assess the risk reduction from improved navigator training, and in the study on passenger ships this was done using risk models that was developed based on Bayesian networks. According to this model, improved navigator training has the potential to reduce the collision risk by 3% and grounding risk by 8% for passenger ships, resulting in an overall risk reduction in collision and grounding events of 6%. Contact events were not assessed in the study on passenger vessels, but it can be assumed that a risk reduction similar to the overall risk reduction of collision and grounding can be obtained for these events as well. For the purpose of this study on LNG carriers, estimates based on the cruise study is adopted, i.e. it is assumed that the risk reduction that can be achieved from implementation of this risk control option will be 3% for collision scenarios, 8% for grounding scenarios and 6% for contact scenarios. I.e. Δ risk = 4.3 x 10-4 per shipyear or 1.7 x 10-2 per ship for a vessel lifetime of 40 years.

The economic benefit from implementing this risk control option will be related to reduced cost of ship damages and downtime due to ship repairs. In general, it is distinguished between two damage cases, i.e. total loss and hull damages. It is assumed that leakage of LNG cargo due to a serious collision or grounding is equivalent to a total loss as well as receiving other critical damages the ship will not survive, whereas damages that do not penetrate the cargo tanks involve repair costs. For the purpose of this study, the cost of a total loss is assumed equivalent to the newbuilding price of a typical LNG vessel. In

[1] Website: http://www.smsc.no/

[2] Website: http://www.idess.com/

addition, if the ship is in loaded condition, the loss of cargo should be taken into account. In the previous annex, the newbuilding price was estimated to USD 170 million for a typical LNG carrier, and this estimate will be assumed in this study as well. Hence, the cost of a total loss is assumed to be USD 170 million.

The value of LNG that can be loaded on a typical LNG carrier will vary according to the price of natural gas, but an average price of USD 6 per thousand cubic feet has been assumed[1]. This is the price for natural gas, and it should be kept in mind that the volume of natural gas is greater by a factor 600 compared to LNG. Converted from cubic feet to cubic meters and from natural gas to LNG, this corresponds to an average price of USD 127 per cubic meter of LNG. For an LNG carrier with capacity of 138,000 m^3, the total value of the LNG cargo onboard is estimated to USD 17.5 million. This cost is added to the total loss cost for total losses that occurs when the vessel is in loaded condition.

The cost of an impact damage that is not resulting in total loss is assumed to consist of repair costs and downtime. For the purpose of this study, average repair costs are assumed to amount to USD 1.5 million per accident, and average downtime due to the repairs are 30 days. Assuming a daily rate of USD 60,000, the average downtime costs per accident (not total loss) are estimated to be USD 1.8 million. The total costs of typical hull damages are hence estimated to be USD 3.3 million.

According to the risk analysis, the probability of a collision, powered grounding or contact damage that results in total loss is 5.6×10^{-4} per shipyear. Of these, 3.1×10^{-4} is in loaded condition. The probability of a damages extending through the outer hull only from these scenarios were assessed to be 6.5×10^{-3} per shipyear. Thus, a risk reduction of 3% (collision), 8% (grounding) and 6% (contact), corresponding to implementation of the risk control option, would result in the following average reduction in the following probabilities:

Total loss:	2.8×10^{-5}	Per shipyear
- Total loss – loaded condition	1.5×10^{-5}	Per shipyear
Outer hull damage:	2.9×10^{-4}	Per shipyear

With the assumed costs associated with total loss, cargo loss and repairs of hull damages outlined above, this probability reductions corresponds to an average economic benefit associated this risk control option of USD 5,900 per shipyear. Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of NPV = USD 107,000

Putting these estimates of cost, risk reduction and economic benefit together, one arrives at the following cost effectiveness associated with these risk control options:

GCAF	12 million	USD/ fatalities
NCAF	5.8 million	USD/ fatalities

Compared to the limit for cost effectiveness of USD 3 million per averted fatality, it can be seen that this is not a cost effective risk control option. However, it is noted that use of simulator or navigator training can be important and even necessary for specific ports/trades, and this risk control option may emerge as cost effective in many cases. However, what was evaluated in this high-level FSA was to require increased simulator training as a general requirement through IMO legislation. Indeed, most LNG operators have trained their crew above minimum SOLAS requirements, and it is encouraged that such training should be continued. However, it is believed that the implementation of such training should be the responsibility of the owner or operator, based on commercial considerations, or possibly requirements from certain port states or terminal owners applicable to ships operating particular trades.

A.6.8 RCO 8: Periodic thermal image scanning of engine room

The costs related to this risk control option are divided into two parts. First, there is the cost of performing the actual thermoscanning, and then there is the cost of possible corrective actions. However,

[1] Estimates based on statistics of U.S. Natural Gas LNG Imports from Energy Information Administration. Available online at: http://tonto.eia.doe.gov/dnav/ng/hist/n9103us3M.htm.

even if performing thermoscanning every year, it is not assumed that the need for corrective measures will be revealed each year. For the purpose of this study, it is assumed that a need for corrective measures will be identified every third year on average. There are no initial investments or other cost elements assumed for this risk control option. For the purpose of this study, the following average costs incurred by implementing this risk control options are assumed:

- Average cost of thermoscanning survey: USD 1,000
- Average cost of corrective measures, every third year: USD 10,000

Hence, an average annual cost of USD 1,000 and an average triennial cost of USD 10,000 per ship are assumed for this risk control option. Assuming a vessel lifetime of 40 years and a 5% depreciation rate, this amounts to a net present value of NPV = USD 82,000.

According to the risk analysis, the annual frequency of engine room fires was estimated to 1.458×10^{-3} per shipyear. It is assumed that between 50 – 60 % of these fires are due to hot surfaces, and the annual frequency of fires due to hot surfaces is assumed to be 8.0×10^{-4}. Furthermore, an average fatality rate of 0.37 fatalities per engine room fire was assumed. According to DNV data, the direct costs of an engine room fire onboard a cargo vessel will be in the range of USD 1 – 4 million, and the average claim for a fire or explosion accident is USD 2 million. However, LNG vessels are sophisticated vessels, and it is believed that an engine room fire on these vessels will be costlier than average. For the purpose of this study, it is assumed that an average engine room fire on LNG carriers will have direct cost of approximately USD 4 million. On top of this there are the costs due to vessel being out of hire during repairs. For the purpose of this study, an average dayrate of USD 60,000 is assumed, and according to statistics from Navantia shipyard, the average repair time for an engine room fire is about 40 days. Hence, an additional average cost of USD 2.4 million will be assumed for an engine room fire. Thus, for the purpose of this study, the average number of lives saved and the average economic benefit from averting an engine room fire is assumed to be 0.37 and USD 6.4 million respectively.

The expected risk reduction from implementation of this risk control option can be somewhat more difficult to assess. It is noted that implementation of the voluntary F-M class is assumed to have the potential to reduce the frequency of engine room fires due to hot surfaces with a maximum of 50%, but this class notation contains several other measures in addition to thermoscanning. Thus, the risk reduction that can be expected from thermoscanning alone is assumed to be less. For the purpose of this study, it is conservatively assumed that 25% of all engine room fires due to hot surfaces can be avoided by introducing an annual thermoscanning routine. This corresponds to an annual risk reduction of 2.0×10^{-4} averted engine room fires, and translates to the following reduction in terms of number of fatalities and the following economic benefit per shipyear:

Δ risk	7.4×10^{-5} fatalities per shipyear
Δ economic benefit	USD 1300 per shipyear

Table 45: Risk Reduction

Required Input	Scenario	Initial Frequency	Initial Fatalities per ship year	% reduction	Risk Frequency Reduction per year	N. Lives Saved (Δ risk per ship year)
RCO - 8	Engine room fire due to hot surface	8.0×10^{-4}	2.9×10^{-4}	25%	2×10^{-4}	7.4×10^{-5}

Over a lifetime of 40 years and assuming 5% depreciation rate, this amounts to a total risk reduction of approximately 3.0×10^{-3} fatalities per ship and an economic benefit of NPV = USD 23,300.

This corresponds to the NCAF and GCAF values presented below for this risk control option, and it can be seen that according to this assessment, annual thermoscanning of engine rooms is not a cost effective risk control option.

GCAF	28 million	USD/ fatalities
NCAF	20 million	USD/ fatalities

The assessed cost effectiveness exceeds the cost effectiveness criteria of USD 3 million, and this risk control option is therefore assessed to be not cost effective.

A.6.9 RCO 9: Redundant radar sounding for filling level check

The input to the cost estimates are given in the table below:

Table 46: Input to Cost estimate for RCO 9		
Required Input	Input Value	Reference
Initial investment	USD 415,000	Yard Calculation
Annual Cost		

The initial value represents the cost of a radar sounding device for checking the filling level. Annual maintenance costs are assumed negligible. The total cost associated with implementation of this RCO 10 has a net present value NPV= USD 0.415 million.

For the purpose of this study it is assumed that this RCO may reduce the likelihood of overfilling by 30%, corresponding to a 7% reduction of loading/unloading events. According to the risk analysis, the annual frequency of loading/unloading incidents was estimated to 7.75×10^{-3} per shipyear. The potential loss of lives (PLL) in such events is estimated to 6.46×10^{-4} per shipyear. Thus a risk reduction of 6.81%, for such events corresponds to:

- An updated PLL of 6.02×10^{-4}
- An annual total reduction of 4.40×10^{-5} PLL per ship year and
- A risk reduction of 1.76×10^{-3} per ship over the lifetime of 40 years

According to Navantia Data of LNG Repairs the average claim for an spill on deck is around USD 0.8 million. Thus, for the purpose of this study, the average economic benefit from averting an incident is assumed to be USD 0.8 million. As the probability of having an load/unload incident is 7.75×10^{-3} and the % of probability reduction is around 7%, the Annual Benefit for the owner will be approximately USD 400 per shipyear. Over a lifetime of 40 years and assuming a depreciation rate of 5%, this amounts to the net present value of around NPV = USD 7,300.

Putting these estimates of cost, risk reduction and economic per ship benefit together, the following is obtained:

Δ C	USD 0.415 million
Δ R	1.76×10^{-3} fatalities per ship
Δ B	USD 7,300

Hence, one arrives at the following cost effectiveness associated with this risk control options:

GCAF	236	million	USD / fatalities
NCAF	232	million	USD / fatalities

It can be concluded that this RCO is not a cost effective risk control option.

Annex III: Recommendations

16 Recommendations

As basis for the recommendations it is observed that:

- An RCO is considered cost-effective if the GCAF (Gross Cost of Averting a Fatality) is less than \$3M. This is the value used in all decisions made following the FSA studies submitted under Agenda Item 5, Bulk Carrier Safety, at MSC 76, December 2002 and suggested in MSC 72/16.
- An RCO is also considered cost effective if the NCAF is less than USD 3M.
- Failure of navigational equipment in coastal waters, leading to collision or grounding, emerged as the highest ranked hazard from the HAZID.
- The risk level was found to lie in the ALARP region. Notwithstanding, the identification of several cost effective risk control options demonstrates that the risk associated with LNG carriers are not ALARP. In order to bring the risks down ALARP it is therefore recommended that these RCOs should be made a requirement for the LNG tanker fleet.
- Collision, grounding and contact were found to be responsible for 90% of the overall risk according to the risk analysis.
- It is commonly acknowledged that one catastrophic collision or grounding accident has the potential to damage the whole LNG shipping industry.
- Acknowledging the physical properties of LNG, and the difficulties in assuring that the LNG tanks will be able to withstand high energy collision and grounding impacts, consequence mitigation is difficult and the consequences of a major spill event may be severe.
- Thus, preventing such accidents to occur seems intuitively to be the best strategy for mitigating the risk. This may be achieved by measures related to safer navigation.

This FSA study demonstrates that the following RCOs, all related to navigational safety and collision and grounding avoidance, are providing considerable risk reduction in a cost-effective manner:

- RCO 1c: Risk based maintenance – Navigational systems.
- RCO 5a: Improved navigational safety – ECDIS.
- RCO 5b: Improved navigational safety – AIS integrated with radar.
- RCO 5c: Improved navigational safety – Track control system
- RCO 5d: Improved navigational safety – Improved bridge design

These cost-effective RCOs with significant potential to reduce loss of lives are thus recommended as mandatory IMO requirements pertaining to the LNG carrier fleet.

Some RCOs were found to have negative or low NCAF values, and as such they should be regarded as cost-effective. However, they have GCAF values > USD 3 million and their potential for risk reduction is small. The following RCOs are therefore not recommended for mandatory implementation through IMO legislation, but are highlighted as attractive alternatives for voluntary implementation by owners from a commercial point of view:

- RCO 1a: Risk based maintenance – Propulsion systems.
- RCO 1b: Risk based maintenance – Steering systems.

The following RCOs were not found to be cost-effective and are therefore not recommended as mandatory requirements:

- RCO 1d: Risk based maintenance. “Cargo handling systems”
- RCO 2: Strain gauges.
- RCO 3: Increase double hull width, increase double bottom depth or increase hull strength.
- RCO 4: Redundant propulsion system - two shaft lines.
- RCO 6: Restrictions on crew schedule.
- RCO 7: Increased use of simulator training.
- RCO 8: Periodic thermal image scanning of engine room
- RCO 9: Redundant radar sounding for filling level check

As a final note, it is acknowledged that some of the risk control options that were assessed to be not cost effective may turn out to be effective in many cases, i.e. for particular ships or particular trades, and the results from this FSA should not be construed to mean that it will not be sensible to consider them on a case by case basis.

For example, increased use of simulator training or navigator training can be important and even necessary for specific ports/trades, and this risk control option may emerge as cost effective in many cases. However, what was evaluated in this high-level FSA was to require increased simulator training as a general requirement through IMO legislation. Indeed, most LNG operators have trained their crew above minimum SOLAS requirements, and it is encouraged that such training should be continued. However, it is believed that the implementation of such training should be the responsibility of the owner or operator, based on commercial considerations, or possibly requirements from certain port states or terminal owners applicable to ships operating particular trades.

Furthermore, redundant propulsion systems and two shaft lines may be required for future larger LNG carriers or future LNG carriers with diesel engines replacing the conventional steam turbines. However, it was not deemed necessary to make double propellers a mandatory general requirement for the whole fleet of LNG carriers.

16.1 FINAL RECOMMENDATIONS FOR DECISION MAKING

Based on the outcome of this FSA application, it is recommended to formulate mandatory carriage requirements for the following navigational equipment on board LNG carriers:

- ECDIS
- AIS (Automatic Identification System) integrated with radar.
- Track control system

Furthermore, it is recommended that improved bridge design beyond standard/minimum SOLAS bridge design, e.g. corresponding to the voluntary class notation NAUT-AW, is made a requirement for the LNG carrier fleet.

Finally, it is recommended to require a risk based maintenance plan for critical navigational equipment.