International Association of Classification Societies (IACS)

FSA of Bulk Carriers
Fore-end Watertight Integrity

Annex 5
Fore-end Flooding Scenarios

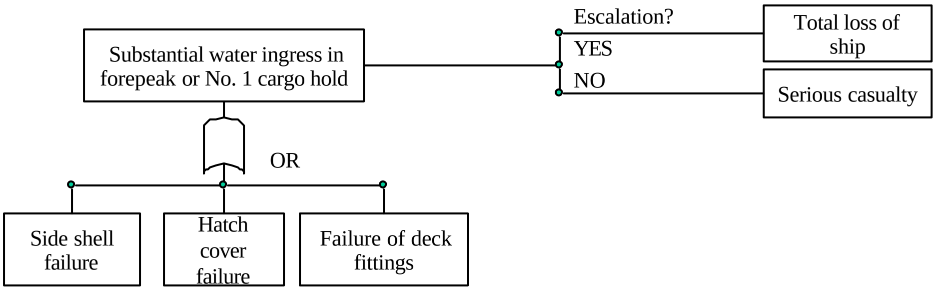
CONTENTS

1 INTRODUCTION

1.1 Background

This annex is a part of the FSA of bulk carriers, *Fore end watertight integrity*, carried out by IACS.
The focus of the overall study has been on the fore end of the bulk carriers, including the evaluation of risk control options aimed at preventing or mitigating fore end flooding scenarios. The scenarios investigated include the flooding of No.1 cargo hold.

The risk contribution from structural failure of the fore-end resulting in water ingress is estimated based on the simple event tree shown in the figure below.



Combination of fault tree and event tree used to quantify the risk contribution from water ingress scenarios resulting in serious casualty (including total losses)

Each event in the fault tree below is analyzed in a dedicated Annex. The present annex deals with the event 'Failure of deck fittings' and its possible escalation.

1.2 Objective

The objective of this annex is to evaluate, by Cost Effectiveness Analysis, the following Risk Control Options (RCOs) related to the watertight integrity of the fore end of bulk carriers:

- implementation of a forecastle
- implementation of a bulwark

- implementation of a system for monitoring the forepeak and hold No.1
- implementation of a stronger design and remote closure of deck fittings.

All these RCOs were evaluated on both new and existing ships.

1.3 Scope

The study of this annex was restricted to the forepeak and hold No.1 of typical bulk carriers, focusing on the three upper typical bulk carrier sizes. The Handysize bulk carriers were not considered, mainly because they exhibit a large variation in size, routes and characteristics, and many of them below 20,000 dwt are not even mentioned in the casualty databases.

In addition to the size, further characteristics of the selected ships are:

- constructed before the entry into force of the new SOLAS Chapter XII
- compliant with IACS UR S21
- flush deck
- B-60 freeboard
- no water ingress alarms in forepeak and holds.

1.4 Approach

The object of this study is the forepeak flooding, due to the loss of watertightness through the various access openings on deck. In theory, a bulk carrier strictly compliant with current regulations is not supposed to withstand the flooding of the forepeak and one hold. If this is the case, the bulk carrier can be rapidly lost, due to either loss of reserve of buoyancy, or capsizing for loss of stability due to free surface effects combined with wave and wind inclining moments, or hull girder collapse.

The accident scenario was assumed to take place in any of the North Atlantic, Pacific Ocean and Indian Ocean, as they are the zones where most commodities are traded (Eknes *et al*,1997) and where most of the bulk carriers were lost.

Two scenarios of fore-end flooding were investigated:

1. flooding starting from the forepeak and propagating to hold No.1 (Scenario A)
2. flooding starting from the hold No.1 and propagating to forepeak (Scenario B).

The water ingress, in this model, was assumed to occur exclusively through to the loss of watertightness of some fittings on the forepeak (air pipes, companionway hatch, etc.) and hatch cover No.1, caused by the loads due to the sea action.

The basic tools used in this study are:

- event tree analysis, to provide a clear picture of the most important accident sequences
- fault tree analysis, to represent the causes of the ET nodes
- a simplified probabilistic methodology to model the sea induced loads.

The risk model was then tuned against the available casualty statistics, which represents the reality of the accidents.

The risk model was used to assess the effectiveness of forecastle/bulwark and monitoring system; for deck fittings, no statistical data is available, furthermore the current regulations do not set any explicit scantling criteria for them. Therefore, this RCO was cursorily assessed by assuming the same effectiveness of the forecastle/bulwark.

2 HAZARD REVIEW

No hazard identification was performed for this study, because the hazards relevant to bulk carriers have already been subject to intensive studies. Only a cursory investigation for further sources was made, which confirmed the main issues of the already available material. The following table summarizes the available sources for the hazards relevant to the fore-end as above defined (see Annex 8).

Source	Pertinent Hazards
MSC 72/INF. 4 (IMO,2000)	All
MSC73/INF.10 (IMO,2000)	All the ones belonging to Accident Category 1 and 2 Entries 4.1 and 4.2 of Accident Category 4
Preliminary Hazard Ranking by MCA	All the ones belonging to categories LOHI BOW and LOHI CARGO
Past RINA survey reports (confidential)	Hazards mainly related to hatch covers and transverse bulkheads. In general, they are consistent with the ones mentioned in the above reports. A statistic of several years ago pointed out that the faults of hatch covers not directly attributable to improper use were mainly due to failures of the sealing system (50%), cover sheet plates (25%) or actuation (opening/closing) systems (25%). This is also confirmed by a recent paper (Byrne, 2000), which proposes the use of appropriate tools and checklists for the survey of hatch covers and coamings. In addition to the typical hazards (undersized seals, mishandling, corrosion and wastage of closing elements like cleats, tracks, wheels etc.), in some cases the transverse and peripheral hatch cover joints are too stiff with respect to the deck, preventing them from adjusting to the hull deformations. This can be viewed as included in the design errors.
	Another hazard, referred to the transverse bulkheads of the water ballast tanks (thus applicable to the forepeak as well), is the structural damage due to dynamic loads consequent to a too fast filling-up procedure. This can be viewed as included in the operational errors.

3 RISK ASSESSMENT

3.1 Definition of the Bulk Carrier Mission

The mission phases considered in the consequence analysis are basically the loaded passage in departure and arrival conditions. The ballast passage was not deemed significant, as the forepeak is already full of water in such condition. Even in the case when the forepeak is not fully flooded, it is estimated that the low free surface of the forepeak cross-section is not sufficient the generate significant sloshing loads on the bulkhead. This is also supported by previous studies of historical data, e.g. Eknes *et al* (1997), where the ballast conditions was found to account for less than 3% of the serious casualties.

It was then necessary to estimate the exposure period of the ships, in laden conditions, in the three zones. Elaborating on the Fearnleys data from Eknes *et al* (1997), and assuming an average bulk carrier speed of 14 knots, an average one-way voyage results to last from 13 to 16 days. Allowing 5 days per voyage for loading/unloading, and neglecting the back trip in ballast, the exposure time results about 150 days per year for each bulk carrier type.

In addition to the previous considerations, the fore-end flooding was not considered a concern during the phases of loading /unloading, port, lay-up, dry-docking etc.

The bulk carriers under study were assumed to be sailing in any of the North Atlantic, Pacific Ocean and Indian Ocean, as they are the zones where most of the commodities are traded (Eknes *et al*,1997) and a great number of bulk carriers were lost.

3.2 Equipment of the Selected Bulk Carriers

The selected bulk carriers are in strict compliance with pre-SOLAS XII regulations, including IACS UR S21, but not IACS UR S24, which is fitted only in a small percentage of the fleet. Therefore, it was assumed that any non-mandatory equipment is not fitted; in particular, no bilge alarms are installed in the forepeak.

The equipment that may be involved in the selected scenarios is the ballast system, assumed to double as an emergency system to pump out the water rapidly in case of flooding. The selected bulk carriers feature a single ballast pump line connected to the forepeak and the holds, with each volume that can be isolated via a dedicated hydraulically operated valve. The typical equipment comprises one ballast pump and another high capacity pump (both located in the machinery spaces at the stern) to be used as a back-up, which may be another ballast pump or a fire protection system pump. Pumps and valves were assumed to be operated from the bridge. The actual equipment is of course subject to some variations on the specific real ships.

The study assumes that :

- the ships analyzed are seaworthy and properly maintained and operated;
- emptying the forepeak of such B-60 bulk carriers is theoretically enough to guarantee their survival, as they are supposed to withstand the flooding of one hold; thus, in case of flooding of both the forepeak and hold No.1, the action of emptying hold No.1 is unnecessary;
- the flooding of the forepeak or hold No.1 does not hamper the correct function of the high-capacity pumps, as they are located at the stern.

3.3 Review of Past History

Cases have been retrieved from LMIS for bulk carriers of 20000+ dwt between 1978 and 1998. From them, the lower and upper bound for the frequency for total loss of bulk carriers due to fore end flooding were estimated to lie between $2.7 \cdot 10^{-5}$ /bulk carrier-y and $2.7 \cdot 10^{-4}$ /bulk carrier-y , or, in terms of fatalities, between $5.98 \cdot 10^{-4}$ /bulk carrier-y (lower bound) and $5.82 \cdot 10^{-3}$ /bulk carrier-y (see Annex 2).

An apparent inconsistency lies in the number of Serious Casualties being much lower than the Total Losses (7 versus up to 20). This implies a lack of data reported, as it is not believable that the accidents with the worst consequences outnumber the others.

The statistical uncertainty in the risk contribution for the fore-end flooding hence is considerable. The reference point was taken as the mean of a lognormal distribution defined by assuming the two values as the 10% and 90% percentile respectively. It results:

F(CTL due to fore-end flooding) = $1.2 \cdot 10^{-4}$ /bulk carrier-y.

An additional review was carried out on Annex 2 to estimate the change in the baseline risk brought about by the introduction of ESP, IACS UR S21, IACS UR S24 and SOLAS XII. For this study, it was reckoned that ESP and SOLAS XII do not significantly improve the vessel's resistance to the scenarios described in § 3.4. On the contrary, IACS UR S21 and S24 play an important role, the former because it increases the hatch cover strength, the latter improves the detection of a flooding and, consequently, the possibility of intervention or, should this fail, the crew evacuation time. UR S24, however, has been fitted only on a limited number of vessels so far.

From the statistics, the following average loss of life was inferred:

- Total loss due to water ingress without detection = 25 lives lost
- Total loss due to water ingress with detection = 5.4 lives lost
- Serious casualty due to water ingress excluding total loss = 0.05 lives lost.

3.4 Probabilistic Evaluation

This section provides a general outline of the methodology followed for the risk assessment. Appendix 2 provides the full details of the analysis.

As said earlier, the accident scenario was assumed to take place in any of the North Atlantic, Pacific Ocean and Indian Ocean.

Two scenarios of fore-end flooding were investigated:
1. flooding starting from the forepeak and propagating to hold No.1 (Scenario A)
2. flooding starting from the hold No.1 and propagating to forepeak (Scenario B).

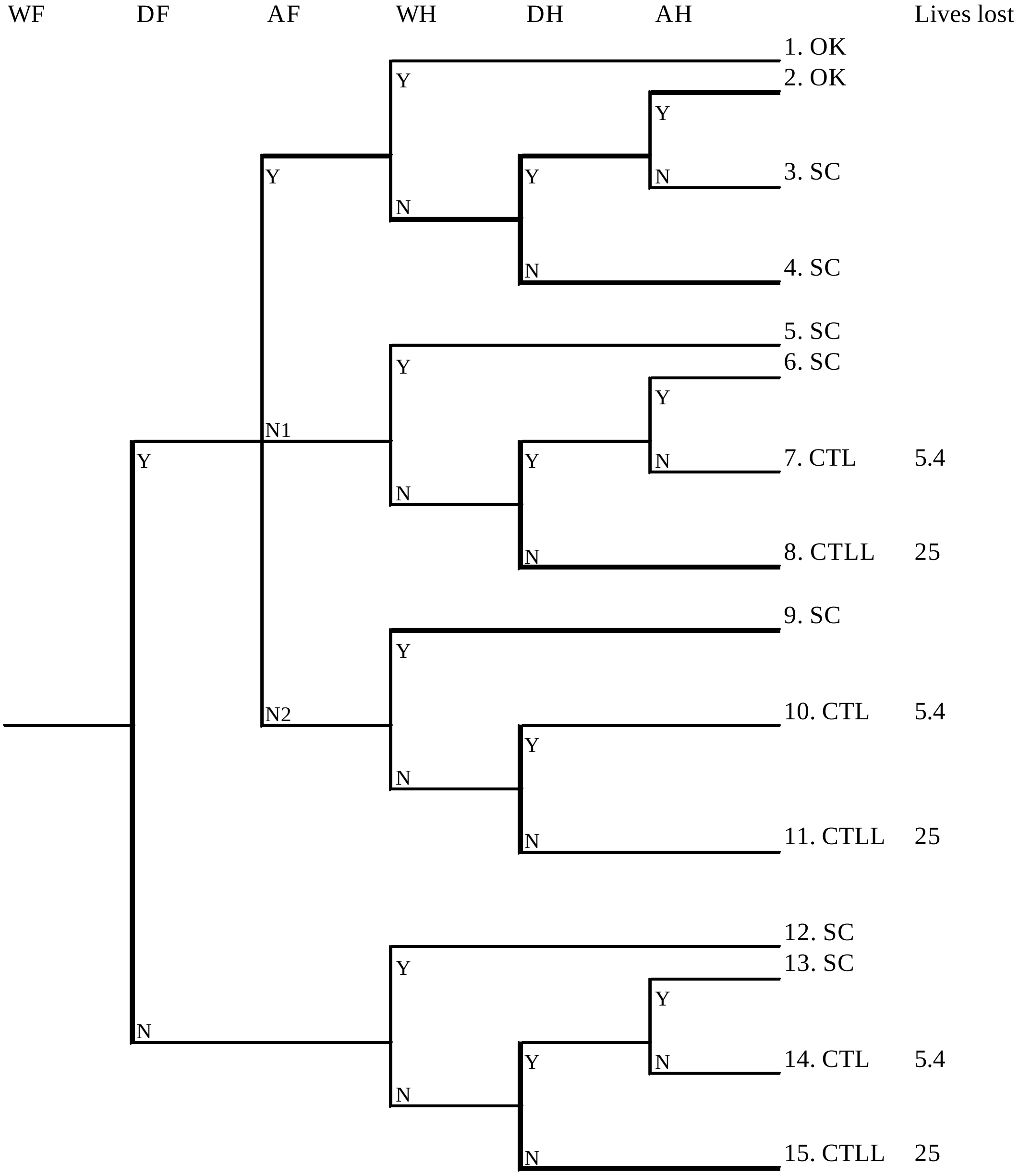
A further possibility of escalation obviously exists, namely, flooding from hold No.1 to the adjacent holds. This scenario was investigated in Annex 4, as the RCOs dealt with in this annex would not be effective in such situations.

The two scenarios were represented by means of Event Trees, that are basically the same with a different order of the nodes (Fig. 3.4.1 and 3.4.2). The ET nodes represent the principal influences that affect the risk. They are described in the following; basically, the same description applies to both ETs, recalling that, for scenario B, the order is: Watertightness of hatch cover No.1 given deck wetness, detection of hold No.1 flooding, corrective action for hold No.1 flooding, watertightness of the forepeak, detection of forepeak flooding, corrective action for forepeak flooding, ship survival.

The frequency of each sequence was obtained by multiplying the frequency of the couple of events WH and AH by the probability of the other nodes, as they are independent.

Figure 3.4.1

ET for Scenario A



LEGENDA

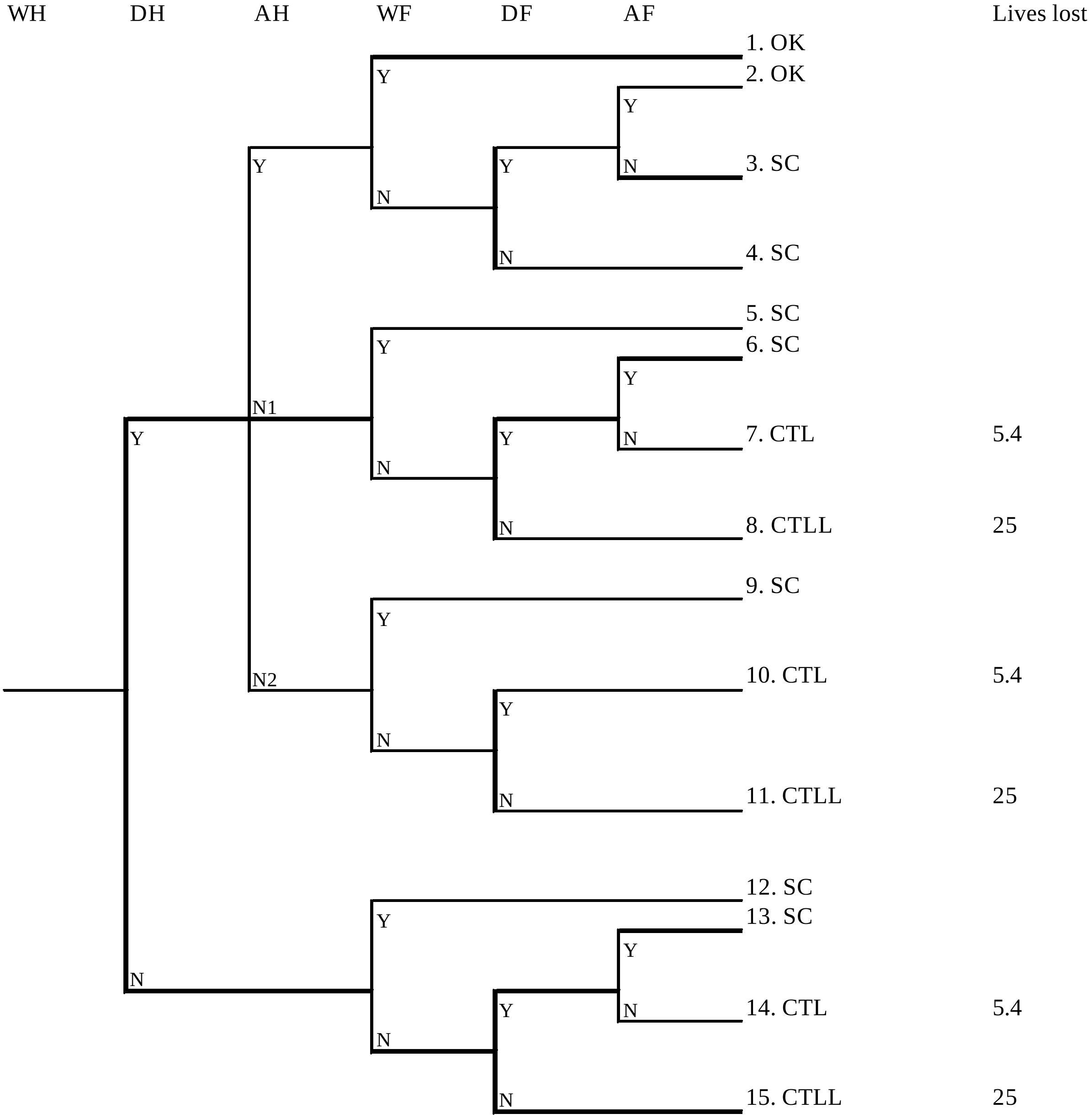
WF	Loss of watertightness of the forepeak given deck wetness
DF	Detection of forepeak flooding
AF	Action of emptying the forepeak
WH	Watertightness of the hatch No. 1
DH	Detection of hold No.1 flooding
AH	Action of emptying hold No.1

N1=human failure
N2=pumping system failure

OK=no consequences
SC=serious casualty
CTL=total loss with early warning
CTLL=total loss without early warning

Figure 3.4.2

ET for Scenario B



LEGENDA

WF	Watertightness of the forepeak
DF	Detection of forepeak flooding
AF	Action of emptying the forepeak
WH	Loss of Watertightness of hatch No. 1 given dek wetness
DH	Detection of hold No.1 flooding
AH	Action of emptying hold No.1

N1=human failure
N2=pumping system failure

OK=no consequences
SC=serious casualty
CTL=total loss with early warning
CTLL=total loss without early warning

3.5 Description of ET Nodes

The nodes are below described for the ET of Scenario A, as those of Scenario B do not differ in nature, but only in the order of their position in the two ETs.

3.5.1 Initiating Event: Loss of Watertightness of the Forepeak (WF)

This event is of course conditioned to the presence of deck wetness, the probability of which was inferred by combining the statistics on bulk carrier routes obtained from Eknes *et al* (1997) and the tables of sea states in the various sea areas.

This node should, in principle, have as many outcomes as the various possibilities of water ingress from the forepeak openings.

However, the events of failure of watertightness of two or more openings are not necessarily independent. For instance, if two ventilating pipes are situated close enough to each other, they both could be carried away by the green sea; operators may commit the same lapse in securing cleats on more than one hatch, etc.

To get around all these vagaries, a fixed opening area was assumed for each reference vessel of the base case, corresponding to the cross sectional area of typical deck fittings (see Appendix 3 for details).

3.5.2 Detection of Forepeak Flooding (DF)

This node represents the possibility that the crew detects the flooding of the forepeak. As already explained, no level alarms or indicators are fitted, thus the detection relies on routine inspections.

3.5.3 Corrective Action of Forepeak Flooding (AF)

The corrective action is the possibility of pumping the water out of the forepeak by using the ballast water pump as a bilging system. The failure of this node can be due to either failure of both pumps or the isolating valve on the piping, or to human failure to perform the action. It was not deemed realistic that the failure of the hardware be restored within the timing of the accident sequence; therefore, if the pumping system fails, it will not be available for the node AH described in § 3.5.6, either.

3.5.4 Watertightness of Hatch Cover No.1 (WH)

For scenario A, the loss of watertightness of hatch cover No.1 is due to the effects of the sea loads, which tend to become more severe if the preceding nodes fail: the waves would impinge on the hatch cover more frequently as a consequence of the forward trim, in turn caused by the forepeak flooding. In the lack of any data, the opening in the hatch cover which is caused by the wave load was assumed to be a fraction of the hatch area.

3.5.5 Detection of Hold No.1 Flooding (DH)

This node represents the possibility of detecting the water entering No.1 in the absence of means of detection as per IACS Unified Requirement S24.

3.5.6 Corrective Action of Hold No.1 Flooding (AH)

The corrective action is the possibility of removing the water from the hold by using the ballast water pump as a bilge system. This action fails if the hold is loaded, if the crew fails to take the proper actions or the isolating valve on the piping fails to open.

The following results were obtained.

Frequency of total loss (per bulk carrier-year)					
Capesize		**Panamax**		**Handymax**	
A	**B**	**A**	**B**	**A**	**B**
$1.6 \cdot 10^{-5}$	**$2.4 \cdot 10^{-5}$**	**$2.1 \cdot 10^{-5}$**	**$9.3 \cdot 10^{-5}$**	**$1.1 \cdot 10^{-4}$**	**$9.5 \cdot 10^{-5}$**

Weighing the results on the percentage of the population corresponding to Capesize, Panamax and Handymax (about 18%, 36% and 46% respectively, from www.intercargo.org), one obtains an overall frequency of total loss of about $1.3 \cdot 10^{-4}$ /bulk carrier-year, which compares favorably with the reference point of § 3.3.

3.6 Consequence Evaluation

This study is focused on the sequences of both ETs leading to loss of life. All the other sequences were not considered to bring serious consequences, and were not analyzed in detail. The consequences were distinguished into Serious Casualty (SC) if the ship survives given flooding of either forepeak or hold No.1, Constructive Total Loss (CTL) if the ship is lost but most crew survive, Constructive Total Loss with Loss of Crew (CTLL) if the ship is lost and the crew (or most of them) do not survive.

The rationale of the separation between CTL and CTLL is that the sequences characterized by detection success and action failure bring different consequences from those characterized by detection failure and action failure; in the former case, the crew is alerted and has a higher probability of evacuating before the ship sinks. This is confirmed by the historic picture (see § 3.3).

It was decided not to include the contribution of loss of life due to SC, as the model yields a frequency of serious casualty much greater than obtained from the historical data, for various sources of conservatism inherent in the model (see Appendix 3). However, as pointed out in § 3.3, it is realistic than the SCs are much more numerous than the CTLs; the result of the model may be on the high side, but it is also very likely that the historical picture is defective.

The full details of the quantification of the two ETs is given in Appendix 2. The results are summarized in the following table.

PLL (in fatalities/bulk carrier-year)					
Capesize		**Panamax**		**Handymax**	
A	**B**	**A**	**B**	**A**	**B**
$\mathbf{3.7 \cdot 10^{-4}}$	$\mathbf{5.9 \cdot 10^{-4}}$	$\mathbf{4.7 \cdot 10^{-4}}$	$\mathbf{2.3 \cdot 10^{-3}}$	$\mathbf{2.6 \cdot 10^{-3}}$	$\mathbf{2.4 \cdot 10^{-3}}$

4 COST-EFFECTIVENESS ANALYSIS

This section provides the Cost-Effectiveness Analysis (CEA) for each of RCOs listed in § 1.2.

In this study, the cost-effectiveness was expressed in terms of Gross Cost of Averting a Fatality (GCAF), defined as follows:

$$\mathrm{GCAF} = \frac{\Delta \mathrm{Cost}}{\Delta \mathrm{Risk}}$$

ΔCost is the marginal (additional) cost of the risk control option, whilst ΔRisk is the reduced risk in terms of fatalities averted, i.e., the expected reduction in number of fatalities. This latter should be measured in terms of Potential Loss of Life (PLL). The unit of PLL is [Expected fatalities per ship-year]. GCAF evaluates the risk control options in terms of additional safety only.

An additional cost-effectiveness measure is given by Net Cost of Averting a Fatality (NCAF), where not only the increase in safety, but also the economic benefits of the investigated risk control options are accounted for. Economic benefits (or risk reduction) may also include the economic value of reduced pollution.

$$\mathrm{NCAF} = \frac{\Delta \mathrm{Cost} - \Delta \mathrm{Economic\ \ Benefits}}{\Delta \mathrm{Risk}} = \mathrm{GCAF} - \frac{\Delta \mathrm{Economic\ \ Benefits}}{\Delta \mathrm{Risk}}$$

The study reports both measures for the risk control options.

In this study, a GCAF criterion of 3,000,000 US $ per averted fatality was adopted, consistently with doc. IMO MSC72/16 submitted by Norway (2000).

The risk variation is the difference in PLL for the two solutions, in both scenarios.
ΔCost is the cost variation due to the implementation of the RCO (excluding the off-hire, which is very much a matter of proper planning organization)
ΔRisk is the corresponding risk decrease in terms of PLL reduction per year, multiplied by the ship's life expectancy in years.
ΔEconomic benefits, in US $ per ship lifetime, should be the sum of the two following terms:

- decrease in the frequency of ship loss per year multiplied by the ship's life expectancy in years, multiplied by the cost of a total loss ($ 24,808,000, see Annex 2)
- decrease in the frequency of serious casualty per year multiplied by the ship's life expectancy in years, multiplied by the cost of a serious casualty ($ 5,608,000, see Annex 2).

Future benefits due to reduced pure economic losses should be discounted at a rate defined as *corporate rate of return*. In this study, a corporate rate of return of 10% is used. Said ΔR_c the reduced economic losses due to the decrease of the frequency of casualty (in US $

per ship-year), r the corporate rate of return (= 0.1) and n the expected ship's lifetime in years (25 or 15 for new and existing ships), it results:

$$\Delta\text{Economic benefits} = \Delta R_c \frac{(1+r)^n - 1}{r(1+r)^n}.$$

In this study, the benefits due to the reduction of Serious Casualty were not included, due to the uncertainties in this calculation. Thus, the RCOs appear less cost-effective than they really are, and the conclusions are more robust.

It is to be noted that, in principle, the NCAF thus defined may assume negative values: this implies that the economic benefits, in terms of reduced risk of losing the ship, exceed the costs of the implementation of the RCO.

4.1 Forecastle

It must be premised that this RCO, along with the Bulwark, can be proposed as a retrofit only on ships whose bridge position still allows to comply with the current regulations of navigation bridge visibility (SOLAS Chapter V, Reg. 22), otherwise other RCOs have to be adopted (modifying the bridge would raise the costs up to an unacceptable level).

The quantification of the long term probability of loss with a 2.5-m increase of the fore-end freeboard brings the following results. The overall PLL is obtained by summing up the PLL resulting from Scenario A and B, which are treated as mutually exclusive.

	PLL (fatalities / bulk carrier-year)					
	Capesize		**Panamax**		**Handymax**	
forecastle [m]	**A**	**B**	**A**	**B**	**A**	**B**
0 (Base Case)	$\mathbf{3.7 \cdot 10^{-4}}$	$\mathbf{5.9 \cdot 10^{-4}}$	$\mathbf{4.7 \cdot 10^{-4}}$	$\mathbf{2.3 \cdot 10^{-3}}$	$\mathbf{2.5 \cdot 10^{-3}}$	$\mathbf{2.4 \cdot 10^{-3}}$
2.5	$8.0 \cdot 10^{-10}$	$1.2 \cdot 10^{-4}$	$5.3 \cdot 10^{-7}$	$8.3 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$
DPLL	**8.45E-04**		**1.97E-03**		**3.73E-03**	

To evaluate the robustness of the CEA, lower and upper cost bounds for the RCO were examined, associated to a life expectancy of 10 years for existing ships and 25 years for newbuildings. It is to be recalled that the RCO cost was estimated to be 70% lower if implemented on newbuildings.
This quantification does not take into account the costs of inspections, but on the other hand the benefits which may accrue from the reduction of sea damages due to the RCO implementation were not considered.

Existing ships

Ship type	**GCAF (Lower bound)**	**GCAF (Upper bound)**	**NCAF (Lower bound)**	**NCAF (Upper bound)**

	US $, millions per averted fatality	US $, millions per averted fatality	US $, millions per averted fatality	US $, millions per averted fatality
Capesize	21	40	20	39
Panamax	4.9	9.2	4.3	8.5
Handymax	1.4	2.7	0.77	2.1

Newbuildings

Ship type	GCAF (Lower bound) US $, millions per averted fatality	GCAF (Upper bound) US $, millions per averted fatality	NCAF (Lower bound) US $, millions per averted fatality	NCAF (Upper bound) US $, millions per averted fatality
Capesize	2.6	4.8	2.2	4.5
Panamax	0.6	1.1	0.24	0.74
Handymax	0.17	0.32	*-4.9*	*-2.0*

4.2 Bulwark

The same probabilities of ship loss and PLL apply as shown in the previous paragraph.

To evaluate the robustness of the CEA, lower and upper cost bounds for the RCO were examined, associated to a life expectancy of 10 years for existing ships and 25 years for newbuildings. It is to be recalled that the RCO cost was estimated to be 70% lower if implemented on newbuildings.

This quantification does not take into account the costs of inspections, but on the other hand the benefits which may accrue from the reduction of sea damages due to the RCO implementation were not considered.

Existing ships

Ship type	GCAF (Lower bound) US $, millions per averted fatality	GCAF (Upper bound) US $, millions per averted fatality	NCAF (Lower bound) US $, millions per averted fatality	NCAF (Upper bound) US $, millions per averted fatality
Capesize	9.5	18	8.8	17
Panamax	2.3	4.2	1.7	3.7
Handymax	0.7	1.3	0.07	0.63

Newbuildings

Ship type	GCAF (Lower bound) US $, millions per averted fatality	GCAF (Upper bound) US $, millions per averted fatality	NCAF (Lower bound) US $, millions per averted fatality	NCAF (Upper bound) US $, millions per averted fatality
Capesize	1.1	2.1	0.8	1.8

Panamax	0.27	0.52	*-0.08*	0.16
Handymax	0.1	0.15	*-0.28*	*-0.22*

4.3 Monitoring System

The inclusion of a monitoring system conceived as described in the previous section is expected to virtually eliminate the contribution of the human element failure for Scenario A, where a prompt detection of the forepeak filling and operation of the pumping system can be really effective to prevent the escalation sequence. This is true, however, if the layout is such as to prevent the pumps from being flooded or disabled.

A continuous monitoring is preferable to an alarm, as it is much more user-friendly and allows for a prompter intervention. As to the requirement of ship fore and aft inclination (5° static and 7.5° dynamic, see e.g. RINA Rules 2000), it corresponds to a trim of the analyzed ship which would not be reached even with the forepeak flooded. In any case, a timely alert of the crew is a matter of proper set point of the instrument, if only an alarm is fitted.

On the other hand, it would be less effective to prevent Scenario B, as it has been shown that the probability of operating successfully the ballast pump to empty hold No.1 is quite low; consequently, this RCO would only be useful to avoid the filling of the forepeak after hold No.1. The trim by bow would not be fully eliminated, but only reduced. According to the initial assumptions of this study, however, the ship would not be lost with only one hold flooded.

It can be concluded that, speaking strictly in terms of potential loss of life, the effectiveness is comparable in both scenarios. In any case, it is indisputable that the presence of a reliable and efficient means of detection contributes at least to alert the crew by giving an early warning, and, definitely, to increase the probability of a successful evacuation if nothing else.

The following PLL results, in both scenarios:

	PLL (fatalities / bulk carrier-year)					
	Capesize		**Panamax**		**Handymax**	
	A	**B**	**A**	**B**	**A**	**B**
Base case	**$3.7 \cdot 10^{-4}$**	**$5.9 \cdot 10^{-4}$**	**$4.7 \cdot 10^{-4}$**	**$2.3 \cdot 10^{-3}$**	**$2.6 \cdot 10^{-3}$**	**$2.4 \cdot 10^{-3}$**
With automation	$1.8 \cdot 10^{-7}$	$2.0 \cdot 10^{-7}$	$2.7 \cdot 10^{-7}$	$7.8 \cdot 10^{-7}$	$1.3 \cdot 10^{-6}$	$8.0 \cdot 10^{-7}$
DPLL	**7.4E-04**		**9.5E-04**		**5.2E-03**	

The solution appears very effective, as the PLL is reduced almost completely. This is due to the elimination of the most significant ET sequences, due to the increased reliability of the detection of water in the forepeak.

It is to be underlined that the cost estimates refer to a particularly complete monitoring system, including redundant means of detection and remote controls, and thus they are on the high side. This explains its great effectiveness, as the crew can always have the situation under control in the forepeak and bos'n store spaces, thus promptly detecting any anomaly. If other solutions are envisaged, it is necessary to re-analyze their cost-effectiveness by the same methodology.

Another point is that, unlike the forecastle or the bulwark, the effectiveness of the Monitoring System relies not only on design aspects (which must achieve an intrinsically high reliability), but also on maintenance, training and spare parts: all issues that have to carried on for all the ship's lifetime.

The GCAF and NCAF for both cases was estimated as follows.

Existing ships

Ship type	**GCAF (Lower bound) US $, millions per averted fatality**	**GCAF (Upper bound) US $, millions per averted fatality**	**NCAF (Lower bound) US $, millions per averted fatality**	**NCAF (Upper bound) US $, millions per averted fatality**
Capesize	5.4	7.7	4.6	6.9
Panamax	4.2	6.0	2.4	4.2
Handymax	0.8	1.1	0.16	0.49

Newbuildings

Ship type	**GCAF (Lower bound) US $, millions per averted fatality**	**GCAF (Upper bound) US $, millions per averted fatality**	**NCAF (Lower bound) US $, millions per averted fatality**	**NCAF (Upper bound) US $, millions per averted fatality**
Capesize	0.65	0.93	0.17	0.44
Panamax	0.51	0.72	*-0.57*	*-0.36*
Handymax	0.1	0.13	*-0.27*	*-0.23*

4.4 Upgrade of Deck Fittings

In the lack of standards to evaluate the corresponding risk decrease, the replacement of current deck fitting with sturdier ones was crudely assumed to be as effective as the implementation of a forecastle. Another important contribution of the proposed upgrade is the remote closure of the fore-deck openings. This will contribute to nullify the possibility of leaving them open, at a price of additional maintenance. However, it is not possible to estimate this effect in probabilistic terms, as it would require the calculation of the contribution to the risk due to the human failures, not deducible from the casualty statistics. In any case, if the upgrade has the same effectiveness as the forecastle or bulwark, which is the most optimistic assumption, the GCAF and NCAF would be better particularly for Capesize and Panamax.

5 SENSITIVITY ANALYSIS

The analysis is affected by the following main several sources of uncertainty:

1. the approximations made in the model of compartment flooding
2. the simplifications inherent in the description of detection and corrective actions
3. the uncertainty of the input data.

The sources of type 1 uncertainties are better described in Appendix 3. They are significant, but do not play the major role one could expect, because the results (admittedly, quite conservative) of the model were tuned on the casualty statistic; thus, the conservatism was someway compensated.

The simplifications of type 2 were due to the generic nature of the bulk carrier equipment takes as reference. The actual procedure of removal of water from the flooding compartments depends very much on the reality of the specific ships, in terms of both crew's characteristics and hardware involved. However, the detailed study of the case-specific tasks was out of the scope of this work.

The sensitivity analysis was restricted to type 3. The data selected for the sensitivity were: the failure of the pumping system hardware (node AF-N2 of Scenario A and AF of Scenario B) and the failure of the detection of forepeak flooding (node DF of both scenarios).

5.1 Sensitivity of Pumping System

The following data were applied.

Electrically driven seawater pump fails to start: unavailability on demand =
=0.25 /dem (OREDA-92, item 1.3.1.3, mean)

Electrically driven seawater pump fails to run: failure rate = $1.0 \cdot 10^{-4}$ /h (OREDA-92, item 1.3.1.3, upper bound)

Hydraulically operated valve fails to open = $6.38 \cdot 10^{-6}$ /h (OREDA-92, item 1.2.2.1.1.1, upper bound)

Hydraulically operated valve spuriously closes = $4.73 \cdot 10^{-6}$ /h (OREDA-92, item 1.2.2.1.1.1, mean)

From the FT quantification, the probability of node failure, in this basic bulk carrier configuration, is therefore:

ET of Scenario A**: P(AF-N2) = $\mathbf{6.4 \cdot 10^{-2}}$.**

ET of Scenario B**: P(AF) = $\mathbf{6.5 \cdot 10^{-2}}$.**

The two ETs were re-quantified with this new values, but the impact on the results was negligible. The CEA is not therefore sensitive to the probability of this event.

5.2 Sensitivity of Detection of Forepeak Flooding

The node DF of both ETs was assigned a value of 0.5 (this means that the forepeak flooding is detected if it occurs in daytime). Both ETs were re-quantified, but the impact on the results is not such as to modify the conclusions. The CEA of the Monitoring System is therefore little sensitive to the probability of this event.

Another quantification was carried out by keeping the 0.9 value in the base case ETs, but assuming that the Automation System has a failure probability of $1.0 \cdot 10^{-2}$ instead of being fully reliable. The impact on the CEA of the Monitoring System is negligible, thus the results hold in this case too.

6 DISCUSSION

As it was explained earlier, the risk picture obtained from the model is affected by various kinds of approximations. It is therefore advisable to refer to the upper bound of the CEA (worst case), to make up, at least partially, for the sources of uncertainty and not be overly optimistic in judging the RCOs.

This premised, the CEA analysis lends itself to the following considerations.

1. According to the analysis model, the risk increases as the vessel size decreases. Likewise, the CE of RCOs increases as the vessel size decreases. This is consistent with the physical model adopted, where the ship is better off the higher the freeboard and the volume of hold No.1; the reason being that, in the same spell of time, it becomes increasingly difficult to fully flood both compartments, which is actually the necessary condition to have a serious casualty of total loss, according to the escalation.

2. For newbuildings, the implementation of any of the RCOs (forecastle, automation system and, especially, bulwark) is cost-effective with the exception of the forecastle in the Capesize.

3. Retrofitting existing ships brings a very different picture. No RCO appears cost-effective for Capesize and Panamax, but only for the Handymax.

4. Some sensitivity analysis carried out on some significant data used as input in the ETs did not change the CE significantly.

As for the specific RCOs, the following considerations can be made.

1. The effectiveness of the forecastle/bulwark is much more significant in preventing scenario A than B

2. The Monitoring System proposed as RCO is even more effective that the forecastle in abating the risk. The sensitivity analysis has shown that the results remain valid even with the assumption of imperfect availability of the system. The underlying reason of this behavior is that, according to the risk model and the boundary of the analysis (restricted to forepeak and hold No.1), the prompt detection of forepeak flooding enables the crew to evacuate the water from it, which, according to the basic assumptions, is sufficient to save the ship (designed to withstand hold No.1 flooding). The detection is therefore instrumental to eliminate the cause of serious casualty or even ship loss.

3. However, the following issues should be borne in mind:
   - unlike the forecastle which is a preventive RCO, the effect of the system in this configuration is corrective;
   - the forecastle is a passive measure totally reliable per se, whilst the monitoring system, as any active system, requires to be designed for reliability and properly managed for the whole ship’s lifetime to maintain its performance;
   - on the other hand, the Monitoring System may be effective for scenarios not addressed in the present study.

4. The improvement of the deck fittings appears to be the most promising RCO, once proper standards are set forth for their scantlings. In the complete version with remote actuating valves, it obtains better results than the bulwark (although of the same order of magnitude), but it becomes cost-effective for both new and existing ships for all sizes if restricted to the basic solution with replacement of the steel parts only. In this case, though, the possibility of human errors remains intact and nothing can be said about its possible impact on the results.

5. As a last consideration, the benefits due to the reduction of risk of serious casualty were not included, thus the aforesaid results are on the pessimistic side, to the advantage of their robustness.

7 RECOMMENDATIONS

The risk control options, ranked in terms of upper bound GCAF, are listed below.

Gross CAF below $ 1 million:

1. Implementation of a forecastle in new Handymax bulk carriers
2. Implementation of a bulwark in new Panamax and Handymax bulk carriers
3. Implementation of a monitoring system in new Capesize, Panamax and Handymax bulk carriers

Gross CAF between $ 1 million and $ 3 million:

1. Implementation of a bulwark in new Capesize bulk carriers
2. Implementation of a forecastle in new Panamax bulk carriers
3. Implementation of a bulwark in existing Handymax bulk carriers
4. Implementation of a monitoring system in existing Handymax bulk carriers

Gross CAF between $ 3 million and $ 10 million:

1. Implementation of a forecastle or bulwark in existing Panamax bulk carriers
2. Implementation of a forecastle in new Capesize bulk carriers
3. Implementation of a monitoring system in existing Capesize and Panamax bulk carriers

Gross CAF above $ 10 million:

1. Implementation of a forecastle or bulwark in existing Capesize bulk carriers

All these RCOs look better if the NCAF is calculated, but it is interesting to note that in no case does NCAF change the conclusions; that is, those non cost-effective RCOs remain such, and vice versa.

Moreover, the following RCOs:

- Forecastle or bulwark for new Handymax
- Monitoring system for new Panamax and Handymax,

are justified from a commercial viewpoint alone (negative NCAF).

It must be noted that a further RCO was taken into consideration, namely the improvement of the deck fittings. The low cost of this solution, estimated from preliminary calculations, makes it very promising. If the effectiveness can be proved to be comparable to the forecastle/bulwark, it becomes more competitive than the bulwark if inclusive of remote actuating valves, and definitely the best all-around (for both new and existing ships of all sizes) if limited to the replacement of the fittings, at a price of maintaining the possibility of human error.

Appropriate criteria for the scantlings of these fittings should be set forth, which account for the real environment where they can operate, in particular, the different type of wave loads which impinge on horizontal and vertical fittings.

8 REFERENCES

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APPENDIX 1

REVIEW OF HISTORICAL DATA

Cases have been retrieved from LMIS for bulk carriers of 20000+ dwt between 1978 and 1998, by searching for the terms ”fore peak”, ”forecastle”, and ”hawsepipe” in the free text, in addition to identifying the cases where the code evC was defined as related to the fore end. The cases are given in the below table, and constitute the cases we know for a fact involved fore ends of bulk carriers. The data can be used to establish a lower limit for the frequency of flooding of the fore end.

12 cases in the below table involves fore end flooding, of which 2 are characterised as Non Serious (NS), 7 as Serious (S), 2 were Actual Total Losses (ATL), and 1 was a Constructive Total Loss (CTL). The number of corresponding bulk carrier years are 73 600. This gives a lower limit for the frequency of flooding:

$$p_{\text{foreendflooding}} = \frac{12}{73600} = 1.6 \cdot 10^{-4} \text{ (per bulk carrier ship year)}$$

Similarly, the lower bound for the frequency of total loss due to fore end flooding becomes:

$$p_{\text{loss}|\text{foreendflooding}}(\text{LB}) = \frac{2}{73600} = 2.7 \cdot 10^{-5} \text{ (per bulk carrier ship year)}$$

There are 17 cases in the database recorded as Foundered (11 cases) and Missing (6 cases). Limited information is given in the database of these cases, and some of them may be caused by progressive flooding initiated in the fore end of the ships. Conservatively, it may be assumed that all the casualties were caused by fore end flooding, giving an upper bound for the frequency for total loss of bulk carriers due to fore end flooding:

$$p_{\text{loss}|\text{foreendflooding}}(\text{UB}) = \frac{19}{73600} = 2.6 \cdot 10^{-4} \text{ (per bulk carrier ship year)}$$

In addition, it is possible that in some of the Hull/Machinery total losses where water ingress into the first cargo hold was reported also included water ingress in the fore end spaces. The following table gives distribution on holds, where reported. In 167 cases flooding was reported and in (167-42) cases, there was an indication of where flooding occurred:

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	fore end	24	6.50	14.37	14.37
	hold No.1	35	9.49	20.96	35.33
	hold 2	13	3.52	7.78	43.11
	hold 3	3	0.81	1.80	44.91
	hold 4	3	0.81	1.80	46.71
	hold 5	8	2.17	4.79	51.50
	hold 6	1	0.27	0.60	52.10
	hold 7	5	1.36	2.99	55.09

	engine room	23	6.23	13.77	68.86
	misc. tanks	7	1.90	4.19	73.05
	unknown hold	42	11.38	25.15	98.20
	pump room	3	0.81	1.80	100.00
	Total	167	45.26	100.00	
Missing	Not flooding	202	54.74		
Total		369	100.00		

LRNO1	LR_NAME	LR_FLAG	CL1	LR_GRT	LR_DWT	BLTYR	RETR	STDAT	Cargo	PTXT1	EV1YR	FATALITY	GRTCLASS	SHIPAGE	SEV_NEW
6706096	SAINT CHRIS	LIB	NV	42273	75763	1967	HM	19790125		SURVEYED AFLOAT DELAWARE RIVER FEBRUARY 1979 IN RESPECT OF HEAVY WEATHER DAMAGE SUSTAINED 25-29/1/79 WHILE ON VOYAGE POINTE A PIERRE TO PHILADELPHIA. SHIP ARRIVED PHILADELPHIA ON 4/2/79. PORT SIDE HAWSEPIPE, LOWER SECTION, PART RENEW, SECTION OF SIDE SHELL PLATING & DECK IN WAY RENEW, UNREPORTED QUANTITY SHIP STORES IN FOREPEAK STORE RENEW TOGETHER WITH SUNDRY DAMAGES & RENEWALS. DRYDOCKING NOT REQUIRED.	1979	0	45000.00	12.00	N
7118753	DASHWOOD	GBI	NV	82985	153321	1971	HM	19791211		ALLEGED HEAVY WEATHER DAMAGE WHILST ON VOYAGE HAY POINT TO FOS BETWEEN 11-22/12/79. ARRIVED FOS.17/1/80 AND SAILED 22/1/80 FOR TARANTO. HAWSEPIPE PART RENEW & SHELL PLATING IN WAY FAIR IN PLACE. FORECASTLE SPACE, DUE FLOODING, TO CLEAN & REINSTATE. VARIOUS HANDRAILS ON DECK & HATCH COAMING BRACKETS TO PART RENEW & FAIR WITH ACCOM. HANDRAILS TO FAIR.	1979	0	75000.00	8.00	N
7411507	CAYUGA	LIB	NV	62295	124228	1977	HM	19790512		DAMAGED HAWSEPIPE WHILST ON VOYAGE NEW ORLEANS TO EUROPOORT ON 12/5/79. ARRIVED EUROPOORT 27/5/79 AND SAILED 1/6/79 FOR GIBRALTAR.	1979	0	65000.00	2.00	N
6812936	CAST BEAVER	GBI	NV	30294	51666	1968	HM	19800228	CONTAINERS	REPORTED AT ANTWERP 28/2/80 WITH BOTTOM DAMAGE, PART CARGO UNLOADED AND PROCEEDED TO ROTTERDAM TO COMPLETE DISCHARGE; SUBSEQUENTLY DRYDOCKED AT ANTWERP 7/3/80 FOR REPAIRS. SAILED 1/5/80 FOR MONTREAL ON COMPLETION. BOTTOM PLATING SET UP	1980	0	35000.00	12.00	S

										BETWEEN FRAMES FORWARD IN WAY OF FOREPEAK AND NO 1 DOUBLE BOTTOM WITH 10 SQ M OF PLATE EXTENSIVELY CRACKED. CAUSE UNKNOWN.					
6503999	CARA	GRC	NV	11940	21164	1965	HM	19810221		SUSTAINED HEAVY WEATHER DAMAGE WHILST ON VOYAGE FROM NUEVITAS TO QINHUANGDAO ON 21-22/2/81. SURVEYED AT QINHUANGDAO. PROCEEDED LIGHT SHIP TO JAPAN FOR FURTHER SURVEY AND REPAIRS. RETURNED TO SERVICE. FORECASTLE DAMAGED. RUDDER KINGPOST PALM BOLTS LOOSE CAUSING LEAKAGE INTO AFTERPEAK TANK.	1981	0	5000.00	16.00	S
6608828	GLYFADA FAITH	GRC	NV	20723	35083	1966	HM	19811113	GRAIN	REPORTED AT GIBRALTAR 13/11/81 WITH HEAVY WEATHER DAMAGE SUSTAINED DURING VOYAGE FROM CHARLESTON. TEMPORARY REPAIRS EFFECTED AT GIBRALTAR. PROCEEDED TO PIRAEUS AND THENCE TO CONSTANTZA FOR PEMANENT REPAIRS. RETURNED TO SERVICE. SUSTAINED CRACKS IN SHELL PLATING IN WAY OF FOREPEAK TANK.	1981	0	25000.00	15.00	S
6611538	MARCONA TRADER	LIB	AB	39586	64427	1966	HM	19810228	COAL, 55000 TONS	LARGE SECTIONS OF SHELL PLATING LOST FROM PORT BOW FORWARD OF COLLISION BULKHEAD IN LAT.31 00N., LONG.171 00E., ON 28/2/81 IN HEAVY WEATHER. SUBSEQUENTLY TOWED TO SASEBO STERN FIRST WHERE REPAIRS EFFECTED. SIDE PLATING FROM COLLISION BULKHEAD AT ABOUT FRAME 244 FORWARD TO FRAME 249 OVER ABOUT 70 SQ M, PORT & STARBOARD, LOST.	1981	0	35000.00	15.00	S
7118753	DASHWOOD	GBI	NV	72010	153321	1971	HM	19810701		REPORTED ON 1/7/81 AT SINGAPORE WITH HEAVY WEATHER DAMAGE. SAILED 11/7/81. PORT HAWSEPIPE AND ADJACENT SHELL PLATE DAMAGE.	1981	0	75000.00	10.00	N
7411507	CAYUGA	LIB	NV	62295	122272	1977	HM	19810409		REPORTED HULL DAMAGE OFF HAMPTON ROADS ON 9/4/81. CONTINUED ON VOYAGE. FRACTURE UPPER FOREPEAK	1981	0	65000.00	4.00	N

										TANK/SHELL PLATING INDENTED.					
7917135	ASIA NO. 12	KRS	LR	14837	25504	1980	HM	19810701		SUSTAINED DAMAGED DECK AND HATCH IN INDIAN OCEAN ON 1/7/81 LATER TRADING. (S) BULWARK COMPLETELY RIPPED OFF IWO NO.4 HOLD. (P) BULWARK BULGING, STANCHIONS IN WAY MISSING/DAMAGED.	1981	0	5000.00	1.00	S
6414277	EPTA DAFNES	GRC	LR	16323	31510	1964	HM	19820913	CEMENT	REPORTED ARRIVED YENBO 13/9/82 WITH DAMAGE TO CARGO DUE TO LEAKAGE IN TANKS, SUSTAINED WHILST ON VOYAGE ALCANAR TO YENBO IN HEAVY WEATHER. DISCHARGED CARGO AND SAILED 22/9/82 AFTER CANAL TRANSIT. VSL HAD INGRESS OF SEAWATER TO NOS. 2 TO 7 HOLDS. CARGO OF CEMENT 62.5 TONNES HARDENED AND 23 TONNES UNSWEPT. TOOK WATER IN HOLDS DUE TO CRACKS IN TANKS AND VENTILATORS AND THROUGH MACGREGOR HATCH COVERS.	1982	0	5000.00	18.00	S
6607991	BANI	PAN	BV	11726	20216	1966	HM	19820218	COAL	TOOK WATER AND DEVELOPED LIST IN LAT. 36 57N., LONG. 71 08W., ON 18-19/2/82 IN HEAVY WEATHER. PROCEEDED TO WILMINGTON & THENCE TO DUBLIN; SUBSEQUENTLY ARRIVED EL FERROL 15/3/82 FOR REPAIRS. SAILED 26/3/82 ON COMPLETION. SUSTAINED SEA WATER DAMAGE OF FORECASTLE, ELECTRIC MOTORS ETC.	1982	0	5000.00	16.00	S
7404891	MINERAL LUXEMBOURG	BLG	LR	39081	75203	1977	HM	19820216		SUSTAINED HEAVY WEATHER DAMAGE WHILST ON VOYAGE FROM NARVIK TO ANTWERP BETWEEN 16-19.2.82. REPAIRING AT ANTWERP TOOK WATER IN FOREPEAK. 3 ELECTRIC MOTORS WATER DAM. AND ELECTRICALS IN WAY DAM. SUNDRY DECK FITTINGS TORN/DESTROYED. MAIN ENGINE EXHAUST COLLECTOR DAM. BY EXPLOSION.	1982	0	35000.00	5.00	S
7393937	MARAT	IND	LR	37870	65085	197	HM	198309	SORGH	SUSTAINED FLOODED FOREPEAK SPACE AND	1983	0	35000.	7.00	S

	HA MARINER					6		20	UM	CONSEQUENT WATER DAMAGE TO 3 ELECTRIC MOTORS AND A STARTER IN PACIFIC OCEAN BETWEEN 20-23/9/83. CONTINUED ON TO JAPAN WHERE REPAIRS EFFECTED. DAMAGE REPORTED EXTENSIVE.			00		
7336549	NYUTA	PAN	NV	55218	103332	1974	HM	19841123		SUSTAINED HEAVY WEATHER DAMAGE WHILST ON VOYAGE FROM HUNTERSTON TO NEWPORT NEWS BETWEEN 22-23/11/84. STARBOARD ANCHOR AND CABLE RENEW, CHAIN LOCKER BULKHEAD PART RENEW, CABLE BITTER END BRACKETS AND PIN RENEW, STARBOARD SIDE FORECASTLE DECK PART RENEW, WINDLASS BRAKE BAND RENEW, STARBOARD HAWSEPIPE GUARDRAILS RENEW.	1984	0	55000.00	10.00	N
6519089	HUANDOY	PER	NV	17411	34602	1965	HM	19861112		REPORTED 12/11/86; LEAKAGE INTO FOREPEAK TANK WHILST ON VOYAGE FROM CALLAO TO HACHINOHE. ARRIVED HACHINOHE 15/11/86 FOR SURVEY AND TEMPORARY REPAIRS. PORT AND STARBOARD BOTTOM PLATING SET IN AND FRACTURED.	1986	0	5000.00	21.00	S
7367550	LANTAU PEAK	HKG	AB	43867	78063	1974	HM	19861217		SUSTAINED HEAVY WEATHER DAMAGE WHILST ON VOYAGE FROM LOS ANGELES TO KASHIMA BETWEEN 5-17/12/86. REPAIRED. STANDARD COMPASS TO REPAIR AND RECALIBRATE, FORWARD LIFE- RAFT ALREADY REPLACED WITH NEW 6-PERSON LIFERAFT, TWO HAWSEPIPE COVERS TO RENEW, FORWARD BULWARK TO RENEW APPROX 8 BY 4 FT AREA, SUEZ LIGHT DAVIT TO REPAIR, PORT SIDE CHAIN STOPPER HOUSING TO REPAIR BRACKET AND ONE PLATFORM STOOL TO FABRICATE.	1986	0	45000.00	12.00	N
7305813	ULTRAMAR	USA	AB	40362	83518	1973	HM	19880311	GASOLINE	SUSTAINED HEAVY WEATHER DAMAGE WHILST ON VOYAGE FROM CONSTANTZA TO NEW YORK ON 8-11/3/88. ARRIVED NEW YORK 12/3/88. SURVEYED. REPAIRED. SAILED 15/3/88 FOR BEAUMONT.	1988	0	45000.00	15.00	N

										FORECASTLE DECK PLATING AND DECK BEAMS DISTORTED, AND FORECASTLE STORAGE SPACE FLOODED.					
8128676	AL MAJEED	LIB	LR	25525	45501	1985	HM	19881202		SUSTAINED HEAVY WEATHER DAMAGE BETWEEN LAT. 40 42N., LONG. 138 44W., AND LAT. 29 29N., LONG. 168 09W., BETWEEN 2-9/12/88. PROCEEDED ON VOYAGE FOR PORT MUHAMMAD BIN QASIM WHERE ARRIVED 10/1/89. PART PERMANENT REPAIRS EFFECTED. SUSTAINED WIDESPREAD DAMAGE TO STRUCTURE AND FITMENTS AND CONTENTS OF FOREPEAK STORE DUE FLOODING.	1988	0	25000.00	3.00	S
8120741	ALBERTA	GRC	LR	17882	30820	1984	HM	19910307		SURVEYED AT WILMINGTON, DE., 7-8/3/91 IN RESPECT OF HEAVY WEATHER DAMAGE SUSTAINED WHILST ON VOYAGE FROM ANTWERP. PART PERMANENT REPAIRS EFFECTED. REMAINING REPAIRS EFFECTED BY CREW WHILE VESSEL CONTINUED VOYAGE. REPORTED FORECASTLE PARTLY FLOODED. PERMANENT REPAIRS TO ELECTRICAL MOTORS AND CONTROL PANELS EFFECTED AT WILMINGTON, DE.	1991	0	5000.00	7.00	S
8800107	CHINA GLORY	MYA	AB	36433	64615	1990	HM	19920505		REPORTED 5/5/92; LEAKAGE IN FOREPEAK BALLAST TANK WHILST ON VOYAGE FROM LOS ANGELES, CA., TO KAOHSIUNG. ARRIVED KAOHSIUNG 17/5/92 AND SAILED 22/5/92.	1992	0	35000.00	2.00	S
7313705	ARTEMIS	LIB	BV	17770	30190	1973	FD	19801227	TIMBER	SANK IN LAT. 31 00N., LONG. 144 00E., ON 28/12/80. AFTER FLOODING IN FOREPEAK AND NO 1 HOLD ON 27/12/80 IN HEAVY WEATHER. 23 CREW RESCUED BY JAPANESE PATROL BOAT BEFORE VESSEL SANK.	1980	0	5000.00	7.00	ATL
6723862	CAPTAIN VENIAMIS	GRC	NV	15472	25575	1967	WS	19920125	CALCIUM NITRATE	BEACHED OFF UI DO IN LAT. 34 35 30N., LONG. 125 52 00E., ON 25/1/92 AFTER SPRANG LEAK IN HEAVY WEATHER. REFLOATED WITH TUG ASSISTANCE 1/2/92. SUBSEQUENTLY TOWED TO YANTAI	1992	0	5000.00	25.00	CTL

										AND THENCE TO QINHUANGDAO. SOLD FOR BREAKING UP. FOREPEAK TANK AND DEEP TANK FLOODED TO SEA LEVEL, AND NOS. 1 & 2 DOUBLE BOTTOM TANKS AND PORT SIDE SLUDGE TANK IN ENGINE ROOM FULL.					
7342457	KILMUN	HKG	LR	16646	26931	1976	HM	19830108	WHEAT	SUSTAINED HEAVY WEATHER DAMAGE BETWEEN 8-25/1/83 WHILST ON VOYAGE FROM VANCOUVER TO NAKHODKA. DIVERTED TO HONOLULU 29/1/83 FOR TEMPORARY REPAIRS, SAILED 6/2/83 FOR NAKHODKA; ARRIVED INNOSHIMA 16/3/83 AND PERMANENT REPAIRS EFFECTED. SUSTAINED DAMAGE TO PORT AND STARBOARD SHELL PLATING IN WAY OF HAWSE PIPES. VARIOUS MISC. DAMAGE TO RAILINGS, VENT. PIPES ETC. AND MINOR FRACTURES IN CARGO HATCHES NOS. 2, 4 AND 5.	1983	0	5000.00	7.00	S
7341324	HELM	HKG	LR	86098	161798	1974	HM	19840117		SUSTAINED HEAVY WEATHER DAMAGE WHILST ON VOYAGE FROM TUBARAO TO REDCAR BETWEEN 13-17/1/84. CONTINUED ON VOYAGE. SURVEYED REDCAR 24/1/84; SUBSEQUENTLY ARRIVED ROTTERDAM 29/1/84 FOR PERMANENT REPAIRS. SAILED 7/2/84 FOR SEPETIBA. PORT AND STARBOARD HAWSEPIPES FRACTURED AND HOLED TOGETHER WITH SHELL PLATING AND INTERNALS IN WAY AND SUNDRY MINOR DAMAGES ON DECK.	1984	0	75000.00	10.00	N
7379216	CISSUS	LIB	AB	18693	33529	1974	HM	19840113		ALLEGED SUSTAINED HEAVY WEATHER DAMAGE WHILST ON VOYAGE FROM KOBE TO PRINCE RUPERT, B.C., BETWEEN 13-30/1/84. TAKEN TO KOBE WHERE SURVEYED FOR REPAIR SPECIFICATION. LATER REPORTED TRADING. KEEL AND BOTTOM PLATES IN WAY OF FOREPEAK AND NO. 1 DOUBLE BOTTOM TANKS RENEWED OR CROPPED AND PART RENEWED OR FAIRED	1984	0	5000.00	10.00	S

										IN PLACE AND INTERNALS IN WAY DEALT WITH AS RECOMMENDED. SEE LATER CASUALTY INCIDENT NO. 8416012.					
7343085	DERBYSHIRE	GBI	LR	91655	169044	1976	XX	19800909	IRON ORE 165000 TONS	REPORTED 230 MILES E.S.E. OF OKINAWA IN APPROXIMATELY LAT. 25 18N., LONG. 133 12E., AT 0300 GMT ON 9/9/80 AND LAST REPORTED AT 0930 GMT ON THE SAME DAY DURING A TYPHOON. PARTS OF A WRECK HAVE BEEN LOCATED APPROXIMATELY 71 KM N.N.E. OF THE LAST REPORTED POSITION OF THE SHIP. AN EXTENSIVE SEARCH BY THE RESEARCH SHIP 'SHIN KAI MARU' IN JUNE, 1994 FOLLOWED BY A FURTHER EXPEDITION IN JULY, 1996 CONFIRMED SECTIONS OF THE WRECK AS BELONGING TO THE 'DERBYSHIRE'. FURTHER VISITS TO THE WRECK SITE HAVE REPORTEDLY TAKEN PLACE. A UK/EC ASSESSORS REPORT INTO THE LOSS OF VSL WAS PUBLISHED 12/3/98.	1980	44	75000.00	4.00	ATL

APPENDIX 2

QUANTIFICATION OF THE EVENT TREES

This section explains how the probability of the sequences of the ETs was quantified.

Basically, the risk associated to each sequence comprises two terms: frequency and consequence. For the purpose of this work, the consequences of interest are in terms of loss of life of the crew onboard.

A2.1 Computation of Frequency

The following failures:

- Loss of watertightness of the forepeak (event WF)
- Loss of watertightness of hatch cover No.1 (node WH),

were assumed as due exclusively to the sea action, with a certain probability computed by the simplified methodology described in Appendix 3.

In turn, the probabilities of detection and action failures were computed. As these nodes are independent on each other, and on the other aforesaid three nodes, the probability of the sequences can be obtained as follows.

The simplified methodology allows to compute the joint probability of nodes WF and WH. Therefore, taking sequence #8 as an example, it results:

$$P(3) = P(WF \cap WH) \times P(DF') \times P(AF\text{-}N1) \times P(DH),$$

where the probability of failure of an event E is denominated as P(E), that of success as P(E').

The whole sequence must then be multiplied by the exposure duration of a bulk carrier in a year, i.e. 150 days/year (see § 3.2) and by 24/18 (= the number of 18-hour intervals within one day). Hence, the frequency of sequence #8 is:

$$F(8) = P(8) \times 200 \text{ events/bulk carrier-year.}$$

The risk model was tuned to the historical frequency of total loss of any Capesize, Panamax and Handymax.

A2.2 Computation of Risk

The quantification was carried out only for the 'failure' sequences, which are defined as those corresponding to loss of life (LL), i.e. leading to Serious Casualty (SC) or Constructive Total Loss (CTL or CTLL). These sequences are all characterized by the failure of WH conditioned to WF or vice-versa (i.e., flooding of both the forepeak and the hold No.1).

Recalling § 3.3, historically a serious casualty (SC), a total loss with early warning (CTL) and a total loss without early warning (CTLL) resulted in 0.05, 5.4 and 25 lives lost (LL) respectively.

However, for the reasons explained in § 3.6 of the main text, the loss of lives for SCs was neglected.

The risk, in terms of the so-called Potential Loss of Life (PLL) (actually an expected loss of life in rigorous statistical terminology), of each sequence was then obtained by multiplying the frequency of each failure sequence by the corresponding LL.

Thus, for the aforesaid sequence #8, the risk in terms of PLL is:

$$PLL(8) = F(8) \times 25.$$

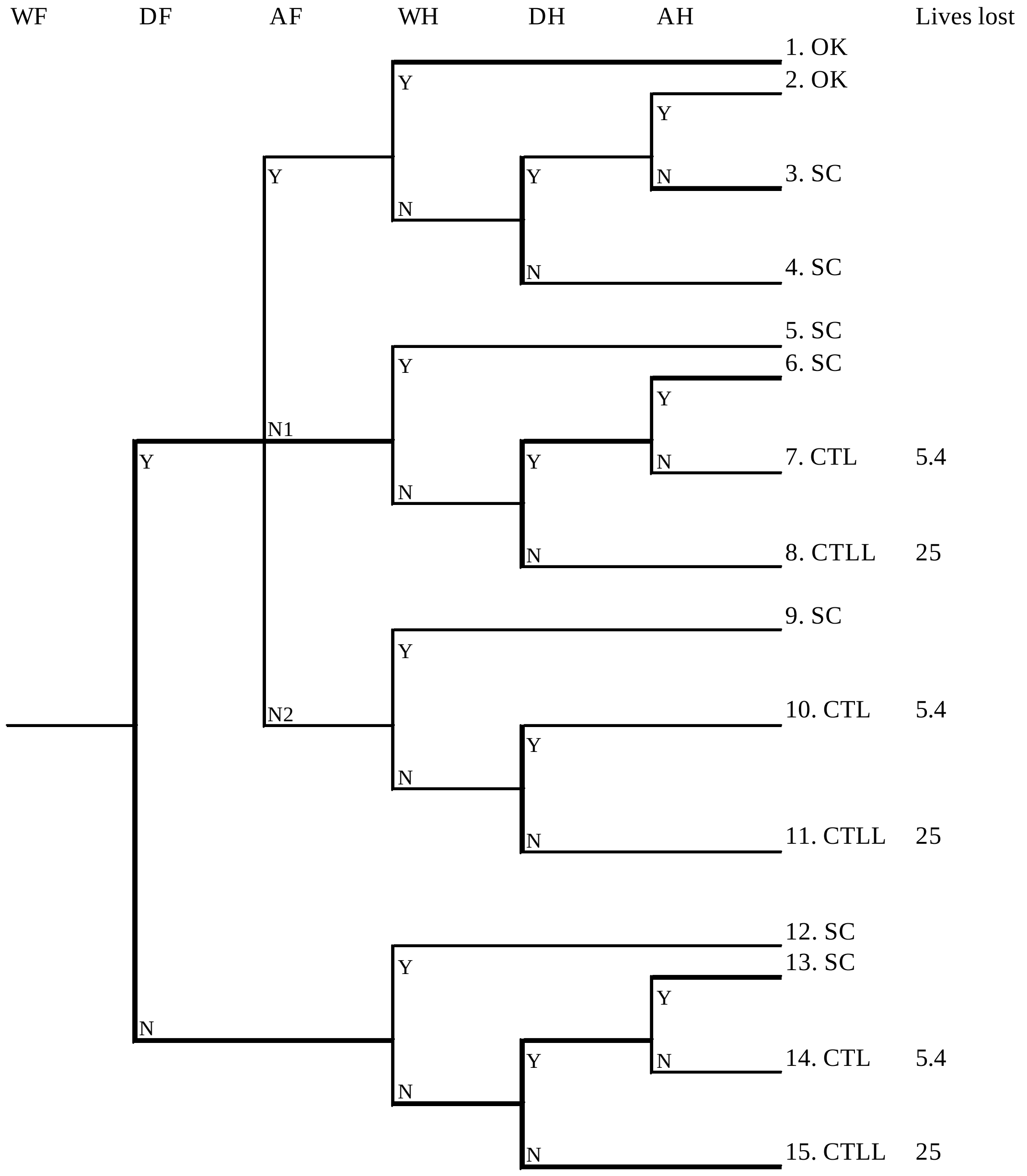
The overall PLL is then given by the sum of the results of all the failure sequences: the result constitutes the risk of the overall scenario under analysis . In mathematical terms, for a number *i* of SC sequences, *j* of CTL sequences and *k* of CTLL sequences, the frequency of the i-th failure sequence, the PLL is given by the following formula:

$$PLL = \sum_j (F_{CTL\ j} \times 5.4) + \sum_k (F_{CTLL\ k} \times 25)$$

The same procedure was repeated for the three bulk carrier sizes selected.

A2.3 QUANTIFICATION OF RISK IN SCENARIO A

The ET of Scenario A is reported below.



LEGENDA

WF	Loss of watertightness of the forepeak given deck wetness
DF	Detection of forepeak flooding
AF	Action of emptying the forepeak
WH	Watertightness of the hatch No. 1
DH	Detection of hold No.1 flooding
AH	Action of emptying hold No.1

N1=human failure
N2=pumping system failure

OK=no consequences
SC=serious casualty
CTL=total loss with early warning
CTLL=total loss without early warning

A2.3.1 Quantification of the ET Nodes

A2.3.1.1 Chain of Events Induced by Sea Action ($WF \cap WH$)

This is constituted by the probability of the loss of watertightness of the forepeak conditioned to deck wetness (i.e. the initiating event), coupled with the failure or success of watertightness of hatch cover No.1, and multiplied by 200 to obtain the annual frequency (see above explanation): in mathematical notation, it corresponds to $P(WF \cap WH)$. The full details, quite complex, of the quantification of this probability are given in Appendix 3. The following results were obtained:

	Capesize	Panamax	Handymax
$P(WF \cap WH)$	1.78E-05 /BC-y	2.29E-05 /BC-y	1.26E-04 /BC-y
$P(WF \cap WH')$	8.73E-04 /BC-y	9.90E-04 /BC-y	8.10E-03 /BC-y

A2.3.1.2 Detection of Forepeak Flooding (DF)

Routine inspections in the forepeak are unlikely to be followed in deck wetness conditions. The probability of detection failure was therefore judged to be 90%. The probability of node failure is therefore:

P(DF) = 0.9

A2.3.1.3 Corrective Action of Forepeak Flooding (AF)

This node was split into two mutually exclusive failure modes: human failure (N1 branch in the ET) and failure of pumping system hardware (N2 branch in the ET). The reason of this split lies in the dependency between this node and node AH, which share the same pumps. Therefore, a human error or a valve on the forepeak failure to open do not affect the subsequent operation of emptying hold No.1; conversely, a failure of both pumps will render the subsequent operation impossible.

A2.3.1.3.1 *Branch N1*

The probability of AF failure in mode N1 represents the following mutually exclusive events:

- crew failing to operate the system when required
- the hydraulic valve connecting the forepeak to the ballast water line fails to open or closes spuriously after opening.

The following data were assumed.

According to NUREG (1994), in most cases the failure to operate a safety system in a nuclear power plant varies between 10^{-2} and 1.0^{-3} including recovery; here, the lower limit was assumed due to the simplicity of the operation and the relatively long available time.

Hydraulically operated valve fails to open = $2.12\cdot 10^{-6}$ /h (OREDA-92, item 1.2.2.1.1.1, mean); assuming a voyage in ballast is made every laden passage, the valve is challenged twice a month. By using the well known formula for the unavailability on demand ($U = \lambda T/2$, where λ is the standby failure rate and T the mean time between two consecutive tests), it results:

$U(\text{valve}) = 2.12\cdot 10^{-6}$ /h × 15 days /2 × 24 h/day = $3.8\cdot 10^{-4}$/dem

Hydraulically operated valve spuriously closes = $1.05\cdot 10^{-6}$ /h (OREDA-92, item 1.2.2.1.1.1, mean)

Finally, the mission time of the pumping system has to be assessed. As an example, the pump flow rate is 1200 m^3/h for the Panamax and 2000 m^3/h for the Capesize, therefore the forepeak can be emptied in short time (about 1 h and 2.5 h respectively). However, while the forepeak is being emptied, further water can get in: it is a competitive process, which, in theory, should be characterized by a convolution of probability distributions. Due to the lack of proper information to undertake such a model, and to be conservative, the mission time of the system was assumed to be 18 hours (i.e., the duration of the complete sequence, see Appendix 3).

It results:

P(AF-N1) = $10^{-3} + 3.8\cdot 10^{-4} + (1.05\cdot 10^{-6}\,/\text{h}\times 18\text{ h})$ **=** $\mathbf{1.4\cdot 10^{-3}}$

A2.3.1.3.2 *Branch N2*

The probability of AF failure in mode N2 represents the failure of both pumps. The following data were assumed:

Electrically driven seawater pump fails to start: unavailability on demand =
=$4.6\cdot 10^{-3}$/dem (OREDA-92, item 1.3.1.3.1, lower bound judged more realistic)

Electrically driven seawater pump fails to run: failure rate = $6.8\cdot 10^{-5}$ /h (OREDA-92, item 1.3.1.3.1, mean)

The probability of node failure, in this basic bulk carrier configuration, is therefore:

P(AF-N2) = $[4.6\cdot 10^{-3} + (6.8\cdot 10^{-5}\,/\text{h}\times 18\text{ h})]^2$ **=** $\mathbf{3.4\cdot 10^{-5}}$**.**

A2.3.1.4 Detection of Hold No.1 Flooding (DH)

The probability of failure of water ingress detection in holds was assumed the same as for node AF, for the same reasons. Thus,

P(DH) = 0.9

A2.3.1.5 Corrective Action for Hold No.1 Flooding (AH)

The probability of AH failure represents the failure of the pumping system, given it has not failed in the previous node AF. Three basic failure causes (mutually exclusive) exist, namely, the failure of the pumping system or human error given hold No.1 drainable and hold No.1 not drainable.

Hold No.1 Drainable

The hold is fully drainable only if it is empty. Evacuating the water from the hold is only possible when the hold is empty, otherwise the bilge wells are closed. In the assumption of laden ship, a condition for hold No.1 to be empty is the alternate loading pattern. However, it is not sufficient; it is necessary that the bulk carrier design envisages to keep odd holds empty. The probability of the two events was estimated from the population of bulk carriers lost from Eknes *et al* (1997) - assumed to be a significant sample of the overall bulk carrier population - as 0.41 and 0.15 respectively, yielding a joint probability of $6.15 \cdot 10^{-2}$.

Pumping System Failure

The same data as for node AF were assumed.

Human Error

The same data as for node AF were assumed.

The overall FT quantification yields the following results:

P(AH) = $(6.15 \cdot 10^{-2} + 10^{-3}) \times (1.4 \cdot 10^{-3} + 3.4 \cdot 10^{-5}) + (1 - 6.15 \cdot 10^{-2} - 10^{-3}) \cong$ **0.9375**

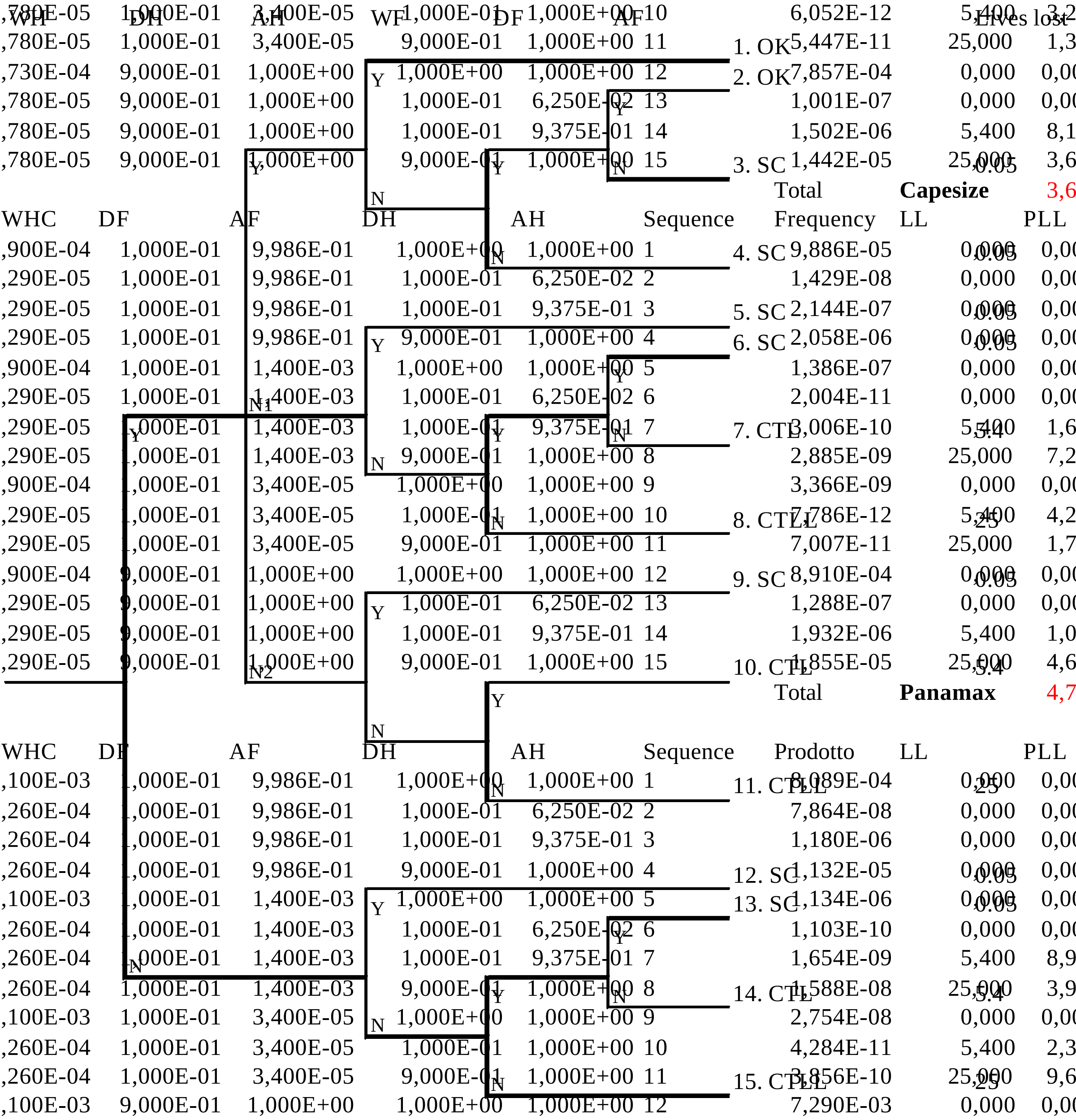
A2.3.2 Results

The results of the quantification of the ET yields the following results. The details of the sequence calculation is given in the next page.

PLL (in fatalities/bulk carrier-year)		
Capesize	**Panamax**	**Handymax**
$3.7 \cdot 10^{-4}$	**$4.7 \cdot 10^{-4}$**	**$2.6 \cdot 10^{-3}$**

A2.4 QUANTIFICATION OF RISK IN SCENARIO B

The ET of Scenario B is reported below



LEGENDA

WF	Watertightness of the forepeak
DF	Detection of forepeak flooding
AF	Action of emptying the forepeak
WH	Loss of Watertightness of hatch No. 1 given dek wetness
DH	Detection of hold No.1 flooding
AH	Action of emptying hold No.1

N1=human failure
N2=pumping system failure

OK=no consequences
SC=serious casualty
CTL=total loss with early warning
CTLL=total loss without early warning

WFWHC	DF	AF	DH	AH	Sequence	Frequency	LL	PLL
8,730E-04	1,000E-01	9,986E-01	1,000E+00	1,000E+00	1	8,718E-05	0,000	0,000E+00
1,780E-05	1,000E-01	9,986E-01	1,000E-01	6,250E-02	2	1,111E-08	0,000	0,000E+00
1,780E-05	1,000E-01	9,986E-01	1,000E-01	9,375E-01	3	1,666E-07	0,000	0,000E+00
1,780E-05	1,000E-01	9,986E-01	9,000E-01	1,000E+00	4	1,600E-06	0,000	0,000E+00
8,730E-04	1,000E-01	1,400E-03	1,000E+00	1,000E+00	5	1,222E-07	0,000	0,000E+00
1,780E-05	1,000E-01	1,400E-03	1,000E-01	6,250E-02	6	1,558E-11	0,000	0,000E+00
1,780E-05	1,000E-01	1,400E-03	1,000E-01	9,375E-01	7	2,336E-10	5,400	1,262E-09
1,780E-05	1,000E-01	1,400E-03	9,000E-01	1,000E+00	8	2,243E-09	25,000	5,607E-08
8,730E-04	1,000E-01	3,400E-05	1,000E+00	1,000E+00	9	2,968E-09	0,000	0,000E+00
1,780E-05	1,000E-01	3,400E-05	1,000E-01	1,000E+00	10	6,052E-12	5,400	3,268E-11
1,780E-05	1,000E-01	3,400E-05	9,000E-01	1,000E+00	11	5,447E-11	25,000	1,362E-09
8,730E-04	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	7,857E-04	0,000	0,000E+00
1,780E-05	9,000E-01	1,000E+00	1,000E-01	6,250E-02	13	1,001E-07	0,000	0,000E+00
1,780E-05	9,000E-01	1,000E+00	1,000E-01	9,375E-01	14	1,502E-06	5,400	8,110E-06
1,780E-05	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	1,442E-05	25,000	3,605E-04
						Total	**Capesize**	3,686E-04

WFWHC	DF	AF	DH	AH	Sequence	Frequency	LL	PLL
9,900E-04	1,000E-01	9,986E-01	1,000E+00	1,000E+00	1	9,886E-05	0,000	0,000E+00
2,290E-05	1,000E-01	9,986E-01	1,000E-01	6,250E-02	2	1,429E-08	0,000	0,000E+00
2,290E-05	1,000E-01	9,986E-01	1,000E-01	9,375E-01	3	2,144E-07	0,000	0,000E+00
2,290E-05	1,000E-01	9,986E-01	9,000E-01	1,000E+00	4	2,058E-06	0,000	0,000E+00
9,900E-04	1,000E-01	1,400E-03	1,000E+00	1,000E+00	5	1,386E-07	0,000	0,000E+00
2,290E-05	1,000E-01	1,400E-03	1,000E-01	6,250E-02	6	2,004E-11	0,000	0,000E+00
2,290E-05	1,000E-01	1,400E-03	1,000E-01	9,375E-01	7	3,006E-10	5,400	1,623E-09
2,290E-05	1,000E-01	1,400E-03	9,000E-01	1,000E+00	8	2,885E-09	25,000	7,214E-08
9,900E-04	1,000E-01	3,400E-05	1,000E+00	1,000E+00	9	3,366E-09	0,000	0,000E+00
2,290E-05	1,000E-01	3,400E-05	1,000E-01	1,000E+00	10	7,786E-12	5,400	4,204E-11
2,290E-05	1,000E-01	3,400E-05	9,000E-01	1,000E+00	11	7,007E-11	25,000	1,752E-09
9,900E-04	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	8,910E-04	0,000	0,000E+00
2,290E-05	9,000E-01	1,000E+00	1,000E-01	6,250E-02	13	1,288E-07	0,000	0,000E+00
2,290E-05	9,000E-01	1,000E+00	1,000E-01	9,375E-01	14	1,932E-06	5,400	1,043E-05
2,290E-05	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	1,855E-05	25,000	4,637E-04
						Total	**Panamax**	4,742E-04

WFWHC	DF	AF	DH	AH	Sequence	Prodotto	LL	PLL
8,100E-03	1,000E-01	9,986E-01	1,000E+00	1,000E+00	1	8,089E-04	0,000	0,000E+00
1,260E-04	1,000E-01	9,986E-01	1,000E-01	6,250E-02	2	7,864E-08	0,000	0,000E+00
1,260E-04	1,000E-01	9,986E-01	1,000E-01	9,375E-01	3	1,180E-06	0,000	0,000E+00
1,260E-04	1,000E-01	9,986E-01	9,000E-01	1,000E+00	4	1,132E-05	0,000	0,000E+00
8,100E-03	1,000E-01	1,400E-03	1,000E+00	1,000E+00	5	1,134E-06	0,000	0,000E+00
1,260E-04	1,000E-01	1,400E-03	1,000E-01	6,250E-02	6	1,103E-10	0,000	0,000E+00
1,260E-04	1,000E-01	1,400E-03	1,000E-01	9,375E-01	7	1,654E-09	5,400	8,930E-09
1,260E-04	1,000E-01	1,400E-03	9,000E-01	1,000E+00	8	1,588E-08	25,000	3,969E-07
8,100E-03	1,000E-01	3,400E-05	1,000E+00	1,000E+00	9	2,754E-08	0,000	0,000E+00
1,260E-04	1,000E-01	3,400E-05	1,000E-01	1,000E+00	10	4,284E-11	5,400	2,313E-10
1,260E-04	1,000E-01	3,400E-05	9,000E-01	1,000E+00	11	3,856E-10	25,000	9,639E-09
8,100E-03	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	7,290E-03	0,000	0,000E+00
1,260E-04	9,000E-01	1,000E+00	1,000E-01	6,250E-02	13	7,088E-07	0,000	0,000E+00
1,260E-04	9,000E-01	1,000E+00	1,000E-01	9,375E-01	14	1,063E-05	5,400	5,741E-05
1,260E-04	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	1,021E-04	25,000	2,552E-03
						Total	**Handymax**	2,609E-03

Scenario B does not exhibit conceptual variations with respect to Scenario A. Basically, it differs in the order of the nodes consistently with the different sequence hypothesized.

A2.4.1 Quantification of the ET Nodes

A2.4.1.1 Chain of Events Induced by Sea Action (WH ∩ WF)

This is constituted by the probability of the loss of watertightness of hatch cover No.1 conditioned to deck wetness (i.e. the initiating event) coupled with the failure of the forepeak: in mathematical notation, it corresponds to P(WH ∩ WF). It is analogous to §A2.3.1.1 The following results were obtained:

	Capesize	**Panamax**	**Handymax**
P(WF ∩ WH)	2.65E-05 /BC-y	1.04E-04 /BC-y	1.06E-04 /BC-y
P(WF ∩ WH')	8.82E-02 /BC-y	1.66E-01 /BC-y	9.86E-01 /BC-y

A2.4.1.2 Detection of Hold No.1 Flooding (DH)

Same as § A2.3.1.2.

A2.4.1.3 Corrective Action for Hold No.1 Flooding (AH)

This node has been split into two branches: failure due to either hold No.1 not drainable or human error or hold No.1 valve failure (N1 branch in the ET), and failure of the pumping system hardware given hold No.1 drainable (N2 branch in the ET). The latter failure would cause the failure of node AF.

The same data and consideration as § A2.3.1.5 apply. This time, however, the failure probability is split between the two branches, as follows:

P(AH-N1) = $(6.25 \cdot 10^{-2}) \times 1.4 \cdot 10^{-3} + (1 - 6.25 \cdot 10^{-2}) \cong$ **0.9375**

P(AH-N2) = $[4.6 \cdot 10^{-3} + (6.8 \cdot 10^{-5}\,/\mathrm{h} \times 18\ \mathrm{h})]^2$ $\mathbf{= 3.5 \cdot 10^{-5}}$

A2.4.1.4 Detection of Forepeak Flooding (DF)

Same as § A2.3.1.2.

A2.4.1.5 Corrective Action of Forepeak Flooding (AF)

This node is conditioned to the success of the pumping system in the previous node AH. The same data as § A2.3.1.3.1 and A2.3.1.3.2 apply, but this time it is unnecessary to keep them separate, so they are summed up, yielding:

P(AF) = $\mathbf{1.44 \cdot 10^{-3}}$

A2.4.2 Results

The results of the quantification of the ET yields the following results. The detail of the sequence calculation is given in the next page.

PLL (in fatalities/bulk carrier-year)		
Capesize	**Panamax**	**Handymax**
$5.9 \cdot 10^{-4}$	**$2.3 \cdot 10^{-3}$**	**$2.4 \cdot 10^{-3}$**

WHWFC	DH	AH	DF	AF	Sequence	Frequency	LL	PLL
8,820E-02	1,000E-01	6,250E-02	1,000E+00	1,000E+00	1	5,513E-04	0,000	0,000E+00
2,650E-05	1,000E-01	6,250E-02	1,000E-01	9,986E-01	2	1,654E-08	0,000	0,000E+00
2,650E-05	1,000E-01	6,250E-02	1,000E-01	1,440E-03	3	2,385E-11	0,000	0,000E+00
2,650E-05	1,000E-01	6,250E-02	9,000E-01	1,000E+00	4	1,491E-07	0,000	0,000E+00
8,820E-02	1,000E-01	9,375E-01	1,000E+00	1,000E+00	5	8,269E-03	0,000	0,000E+00
2,650E-05	1,000E-01	9,375E-01	1,000E-01	9,986E-01	6	2,481E-07	0,000	0,000E+00
2,650E-05	1,000E-01	9,375E-01	1,000E-01	1,440E-03	7	3,578E-10	5,400	1,932E-09
2,650E-05	1,000E-01	9,375E-01	9,000E-01	1,000E+00	8	2,236E-06	25,000	5,590E-05
8,820E-02	1,000E-01	3,500E-05	1,000E+00	1,000E+00	9	3,087E-07	0,000	0,000E+00
2,650E-05	1,000E-01	3,500E-05	1,000E-01	1,000E+00	10	9,275E-12	5,400	5,009E-11
2,650E-05	1,000E-01	3,500E-05	9,000E-01	1,000E+00	11	8,348E-11	25,000	2,087E-09
8,820E-02	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	7,938E-02	0,000	0,000E+00
2,650E-05	9,000E-01	1,000E+00	1,000E-01	9,986E-01	13	2,382E-06	0,000	0,000E+00
2,650E-05	9,000E-01	1,000E+00	1,000E-01	1,440E-03	14	3,434E-09	5,400	1,855E-08
2,650E-05	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	2,147E-05	25,000	5,366E-04
						Total	**Capesize**	5,925E-04

WHWFC	DH	AH	DF	AF	Sequence	Frequency	LL	PLL
1,660E-01	1,000E-01	6,250E-02	1,000E+00	1,000E+00	1	1,038E-03	0,000	0,000E+00
1,040E-04	1,000E-01	6,250E-02	1,000E-01	9,986E-01	2	6,491E-08	0,000	0,000E+00
1,040E-04	1,000E-01	6,250E-02	1,000E-01	1,440E-03	3	9,360E-11	0,000	0,000E+00
1,040E-04	1,000E-01	6,250E-02	9,000E-01	1,000E+00	4	5,850E-07	0,000	0,000E+00
1,660E-01	1,000E-01	9,375E-01	1,000E+00	1,000E+00	5	1,556E-02	0,000	0,000E+00
1,040E-04	1,000E-01	9,375E-01	1,000E-01	9,986E-01	6	9,736E-07	0,000	0,000E+00
1,040E-04	1,000E-01	9,375E-01	1,000E-01	1,440E-03	7	1,404E-09	5,400	7,582E-09
1,040E-04	1,000E-01	9,375E-01	9,000E-01	1,000E+00	8	8,775E-06	25,000	2,194E-04
1,660E-01	1,000E-01	3,500E-05	1,000E+00	1,000E+00	9	5,810E-07	0,000	0,000E+00
1,040E-04	1,000E-01	3,500E-05	1,000E-01	1,000E+00	10	3,640E-11	5,400	1,966E-10
1,040E-04	1,000E-01	3,500E-05	9,000E-01	1,000E+00	11	3,276E-10	25,000	8,190E-09
1,660E-01	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	1,494E-01	0,000	0,000E+00
1,040E-04	9,000E-01	1,000E+00	1,000E-01	9,986E-01	13	9,347E-06	0,000	0,000E+00
1,040E-04	9,000E-01	1,000E+00	1,000E-01	1,440E-03	14	1,348E-08	5,400	7,278E-08
1,040E-04	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	8,424E-05	25,000	2,106E-03
						Total	**Panamax**	2,325E-03

WHWFC	DH	AH	DF	AF	Sequence	Frequency	LL	PLL
9,860E-01	1,000E-01	6,250E-02	1,000E+00	1,000E+00	1	6,163E-03	0,000	0,000E+00
1,060E-04	1,000E-01	6,250E-02	1,000E-01	9,986E-01	2	6,616E-08	0,000	0,000E+00
1,060E-04	1,000E-01	6,250E-02	1,000E-01	1,440E-03	3	9,540E-11	0,000	0,000E+00
1,060E-04	1,000E-01	6,250E-02	9,000E-01	1,000E+00	4	5,963E-07	0,000	0,000E+00
9,860E-01	1,000E-01	9,375E-01	1,000E+00	1,000E+00	5	9,244E-02	0,000	0,000E+00
1,060E-04	1,000E-01	9,375E-01	1,000E-01	9,986E-01	6	9,924E-07	0,000	0,000E+00
1,060E-04	1,000E-01	9,375E-01	1,000E-01	1,440E-03	7	1,431E-09	5,400	7,727E-09
1,060E-04	1,000E-01	9,375E-01	9,000E-01	1,000E+00	8	8,944E-06	25,000	2,236E-04
9,860E-01	1,000E-01	3,500E-05	1,000E+00	1,000E+00	9	3,451E-06	0,000	0,000E+00
1,060E-04	1,000E-01	3,500E-05	1,000E-01	1,000E+00	10	3,710E-11	5,400	2,003E-10
1,060E-04	1,000E-01	3,500E-05	9,000E-01	1,000E+00	11	3,339E-10	25,000	8,348E-09
9,860E-01	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	8,874E-01	0,000	0,000E+00
1,060E-04	9,000E-01	1,000E+00	1,000E-01	9,986E-01	13	9,527E-06	0,000	0,000E+00
1,060E-04	9,000E-01	1,000E+00	1,000E-01	1,440E-03	14	1,374E-08	5,400	7,418E-08
1,060E-04	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	8,586E-05	25,000	2,147E-03
						Total	**Handymax**	2,370E-03

A2.5 RESULTS AFTER IMPLEMENTATION OF THE MONITORING SYSTEM

After fitting the proposed monitoring system, the human failure is assumed to be totally eliminated, passing from 0.9 to zero. The failure of the monitoring system can be neglected, as the proposed configuration is highly redundant. The failure of the node 'Detection of forepeak flooding' disappears. It is to be remarked that these assumptions may change if different solutions for the system are envisaged.

The failure of detection of hold No.1 flooding was conservatively assumed to be 0.1, as the sensor is not necessarily redundant.

The following results were obtained. The details are in the two following pages.

	PLL (fatalities / bulk carrier-year)					
	Capesize		**Panamax**		**Handymax**	
	A	**B**	**A**	**B**	**A**	**B**
Base case	**$3.7 \cdot 10^{-4}$**	**$5.9 \cdot 10^{-4}$**	**$4.7 \cdot 10^{-4}$**	**$2.3 \cdot 10^{-3}$**	**$2.6 \cdot 10^{-3}$**	**$2.4 \cdot 10^{-3}$**
With monitoring	$1.8 \cdot 10^{-7}$	$2.0 \cdot 10^{-7}$	$2.3 \cdot 10^{-7}$	$7.8 \cdot 10^{-7}$	$1.3 \cdot 10^{-6}$	$8.0 \cdot 10^{-7}$
DPLL	**7.4E-04**		**9.5E-04**		**5.2E-03**	

Scenario A with monitoring system

WFWHC	DF	AF	DH	AH	Sequence	Frequency	LL	PLL
8,730E-04	1,000E+00	9,986E-01	1,000E+00	1,000E+00	1	8,718E-04	0,000	0,000E+00
1,780E-05	1,000E+00	9,986E-01	9,000E-01	6,250E-02	2	9,998E-07	0,000	0,000E+00
1,780E-05	1,000E+00	9,986E-01	9,000E-01	9,375E-01	3	1,500E-05	0,000	0,000E+00
1,780E-05	1,000E+00	9,986E-01	1,000E-01	1,000E+00	4	1,778E-06	0,000	0,000E+00
8,730E-04	1,000E+00	1,400E-03	1,000E+00	1,000E+00	5	1,222E-06	0,000	0,000E+00
1,780E-05	1,000E+00	1,400E-03	9,000E-01	6,250E-02	6	1,402E-09	0,000	0,000E+00
1,780E-05	1,000E+00	1,400E-03	9,000E-01	9,375E-01	7	2,103E-08	5,400	1,135E-07
1,780E-05	1,000E+00	1,400E-03	1,000E-01	1,000E+00	8	2,492E-09	25,000	6,230E-08
8,730E-04	1,000E+00	3,400E-05	1,000E+00	1,000E+00	9	2,968E-08	0,000	0,000E+00
1,780E-05	1,000E+00	3,400E-05	9,000E-01	1,000E+00	10	5,447E-10	5,400	2,941E-09
1,780E-05	1,000E+00	3,400E-05	1,000E-01	1,000E+00	11	6,052E-11	25,000	1,513E-09
8,730E-04	0,000E+00	1,000E+00	1,000E+00	1,000E+00	12	0,000E+00	0,000	0,000E+00
1,780E-05	0,000E+00	1,000E+00	9,000E-01	6,250E-02	13	0,000E+00	0,000	0,000E+00
1,780E-05	0,000E+00	1,000E+00	9,000E-01	9,375E-01	14	0,000E+00	5,400	0,000E+00
1,780E-05	0,000E+00	1,000E+00	1,000E-01	1,000E+00	15	0,000E+00	25,000	0,000E+00
							Capesize	1,803E-07

WFWHC	DF	AF	DH	AH	Sequence	Frequency	LL	PLL
9,900E-04	1,000E+00	9,986E-01	1,000E+00	1,000E+00	1	9,886E-04	0,000	0,000E+00
2,290E-05	1,000E+00	9,986E-01	9,000E-01	6,250E-02	2	1,286E-06	0,000	0,000E+00
2,290E-05	1,000E+00	9,986E-01	9,000E-01	9,375E-01	3	1,929E-05	0,000	0,000E+00
2,290E-05	1,000E+00	9,986E-01	1,000E-01	1,000E+00	4	2,287E-06	0,000	0,000E+00
9,900E-04	1,000E+00	1,400E-03	1,000E+00	1,000E+00	5	1,386E-06	0,000	0,000E+00
2,290E-05	1,000E+00	1,400E-03	9,000E-01	6,250E-02	6	1,803E-09	0,000	0,000E+00
2,290E-05	1,000E+00	1,400E-03	9,000E-01	9,375E-01	7	2,705E-08	5,400	1,461E-07
2,290E-05	1,000E+00	1,400E-03	1,000E-01	1,000E+00	8	3,206E-09	25,000	8,015E-08
9,900E-04	1,000E+00	3,400E-05	1,000E+00	1,000E+00	9	3,366E-08	0,000	0,000E+00
2,290E-05	1,000E+00	3,400E-05	9,000E-01	1,000E+00	10	7,007E-10	5,400	3,784E-09
2,290E-05	1,000E+00	3,400E-05	1,000E-01	1,000E+00	11	7,786E-11	25,000	1,947E-09
9,900E-04	0,000E+00	1,000E+00	1,000E+00	1,000E+00	12	0,000E+00	0,000	0,000E+00
2,290E-05	0,000E+00	1,000E+00	9,000E-01	6,250E-02	13	0,000E+00	0,000	0,000E+00
2,290E-05	0,000E+00	1,000E+00	9,000E-01	9,375E-01	14	0,000E+00	5,400	0,000E+00
2,290E-05	0,000E+00	1,000E+00	1,000E-01	1,000E+00	15	0,000E+00	25,000	0,000E+00
							Panamax	2,320E-07
						#RIF!		

WFWHC	DF	AF	DH	AH	Sequence	Frequency	LL	PLL
8,100E-03	1,000E+00	9,986E-01	1,000E+00	1,000E+00	1	8,089E-03	0,000	0,000E+00
1,260E-04	1,000E+00	9,986E-01	9,000E-01	6,250E-02	2	7,078E-06	0,000	0,000E+00
1,260E-04	1,000E+00	9,986E-01	9,000E-01	9,375E-01	3	1,062E-04	0,000	0,000E+00
1,260E-04	1,000E+00	9,986E-01	1,000E-01	1,000E+00	4	1,258E-05	0,000	0,000E+00
8,100E-03	1,000E+00	1,400E-03	1,000E+00	1,000E+00	5	1,134E-05	0,000	0,000E+00
1,260E-04	1,000E+00	1,400E-03	9,000E-01	6,250E-02	6	9,923E-09	0,000	0,000E+00
1,260E-04	1,000E+00	1,400E-03	9,000E-01	9,375E-01	7	1,488E-07	5,400	8,037E-07
1,260E-04	1,000E+00	1,400E-03	1,000E-01	1,000E+00	8	1,764E-08	25,000	4,410E-07
8,100E-03	1,000E+00	3,400E-05	1,000E+00	1,000E+00	9	2,754E-07	0,000	0,000E+00
1,260E-04	1,000E+00	3,400E-05	9,000E-01	1,000E+00	10	3,856E-09	5,400	2,082E-08
1,260E-04	1,000E+00	3,400E-05	1,000E-01	1,000E+00	11	4,284E-10	25,000	1,071E-08
8,100E-03	0,000E+00	1,000E+00	1,000E+00	1,000E+00	12	0,000E+00	0,000	0,000E+00
1,260E-04	0,000E+00	1,000E+00	9,000E-01	6,250E-02	13	0,000E+00	0,000	0,000E+00
1,260E-04	0,000E+00	1,000E+00	9,000E-01	9,375E-01	14	0,000E+00	5,400	0,000E+00
1,260E-04	0,000E+00	1,000E+00	1,000E-01	1,000E+00	15	0,000E+00	25,000	0,000E+00
							Handymax	1,276E-06

Scenario B with monitoring system

WHWFC	DH	AH	DF	AF	Sequence	Frequency	LL	PLL
8,820E-02	9,000E-01	6,250E-02	1,000E+00	1,000E+00	1	4,961E-03	0,000	0,000E+00
2,650E-05	9,000E-01	6,250E-02	1,000E+00	9,986E-01	2	1,489E-06	0,000	0,000E+00
2,650E-05	9,000E-01	6,250E-02	1,000E+00	1,440E-03	3	2,147E-09	0,000	0,000E+00
2,650E-05	9,000E-01	6,250E-02	0,000E+00	1,000E+00	4	0,000E+00	0,000	0,000E+00
8,820E-02	9,000E-01	9,375E-01	1,000E+00	1,000E+00	5	7,442E-02	0,000	0,000E+00
2,650E-05	9,000E-01	9,375E-01	1,000E+00	9,986E-01	6	2,233E-05	0,000	0,000E+00
2,650E-05	9,000E-01	9,375E-01	1,000E+00	1,440E-03	7	3,220E-08	5,400	1,739E-07
2,650E-05	9,000E-01	9,375E-01	0,000E+00	1,000E+00	8	0,000E+00	25,000	0,000E+00
8,820E-02	9,000E-01	3,500E-05	1,000E+00	1,000E+00	9	2,778E-06	0,000	0,000E+00
2,650E-05	9,000E-01	3,500E-05	1,000E+00	1,000E+00	10	8,348E-10	5,400	4,508E-09
2,650E-05	9,000E-01	3,500E-05	0,000E+00	1,000E+00	11	0,000E+00	25,000	0,000E+00
8,820E-02	1,000E-01	1,000E+00	1,000E+00	1,000E+00	12	8,820E-03	0,000	0,000E+00
2,650E-05	1,000E-01	1,000E+00	1,000E+00	9,986E-01	13	2,646E-06	0,000	0,000E+00
2,650E-05	1,000E-01	1,000E+00	1,000E+00	1,440E-03	14	3,816E-09	5,400	2,061E-08
2,650E-05	1,000E-01	1,000E+00	0,000E+00	1,000E+00	15	0,000E+00	25,000	0,000E+00
							Capesize	1,990E-07

WHWFC	DH	AH	DF	AF	Sequence	Frequency	LL	PLL
1,660E-01	9,000E-01	6,250E-02	1,000E+00	1,000E+00	1	9,338E-03	0,000	0,000E+00
1,040E-04	9,000E-01	6,250E-02	1,000E+00	9,986E-01	2	5,842E-06	0,000	0,000E+00
1,040E-04	9,000E-01	6,250E-02	1,000E+00	1,440E-03	3	8,424E-09	0,000	0,000E+00
1,040E-04	9,000E-01	6,250E-02	0,000E+00	1,000E+00	4	0,000E+00	0,000	0,000E+00
1,660E-01	9,000E-01	9,375E-01	1,000E+00	1,000E+00	5	1,401E-01	0,000	0,000E+00
1,040E-04	9,000E-01	9,375E-01	1,000E+00	9,986E-01	6	8,763E-05	0,000	0,000E+00
1,040E-04	9,000E-01	9,375E-01	1,000E+00	1,440E-03	7	1,264E-07	5,400	6,823E-07
1,040E-04	9,000E-01	9,375E-01	0,000E+00	1,000E+00	8	0,000E+00	25,000	0,000E+00
1,660E-01	9,000E-01	3,500E-05	1,000E+00	1,000E+00	9	5,229E-06	0,000	0,000E+00
1,040E-04	9,000E-01	3,500E-05	1,000E+00	1,000E+00	10	3,276E-09	5,400	1,769E-08
1,040E-04	9,000E-01	3,500E-05	0,000E+00	1,000E+00	11	0,000E+00	25,000	0,000E+00
1,660E-01	1,000E-01	1,000E+00	1,000E+00	1,000E+00	12	1,660E-02	0,000	0,000E+00
1,040E-04	1,000E-01	1,000E+00	1,000E+00	9,986E-01	13	1,039E-05	0,000	0,000E+00
1,040E-04	1,000E-01	1,000E+00	1,000E+00	1,440E-03	14	1,498E-08	5,400	8,087E-08
1,040E-04	1,000E-01	1,000E+00	0,000E+00	1,000E+00	15	0,000E+00	25,000	0,000E+00
							Panamax	7,809E-07

WHWFC	DH	AH	DF	AF	Sequence	Frequency	LL	PLL
9,860E-01	9,000E-01	6,250E-02	1,000E+00	1,000E+00	1	5,546E-02	0,000	0,000E+00
1,060E-04	9,000E-01	6,250E-02	1,000E+00	9,986E-01	2	5,954E-06	0,000	0,000E+00
1,060E-04	9,000E-01	6,250E-02	1,000E+00	1,440E-03	3	8,586E-09	0,000	0,000E+00
1,060E-04	9,000E-01	6,250E-02	0,000E+00	1,000E+00	4	0,000E+00	0,000	0,000E+00
9,860E-01	9,000E-01	9,375E-01	1,000E+00	1,000E+00	5	8,319E-01	0,000	0,000E+00
1,060E-04	9,000E-01	9,375E-01	1,000E+00	9,986E-01	6	8,931E-05	0,000	0,000E+00
1,060E-04	9,000E-01	9,375E-01	1,000E+00	1,440E-03	7	1,288E-07	5,400	6,955E-07
1,060E-04	9,000E-01	9,375E-01	0,000E+00	1,000E+00	8	0,000E+00	25,000	0,000E+00
9,860E-01	9,000E-01	3,500E-05	1,000E+00	1,000E+00	9	3,106E-05	0,000	0,000E+00
1,060E-04	9,000E-01	3,500E-05	1,000E+00	1,000E+00	10	3,339E-09	5,400	1,803E-08
1,060E-04	9,000E-01	3,500E-05	0,000E+00	1,000E+00	11	0,000E+00	25,000	0,000E+00
9,860E-01	1,000E-01	1,000E+00	1,000E+00	1,000E+00	12	9,860E-02	0,000	0,000E+00
1,060E-04	1,000E-01	1,000E+00	1,000E+00	9,986E-01	13	1,059E-05	0,000	0,000E+00
1,060E-04	1,000E-01	1,000E+00	1,000E+00	1,440E-03	14	1,526E-08	5,400	8,243E-08
1,060E-04	1,000E-01	1,000E+00	0,000E+00	1,000E+00	15	0,000E+00	25,000	0,000E+00
							Handyma	7,959E-07

A2.6 RESULTS AFTER THE IMPLEMENTATION OF FORECASTLE/BULWARK

The same ETs of A2.3 and A2.4 apply, but with a different probability of the couple of nodes WH and WF. Forecastle and bulwark differ only in their implementation cost, as their influence is the same.

The following results were obtained. The details are in the following 2 pages.

	PLL (fatalities / bulk carrier-year)					
	Capesize		**Panamax**		**Handymax**	
forecastle [m]	**A**	**B**	**A**	**B**	**A**	**B**
0 (Base Case)	$\mathbf{3.7 \cdot 10^{-4}}$	$\mathbf{5.9 \cdot 10^{-4}}$	$\mathbf{4.7 \cdot 10^{-4}}$	$\mathbf{2.3 \cdot 10^{-3}}$	$\mathbf{2.5 \cdot 10^{-3}}$	$\mathbf{2.4 \cdot 10^{-3}}$
2.5	$8.0 \cdot 10^{-10}$	$1.2 \cdot 10^{-4}$	$5.3 \cdot 10^{-7}$	$8.3 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$
DPLL	**8.45E-04**		**1.97E-03**		**3.73E-03**	

Scenario A with forecastle/bulwark

WFWHC	DF	AF	DH	AH	Sequence	Frequency	LL	PLL
8,380E-07	1,000E-01	9,986E-01	1,000E+00	1,000E+00	1	8,368E-08	0,000	0,000E+00
3,880E-11	1,000E-01	9,986E-01	1,000E-01	6,250E-02	2	2,422E-14	0,000	0,000E+00
3,880E-11	1,000E-01	9,986E-01	1,000E-01	9,375E-01	3	3,632E-13	0,000	0,000E+00
3,880E-11	1,000E-01	9,986E-01	9,000E-01	1,000E+00	4	3,487E-12	0,000	0,000E+00
8,380E-07	1,000E-01	1,400E-03	1,000E+00	1,000E+00	5	1,173E-10	0,000	0,000E+00
3,880E-11	1,000E-01	1,400E-03	1,000E-01	6,250E-02	6	3,395E-17	0,000	0,000E+00
3,880E-11	1,000E-01	1,400E-03	1,000E-01	9,375E-01	7	5,093E-16	5,400	2,750E-15
3,880E-11	1,000E-01	1,400E-03	9,000E-01	1,000E+00	8	4,889E-15	25,000	1,222E-13
8,380E-07	1,000E-01	3,400E-05	1,000E+00	1,000E+00	9	2,849E-12	0,000	0,000E+00
3,880E-11	1,000E-01	3,400E-05	1,000E-01	1,000E+00	10	1,319E-17	5,400	7,124E-17
3,880E-11	1,000E-01	3,400E-05	9,000E-01	1,000E+00	11	1,187E-16	25,000	2,968E-15
8,380E-07	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	7,542E-07	0,000	0,000E+00
3,880E-11	9,000E-01	1,000E+00	1,000E-01	6,250E-02	13	2,183E-13	0,000	0,000E+00
3,880E-11	9,000E-01	1,000E+00	1,000E-01	9,375E-01	14	3,274E-12	5,400	1,768E-11
3,880E-11	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	3,143E-11	25,000	7,857E-10
							Capesize	8,035E-10

WFWHC	DF	AF	DH	AH	Sequence	Frequency	LL	PLL
7,820E-06	1,000E-01	9,986E-01	1,000E+00	1,000E+00	1	7,809E-07	0,000	0,000E+00
2,540E-08	1,000E-01	9,986E-01	1,000E-01	6,250E-02	2	1,585E-11	0,000	0,000E+00
2,540E-08	1,000E-01	9,986E-01	1,000E-01	9,375E-01	3	2,378E-10	0,000	0,000E+00
2,540E-08	1,000E-01	9,986E-01	9,000E-01	1,000E+00	4	2,283E-09	0,000	0,000E+00
7,820E-06	1,000E-01	1,400E-03	1,000E+00	1,000E+00	5	1,095E-09	0,000	0,000E+00
2,540E-08	1,000E-01	1,400E-03	1,000E-01	6,250E-02	6	2,223E-14	0,000	0,000E+00
2,540E-08	1,000E-01	1,400E-03	1,000E-01	9,375E-01	7	3,334E-13	5,400	1,800E-12
2,540E-08	1,000E-01	1,400E-03	9,000E-01	1,000E+00	8	3,200E-12	25,000	8,001E-11
7,820E-06	1,000E-01	3,400E-05	1,000E+00	1,000E+00	9	2,659E-11	0,000	0,000E+00
2,540E-08	1,000E-01	3,400E-05	1,000E-01	1,000E+00	10	8,636E-15	5,400	4,663E-14
2,540E-08	1,000E-01	3,400E-05	9,000E-01	1,000E+00	11	7,772E-14	25,000	1,943E-12
7,820E-06	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	7,038E-06	0,000	0,000E+00
2,540E-08	9,000E-01	1,000E+00	1,000E-01	6,250E-02	13	1,429E-10	0,000	0,000E+00
2,540E-08	9,000E-01	1,000E+00	1,000E-01	9,375E-01	14	2,143E-09	5,400	1,157E-08
2,540E-08	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	2,057E-08	25,000	5,144E-07
							Panamax	5,260E-07

WFWHC	DF	AF	DH	AH	Sequence	Frequency	LL	PLL
2,950E-04	1,000E-01	9,986E-01	1,000E+00	1,000E+00	1	2,946E-05	0,000	0,000E+00
4,930E-06	1,000E-01	9,986E-01	1,000E-01	6,250E-02	2	3,077E-09	0,000	0,000E+00
4,930E-06	1,000E-01	9,986E-01	1,000E-01	9,375E-01	3	4,615E-08	0,000	0,000E+00
4,930E-06	1,000E-01	9,986E-01	9,000E-01	1,000E+00	4	4,431E-07	0,000	0,000E+00
2,950E-04	1,000E-01	1,400E-03	1,000E+00	1,000E+00	5	4,130E-08	0,000	0,000E+00
4,930E-06	1,000E-01	1,400E-03	1,000E-01	6,250E-02	6	4,314E-12	0,000	0,000E+00
4,930E-06	1,000E-01	1,400E-03	1,000E-01	9,375E-01	7	6,471E-11	5,400	3,494E-10
4,930E-06	1,000E-01	1,400E-03	9,000E-01	1,000E+00	8	6,212E-10	25,000	1,553E-08
2,950E-04	1,000E-01	3,400E-05	1,000E+00	1,000E+00	9	1,003E-09	0,000	0,000E+00
4,930E-06	1,000E-01	3,400E-05	1,000E-01	1,000E+00	10	1,676E-12	5,400	9,051E-12
4,930E-06	1,000E-01	3,400E-05	9,000E-01	1,000E+00	11	1,509E-11	25,000	3,771E-10
2,950E-04	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	2,655E-04	0,000	0,000E+00
4,930E-06	9,000E-01	1,000E+00	1,000E-01	6,250E-02	13	2,773E-08	0,000	0,000E+00
4,930E-06	9,000E-01	1,000E+00	1,000E-01	9,375E-01	14	4,160E-07	5,400	2,246E-06
4,930E-06	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	3,993E-06	25,000	9,983E-05
							Handymax	1,021E-04

Scenario B with forecastle/bulwark

WHWFC	DH	AH	DF	AF	Sequence	Frequency	LL	PLL
8,040E-03	1,000E-01	6,250E-02	1,000E+00	1,000E+00	1	5,025E-05	0,000	0,000E+00
5,100E-06	1,000E-01	6,250E-02	1,000E-01	9,986E-01	2	3,183E-09	0,000	0,000E+00
5,100E-06	1,000E-01	6,250E-02	1,000E-01	1,440E-03	3	4,590E-12	0,000	0,000E+00
5,100E-06	1,000E-01	6,250E-02	9,000E-01	1,000E+00	4	2,869E-08	0,000	0,000E+00
8,040E-03	1,000E-01	9,375E-01	1,000E+00	1,000E+00	5	7,538E-04	0,000	0,000E+00
5,100E-06	1,000E-01	9,375E-01	1,000E-01	9,986E-01	6	4,775E-08	0,000	0,000E+00
5,100E-06	1,000E-01	9,375E-01	1,000E-01	9,375E-01	7	4,482E-08	5,400	2,421E-07
5,100E-06	1,000E-01	9,375E-01	9,000E-01	1,000E+00	8	4,303E-07	25,000	1,076E-05
8,040E-03	1,000E-01	3,500E-05	1,000E+00	1,000E+00	9	2,814E-08	0,000	0,000E+00
5,100E-06	1,000E-01	3,500E-05	1,000E-01	1,000E+00	10	1,785E-12	5,400	9,639E-12
5,100E-06	1,000E-01	3,500E-05	9,000E-01	1,000E+00	11	1,607E-11	25,000	4,016E-10
8,040E-03	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	7,236E-03	0,000	0,000E+00
5,100E-06	9,000E-01	1,000E+00	1,000E-01	9,986E-01	13	4,584E-07	0,000	0,000E+00
5,100E-06	9,000E-01	1,000E+00	1,000E-01	9,375E-01	14	4,303E-07	5,400	2,324E-06
5,100E-06	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	4,131E-06	25,000	1,033E-04
							Capesize	1,166E-04

WHWFC	DH	AH	DF	AF	Sequence	Frequency	LL	PLL
1,560E-02	1,000E-01	6,250E-02	1,000E+00	1,000E+00	1	9,750E-05	0,000	0,000E+00
3,630E-05	1,000E-01	6,250E-02	1,000E-01	9,986E-01	2	2,266E-08	0,000	0,000E+00
3,630E-05	1,000E-01	6,250E-02	1,000E-01	1,440E-03	3	3,267E-11	0,000	0,000E+00
3,630E-05	1,000E-01	6,250E-02	9,000E-01	1,000E+00	4	2,042E-07	0,000	0,000E+00
1,560E-02	1,000E-01	9,375E-01	1,000E+00	1,000E+00	5	1,463E-03	0,000	0,000E+00
3,630E-05	1,000E-01	9,375E-01	1,000E-01	9,986E-01	6	3,398E-07	0,000	0,000E+00
3,630E-05	1,000E-01	9,375E-01	1,000E-01	9,375E-01	7	3,190E-07	5,400	1,723E-06
3,630E-05	1,000E-01	9,375E-01	9,000E-01	1,000E+00	8	3,063E-06	25,000	7,657E-05
1,560E-02	1,000E-01	3,500E-05	1,000E+00	1,000E+00	9	5,460E-08	0,000	0,000E+00
3,630E-05	1,000E-01	3,500E-05	1,000E-01	1,000E+00	10	1,271E-11	5,400	6,861E-11
3,630E-05	1,000E-01	3,500E-05	9,000E-01	1,000E+00	11	1,143E-10	25,000	2,859E-09
1,560E-02	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	1,404E-02	0,000	0,000E+00
3,630E-05	9,000E-01	1,000E+00	1,000E-01	9,986E-01	13	3,262E-06	0,000	0,000E+00
3,630E-05	9,000E-01	1,000E+00	1,000E-01	9,375E-01	14	3,063E-06	5,400	1,654E-05
3,630E-05	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	2,940E-05	25,000	7,351E-04
							Panamax	8,299E-04

WHWFC	DH	AH	DF	AF	Sequence	Frequency	LL	PLL
5,590E-02	1,000E-01	6,250E-02	1,000E+00	1,000E+00	1	3,494E-04	0,000	0,000E+00
5,030E-05	1,000E-01	6,250E-02	1,000E-01	9,986E-01	2	3,139E-08	0,000	0,000E+00
5,030E-05	1,000E-01	6,250E-02	1,000E-01	1,440E-03	3	4,527E-11	0,000	0,000E+00
5,030E-05	1,000E-01	6,250E-02	9,000E-01	1,000E+00	4	2,829E-07	0,000	0,000E+00
5,590E-02	1,000E-01	9,375E-01	1,000E+00	1,000E+00	5	5,241E-03	0,000	0,000E+00
5,030E-05	1,000E-01	9,375E-01	1,000E-01	9,986E-01	6	4,709E-07	0,000	0,000E+00
5,030E-05	1,000E-01	9,375E-01	1,000E-01	9,375E-01	7	4,421E-07	5,400	2,387E-06
5,030E-05	1,000E-01	9,375E-01	9,000E-01	1,000E+00	8	4,244E-06	25,000	1,061E-04
5,590E-02	1,000E-01	3,500E-05	1,000E+00	1,000E+00	9	1,957E-07	0,000	0,000E+00
5,030E-05	1,000E-01	3,500E-05	1,000E-01	1,000E+00	10	1,761E-11	5,400	9,507E-11
5,030E-05	1,000E-01	3,500E-05	9,000E-01	1,000E+00	11	1,584E-10	25,000	3,961E-09
5,590E-02	9,000E-01	1,000E+00	1,000E+00	1,000E+00	12	5,031E-02	0,000	0,000E+00
5,030E-05	9,000E-01	1,000E+00	1,000E-01	9,986E-01	13	4,521E-06	0,000	0,000E+00
5,030E-05	9,000E-01	1,000E+00	1,000E-01	9,375E-01	14	4,244E-06	5,400	2,292E-05
5,030E-05	9,000E-01	1,000E+00	9,000E-01	1,000E+00	15	4,074E-05	25,000	1,019E-03
							Handymax	1,150E-03

APPENDIX 3

PROCEDURE FOR THE QUANTIFICATION OF THE FLOODING SEQUENCE

A3.1 SEQUENCE OF EVENTS (ESCALATION)

In the worst sequences, the following accident escalation is hypothesised in a given sea state:

- due to exceeding by water on deck of the h_r value, an opening is generated in the fore peak deck, creating a way for flooding.
- A progressive flooding of the fore peak takes place, up to complete filling of the peak
- The ship sails now with a trim by bow: the hatch cover of hold No.1 deforms due to actual water head over the deck exceeding the value h_{r1} : a way for flooding is created.
- A progressive flooding of hold No.1 takes place up to complete filling.
- The early and late corrective actions are unsuccessful.
  At this point, both the forepeak and hold No.1 are fully flooded.

The first physical model consists of the sequence of the above mentioned events, considered as independent and referred to the same sea state characteristics.

Another sequence (named in the following as "B") was added, in which the order of events is changed and they occur in the following order:

- deformation of covers of hatch cover 1
- filling of hold No.1
- trim by bow and collapse of fittings above deck in the fore area.
- filling of forepeak
- the early and late corrective actions are unsuccessful.

The model of the pivotal events that control the phenomenon is described in the following. The results were adjusted to the frequency of total loss obtained from the available casualty statistics (§ 3.3).

A3.1.1 Environmental data

The sea model is represented by a scatter diagram derived for bulk carriers . The scatter diagram was obtained with the following procedure:

a) the three above mentioned main routes for bulk carrier traffic were defined: Atlantic (South America – North Europe) Indian Ocean South Africa-Far East and Pacific (Japan – Far East). The scatter diagrams (SDs) of the sea zones crossed by each route were weighted over the segments of the route within the zone.

b) the SDs corresponding to the three routes were weighted over the number of ships sailing on each route (taking therefore into account both traffic data from Eknes *et al* (1997) and the average length of the route). The results are shown in Appendix 4.

A3.1.2 Relative motions

The response in terms of relative motions (at fore peak and at hold No.1) was studied in the frequency domain by means of response amplitude operators (RAOs) provided by DNV (see Appendix 4 of Annex 4). This allowed to compute moments of order 0 and 2 of the response spectra and then to derive the probability distributions for the relative motions and for the height of water on deck.

Calculation have been performed for intact ships, but the RAOs have been associated to both the initial condition and the inclined waterline due to the flooding of the first compartment (forecastle in sequence A and hold No.1 in sequence B), neglecting the inherent trim by bow.

The relative motion is treated as a Gaussian stationary process with zero mean, similar to the originating sea wave process, but with different significant height and period (H_{sr}, T_{zr})

A narrow band model is applied, resulting in a Rayleigh distribution (Figure 1) for the amplitudes of relative motions, depending only on H_{sr}. The number n_w of waves in each sea state is obtained as the ratio between the time duration of the sea state and the mean period of the relative motion T_{zr}

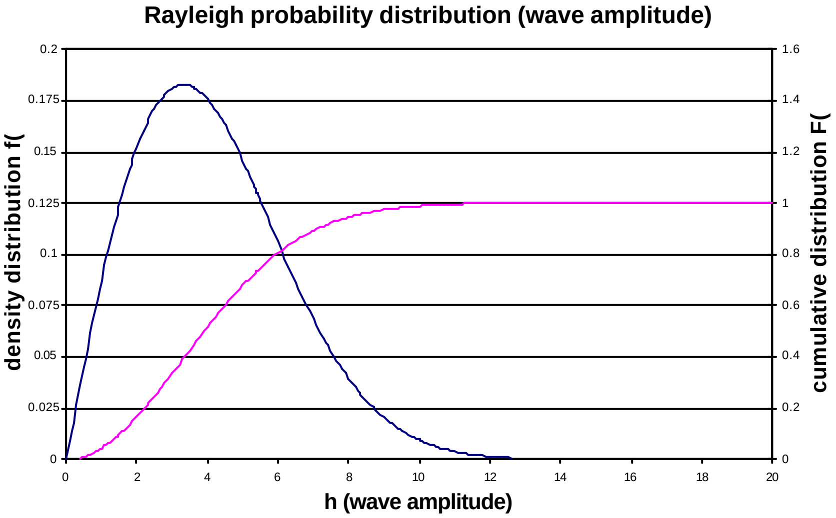


Figure 1

A3.1.3 Deck Wetness

The phenomenon "water on deck" is in principle controlled by the relative motion of the water free surface and of the deck of the ship in waves and by a complex interaction between water flow and local hull and deck geometry.

In the present simplified model, the geometry of the fore body is described only in terms of local freeboard h_{fb} (local vertical distance between deck and still water level): every time the amplitude of the relative motion h_{rm} exceeds the static freeboard, a deck wetness event is assumed to occur (Figure 2).

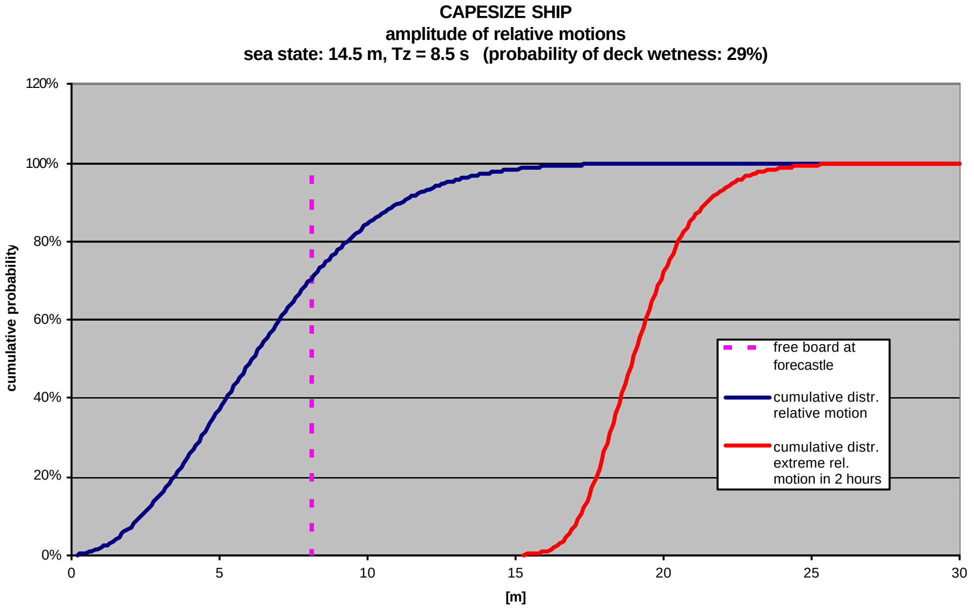


Figure 2

The difference between the amplitude of the relative motion h_{rm} and the static freeboard gives the effective water height on deck:

$$h_w = h_{rm} - h_{fb} \tag{1}$$

This quantity results to distributed as a truncated Rayleigh distribution (Figure 3)

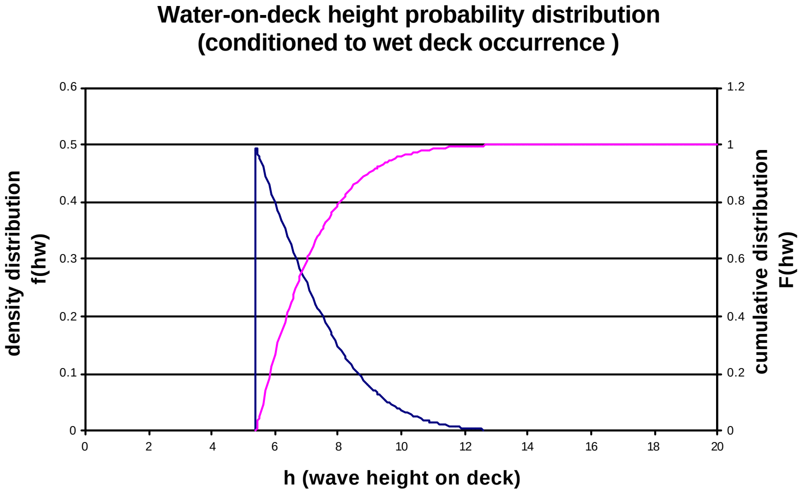


Figure 3

A3.1.4 Creation of openings due to structural failures

The load pressure on the deck structure is modelled according to the static water height on deck. Actually, dynamic effects due to ship motions and to horizontal components of the velocity of water on deck affect significantly the structural load. To account for that, Buchner (1995) considers a dynamic amplification factor α applied to the static water height and from experiments, for example at 10 kn.-speed, α is seen to vary up to 3-4.

On the other hand, the actual collapse load of hatch covers, ventilation and air pipes is higher than the nominal value as derived from scantlings and from the minimum yield stress for the material .
In the present simplified model, an opening is assumed to be created when the static water height on deck h_w overcomes a given collapse load h_r.

For this study, a collapse load of 8 m was assumed for deck fittings in the forecastle area, and a deformation load of 5.2 m for hatch covers.

No amplification has been applied (α=1).

A3.1.5 Water flow through openings

To model the water flow due to a single wave through an opening, a simplified method is applied:

$$Q = mAT_z\sqrt{2gh_w} \quad [\mathrm{m}^3] \tag{2}$$

where:
m = 0.1 empirical coefficient corresponding to head loss coefficient=0.5 divided by 6, which is assumed to be the part of the wave period active for filling the compartments, A = area of opening [m^2],
g = gravity acceleration,
h_w = maximum water height on deck in a single wave cycle [m],
T_z = mean period of the relative motions [s].

The area A is considered as constant with time and correspondent to one or more openings created by the collapse of different covers (access hatches, ventilation and air pipes) in the fore area, and to an opening created by hatch cover deformation at hold No.1.
When considering the total water entry Q_{tot} in a sea state, the quantity Q is multiplied by the number n_{wd} of waves which exceeds the freeboard in a sea state:

$$Q_{tot} = Q\, n_{wd} \tag{3}$$

The distribution for Q_{tot} is then derived from the characteristics of the distribution of h_w (Figure 4)

The probability for Q_{tot} to exceed the value of the volume of the forepeak yields the probability of filling the forepeak. Such probability is strongly dependent (among the various parameters) on the area of the way for flooding (Figure 5, where Q_{tot} is indicated as q).

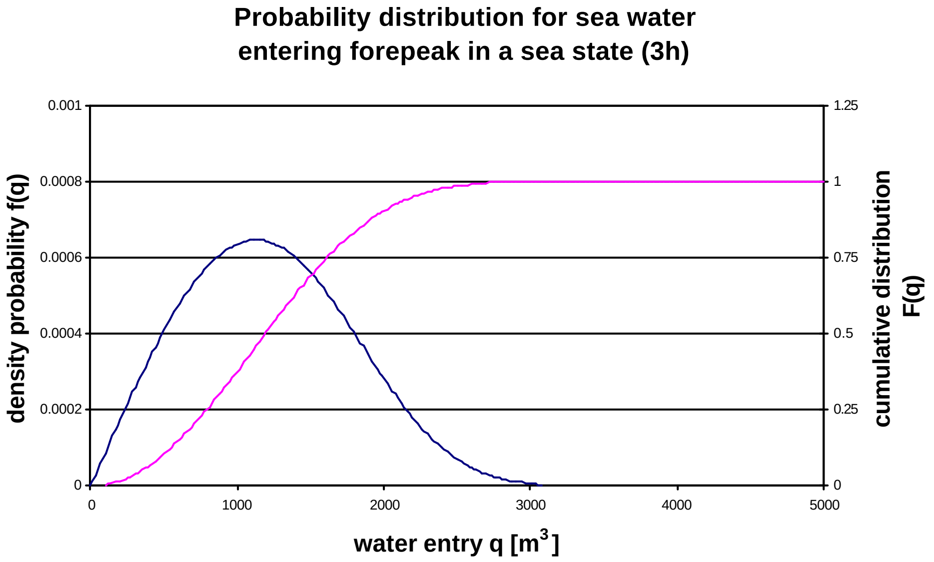


Figure 4

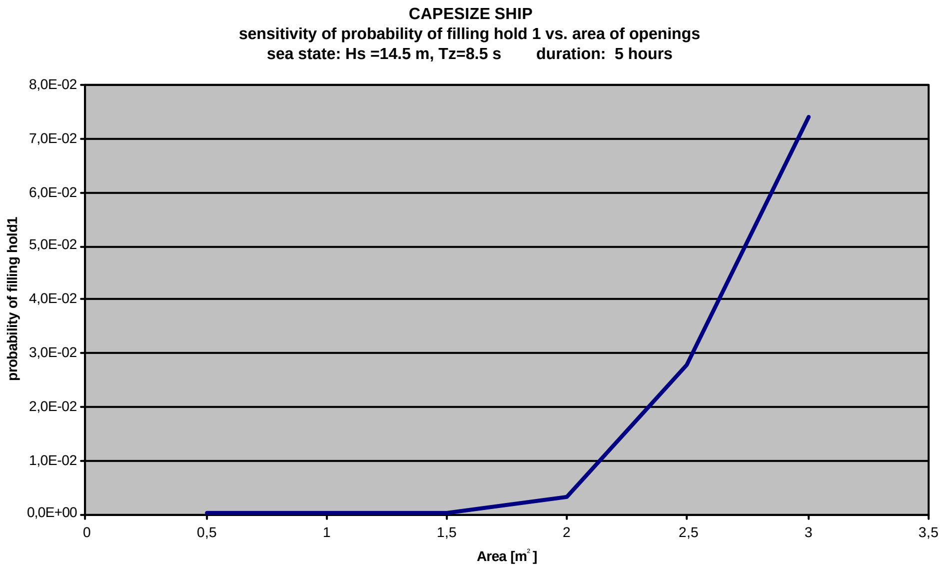


Figure 5

A3.2 SHORT TERM PROBABILITY OF FLOODING

According to the escalation of events above mentioned, a procedure was set up to calculate the following quantities (for each sea state in the scatter diagram):

- for a freeboard corresponding to the summer load line draught even keel
- *pwd*: probability of deck wetness on the fore peak deck $P[h > h_{fb}]$
- *pr*: probability that the highest wave in the considered time duration (featuring an amplitude h_{extr}) produces structural failures in the fore peak deck $P[h_{extr} > h_r]$
- pV_{fore}: probability to fill completely the fore peak, conditioned to deck wetness occurrence

$$P\ [Q_{tot}½(h > h_{fb})\ > V_{fore}]$$

- for a freeboard corresponding to the actual trim due to flooding of the fore peak, calculated at the forward end of the hatch cover
- $pwd1$: probability of deck wetness at the forward end of the hatch of hold No.1 $P[\ h > h_{fb1}]$
- $pr1$: probability of deformation of hatch cover, creating a water way into hold No.1: $P[\ h_{extr} > h_{r1}]$
- $pV_{hold}1$: probability to fill completely hold No.1, conditioned to deck wetness occurrence $P\ [Q_{tot}½(h > h_{fb1})\ > V_{hold1}]$

The probability P_{Lst} of flooding both forepeak and hold No.1 (hereinafter denominated simply as ‘flooding’) on the short term is computed as the product probabilities of the four independent events.

$$P_{Lst} = p_r \cdot (pwd \cdot\ pV_{fore}) \cdot p_{r1} \cdot (pwd1 \cdot pV_{hold1}) \qquad (4)$$

The calculation procedure is illustrated by the flowchart in

Figure 6, where h_{fb}, hr, V_{fore1}, aV_{fore} are respectively: freeboard, nominal collapse head, volume and opening area of fore peak; h_{fb1}, $hr1$, V_{hold1}, aV_{hold1} represent the same input data for hold No.1. The same procedure applies for both sequences A and B, with the obvious difference in the events order.

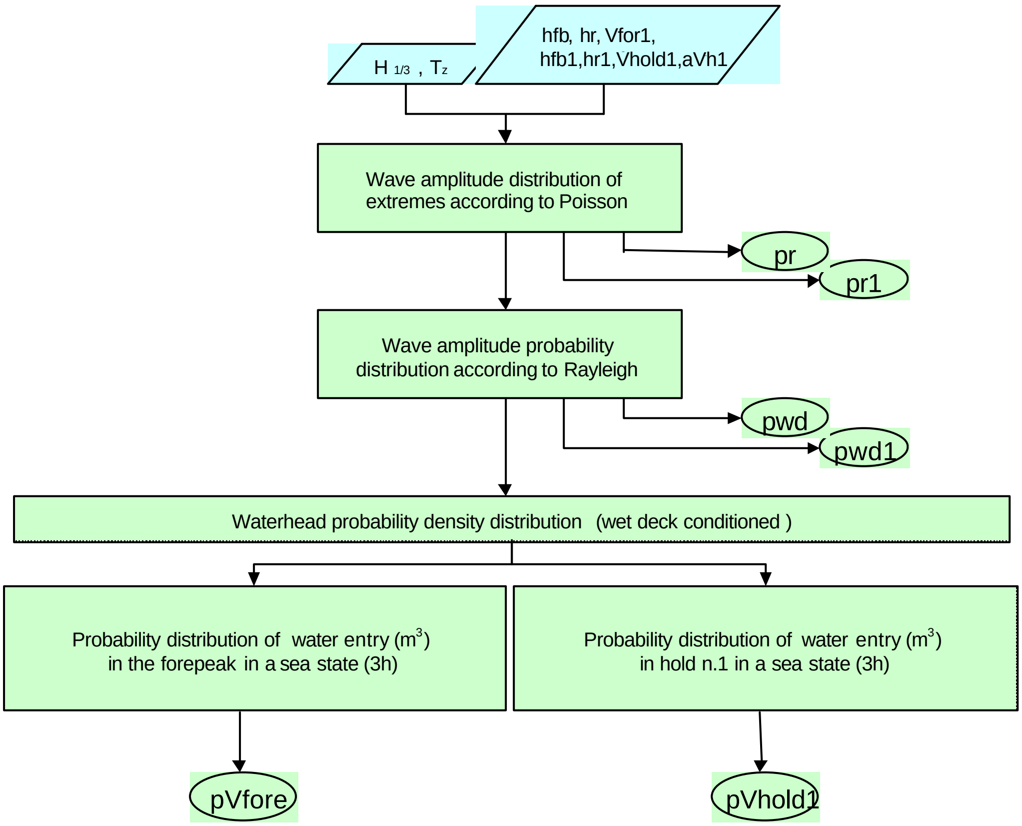


Figure 6

A3.2.1 Exposure time duration

The probability of occurrence of each of the four events depends on the exposure time allocated to the event: increasing the exposure time always brings an increase in the probability of occurrence. This applies also to the whole sequence.

The total duration of the sequence was set to 18 hours, on the basis of empirical considerations.

In this period the sea conditions are supposed to be stationary hence the term of short term prediction is applied to the sequence.

Such value appears to be compatible with the exposure time experienced by ships in distress in severe storms.

A subdivision of the total sequence duration was selected case by case to allocate to each of the four events a suitable time duration. The subject is discussed in more detail in a following chapter.

A3.3 LONG TERM PROBABILITY OF FLOODING

Once determined the probability for the flooding on the short term (i.e. in a sequence of events conditioned to given sea characteristics), an evaluation of the probability in a year P_{Ly} is obtained by two different operations

- unconditioning the short term probability on the scatter diagram (i.e. weighing the probability of loss by means of the probability of occurrence of the various sea states).

The result is expressed in terms of probability of flooding P_{Llt} in a single sequence of events (18 hours of exposure to a sea state with random characteristics according to the scatter diagram)

$$P_{Llt} = \sum_{Hs}\sum_{Tz} P_{Lst}\Big|\left(Hs,Tz\right) \cdot p\left(Hs,Tz\right)$$

- taking into account the number of times the sequence of exposure is repeated in a year (i.e. computing the probability P_{Ly} that flooding occurs in one of the exposure periods with duration T_{seq} during the total time of exposure to sea in a year, in the considered loading condition: T_y.

$$P_{Ly} = 1-\left(1 - P_{Llt}\right)^{T_y/T_{seq}} \approx T_y/T_{seq}\, P_{Llt}$$

A3.4 TUNING OF THE MODEL

The model developed for the prediction of the flooding sequence has been applied to the three ships, which have been selected as test cases for the numerical procedure.
The application to this sample was also utilised to calibrate the model itself.
In this chapter some considerations are presented about numerical values of input data and parameters for computation.

A3.4.1 Test cases

Three ships have been selected to represent different sizes of Bulk Carriers: the main characteristics are summarised in Table 1.

Ship	Moulded dimensions (m)	Displ. (tons)	Summer freeboard (m)	Capacity of forepeak (m^3)
Handymax	181 x 30 x 16.3	51,326	4.718	1,450
Panamax	217 x 32.25 x 19	83,980	5.250	1,555
Capesize	271 x 45 x 24.6	188,968	6.483	4,507

Table 1

A3.4.2 Ship data

This paragraph summarizes basic data and assumptions for the calculation.

Free board data of the ships were derived from ships' characteristics and drawings: all the considered ships are flush deck.

A decrease in the free board at hold No.1 is due to the trim by bow due to flooding of the fore peak (which is considered to occur first in sequence A).

On the opposite, in sequence B, the free board at hold No.1 corresponds to the intact ship, while the one at fore peak corresponds to the trim due to flooding of hold No.1

Volumes to be accounted for in flooding are derived from ship's capacity plans (90% permeability in hold No.1, as per SOLAS)

The structural collapse head for all watertight means of closure of fore peak was assumed as 8 m. The deformation load for hatch covers was set to 5.2 m, which is below the actual collapse load.

The area of ways for flooding should be a stochastic variable, but it was included in the simplified model as a constant.

For calculating the water flow into the forepeak, different values for area A were assumed for the various ships: this variable has been selected as “tuning parameter” in order to fit historical data with numerical simulations.

As regards the area for the water flow towards hold No.1, this was empirically set to approximately 2.2 times the area of openings towards the forepeak.

The final choice of the values of these parameters of the model is reported in Table 2.

All the values found for the forepeak area are compatible with the dimensions of closures actually present in the forecastle area (companionway hatch to bos’n store, air pipes or other).

The areas inherent to hold No.1 do not correspond to any physical opening: they are seen as ways for flooding created by hatch cover deformations.

Ship	**Location**	**Free board Seq. A [m]**	**Free board Seq. B [m]**	**Volume [m^3]**	**Collapse head [m]**	**Water access area [m^2]**
Capesize	fore peak	8.134	$hfb = 2.464$	$v_{gav} = 4507$	$h_r = 8.0$	0.82
	hold No.1	5.92	$hfb_1 = 7.357$	$v_{stiv1} = 16013$	$h_{r1} = 5.2$	1.54
Panamax	fore peak	7.38	$hfb = 1.87$	$v_{gav} = 1555$	$h_r = 8.0$	0.32
	hold No.1	5.44	$hfb_1 = 6.19$	$v_{stiv1} = 10234$	$h_{r1} = 5.2$	0.73
Handymax	fore peak	4.918	$hfb = 0.2$	$v_{gav} = 1450$	$h_r = 8.0$	0.24
	hold No.1	3.98	$hfb_1 = 4.765$	$v_{stiv1} = 8841$	$h_{r1} = 5.2$	0.52

Table 2 Ships’ input data

A3.4.5 Duration of events

During the first runs of the computer program based on the model, it was realised that, among the terms of the right side of the equation (4) for P_{loss} on the short term (Sec. A3.2), p_r and p_{r1} were very often close either to 0 or to 1.
This is due to the “steepness” of the curve inherent to extreme values h_{extr} of amplitudes in period t_{sr} and t_{sr1} (see e.g. Figure 7). In other words, very often the value correspondent to failure ($hfb+h_r$) falls on the horizontal parts of the diagram either on the left (values close to 0) or on the right (values close to 1).

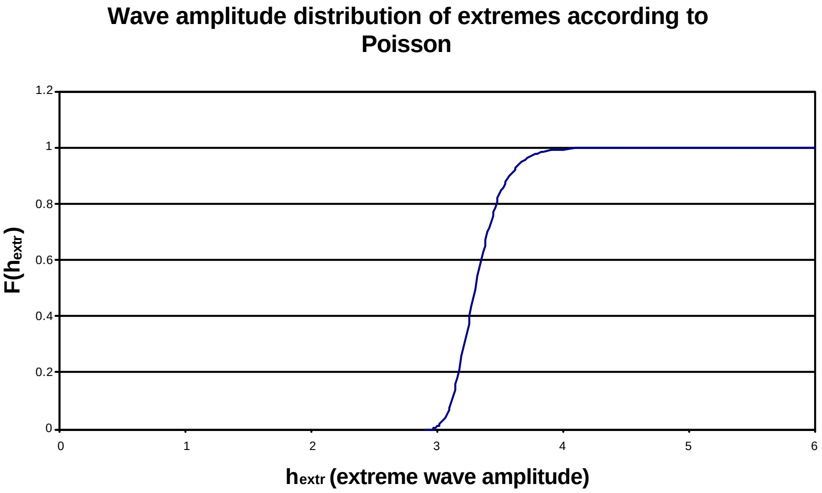


Figure 7

In practical terms, the action of these variables is to select in the scatter diagram the sea states over a certain level, "filtering out" the least severe ones, (like a high-pass filter). On the other hand, these variables do not affect the numerical value of the probability of loss, as the major contributions come from severe sea states, for which the probability of exceeding the collapse threshold is 1.

What above has an important effect on the selection of the time allocated to the collapse events: in the most significant sea conditions, the threshold for collapse is reached quite rapidly: the selection of a long exposure time in this phase subtracts time and cycles to the filling phases, which are characterised by lower probability of occurrence.

In the following, a time duration of 1.5 hours was allocated to the creation of a water access both to forepeak and hold No.1, leaving 15 hours for the two remaining events.

The dependence of the probability of occurrence of the other two events (filling of volumes) on time duration was studied for the most representative sea states (generally correspondent to H_s = 14.5m, with T_Z = 6.5, 7.5 and 8.5 respectively for the three ship types) responsible, for each ship, for a major part of the total long term probability of loss .

For the selected sea states, plots like the one presented in Figure 8 are obtained, representing the probability of filling fore peak vs. time T, the probability of filling hold No.1 in a time correspondent to (15 hours – T) and the probability of ship loss, which is basically the product of the former two.

Actually, the probability of ship loss includes also the product of the two probabilities of creation of an access to forepeak and hold No.1, but these two probabilities are very close to 1 in the extreme sea state considered.

The plots have been used selecting the point of maximum, which corresponds to a specific subdivision of the total 15 hours between the two events (filling of forepeak and filling of hold No.1): this combination is the one that maximises the probability of loss in the most severe sea state. It has been adopted for all the sea states contained in the scatter diagram.

The procedure is shown with reference to Figure 8, which shows in a specific case the sensitivity of the probability of flooding to the combination of filling times of forepeak and hold No.1.

The assumptions were : 1.5 h employed by waves to collapse the fittings on deck, and another 1.5 h employed by waves to deform the hatch No.1. The remaining 15-h time is the sum of filling time of forepeak and filling time of hold No.1. E.g., take the abscissa t = 1 h; this means that 1 h is devoted to fill the forepeak and the complementary 14 h to fill hold No.1. This way, the probability of filling the hold (purple line) is 0.3, but the probability of filling the forepeak (blue line) in so short time is negligible - since the probability of ship loss is proportional to the product of the two, this is also negligible (yellow line). Conversely, if 14 h are spent to fill the forepeak, the probability of this event will be high(about 0.25), but the probability of filling hold No.1 in the remaining hour would be negligible, and the probability of ship loss would be negligible, as well.

According to the model, there is a single combination of probabilities that maximises the flooding (about 7.5 h for each filling time in this particular case), i.e. the product is highest, even if the two separate probabilities are not.

This was the combination used in the risk assessment, which in this respect yields conservative results.

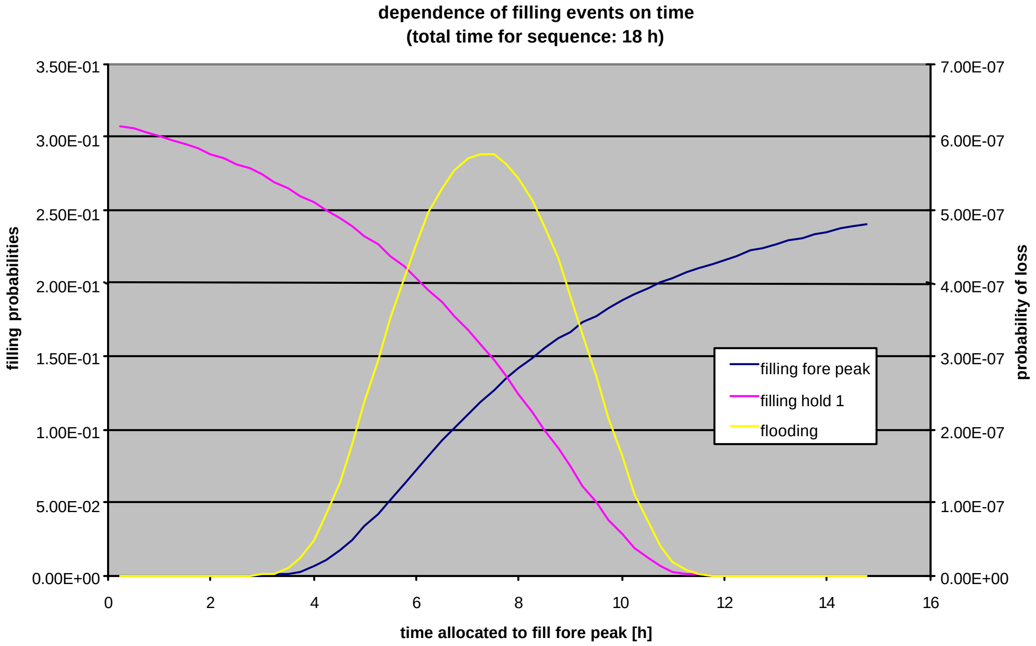


Figure 8

On the basis of such kind of investigations, performed for each ship in the worst sea state, the time duration reported in Table 3 has been selected for the four events as the one giving the higher probability of loss (the total duration was kept constant and equal to 18 hours, as above mentioned).

Time duration of the various events [hours] - Sequence A

SHIP	Collapse in fore peak	Deformation in hold No.1	Filling of fore peak	Filling of hold No.1
Capesize	1.5	1.5	6.5	8.5
Panamax	1.5	1.5	4.75	10.25
Handymax	1.5	1.5	4.5	10.5
Time duration of the various events [hours] - Sequence B				
SHIP	Collapse in fore peak	Deformation of hatch 1	Filling of fore peak	Filling of hold No.1
Capesize	1.5	1.5	2.25	12.75
Panamax	1.5	1.5	2	13
Handymax	1.5	1.5	2.5	12.5

Table 3

A3.5 RESULTS

The results are presented in the following tables, which report, for each combination of ship/sequence, the probability of flooding P_{LIt}

FCSTL	**long term probabilities of ship loss**								
	CAPESIZE			**PANAMAX**			**HANDYMAX**		
	A	**B**	**A+B**	**A**	**B**	**A+B**	**A**	**B**	**A+B**
0.00	1.78E-05	2.65E-05	4.42E-05	2.29E-05	1.04E-04	1.27E-04	1.26E-04	1.06E-04	2.31E-04
2.50	3.88E-11	5.10E-06	5.10E-06	2.54E-08	3.63E-05	3.64E-05	4.93E-06	5.03E-05	5.52E-05

The second row represents the evaluation of probability of flooding with the insertion of a forecastle which increases the freeboard at fore peak by 2.5 m.

A.3.6 CONSIDERATIONS

The results fit the historical total loss frequency quite well, but on the other hand the frequency of serious casualty is significantly higher than the historical picture, for a series of reasons. Basically, any risk model is expected to yield results where the probabilities of success, minor failures and major failures decrease in that order. Therefore, as said in § 3.3, the statistics relevant to the serious casualties must be incomplete.

A discussion on the limitations and possible improvements is shown below.

The model above described is meant to provide a simple mean to investigate the phenomenon of a progressive flooding in a bulk carrier. The extreme complication of the of the actual physical phenomenon has been handled quite at a basic level, keeping to a minimum the amount of information required and the computational effort.

Accordingly, the predetermined sequence of discrete events (creation of an opening in the fore peak, filling of the fore peak, creation of a way for flooding in hold No.1, filling of the hold), cannot be considered as realistic in absolute sense, as such events are actually competitive, at least up to a certain extent. However, the model is deemed to be able to capture a significant part of the phenomenon and to provide valid comparative information. The uncertainties inherent in the model (actual collapse loads, opening areas etc.) were compensated by tuning the model against the casualty statistics, thus they are not expected to affect the variation of the results consequent to the introduction of the RCOs.

Areas of possible improvements of the model are listed below.

1. The actual amount of water on deck is very difficult to obtain, being dependent on non linear interactions between waves and fore body of the ship and on a complicate patterns of the flow of water once onboard.
2. Adoption of different types of probability distributions for wave (or dynamic free board) amplitudes can improve the realism in the description of the phenomenon (more detailed

formulations than the adopted Rayleigh distributions are available to model non narrow band processes).

3. Local structural loads induced by the presence of water on deck should take into consideration also effects due to horizontal water velocities and to ship motions. This is however an open research field: a satisfactory representation of this aspect is probably not at hand.
4. To improve the description of the filling event, joint distributions of wave amplitudes and periods could be adopted (e.g. the one proposed by Longuet & Higgins, 1983), which should result in slightly more conservative predictions (high waves have in general longer periods than the average one, which is presently included in the model for all waves (Eq.2).
5. The area of the way for flooding is in principle a time-variant stochastic variable: presently it is treated as a deterministic quantity, with somewhat arbitrary assumptions on the water ingress area. A more realistic model would however require statistical data, which are however very difficult to be obtained.
6. The selection of the combination of filling time of forepeak and hold No.1 is conservative, on the other hand any other choice would have been arbitrary.
7. The adopted scatter diagram is based on three ocean zones, whilst the bulk carriers may follow other routes.

APPENDIX 4

SCATTER DIAGRAM WEIGHTED OVER THE bulk carrier ROUTES

<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13
6.966E-03	3.215E-02	4.697E-02	3.230E-02	1.276E-02	3.201E-03	5.627E-04	7.687E-05	8.790E-06	1.230E-06	0.000E+00
1.560E-03	2.206E-02	7.193E-02	9.888E-02	7.616E-02	3.632E-02	1.157E-02	2.688E-03	4.943E-04	7.724E-05	1.073E-05
2.022E-04	5.268E-03	2.796E-02	6.019E-02	7.355E-02	5.513E-02	2.653E-02	8.871E-03	2.247E-03	4.639E-04	8.279E-05
2.499E-05	1.009E-03	7.526E-03	2.201E-02	3.716E-02	3.862E-02	2.518E-02	1.106E-02	3.564E-03	9.112E-04	1.967E-04
3.430E-06	1.967E-04	1.885E-03	6.872E-03	1.466E-02	1.939E-02	1.588E-02	8.575E-03	3.324E-03	1.001E-03	2.504E-04
4.900E-07	4.337E-05	5.000E-04	2.129E-03	5.363E-03	8.487E-03	8.270E-03	5.245E-03	2.351E-03	8.053E-04	2.254E-04
0.000E+00	1.127E-05	1.478E-04	7.008E-04	1.982E-03	3.582E-03	3.995E-03	2.878E-03	1.451E-03	5.526E-04	1.698E-04
0.000E+00	3.430E-06	4.940E-05	2.513E-04	7.690E-04	1.535E-03	1.904E-03	1.524E-03	8.474E-04	3.530E-04	1.181E-04
0.000E+00	9.800E-07	1.835E-05	9.835E-05	3.177E-04	6.831E-04	9.238E-04	8.068E-04	4.878E-04	2.200E-04	7.886E-05
0.000E+00	4.900E-07	7.320E-06	4.227E-05	1.403E-04	3.180E-04	4.615E-04	4.351E-04	2.830E-04	1.363E-04	5.234E-05
0.000E+00	0.000E+00	3.170E-06	1.943E-05	6.583E-05	1.547E-04	2.385E-04	2.393E-04	1.663E-04	8.532E-05	3.441E-05
0.000E+00	0.000E+00	1.470E-06	9.730E-06	3.252E-05	7.874E-05	1.271E-04	1.345E-04	9.904E-05	5.402E-05	2.296E-05
0.000E+00	0.000E+00	4.900E-07	4.610E-06	1.736E-05	4.187E-05	6.918E-05	7.691E-05	5.920E-05	3.412E-05	1.559E-05
0.000E+00	0.000E+00	4.900E-07	2.910E-06	9.170E-06	2.257E-05	3.859E-05	4.453E-05	3.613E-05	2.185E-05	9.770E-06
0.000E+00	0.000E+00	4.900E-07	3.660E-06	1.304E-05	3.096E-05	5.380E-05	6.570E-05	5.771E-05	3.756E-05	1.958E-05

APPENDIX 5

COST ESTIMATE OF THE RISK CONTROL OPTIONS

This section deals with the estimates of fitting the following RCOs (for which Risk Control Measures is perhaps a more appropriate denomination) on existing ships:

1. construction of a forecastle
2. construction of a bulwark
3. installation of a monitoring system to detect the presence of water in the forepeak
4. fitting sturdier deck fittings and a system for remotely closing the deck openings.

The estimates were carried out in detail for the Panamax and Capesize vessels; for the other two a proportional variation can be expected, as explained below. The prices are consistent with the typical quotations of the major Western shipyards.
The quantification was made for retrofits, as it is the most expensive situation. For a new design, it is much more difficult to make accurate estimates, but it can be presumed that the costs, with respect to existing ships, are abated by 70% or even more.
For existing ships, off-hire is excluded as a cost element, as it is assumed that such works be planned during special surveys or other ship repairs, i.e., at the most convenient time. Furthermore, a proper notice to the yard (of the order of 6 months) can further reduce the retrofitting time.

A5.1 Forecastle

Description of the main works

Construction of a forecastle by elevating the existing one by 3 m between frames 287-316 (Capesize) and between frames 233-250 (Panamax), by prolonging the inclination of the existing forecastle as far as possible and using the same material.
Transfer upwards of the current weather deck fittings and structure, stiffeners in way of the anchor winch area, mooring capstans, parallel-pillar bollards, fairleads, roller chocks etc.
Transfer upwards of 2 anchor winches and two mooring capstans, booby hatch and ladder to access the bos'n store.
Modification of the hawsing pipes.
Fitting of new handrails and two stairways accessing to the new forecastle.
Extension of electric cables and hydraulic and compressed air pipes as required by the new deck layout.
Raise of ventilators, cowls, sounding pipes.

The tables below report the detail of the cost estimates. The basic unit cost was estimated as 400 US $ per metric ton of steel, and 19 US $ per man-hour. It can be seen that the estimates vary by a factor of 2 between the two vessels; grossly, the same variation can be expected for Handymax vessels with respect to a Panamax, whilst Handysize bulkers are already usually fitted with a forecastle.

Capesize			
Material	**Cost (US $)**	**Manpower**	**Cost (US $)**
Steel plates (107 metric tons) Forecastle Weather deck modifications Stiffeners Booby hatch, stairways, handrails Side shell (port and starboard) Miscellaneous	42,750	Scaffolding, construction and demolition, laying off and material preparation, fabrication onboard, anchor removals (2.5 US $ / kg)	260,000
Welding oxygen and electrodes	15,350	Coating including material) (0.2 US $/ kg)	20,400
Cleaning	4,800	Total	280,400
Total	62,900		
Grand Total	**343,300**		

Panamax			
Material	**Cost (US $)**	**Manpower**	**Cost (US $)**
Steel plates (107 metric tons) Forecastle Weather deck modifications Stiffeners Booby hatch, stairways, handrails Side shell (port and starboard) Miscellaneous	22,750	Scaffolding, construction and demolition, laying off and material preparation, fabrication onboard, anchor removals (2.5 US $ / kg)	136,000
Welding oxygen and electrodes	8,000	Coating including material) (0.2 US $/ kg)	10,700
Cleaning	2,800	Total	146,700
Total	33,550		
Grand Total	**180,250**		

A5.2 Bulwark

This solution envisages the fore bulwark to be raised up to 4 m. It is cheaper to build up a new 4-m bulwark rather than to raise the currently fitted fore bulwark by 1.8 m. Of course, this solution is cheaper than the forecastle, as well, in that it does not require the deck to be raised. However, this also implies to have less available space in the forepeak. This negative effect was not quantified.

The structure of the new bulwark must be composed of 500 x 12 brackets with 200 x 15 plates, spaced by 700 mm intervals. The brackets must be placed on 300 x 500 x 12 gussets, laid out on the weather deck across the beams. The brackets must be laid out so as to allow the gussets to be welded continuously.

The bulwark must be strengthened by longitudinals spaced by 850/900 mm intervals. Furthermore, it has to be equipped with a catway running along it, about 2.7 m above deck, with adequate access stairways.

This solution does not require any removal of winches, hawse pipes, deck fittings etc.

The tables below report the detail of the cost estimates. The basic unit cost was estimated as:

- 400 US $ per metric ton of steel
- 140 US $ of consumables per metric ton of steel
- 190 US $ of coating per metric ton of steel
- 19 US $ per man-hour.

It can be seen that the estimates vary by a factor of 2 between Capesize and Panamax; grossly, the same variation can be expected for Handymax vessels with respect to a Panamax, whilst Handysize bulkers are usually already equipped with a forecastle.

Capesize			
Material	**Cost (US $)**	**Manpower**	**Cost (US $)**
Steel plates, stiffeners, tapered structures, brackets, longitudinals (48 metric tons) Catway Miscellaneous	26,300	Scaffolding, construction and demolition, laying off and material preparation, fabrication onboard, anchor removals (2.5 US $ / kg)	108,000
Welding oxygen and electrodes	6,900	Coating including material) (0.2 US $/ kg)	9,200
Cleaning	2,400	Total	117,200
Total	37,900		
Grand Total	**152,800**		

Panamax			
Material	**Cost (US $)**	**Manpower**	**Cost (US $)**
Steel plates, stiffeners, tapered structures, brackets, longitudinals (26 metric tons) Catway Miscellaneous	14,200	Scaffolding, construction and demolition, laying off and material preparation, fabrication onboard, anchor removals (2.5 US $ / kg)	58,800
Welding oxygen and electrodes	3,700	Coating including material) (0.2 US $/ kg)	5,000
Cleaning	2,400	Total	63,800
Total	20,300		
Grand Total	**84,100**		

A5.3 Monitoring System

This solution constitutes an upper limit of what can be conceived, in terms of monitoring, to ensure a prompt detection of forepeak flooding.

This automation system is applicable on any vessel between about 50,000 to 130,000 dwt, at costs which do not vary significantly with the deadweight. The quotations were made on the basis of commercial equipment delivered by major companies, that is therefore realistic and readily available. It features the following items.

a) Detection system for the unwanted flooding of the forepeak/deep tanks, through electronic sea water sensors featuring the consistency control of the water ingress volume, and alarming the bridge for the ballast pump startup. The system can envisage the automatic pump startup, but in this case it is advisable that it is left to the bridge personnel to confirm the pump action. The system would of course envisage the detection and transmission of pumps' and valves' conditions (open/closed, on/off).

b) Possibility of evacuation of small water volumes from the forepeak through the stripping pumps of the port and starboard deep tanks, by connecting these spaces with lines equipped with a couple of butterfly valves.

c) Monitoring system for the remote control of bos'n store spaces, equipped with 4 monitors and a single screen on the bridge.

It is assumed that the ships are IAQ-1 automated, thus the aforesaid maneuvers of pumps and valves are carried out from the bridge.

The monitoring system above described was itemized as follows. The prices (in US $) are comprehensive of supply and installation. Prices are assumed not to vary too much for newbuildings.

Computer-based automation system	24,000
Programmable level detection and analysis system	9,600
Water ingress alarm in hold No.1 as per IACS UR S24	3,000
Two microwave level sensors	4,800
Four monitors with accessories	19,000
Total	**57,400**

This estimate is relevant to anti-spark equipment for OBOs, and constitutes therefore an upper bound. For bulk carriers, the cost can be abated by about 25%. Allowances have to be made for spare parts to be kept onboard and periodical survey (say, once per year).

A5.4 Upgrade of the Deck Fittings Design

This RCO envisages the following interventions:

a) Replacement of the deck fittings with sturdier ones; in the absence of a proper standard, it was assumed that the new ones are double as thick as the existing ones. To make a gross estimation, the following works are envisaged.

   Replacement of the existing cowls, ventilators, air pipes and hatches. The new pipes can be of the type ASA B. 36.10 extra strong, not welded, external diameter from 1.5 up to 30 in, thickness 12.7 mm to 5 mm according to the needs. In case a diameter greater than 30 in is required, welded steel pipes can be employed, of the type UNI 7070.82 (Fe 360B, 430B, 510B) or UNI 5969.75 (Fe 410.1 KW, 410.2 KW, 510.4 KW, 510.2 KW), 13 to 15 mm thick. Additional weight about 9 tonnes for the Capesize and 8 for the Panamax.

b) Valves, fitted below the weather deck, to provide a watertight closure of fore deck openings such as cowls, ventilating pipes, sounding pipes etc. The valves of this quotation are double piston actuated, operated through a hydraulic unit equipped with an 8-point distribution panel transmitting the signals to the bridge.

The package above described was itemized as follows. The prices (in US $) are comprehensive of supply and installation. The cost of the deck fittings can be abated by about 80%, and the remote system by about 10% in Far Eastern yards. For newbuildings, the whole estimates can be reduced by 70%.

Sturdier deck fittings	27,000
Six butterfly valves	20,000
Hydraulic unit	7,200
Eight-point distribution panel	3,800
Connections between valves and unit and extension of cables to the bridge	22,400
Total(Existing ships)	**80,000**

A5.5 Sensitivity

To provide a sensitivity, the erection of the forepeak or bulwark and new pipes would be abated by over 50% if carried out in Far Eastern shipyards and by about 33% in Eastern Europe shipyards. For the items related to automation system, the cost was estimated to be 10% lower in Far East and 20% higher in Eastern Europe, where no specialized suppliers are available.

The overall approximate cost of RCOs can be summarized in the table below.

RCO	Cost range (US $)
Forecastle	180,000÷340,000 (Capesize) 97,000÷180,000 (Panamax) 52,000÷100,000 (Handymax)

Bulwark	80,000÷150,000 (Capesize) 45,000÷84,000 (Panamax) 26,000÷47,000 (Handymax)
Monitoring system	40,000÷57,000 (All bulk carriers)
Upgrade of deck fittings with remote closing system	63,000÷80,000 (Capesize) 53,000÷70,000 (Panamax) 43,000÷60,000 (Handymax)