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FORMAL SAFETY ASSESSMENT

FSA – Liquefied Natural Gas (LNG) carriers

Submitted by Denmark

SUMMARY

Executive summary:	This document reports on the Formal Safety Assessment study on Liquefied Natural Gas carriers carried out within the research project SAFEDOR.
Action to be taken:	Paragraph 10
Related documents:	MSC 83/INF.3, MSC 72/16, MSC/Circ.1023 – MEPC/Circ.392 and MSC 83/INF.2

Introduction

1 The Maritime Safety Committee, at its seventy-fourth session (2001), and the Marine Environment Protection Committee, at its forty-seventh session (2002), approved Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process, as set out in MSC/Circ.1023 – MEPC/Circ.392 (consolidated with amendments in MSC 83/INF.2).

2 Member Governments and non-governmental organizations were invited to apply FSA in accordance with the Guidelines and to submit the results thereof to the Organization in accordance with the Standard Format for Reporting shown in appendix 8 of the Guidelines.

3 As part of the research project SAFEDOR[1], a high-level FSA study on Liquefied Natural Gas (LNG) carriers has been undertaken. The main results of the FSA study are provided in the annex and a more comprehensive report is submitted as document MSC 83/INF.3.

[1] SAFEDOR: EU-funded research project entitled: Design, Operation and Regulation for Safety.

Summary of the study results

4 The FSA study on LNG carriers demonstrated that:

.1 the safety level of LNG carriers lies within the ALARP[2] region;

.2 the risk level is dominated by collision, grounding and contact scenarios resulting in accidental release of LNG; and

.3 some identified risk control options were found to be cost effective according to the cost effectiveness criteria in document MSC 72/16.

5 The following risk control options were found to be cost effective:

.1 risk-based maintenance of navigational systems;

.2 ECDIS for improved navigational safety;

.3 AIS integrated with radar for improved navigational safety;

.4 track control system for improved navigational safety;

.5 improved bridge design for improved navigational safety;

.6 risk-based maintenance of propulsion system; and

.7 risk-based maintenance of steering systems.

Proposal

6 Based on the FSA study reported in document MSC 83/INF.3, the following risk control options may be proposed to be made mandatory IMO requirements for the LNG carrier fleet:

.1 risk-based maintenance of navigational systems;

.2 ECDIS for improved navigational safety;

.3 AIS integrated with radar for improved navigational safety;

.4 track control system for improved navigational safety; and

.5 improved bridge design for improved navigational safety.

7 In addition, the following risk control options are cost effective, but with limited risk reduction effects:

.1 risk-based maintenance of propulsion system; and

.2 risk-based maintenance of steering systems.

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2 ALARP: As Low As Reasonably Practicable.

8 An abridged version of the full FSA report is attached at annex.

Further information on SAFEDOR

9 Further information on the SAFEDOR project can be found on the consortium's website: http://www.safedor.org.

Action requested of the Committee

10 The Committee is invited to consider the information provided and take action as appropriate.

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ANNEX

FORMAL SAFETY ASSESSMENT OF LIQUEFIED NATURAL GAS (LNG) CARRIERS

1 SUMMARY

A full Formal Safety Assessment (FSA) is performed to estimate the risk level and to identify and evaluate possible risk control options (RCOs) for Liquefied Natural Gas (LNG) carriers.

The FSA study concluded that both the individual and the societal risk associated with LNG carriers are within the ALARP area. This means that risks should be made ALARP by implementing cost effective risk control options. It was further concluded that three generic accident scenarios together are responsible for about 90% of the total risk, i.e. collision, grounding and contact accidents.

The basis for the recommendations given in this study is the following:

- An RCO is considered cost-effective if the GCAF (Gross Cost of Averting a Fatality) is less than US$ 3 million. 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 proposed in document MSC 72/16.

- An RCO is also considered cost effective if the NCAF (Net Cost of Averting a Fatality) is less than US$ 3 million.

The study demonstrates that the following RCOs are providing considerable risk reduction in a cost-effective manner:

- Risk-based maintenance of navigational systems
- ECDIS
- AIS (Automatic Identification System) integrated with radar
- Track control system
- Improved bridge design.

These five cost-effective RCOs with significant potential to reduce loss of lives are strongly recommended as IMO requirements. Some of these RCOs are already implemented on most LNG carriers. The measures are not, however, required by IMO. The cost benefit assessment is based on the introduction of one RCO at a time, but the conclusions are believed to be robust in any case.

In addition, the following risk control options are cost effective, but with limited risk reduction effects:

- Risk-based maintenance of propulsion system
- Risk-based maintenance of steering systems.

2 DEFINITION OF THE PROBLEM

LNG carriers are normally considered to be among the safest vessels in the merchant fleet today and they have a general reputation within the industry of being well designed, constructed, maintained, manned and operated with a high focus on safety in every aspect. Indeed, accident statistics for LNG carriers to date substantiates this view, and no major accident involving accidental release of large amounts of LNG have ever occurred in the history of LNG shipping.

Nevertheless, there have been major concerns regarding safety of LNG shipping and it is commonly acknowledged that one catastrophic accident has the potential to damage the whole LNG shipping industry.

Hence, in an attempt to quantify a baseline risk level for the world fleet of conventional LNG carriers, and also to identify and evaluate alternative risk control options for improved safety, the full Formal Safety Assessment methodology has been applied on the world fleet of LNG carriers.

In addition to a number of regulations pertaining to all ship types there is an International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk – the IGC Code. This Code is applicable to LNG carriers and it is made mandatory under the SOLAS Convention.

The scope of the study is limited to embrace safety issues and loss of life. Thus, security risks and property risks are regarded as out of scope. LNG is neither toxic nor persistent so environmental risks due to pollution from LNG shipping were considered to be minimal. Furthermore, the scope only covers credible accidents of a certain scale, while occupational hazards associated with high frequency and low consequence incidents are defined as out of scope. Additionally, the study only covers the operational phase of an LNG carrier's life-cycle. Risks associated with vessels at yards or in dock under construction, repair or maintenance or in the decommissioning and scrapping phase are considered to be out of scope. Furthermore, only the shipping stage in the LNG value chain will be considered, i.e. covering loading of LNG at the export terminal, the actual shipping of LNG in special purpose vessels and unloading of LNG at the receiving terminal. Third party risks to people onshore or onboard other vessels are considered to be out of scope, and only risks to LNG crew will be considered.

Currently, the LNG shipping industry is undergoing considerable changes, e.g. an expected doubling of the fleet over a 10-year period, emergence of considerable larger vessels, alternative propulsion systems, new operators with less experience with LNG shipping, new LNG trades, LNG offshore operations and an anticipated shortage of qualified and well trained crew to man LNG carriers in the near future. This development has caused some worry that the LNG shipping may experience an increasing risk level in the time to come. Notwithstanding, the ongoing development in the LNG fleet has not been considered in this FSA and the scope has been on conventional LNG carriers currently in operation, facilitating the use of available accident statistics pertaining to the fleet of LNG carriers.

3 BACKGROUND INFORMATION

Risk acceptance criteria

In order to assess the risk as estimated by the risk analysis, appropriate risk acceptance criteria for LNG tankers were established prior to and independent of the actual risk analysis. Acceptance criteria for individual crewmembers and societal risk for crew were established, as outlined in the following.

Criteria for individual risk to crew have been established for previous FSA applications. These are deemed appropriate for LNG carriers and have been adopted for the purpose of this study. The following risk acceptance criteria have been employed, corresponding to the risk levels experienced by an exposed crewmember. Individual risk to third parties is intuitively regarded as negligible.

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

Societal risk acceptance criteria for LNG crew were established according to the approach presented in document MSC 72/16, i.e. based on the economic value of LNG shipping. Based on estimates of daily rates, operational costs and initial investments, the economic value of a typical LNG carrier was assessed to be about US$ 1.6 million per year. From these estimates the risk acceptance criteria illustrated in Figure 1 may be derived. It is noted that these criteria are somewhat stricter than the criteria proposed for tankers in general by document MSC 72/16.

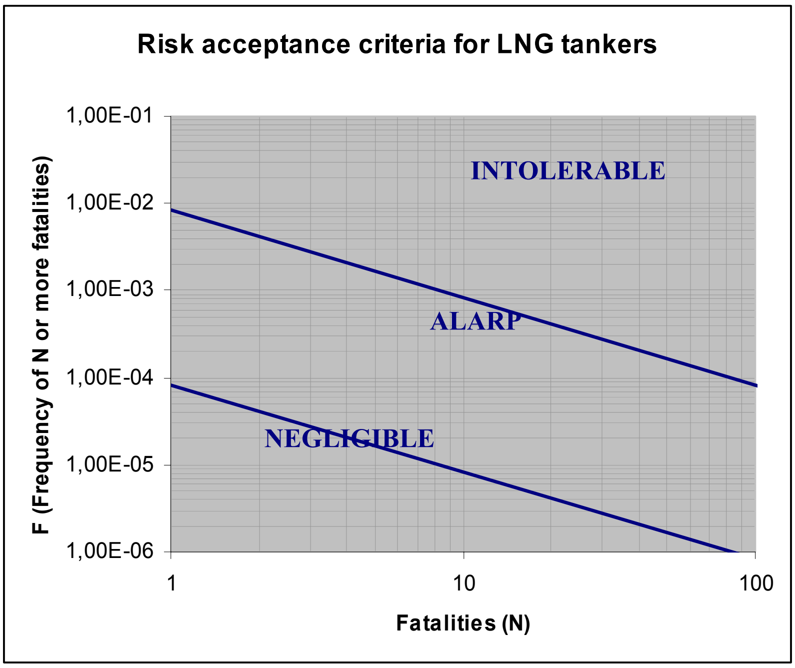

Figure 1: Societal risk acceptance criteria for crew

Liquefied Natural Gas (LNG)

LNG is produced by liquefaction of natural gas. It consists of mostly methane with small amount of other hydrocarbons and nitrogen, at cryogenic temperatures around ÷162°C. 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. The weight of LNG is less than the weight of water, thus LNG spilled on water will float.

When vaporized, LNG forms visible vapour cloud which can become flammable and explosive under certain well-known conditions. For methane, the dominant component of LNG vapour, the flammability range is approximately between 5 and 15 percent by volume. 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. For a mixture of about 10% methane vapour and air at atmospheric pressure, the auto-ignition 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 main LNG hazards, due to the physical properties of LNG and LNG vapour are:

- *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 cannot easily be extinguished and all the LNG must normally be consumed before they go out. The thermal radiation from a pool fire may injure unprotected people and damage property a considerable distance away from the fire itself.

- *Vapour clouds.* If not immediately ignited, the evaporating natural gas may form a vapour cloud that can drift some distance from the spill site. 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.

- *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.

- *Asphyxiation*. Although not toxic, a non-ignited LNG vapour could cause asphyxiation because it is displacing breathable air.

- *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 creating an 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.

- *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. Such a rapid phase transition might have the potential to shatter windows and glass nearby but is only assumed to constitute a minor hazard to nearby people and structures.

- *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.

- *Pollution*. LNG is neither toxic nor persistent, thus LNG spills will cause minimal pollution or damage to the marine environment.

- *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.

LNG shipping

The first purpose built LNG tanker transported the first commercial cargo 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.

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. As of April 2007, the LNG fleet contains 223 ships, with another 140 vessels in the order books. The total size of the current fleet is almost 28 million cubic metres, giving an average size of 125,000 cubic metres for the present fleet of LNG carriers. LNG super-tankers with capacities of 200,000 to 250,000 cubic metres are foreseen in the near future.

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 about 50% membrane ships, 45% spherical tankers and 5% of other types of ships, although membrane tankers are dominant among LNG newbuildings.

The main exporters of LNG are in the North-Africa/Middle East region, in Southeast Asia and Australia as well as Nigeria and Alaska. The main importers are in the USA, Japan and South Korea, Southern Europe including Turkey and India. Typical LNG trades are unilateral, thus an LNG tanker will normally sail in ballast condition about 50% of the time.

Accident statistics

Very few fatalities have been reported as a result of LNG carriers operation: there has been one incident where a terminal worker died and another incident where a fatality among the crew on a bulk carrier that collided with a LNG carrier occurred. In addition to this, there have been some fatalities associated with LNG carriers not in normal operation, i.e. during construction and ship trials.

In all, information on 182 incidents involving LNG carriers of more than 6,000 GRT is known from different sources (covering the period up to and including 2005). Twenty-four of these will be out of the scope of this FSA application (incidents in yards or dry-dock during construction, repair or maintenance, piracy and incidents to ships while in tow, during sea trials or when laid up). This results in 158 known and relevant incidents involving LNG carriers. Information about these has been utilized in the FSA study. The available material indicates that incidents occur on all types of LNG carriers, and that the accident frequencies are comparable for membrane and spherical LNG carriers.

The accident statistics, broken down by accident categories, is summarized in table 1.

Table 1: Breakdown of historic accident data on accident categories

Accident category	**Number of accidents**	**Accident frequency** (per ship year)
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}

4 METHOD OF WORK

The five-step FSA methodology outlined in the FSA Guidelines has been used in this study. The FSA application has been carried out as a joint effort between Det Norske Veritas (Norway), Navantia shipyards (Spain), Instituto Superior Técnico (Portugal) and LMG Marin (Norway) and the project team has comprised risk analysts, naval architects and other experts from the above partners. Technical experts have been extensively consulted throughout the work with the FSA.

The FSA commenced with a HAZID meeting in April 2005, and the final report with cost benefit assessments and recommendations was completed in January 2007. In addition to the initial HAZID meeting, three co-ordination meetings were held between the partners and three technical workshops were arranged with additional experts in order to identify and prioritize risk control options. In addition, a Delphi session was conducted in order to estimate fatality rates in case of major accidents for which no statistics are available.

The HAZID (step 1 of the FSA) was conducted as a one-day technical meeting including brainstorming sessions. The outcome of the HAZID was a risk register containing the hazards and their subjective risk ratings from which a list of the highest ranked hazards could be extracted.

The risk analysis (step 2 of the FSA) comprises a thorough investigation of accident statistics for LNG carriers as well as risk modelling utilizing event tree methodologies for the most important accident scenarios. Based on the survey of accident statistics and the outcome of the HAZID, generic accident scenarios were selected for further risk analysis.

The risk analysis essentially contains two parts, i.e. a frequency assessment and a consequence assessment. For the frequency assessment, estimating the initiating frequency of generic incidents, accident statistics have been utilized for the selected accident scenarios. The estimates arrived at in this way was compared to similar studies for LNG carriers as well as other ship types, and it was concluded that the estimates were reasonable and that the estimates derived from available statistics were adequate.

The consequence assessment was performed using event tree methodologies. First, conceptual risk models were developed for each accident scenario and event trees were constructed according to these risk models. The event trees were subsequently quantified using different techniques for each branch probability according to what was deemed the best approach in each case. The approaches employed include utilizing accident statistics, damage statistics, fleet statistics, simple calculations and modelling and expert opinion elicitation.

The frequency and consequence assessments provide the risk associated with the different generic accident scenarios and these risks were summarized in order to estimate the individual and societal risks pertaining to LNG carrier operations.

Risk control options (step 3 of the FSA) were identified and prioritized at technical workshops; in all, three workshops were held in conjunction with the identification and selection of risk control options for further evaluation and cost benefit assessment. This part of the FSA also contained a high-level review of existing measures to prevent accidental release of LNG.

Cost benefit assessments (step 4 of the FSA) were performed on selected risk control options based on the outcome of step 3. The cost effectiveness for each risk control option was estimated in terms of the Gross Cost of Averting a Fatality (GCAF) and the Net Cost of Averting a Fatality (NCAF). I.e., the expected costs, economic benefit and risk reduction in terms of averted fatalities were estimated for all risk control options.

All costs and benefits were depreciated to a Net Present Value (NPV) using a depreciation rate of 5% and assuming an expected lifetime of 40 years for LNG vessels. A typical LNG crew of 30 persons were assumed. Cost estimates were based on information from suppliers, service providers, training centres, yards, technical experts or previous studies as deemed appropriate. The economic benefit and risk reduction ascribed to each risk control options were based on the event trees developed during the risk analysis and on considerations on which accident scenarios would be affected. Estimates on expected downtime and repair costs in case of accidents were based on statistics from shipyards.

Recommendations for decision-making (step 5 of the FSA) were suggested based on the cost benefit assessment of risk control options carried out in step 4 and on the evaluation criteria GCAF < US$ 3 million and NCAF < US$ 3 million. Considerations on the potential for risk reduction for each evaluated risk control option were also taken into account in suggesting recommendations.

5 DESCRIPTION OF THE RESULTS ACHIEVED IN EACH STEP

STEP 1 – Hazard identification

The HAZID was conducted as a one-day workshop with participants from various sectors within the LNG industry, i.e. ship owner/operator, shipyard, ship design office/maritime engineering consultancy, equipment manufacturer, classification society and research centre/university.

The results from the HAZID were recorded in a risk register, which contains a total of 120 hazards within 17 different operational categories. The top ranked hazards according to the outcome of the HAZID is presented in table 2. Each hazard is associated with a risk index based on qualitative judgement by the HAZID participants.

Table 2: Results from hazard identification: Top-ranked hazards

No.	Hazard	Risk index
4-5	Faults in navigation equipment (in coastal waters)	7.0
17-4	Crew falls or slips onboard	7.0
14-1	Shortage of crew when LNG trade is increasing	6.8
4-3	Rudder failure (in coastal waters)	6.8
3-4	Rudder failure (in manoeuvring)	6.8
5-4	Severe weather causing vessel to ground/collide (in transit)	6.6
3-3	Steering and propulsion failure (in manoeuvring)	6.6
3-5	Severe weather causing vessel to ground/collide (in manoeuvring)	6.6
3-7	Faults in navigation equipment (in manoeuvring)	6.6
4-2	Steering and propulsion failure (in coastal waters)	6.6
6-1	Collision with other ships or facilities (in port)	6.6
17-3	Terrorist attacks/intentional accidents	6.5

STEP 2 – Risk analysis

First, a survey of historic accidents of LNG carriers was carried out in order to establish the historic risk level associated with these vessels. The accident statistics from this survey is presented in table 1 above.

Based on available accident statistics and results from the HAZID, seven generic accident scenarios were defined and selected for further analysis. These were:

1 Collision
2 Grounding
3 Contact
4 Fire or explosion
5 Heavy weather/loss of intact stability
6 Incidents while loading or unloading cargo (LNG)
7 Failure/leakage of the cargo containment system.

It is noted that the first five generic accident scenarios are general in the sense that they pertain to all types of ships, although the consequences might be particular to LNG carriers, whereas the last two accident scenarios are specific to LNG carriers.

Following the selection of accident scenarios to investigate, a frequency assessment was performed in order to estimate the initiating frequencies associated with each of the selected scenarios. It was concluded that previous accident experience would provide a sufficiently accurate estimate of initiating frequencies for the seven selected accident scenarios. Hence, these estimates were adopted for the FSA study, as presented in table 3.

Table 3: Accident frequency estimates	
Accident scenario	**Accident frequency** (per ship year)
Collision	6.7×10^{-3}
Grounding	2.8×10^{-3}
Contact	2.8×10^{-3}
Fire or explosion	3.5×10^{-3}
Heavy weather/Loss of intact stability	3.2×10^{-3}
Incidents while loading/unloading of cargo	7.8×10^{-3}
Failure/leakage of cargo containment system	9.5×10^{-3}

The next step in the risk analysis was to assess the expected consequences for each of the identified scenarios. This was done using event tree techniques, i.e. by constructing and quantifying event trees representing each generic accident scenario. However, first each scenario was described by creating a high level risk model. These models are illustrated in figures 2 to 6 for the collision, grounding, contact, fire or explosion and incidents while loading or unloading of cargo respectively. For the two remaining accident scenarios, loss of intact stability due to heavy weather and failure/leakage of the cargo containment system, no detailed risk models or event trees were deemed necessary to estimate the risk. The analysis revealed that the risk contributions from these accident scenarios were negligible in comparison with overall risk, and these scenarios were hence ignored for the remainder of the study.

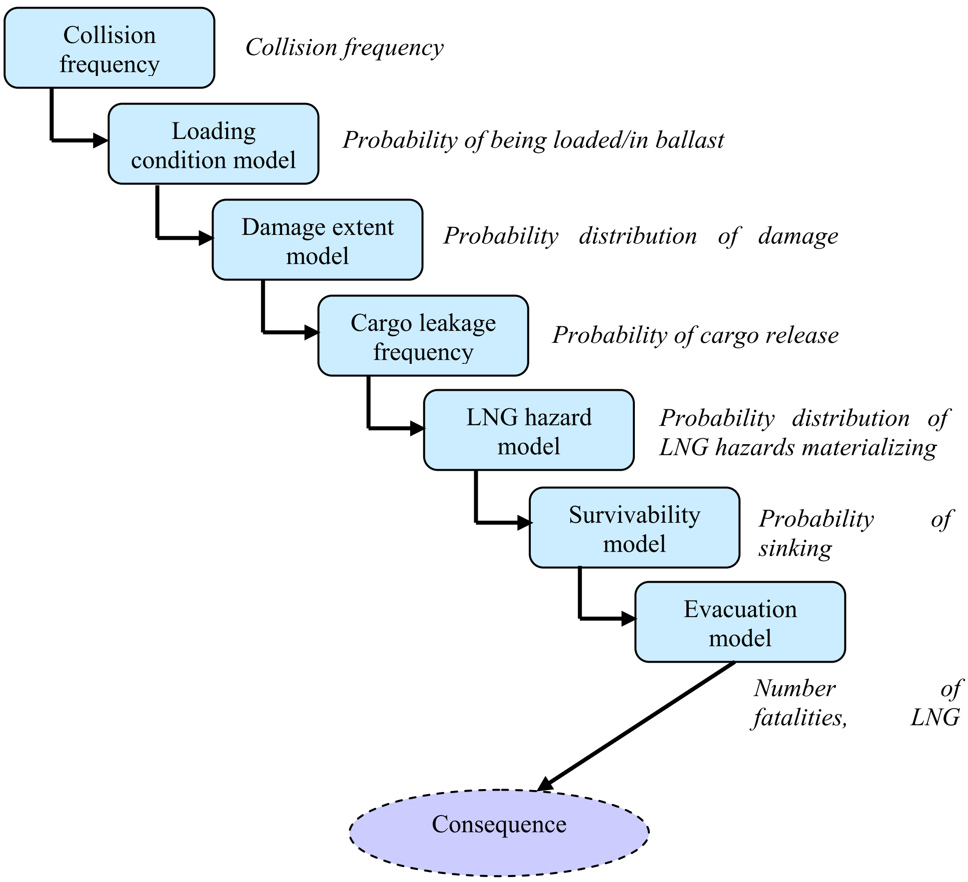

Figure 2: Risk model for collision accident scenarios of LNG carriers

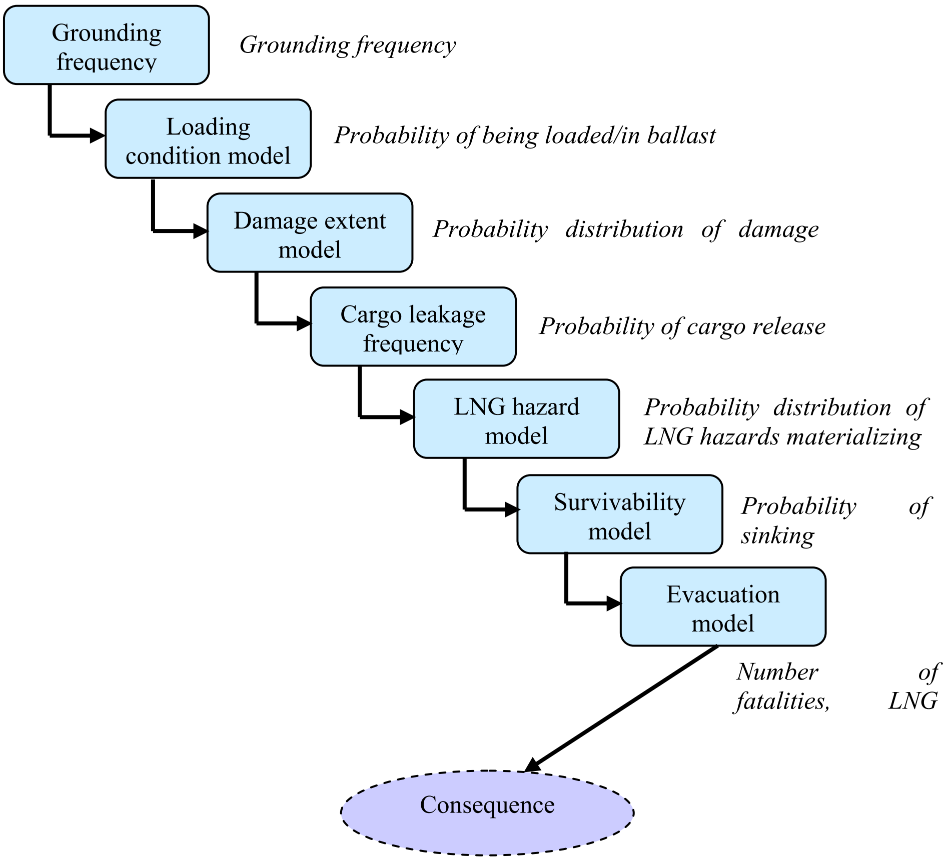

Figure 3: Risk model for grounding accident scenarios of LNG carriers

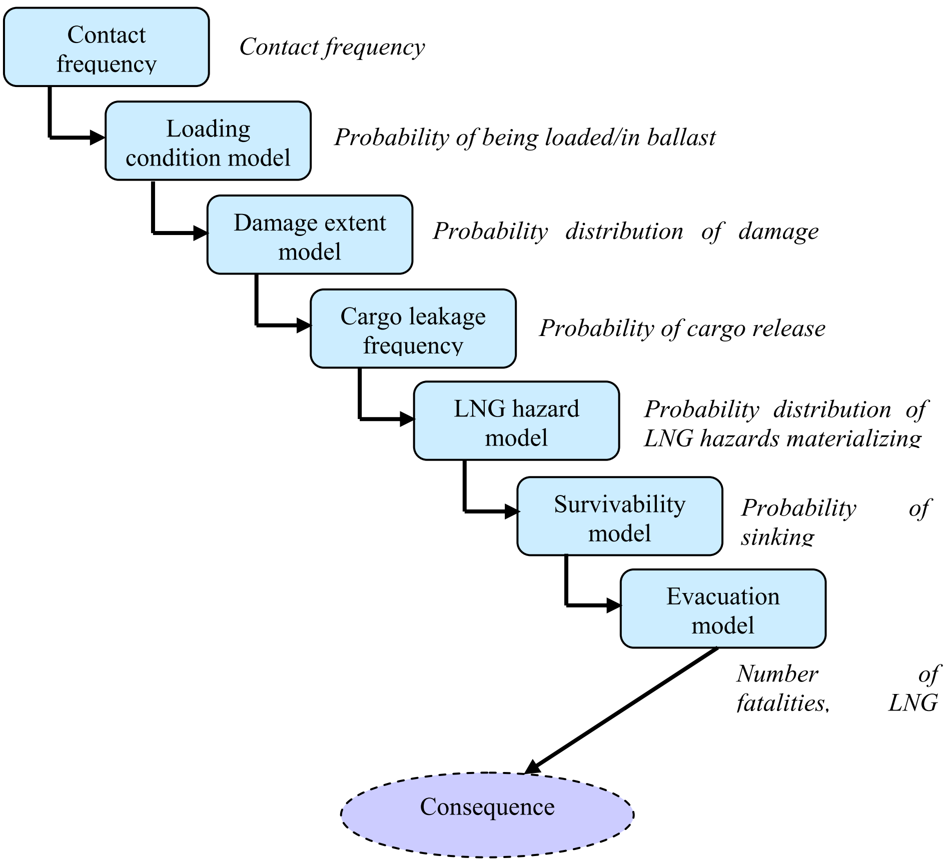

Figure 4: Risk model for contact accident scenarios of LNG carriers

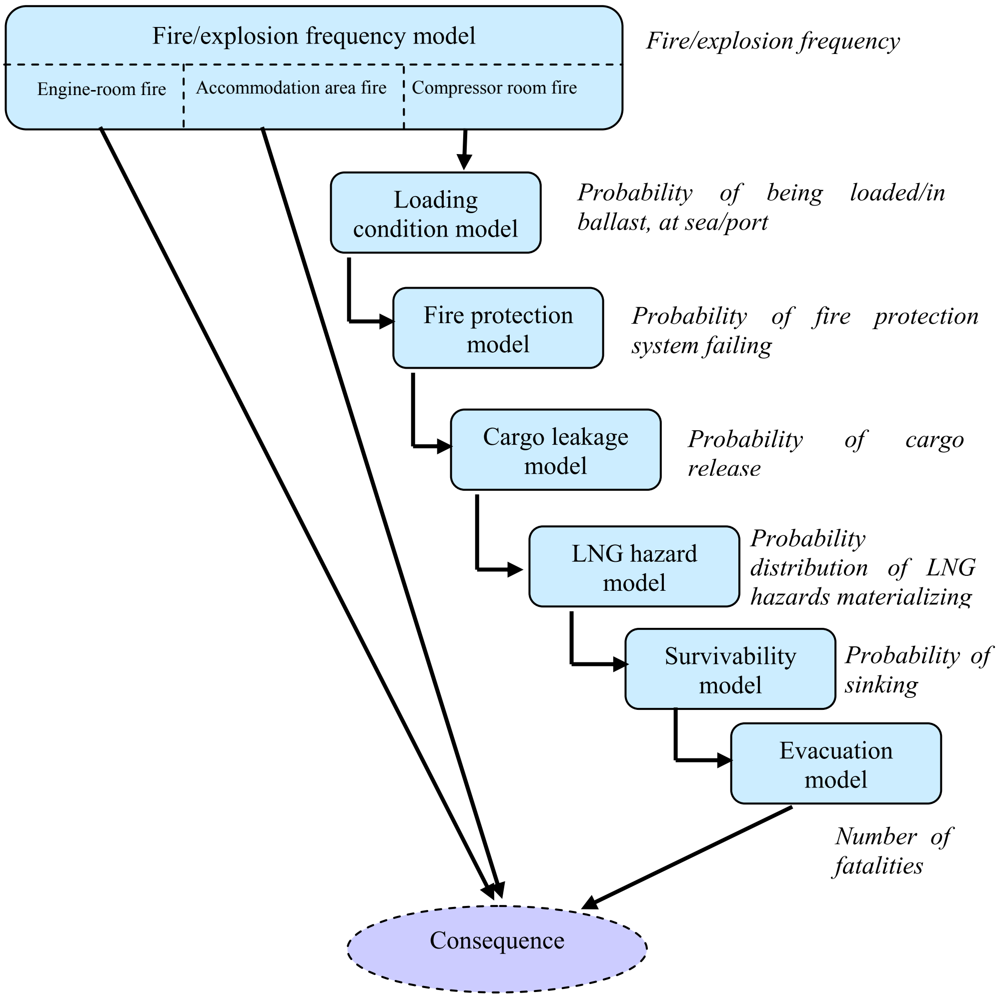

Figure 5: Risk model for fire and explosion accident scenarios of LNG carriers

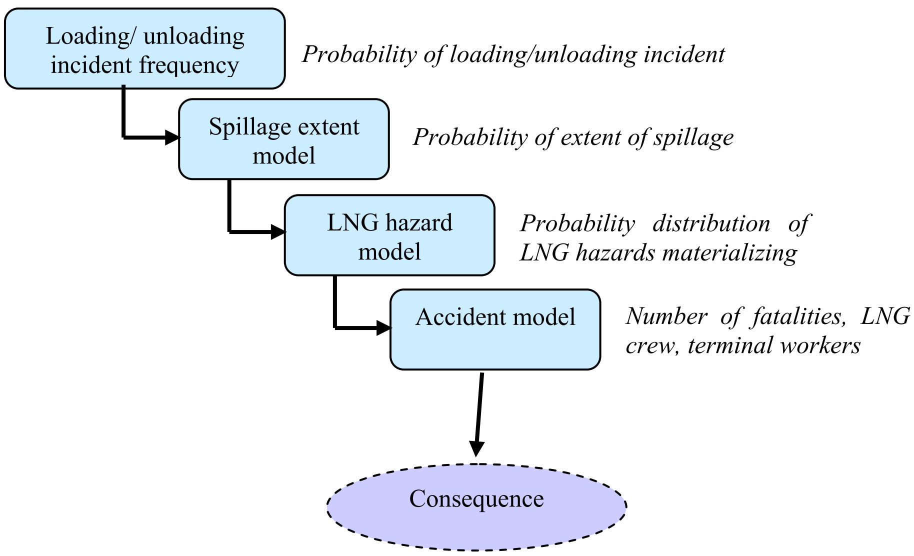

Figure 6: Risk model for loading/unloading accident scenarios of LNG carriers

In order to assign probabilities for the various escalating events and quantify the event trees accordingly, a set of different approaches and techniques was used. For each sub-model and each branch of the event trees, the method that was found to be most practical and the information sources that were assumed most relevant was utilized. These are explained in document MSC 83/INF.3 and in the full SAFEDOR reports together with illustrations of the complete event trees.

Based on the risk modelling and the event tree construction and quantification, the contributions from the different accident scenarios to the total potential loss of lives (PLL) from LNG shipping was extracted. This risk summation is presented in table 4. These results were then used to estimate the individual and societal risk for LNG crew.

Table 4: Potential loss of lives from LNG carrier operations (per ship year)

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	$\mathbf{9.32 \times 10^{-3}}$

Intuitively, individual risks for third parties or passengers are not an issue, and only the individual risk for the LNG crew was 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, and a 50-50 rotation scheme, the individual risk for LNG crew members is estimated to be 1.6×10^{-4} per year. According to the individual risk acceptance criteria the individual risk level falls within the ALARP area. The historic individual risk for crewmembers of LNG carriers has been reported as 1.2×10^{-4} per year, which agrees reasonably well with the results from the risk analysis. 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 risk of 6.5×10^{-4} per year.

The societal risk to crew may be expressed through FN diagrams. Such FN diagrams, including risk acceptance criteria, are presented in figure 7. It can be seen from these diagrams that also the societal risk associated with LNG shipping falls within the ALARP area.

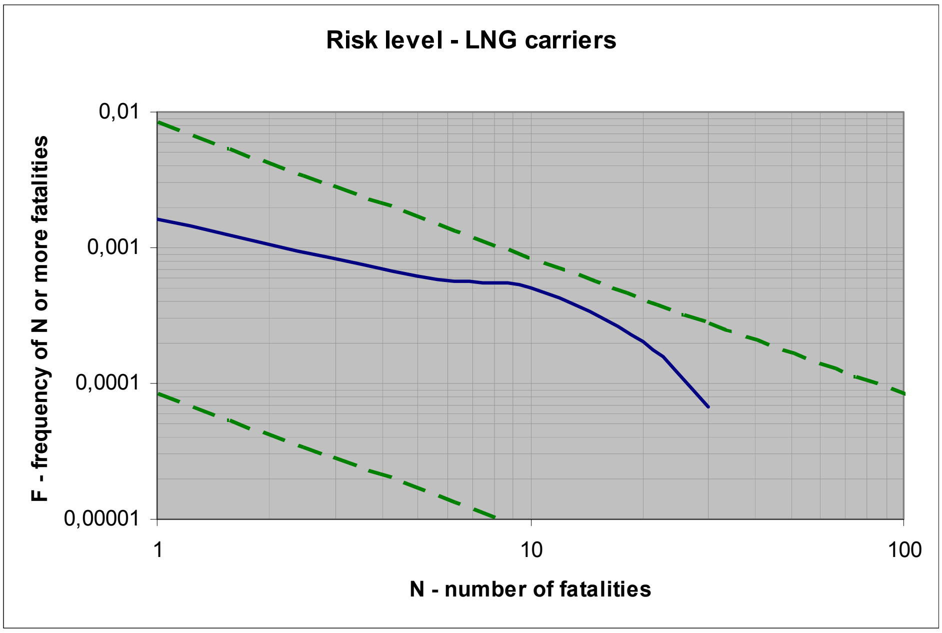

Figure 7: FN-diagram for total risk to crew

Uncertainties and assumptions

As a final exercise, a critical review of assumptions and sources of uncertainties related to the risk analysis were carried out. This identified some assumptions that would bias the results in a conservative direction and others that tended to be somewhat optimistic. However, it was concluded that the overall effect of all assumptions and uncertainties was more likely to be conservative than optimistic. Hence, the results from the risk analysis should be regarded as conservative estimates of the actual risk.

STEP 3 – Identification of risk control options (RCOs)

The main risk drivers according to the risk analysis were presented to a group of experts in a workshop. Through a brainstorming session, a list of 33 alternative risk control options (RCOs) was then produced. These were then prioritized in terms of perceived risk reduction potential by the group of experts in order to select a set of risk control options for further evaluation and cost benefit assessment. In order to verify the list of selected risk control options and to obtain a second opinion, another workshop involving another group of experts were held. The outcome of this iteration process was a list of 9 risk control options for further assessment. The following risk control options were selected for further investigation:

RCOs to reduce the risk related to 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 and explosion risks:

- 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 risks related to incident while loading and unloading of cargo:

- Redundant radar sounding for checking filling level.

RCOs to reduce risks related to failure/leakage of cargo containment system:

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

Further descriptions of these risk control options can be found in document MSC 83/INF.3.

STEP 4 – Cost benefit assessment

The objective for the cost benefit assessment is to evaluate the cost effectiveness of implementing the alternative risk control options. The aim of performing such an analysis is to establish a list of recommendations on cost effective risk control options that will reduce the risk of accidents on LNG carriers. The GCAF and NCAF values are presented in table 5.

Table 5: GCAF and NCAF values associated with each risk control option.		
Risk Control Options Description	**Gross CAF** (10^6 US$/fatality)	**Net CAF** (10^6 US$/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

Cost estimates have been based on information from suppliers, service providers, training centres, yards, technical experts or previous studies where appropriate. The economic benefit and risk reduction ascribed to each risk control options were based on the event trees developed during the risk analysis and on considerations on which accident scenarios would be affected. Estimates on expected downtime and repair costs due to accidents were based on statistics from shipyards. As a basis for the cost benefit calculations, the following important assumptions were made:

- The size of a typical LNG crew: 30
- The average lifetime of an LNG carrier: 40 years
- Depreciation rate: 5%

All numbers are based on introduction of one risk control option only. Introduction of more than one risk control option will lead to higher NCAF/GCAFs for other risk control options addressing the same accident scenarios as the remaining risk will be less. However, the results are believed to be robust in any case. The results from the cost effectiveness assessments demonstrate 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 US$ 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 effect from 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 checking filling level" have GCAF ranges from 12 to very high. The NCAF values ranges from 5.8 to 351. Hence these RCOs are not cost effective according to the assessment carried out.

Some of the above RCOs are already implemented on most LNG carriers. However, they are not a requirement under SOLAS.

STEP 5 – Recommendations

As a 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 US$ 3 million. 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 proposed in document MSC 72/16.

- An RCO is also considered cost effective if the NCAF is less than US$ 3 million.

- 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 > US$ 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.

6 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.

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