UNIVERSITY
of
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Department of Naval Architecture and Ocean Engineering

Probabilistic Concept of Ship Subdivision

Applied to

Tankers Oil Outflow Assessment

by

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Thesis submitted for the Degree of Master of Science

I would like to dedicate this work to my son and my wife.

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ABSTRACT

The oil tanker designs have suffered significant changes during the last few years. These forced modifications were a result of the introduction of recent international (IMO, 1995) and domestic (OPA '90) regulatory actions. Intensification in the research work was also noted during this last decade, giving special attention to the prediction of tanker environmental performance in collisions and groundings.

Agreeing that the probabilistic concept is the only rational tool that enables a true comparison of different tanker designs, the mathematical basis for the probabilistic concept is described with references to the most important authors and their contribution to the development of probabilistic based regulations.

A review on the development of international regulations for control of oil pollution from tankers is presented, with statistics of the most important accidents, in terms of oil spills.

A mathematical model was developed, integrating the latest IMO regulations, using a direct probabilistic methodology. This methodology incorporates distributions of damage location and damage penetration as derived by several Classification Societies and compiled by IMO. The method was enhanced with the characteristic of not assuming total width extent of damage in case of groundings, enabling this way the assessment of the influence of longitudinal subdivision in the cargo space and in the double-bottom.

Expected oil outflow calculations were performed for 107 different tankers, including Pre-MARPOL, MARPOL, Double-Hull and Mid-Deck designs. Initial oil losses following impact and oil retention in the double-hull space were taken into consideration, as well as tidal drop and dynamic effects.

ABSTRACT

The work carried out include: parametric studies, varying double sides width, double-bottom heights, number and location of longitudinal bulkheads, number and location of transversal bulkheads and location of horizontal bulkheads; double-hulls comparison; different design types comparison and environmental performance ranking.

A discussion of the resulting probabilistic oil outflows is presented with comparisons of the environmental characteristics of the sample tankers. These sample tankers include both variations of internal subdivision within the same ship type and also among different design types.

From the analysis it was found that, in general, the mid-deck tanker designs have lower oil outflow rates, when compared with the other designs, including double-hulls. It was also concluded that the subdivision of the cargo block region has a determinant influence on the calculated expected oil outflows.

A short description of new design concepts is made, presenting the different characteristics of each and the advantages claimed by each author.

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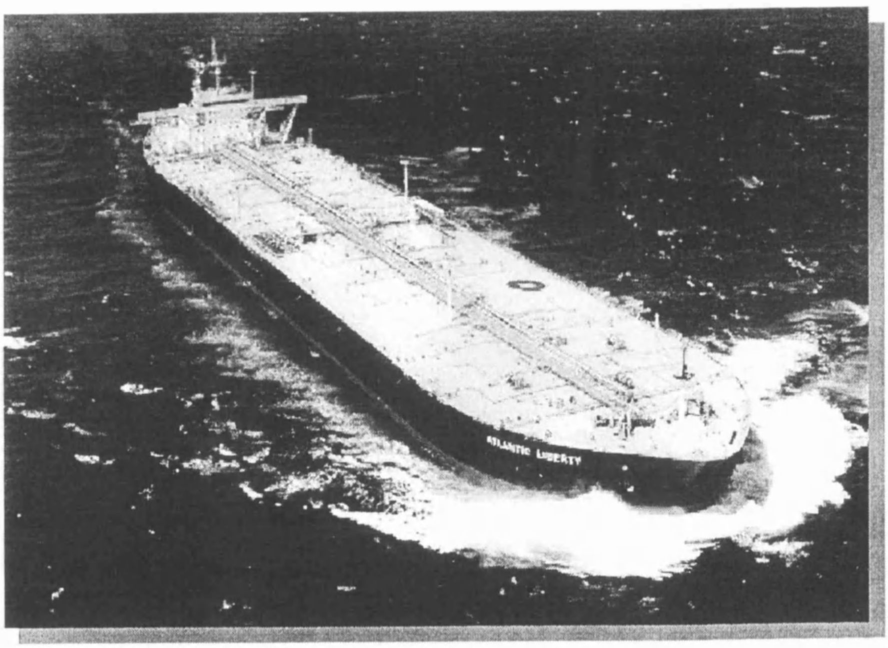
INTRODUCTION



CHAPTER 1 - INTRODUCTION

For many years all interested parties in the maritime activity have addressed the importance of ship safety. However, to achieve this goal in the shipping business it is necessary to satisfy the client's specification, the cost effectiveness and an acceptable level of safety at the same time.

This acceptable level of safety is not easily quantifiable, because it does not involve only engineering aspects, but also operational and management aspects.

Because shipping is a worldwide activity with many risks, it is understandable that in a time when safety and the environment are primary aspects of human concern, the different countries involved have tried, during the last decades, to reduce the threat from the transportation of goods by sea. This work has been undertaken through the IMO, an International Organisation that regulates and insures the safety of sea transportation in terms of human life and pollution.

It is certain that it is necessary to find a balance between modern existence and maintaining the environment. It is also accepted that tankers operate only because of the demand for oil. Thus, to have tankers operating in the seas, it is necessary to cope with the responsibility associated with this type of transportation. The oil must be transported as safely and efficiently as possible.

However, the essential question still remains: "*Is it possible to design an oil tanker that meets complex demands for economical operation, crew safety and is still environmentally friendly?*" (NRC, 1991).

The answer to this question is neither direct nor easy, but there are three main methods to reduce accidental oil outflow: specification of a double hull, reduced tank size and use of outflow prevention measures inside a tank. The three methods will be discussed in detail later.

Chapter 1 - Introduction

Until the XIX century the concern about the risks involving trade by sea were almost not existent when compared to the present day, the number of ships was small as well as the amount of goods transported.

However, with the industrial revolution this picture was completely changed. All sectors suffered major developments and the shipping activity increased exponentially with the explosion in number of products to carry by sea. In addition to this increase in the amount of products carried, the characteristics of this merchandise became more dangerous, with a lot of chemical products travelling from one country to another; IMO considers that more than 50% of the cargo transported by sea is dangerous.

The constant effort by man to make the shipping activity as safe as possible, led to the development of a wide group of legislation covering different areas of the maritime activity.

However, one of the main drawbacks of the existing regulations towards safety aspects is the fact that a great majority of them were compulsively taken as a result of major accidents. Their implementation was so fast that some of the important aspects were forgotten and not taken into account.

Although the present work only investigates a specific type of ship: *tankers*, these represent a major threat to the environment that justifies all the research and studies that have been carried out, trying to solve the questions and problems involving this specific kind of vessel.

The explosion in the demand for oil transportation by sea occurred at the end of the 60's decade. As a consequence larger ships became a reality and the VLCC (Very Large Crude Carriers) concept appeared. With them came the biggest pollution accidents in history, the Torrey Canyon accident in 1967 being the largest one (the largest oil spill of ship accidents history is still the Atlantic Empress collision in 1979 – 274,854 t).

Ships that transport dangerous cargo are covered in first place, by regulations intended to protect the marine environment and, as other ship types, by regulations regarding damage stability. Unfortunately, these regulations are based on deterministic concepts. The flaws of the deterministic approach have been widely demonstrated by several authors. Thus, the use of regulations for the prevention of pollution based on the probabilistic approach is the solution for a better evaluation of the environmental safety of different ship designs.

The introduction of the probabilistic concept in the safety legislation has a history of approximately three decades. However, Resolution A.265 - probabilistic IMO equivalent passenger ship regulations (IMO, 1973), only came into force fifteen years after Wendel's first publication in 1960 (Wendel, 1960). In comparison with the deterministic regulations of the time - the subdivision factor - this was a major progress towards safety improvement.

In 1982, Tagg (Tagg, 1982) published a paper were he assessed the survivability indices of a number of cargo ships including a tanker. Once again it took over eight years until the adoption of SOLAS'90 amendments, which introduced the probabilistic concept for the evaluation of damage survivability of cargo ships over 100m in length. They entered into force in 1992.

The second important safety aspect of hull division apart from survivability is pollution prevention. Abicht (Abicht, 1975, 1977) first proposed the minimisation of oil outflow from damaged tankers in 1975. However, the real research using this methodology on tankers only began after the Exxon Valdez disaster with the unilateral legislation introduced by the U.S - Oil Pollution Act 1990 (OPA 90). Pressured by this move, IMO has developed guidelines for approving alternatives to new tanker construction to be compared with reference to double-hull tankers.

The research activities led to new solutions, which changed the design concepts and induced various new designs and engineering solutions. However, they had to be compared in their environmental impact. The regulatory bodies were then asked to evaluate and check these new concepts.

A reduction in the risk of oil pollution from tankers can be accomplished by a number of operational and design measures. Different tanker design configurations may therefore have different protection capabilities. The oil outflow from a specific damage scenario may be relatively straightforward to evaluate, but an overall objective measure of merit to evaluate dissimilar configurations is not as easy to develop.

The main aim and objective of this work is the evaluation of the environmental performance of different tanker designs, through the use of the latest probabilistic regulations proposed by IMO. The resulting probabilistic oil outflow parameters should give a basis for a wide discussion over the environmental characteristics of the sample tankers and the methodology used for the assessment of such measures. It is also a purpose to provide comments on the IMO Guidelines for approval of alternative designs referred to in Regulation 13F and 13G.

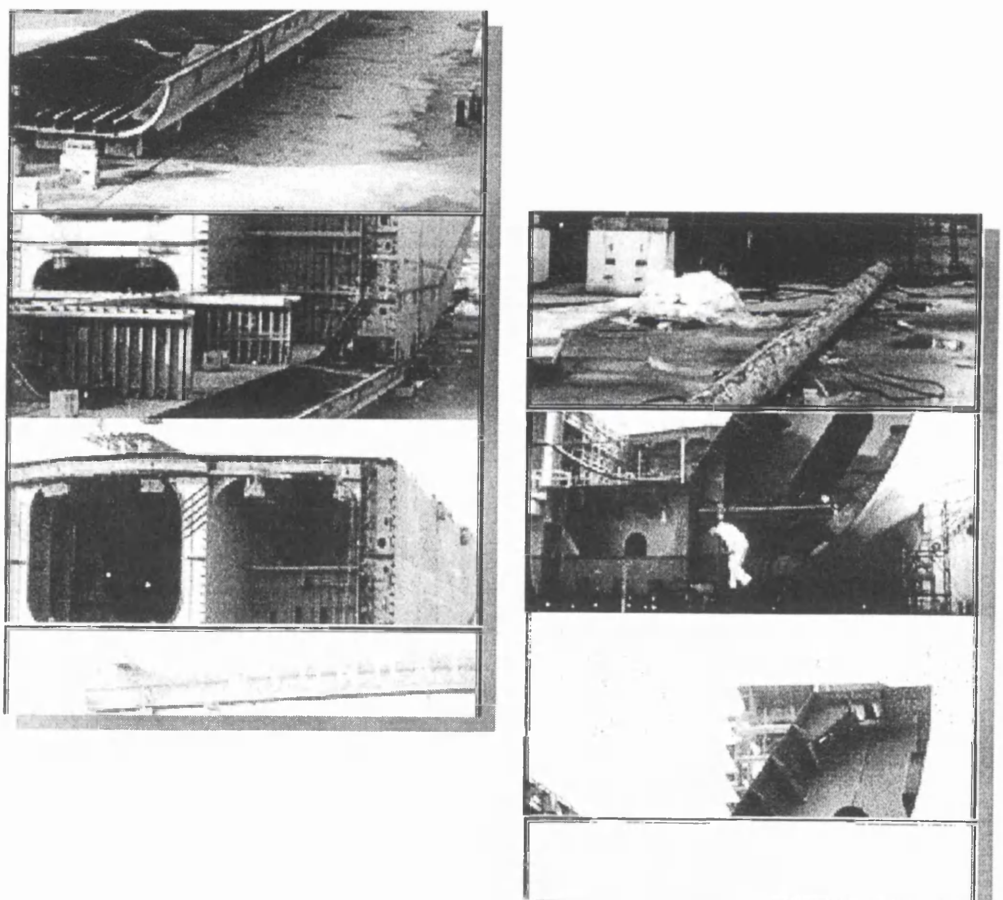
Another objective of this work is the investigation of the effect of subdivision, principal ship dimensions and ratios between these characteristics, on the measures of merit, both numerically and analytically. This would make possible the identification of appropriate designs, both for double-hull and mid-deck tankers.

The probabilistic investigations, which are necessary to establish the outflow parameters of a tanker, are so extensive that they can only be done by computer simulation. Thus a computational model is developed and implemented incorporating the last IMO regulations on prevention of pollution from tankers.

This analysis is what is called a *conceptual analysis*, because it does not include a survivability check of the critical damage cases.

CHAPTER 2

SHIP SUBDIVISION



CHAPTER 2 - SHIP SUBDIVISION

2.1 Introduction

An important purpose of the subdivision of ships is to preserve their floatability and stability, whenever a casualty occurs involving water ingress. The contingency effect is achieved by the limitation of the maximum amount of flooding associated with any hull penetration.

Collisions are common accidents among ships. They are random events and their consequences in terms of structural damage are also uncertain. The structural consequences of collisions can be described in terms of the dimensions and locations of the hull penetrations that cause flooding, parameters that can also be modelled by random variables.

In view of the uncertainties about the occurrence of collisions and their consequences, any decision about the location of watertight bulkheads should be based on a probabilistic formulation.

Wendel and his associates introduced the probabilistic approach for the assessment of ship subdivision, (Wendel, 1968), making possible the calculation of a numeric value that could be related to the achieved level of safety and to the residual risk of ship loss associated with a specific subdivision. Their principal concern was the increase of ship safety.

IMO only adopted the probabilistic concept in 1973 in Resolution A.265 (VIII), (IMO, 1974) – IMO Passenger Ship Regulations. No international requirements for the damage stability of cargo ships existed until February 1992, when an international, probabilistic damage standard for dry cargo ships was adopted by the International Maritime Organisation (IMO).

The Dry Cargo Ship Regulations (IMO, 1992) then developed more than fifteen years later than the issue of the Passenger Ship Equivalent Regulations. Originally they were applied to cargo ships of 100m in length, or above. Recently, this lower limit was lowered to 80m.

For the evaluation of tankers subdivision, it was only in 1995 that the International Maritime Organisation introduced guidelines, based on the probabilistic concept, for approving alternatives to the new tanker construction requirements (IMO, 1995b).

The probability of an oil spill event (P_e) can be expressed as the product of the probability of the casualty occurring (P_c) and the probability of a spill (P_s) in the event of a casualty:

$$P_e = P_c \times P_s \qquad (1)$$

The double-hull requirements of OPA '90 and MARPOL address the second factor in the equation, the probability of a spill in the event of a casualty. The structural and operational modifications to single-hull vessels are also directed toward the second factor, although some elements, such as bridge management training, and manoeuvring regulations focus on the first factor, i.e., reducing the probability of a casualty.

The methodology contained in the MARPOL guidelines is rigorous and allows the computation of the oil outflow in accidental groundings and collisions. It also provides the calculation of a "Pollution Prevention Index", which enables the comparison between the new tanker and a series of "reference" double hulls. This index is composed of three measures of merit of the oil outflow performance of any tanker:

- probability of zero outflow;
- mean outflow;

- and extreme outflow.

This methodology only addresses the calculations of the second factor of equation (1), P_s, the probability of a spill in the event of a casualty.

2.2 Damage Stability Regulations for Different Ship Types

2.2.1 Background

The first international efforts to upgrade vessel safety focused mainly on passenger ships, due to the heavy loss of life attributable to the sinking or capsizing of such ships.

Due to the tragic loss of several Ro-Ro ferries in recent years, the damage stability of ships has received again a great deal of attention. As a consequence of these disasters IMO decided that there was a need to both derive rational procedures for assessing the damage stability characteristics of ships and to set up reasonable minimum requirements.

The British Marine Shipping Act in 1854 established the first regulations on ship subdivision and damage survivability. These regulations required transverse bulkheads at the peaks and engine room.

During the following years, the International Conferences on the Safety of Life at Sea (SOLAS) have been one of the primary initiators of international safety regulations, including subdivision standards.

Due to the tragic accident and loss of Titanic, in 1914, the SOLAS Conference (SOLAS '14) established subdivision and lifesaving standards for passenger ships. However, because of World War I the participating countries never officially adopted the conference.

The important *Factorial Method* and *Criterion of Service* was introduced in the 1929 SOLAS Conference (SOLAS '29). For the first time a procedure for determining statutory minimum levels of subdivision was laid down. In effect it was the establishment of a minimum bulkhead spacing based on the ship length and the number of passengers, which are to be achieved by all sea-going passenger vessels. It also established a one-compartment standard of subdivision for passenger ships engaged in international service.

Once again, following the *Mohawk* and *Morro Castle* losses in the early 1930's, the United States adopted SOLAS 29 in 1936. Only one year later a U.S. Senate Report established more stringent criteria based on the SOLAS "Factor of Subdivision" format and established the one-compartment standard for U.S. cargo ships. In the 1948 SOLAS (SOLAS '48) convention, regulations on flooded criteria were added to SOLAS 29.

During the early 1950's it was becoming increasly recognised that combined fuel and ballast double-bottom tanks were becoming an operational problem, because they were often required to be ballasted following emptying of fuel to meet damage stability requirements. When these tanks were used according to the designer's instructions, they were causing oil pollution of harbours. They also caused fuel contamination and tank cleaning problems. If these tanks were not used as designed, as was generally the case, the ships could often not meet damage stability criteria.

In 1954 a 32-nation conference convened on the Prevention of Pollution of the Sea by Oil (OILPOL '54). This convention banned oil discharge within 50 miles of land and called for the installation of oily-ballast receiving facilities at all ports.

Following the *Andrea Doria* loss in 1956, the Inter-Governmental Maritime Consultative Organisation (IMCO) was established, and shortly thereafter the SOLAS 60 Conference was convened (SOLAS '60). In recognition of the many inherent deficiencies in the SOLAS 48 regulations, a number of delegations proposed new approaches and substantial changes to the passenger ships rules. However, agreement could not be reached and the basic approach of SOLAS 48 was left unchanged. This SOLAS 60 Conference also made General Recommendations No. 6 and No. 8 for further study on the standards for watertight subdivision of passenger and cargo ships. In 1961, acknowledging the recommendations of SOLAS 60, IMCO established the Subcommittee on Subdivision and Stability. Among other issues the work of the committee was to consider the deficiencies in SOLAS 60, new trends in ship design, and the possible range of damage lengths.

In 1966, the International Conference on Load Lines (ICLL '66) proposed a one-compartment standard for tankers and also for other reduced freeboard (B-60 percent) cargo ships (IMO, 1966). Dry-cargo ships with minimum freeboard (B-100 percent) were required to meet a two-compartment standard, exclusive of the engine room. All damage requirements applied to the summer load line (SLL) draft only. Cargo ships with conventional freeboards were required only to have forepeak, aft peak, and engine room watertight bulkheads in addition to those normally required by the classification society.

During the mid 1960's several technical changes in tanker design and operation were affecting their safety. Prior to the mid-60's tankers had a high degree of safety in the loaded condition due to the high watertight integrity of their main decks, adequate compartimentation, and the low permeability of the loaded cargo spaces. Following the closing of the Suez Canal in 1967, the trend towards larger tankers gained momentum rapidly. Along with this increase in overall size, the increase in tank sizes, the incorporation of segregated wing ballast tanks, and an increase in multiple-port operations with partial loadings, all tended to reduce tanker safety. In 1971, in the wake of the Torrey Canyon disaster and with these factors in mind, the U.S. Coast Guard imposed a two-compartment standard for tankers.

2.2.2 IMCO Equivalent Passenger Ship Rules

IMO members were favourably impressed by the argument put forward in a paper read in 1968 at SNAME – 'Subdivision of Ships' – presented by Prof. Kurt Wendel (Wendel, 1968). In this paper, Wendel outlined a procedure that intended to provide efficient subdivision for ships through the application of probabilistic principles.

This procedure made possible the quantification of the level of subdivision achieved in a particular ship design, having a fixed arrangement of main watertight bulkheads. Such quantification is achieved using a Subdivision Index, which is an estimate of the proportion of all possible damages that a ship is likely to survive, i. e. it will not sink or capsize.

In 1971, only one decade later and culminating many years of research, the IMCO Subcommittee on Subdivision and Stability submitted new passenger ship rules based on probability of damage principles. These rules were adopted in 1973 as an alternative to the provisions of SOLAS 60. This approach was incorporated in passenger ship regulations as "The Equivalent International Regulations on Subdivision and Stability of Passenger Ships". Three basic factors were considered in subdivision and damage stability criteria:

1. Probability that a ship may be damaged;
2. If the ship is damaged, the probability of the location and extent of flooding;
3. Probability that the ship may survive such flooding.

The probability of ship survival can be calculated as the sum of probability of its survival after flooding each single compartment, each group of two, three or more adjacent compartments multiplied, respectively. In other words, the ship survival probability is calculated multiplying the probability of flooding each single compartment, and the probability of flooding each group of two adjacent compartments, and the probability of flooding each group of three and so on until all combinations are calculated.

The regulation requires that the ship's attained subdivision index "A" must be equal or greater than its required subdivision index "R". "A" is equal to the summation over the ship length of the expression $\sum aps$, where

- a accounts for the probability of damage as related to the position of damage along the ship's length;
- p evaluates the effect of the variation in longitudinal extent of damage on the probability that only the compartment or group of compartments under consideration may be flooded;
- s evaluates the effect of freeboard, stability and heel in the final flooded condition for the compartment or group of compartments under consideration.

Besides the general acceptance of these regulations by the leading authorities of the maritime nations they have not been used largely because they are considered more stringent than deterministic rules.

One of the main drawbacks of these regulations was that they were only applicable to passenger ships. Among the aspects of this regulation regarded as unsuitable for cargo ship application, and in addition to the obvious need to reassess the survival criteria, were:

- they do not consider the effect of the damage on vertical extent and location, i.e., vertical damage is assumed from the baseline upward without limit;
- and that most probability functions are linear functions, which may not be appropriate for cargo ships.

In order to extend the probabilistic principles of these regulations to other types of vessel, it is indispensable to determine more realistic distribution functions, work that has been carried out by several authors during the last few years.

2.2.3 IMO Dry Cargo Ship Damage Stability Regulations

The development of a probabilistic approach for cargo ships, similar to the one adopted previously for passenger ships, was the only solution to the one-compartment standard for damage survival of cargo ships. In 1983, the U.S. Cost Guard tried to introduce this standard, but the flaws inherent in this approach immediately raised wide opposition. The fact that it does not consider the effects of subdivision, does not reflect the true level of safety and penalises economically some ship designs was more than sufficient to stop this move from the U.S. authority.

Following the losses of two RO/RO passenger ferries in the 80's – the European Gateway and the Herald of Free Enterprise – IMO intensified its efforts to complete the development and adoption of a damage standard for dry cargo ships.

As a consequence of this effort, in 1987, IMO issued a draft regulation on Subdivision and Damage Stability of Dry Cargo Ships including Roll-On/Roll-Off (RO/RO) Ships in IMO SLF 32/21 Annex 2 (IMO, 1991c). The new regulations were modelled after the IMCO equivalent passenger ship regulations, but with different survival criteria:

- the relaxation of the allowable heel angle to 25-30 deg;
- a modified treatment of cargo space permeability, standardised at 70 percent;
- and the incorporation of a vertical extent of damage probability distribution function.

In addition to these differences, the number of drafts considered was also reduced to two. In the absence of a significant number of passengers, the required subdivision index "*R*" also was modified to consider the ship length only. The attained subdivision index "*A*" is calculated as follows:

$$A = 0.5A_L + 0.5A_P \qquad (2)$$

where:

- A_L is that part of the attained subdivision index for the ship obtained at the deepest subdivision load line;
- and A_P is that part of the attained subdivision index obtained at the partial load line.

In calculating A_L and A_P level trim shall be used, except when inconsistent with the ship's operation.

For both A_L and A_P the following summation shall be used:

$$A_L or A_P = \sum_i p_i s_i v_i \qquad (3)$$

where:

i represents each compartment or group of compartments under consideration;

p_i accounts for the probability that only the compartment or group of compartments under consideration may be flooded;

s_i accounts for the probability of survival after flooding the compartment or group of compartments under consideration;

v_i accounts for the probability that only the compartment(s) under consideration are flooded within the assumed vertical extent of damage.

2.2.4 Tankers Pollution Prevention Regulations

The base for the current international regulations governing the damage stability and oil outflow for tankers is still the International Conference for the Prevention of Pollution from Ships, 1973 (MARPOL '73) and the Protocol of 1978 Relating to MARPOL '73 (Protocol '78).

In 1973 the International Conference on Marine Pollution (MARPOL 73) established:

- a two-compartment standard for most tankers;
- regulations regarding tank size and volume limitations;
- requirements for "hypothetical outflow of oil", and for segregated ballast.

The IMCO Protocol of 1978 relating to SOLAS 74 provides additional requirements for crude oil washing and the protective location of segregated ballast spaces for tankers. No substantial changes were made to the MARPOL 73 damage stability standards.

Current international regulations for oil tankers intended to minimise pollution from accidental side and bottom damage are one example of a prescriptive standard. While such standards are relatively straightforward in their application, new oil outflow calculation techniques have demonstrated (IMO, 1995a) that these regulations need to be revised.

The major impulsive change in the regulations governing tankers came unfortunately following the tragic incident, on the 24th March 1989 with the Exxon Valdez, a 215000 tonnes deadweight tanker, that ran aground in Prince William Sound, Alaska, spilling 36000 tonnes of crude oil (Moore, 1994). This vessel was only four years old and was built in accordance with the MARPOL '73/78 Convention.

There was now a wide understanding that the present deterministic regulations were prescriptive in nature (rather than goal setting) and that the environmental performance of existing tankers differed considerably. Therefore existing regulations did not produce consistent results.

In the beginning of this decade activities at IMO regarding tank ship regulation were primarily involved with the completion of the double hull regulations. Inspired by the grounding of Exxon Valdez, and as a reaction to the subsequent unilateral legislation (US Oil Pollution Act, OPA '90), these regulations were intended to speed implementation of an international standard applicable for new tanker construction. OPA '90 and the IMO regulations prescribe double-hull "equivalent environmental protection" for all new constructions and intend to phase out the carriage of oil in single-hull tankers.

Computing oil outflow from a tanker that has been involved in a grounding or collision is based upon applying an assumed extent of damage and calculating the oil outflow based on physical hydrostatic and “quasi-hydrodynamic” principles.

During the first half of this decade a committee of IMO has been occupied in the development of guidelines for approving new tanker designs. This new methodology uses the concept of a merit index (Pollution Prevention Index), that enables the comparison between the new design and a series of Double-

Hull reference designs, through the calculation of three characteristics of the oil outflow performance of a tanker, when involved in accidental groundings or collisions.

During the development of these guidelines the importance of these parameters was realised; however, their *relative* importance was determined in an arbitrary manner. This was, in part, due to the fact that the variation in the environmental effects of a "unit spill" as a function of spill size was not included in the formulation for the "pollution prevention index."

Furthermore, the assumed extents of damage that are used in the guidelines are based upon actual data compiled from various collisions and grounding incidents (IMO, 1992), (DnV, 1993), all of which were *single hull* tankers. This data was compiled by the classification societies at IMO's request, from sources including LR, ABS, DnV, ClassNK, and RI. This data was derived from casualties to oil tankers, chemical tankers, OBOs, OROs of 30,000 tonnes deadweight and above, for the period 1980 to 1990.

2.3 The Environmental Threat

During the last 30 years the pollution of the world's oceans has become a matter of increasing international concern. Most of it comes from land-based sources and includes the by-products of industry, run-off from agricultural pesticides and herbicides and effluents discharged from urban areas.

Nevertheless, a significant amount of pollution is caused by shipping and maritime activities generally. In tonnage terms, the most important pollutant resulting from shipping operations is oil.

The best known cause of oil pollution, is that arising from tanker accidents. Although this may contribute a comparatively small percentage of the total oil entering the sea in a year, the consequences of an accident can be disastrous to the immediate area, particularly if the ship involved is a large one and the accident occurs close to the coast. The wrecks of the Torrey Canyon (1967), the Amoco Cadiz (1978) and the Exxon Valdez (1989) are examples.

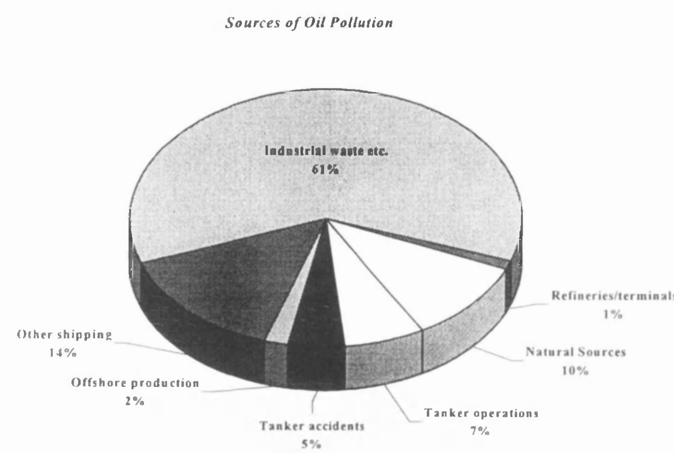


Figure 2.1. - Sources Oil Pollution (source: ITOPF 1998).

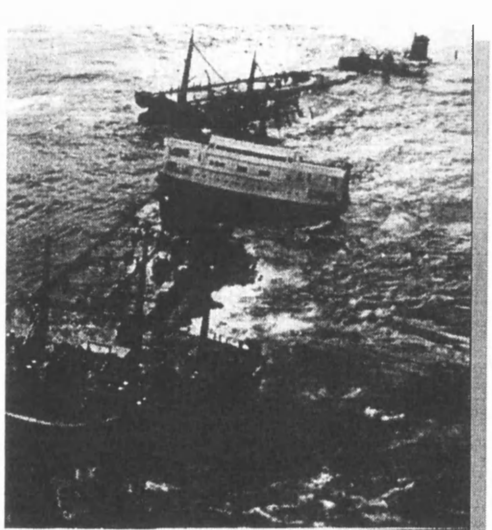


Figure 2.2. - Torrey Canyon (source: Internet).

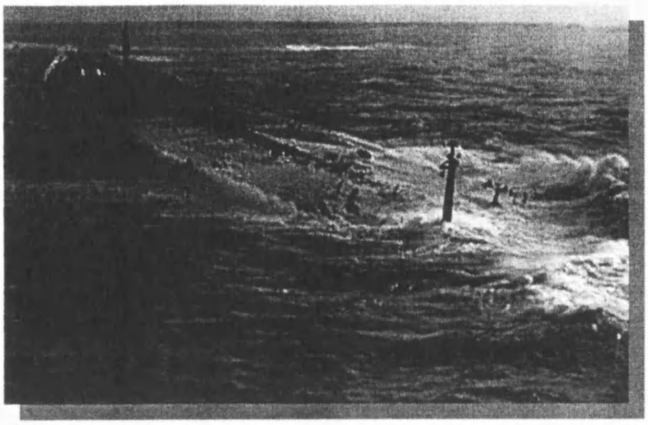


Figure 2.3. - Amoco Cadiz (source: Internet).

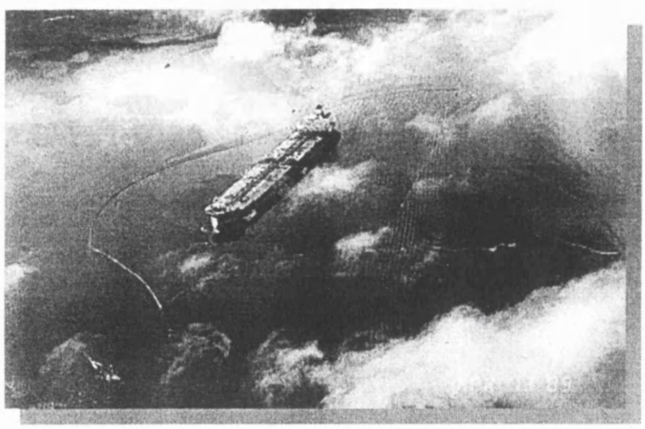


Figure 2.4. - Exxon Valdez (source: Internet).

The most common pollution incidents occur during terminal operations when oil is being loaded or discharged - perhaps as many as 53% of oil spills, according to figures published by the International Tanker Owners' Pollution Federation.

A much greater quantity of oil enters the sea as a result of normal tanker operations, usually associated with the cleaning of cargo residues (clingage), which takes place when the ship is returning from the port of discharge to take on another cargo of oil.

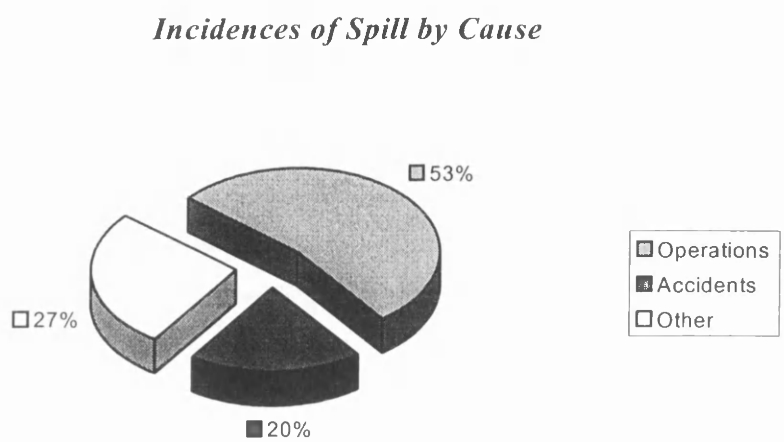


Figure 2.5. - Incidences of spill by cause - 1970 - 1997 (source: ITOPF).

Other causes of oil pollution include tank cleaning in connection with dry docking; bilge and fuel oil (from dry cargo ships as well as tankers) and non-tanker accidents.

Although most public concern about marine pollution has concentrated on problems associated with oil, many of the chemicals carried by sea are far more dangerous to the marine environment.

Fortunately, perhaps, the amount of noxious substances carried at sea is only a fraction of the amount of oil transported each year. Many are carried in bulk form in tankers especially designed for the purpose.

The ships themselves are generally much smaller in size than oil tankers, ranging from 500 grt to about 40,000 grt. They are, however, often extremely complex (and hence expensive) to build. Not only must the cargo be given maximum protection, but the ship may also carry many different substances at the same time - each one of which may have particular properties and require different handling.

Other chemical substances are carried in packaged form, such as in drums or portable tanks. Again, the environmental threat which some of these substances represent bears no relation to the size of the unit in which they are carried. As an example, polychlorinated biphenyls (PCBs) are potentially so harmful that IMO have recommended that their carriage in bulk form by ship should be banned.

Many of these substances are not only a pollution threat - they can also be extremely hazardous both to ships and equipment and, more importantly, to people.

The number of different chemicals and other goods of this type is growing all the time as the world becomes more industrialised and industry itself becomes more complex.

Garbage and sewage from ships have traditionally been dumped into the sea as a natural and usual procedure, and in relation to the amount of similar wastes poured into the sea each year from the land, the quantities were not considered excessive in the past.

Today, however, the situation is very different. One reason is the growing everyday use of substances such as plastics, which are non-biodegradable: once thrown into the sea they can stay there for many years.

In a number of countries, quantities of industrial and municipal waste (mainly sewage sludge) generated on shore are disposed of by dumping at sea. Most of these materials are such that the marine environment without harmful effects can assimilate them (although the sheer scale of dumping operations has caused concern in some areas). But other materials - such as radioactive wastes - are much more controversial.

Account must also be taken of the many harmful substances transported in packaged forms, which can have a polluting effect if released into the marine environment. The labelling and stowage of such packages should be such as to minimise hazards arising from shipment.

No matter what substance is involved, marine pollution is an international problem. The risk of a major tanker accident is greater in some areas than in others but pollution can happen almost anywhere and can affect coastlines, which are often many miles away from the incident, which caused it.

2.3.1 Analysis of Oil Spills Statistics

2.3.1.1 Introduction

At the present moment about 100 million tonnes of crude and oil products are under transportation by ship over the oceans. Some of the International Organisations (ITOPF) claim that that most of it is being transported in safe ships, with skilled crew under competent management. However, there are still a few where the doubtful condition of these ships leads to the idea of not compliance with today's standards of safety and thus imposing important threats to the lives of their crew and to the environment.

Although some of these situations are not solved yet, it is clear that a significant improvement has been reached over the past few decades. This was achieved mainly through international co-operation. The oil spill statistics over the past few decades indicate these positive trends.

2.3.1.2 Numbers of Oil Spills and Total Amount Spilt

The incidence of large spills is relatively low and detailed statistical analysis is rarely possible, and so emphasis is placed on identifying trends.

The examination of the statistical data from the ITOPF shows some interesting results. The accident statistics over the past twenty-five years show a significant reduction in the number of large-scale spills. A clear drop can be seen from about 1980 for spills over 700 tonnes (see Figure 2.6). Through the last decades the average number of major oil spills each year had dropped to one-third of that witnessed in the previous decade. This drop can clearly be associated with the introduction of MARPOL 73/78, but also with a drop in the total amount and volume of transported crude.

The great majority of spills are small, i.e. less than 7 tonnes. However, in most years it is probable that they make a relatively small contribution to the total quantity of oil spilled into the marine environment.

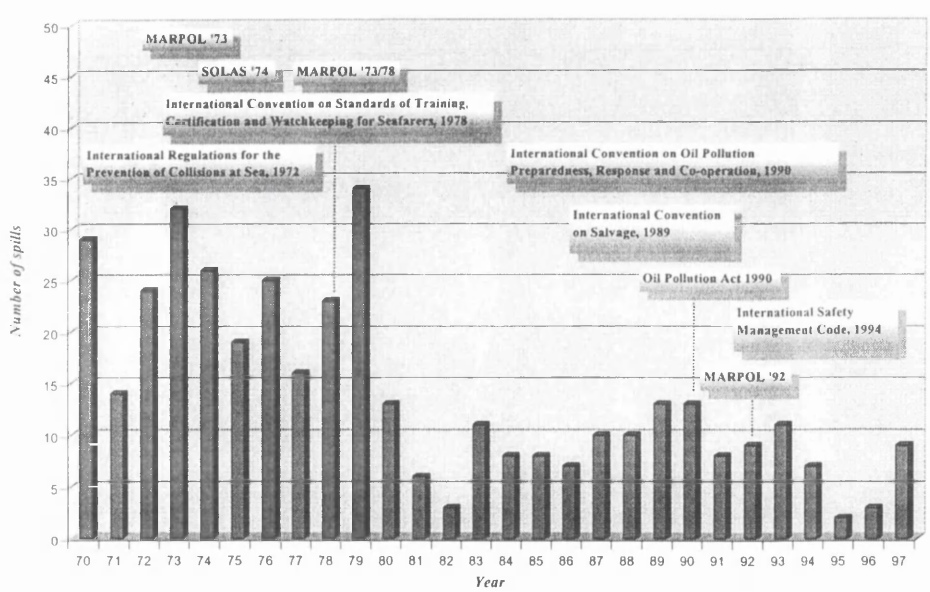


Figure 2.6. - Major accidental oil spills (spill > 700 tonnes) worldwide from tankers, combined carriers and barges - 1970 - 1997 (source: ITOPF, 1998)

Table 2.1 - Numbers of spills over 7 tonnes and total quantity of oil spilt - 1970 - 1997 (source: ITOPF, 1998).

Year	7-700 tonnes	Over 700 tonnes	Quantity (10^3	Year	7-700 tonnes	Over 700 tonnes	Quantity (10^3

			tonnes)				tonnes)
1970	6	29	301	**1984**	25	8	28
1971	18	14	167	**1985**	29	8	88
1972	49	24	311	**1986**	25	7	19
1973	25	32	166	**1987**	27	10	30
1974	91	26	222	**1988**	11	10	198
1975	97	19	342	**1989**	32	13	178
1976	67	25	369	**1990**	50	13	61
1977	65	16	298	**1991**	27	8	435
1978	54	23	395	**1992**	31	9	162
1979	59	34	608	**1993**	30	11	144
1980	51	13	206	**1994**	27	7	105
1981	49	6	44	**1995**	21	2	9
1982	44	3	11	**1996**	20	3	79
1983	52	11	384	**1997**	26	9	67

It is notable that a few very large spills are responsible for a high percentage of the oil spilt. For example, in the ten-year period 1988-1997 there were 360 spills over 7 tonnes, totalling 1439 thousand tonnes, but 1003 thousand tonnes (70%) were spilt in just 10 incidents (less than 3%). The figures for a particular year may therefore be severely distorted by a single large incident. This is clearly illustrated by 1979 (Atlantic Empress - 287,000 tonnes), 1983 (Castillo de Bellver - 252,000 tonnes) and 1991 (ABT Summer - 260,000 tonnes).

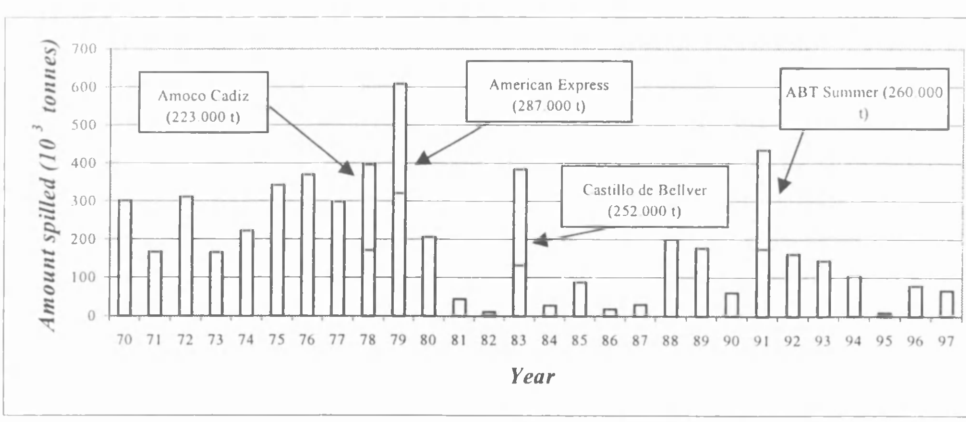


Figure 2.7. - Quantities of oil spill - 1970 - 1997 (source: ITOPF, 1998)

Major oil spill accidents may cause severe local impacts and contaminate hundreds of kilometres of shoreline, but one must not forget that the large number of small-scale spills also constitute serious environmental threats in many areas. If the spill size interval is extended to include also small-scale, so-called operational spills, the figures do not demonstrate a clear-cut decrease (see Figure 2.8). Even though many of the provisions of MARPOL are aimed at reducing all operational discharges of oil and contaminated water, illegal operational spills are still frequently reported.

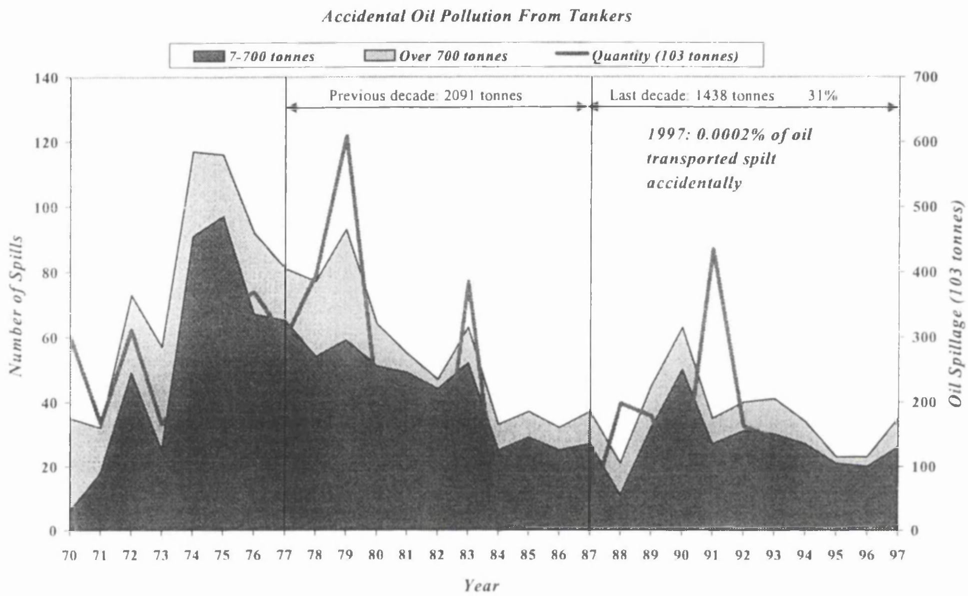


Figure 2.8. - Numbers of spills/Oil spilled - 1970 - 1997 (source: ITOPF, 1998)

The following table gives a brief summary of the 20 major oil spills. A number of these incidents, despite their large size, caused little or no environmental damage, as the oil did not impact coastlines.

Table 2.2 - Selected major oil spills - 1974 - 1997 (source: ITOPF, 1998)

SHIPNAME	Year	Location	Oil lost (tonnes)
Atlantic Empress	1979	Off Tobago, West Indies	287,000
ABT Summer	1991	700 naut. Miles off Angola	260,000
Castillo de Bellver	1983	Off Saldanha Bay, South Africa	252,000
Amoco Cadiz	1978	Off Brittany, France	223,000
Haven	1991	Genoa, Italy	144,000
Odyssey	1988	700 naut. Miles off Nova Scotia, Canada	133,000
Torrey Canyon	1967	Scilly Isles, UK	119,000
Urquiola	1976	La Coruna, Spain	100,000
Hawaiian Patriot	1977	300 naut. Miles off Honolulu	95,000
Independenta	1979	Bosphorus, Turkey	95,000
Jakob Maersk	1975	Porto, Portugal	88,000
Braer	1993	Shetland Islands, UK	85,000
Khark 5	1989	120 naut. Miles off Atlantic coast of Morocco	80,000
Aegean Sea	1992	La Coruna, Spain	74,000
Sea Empress	1996	Milford Haven, UK	72,000
Katina P.	1992	Off Maputo, Mozambique	72,000
Assimi	1983	55 naut. Miles off Muscat, Oman	53,000
Metula	1974	Magellan Straits, Chile	50,000
Wafra	1971	Off Cape Agulhas, South Africa	40,000
Exxon Valdez	1989	Prince William Sound, Alaska, USA	37,000

With the intention of getting some explanations for the main causes of spills, the following table explores the incidence of spills of different sizes in terms of the primary event or operation in progress at the time of the spill. A large majority of the incidents are the result of a combination of actions and circumstances, all of which contribute in varying degrees to the final outcome. These "causes" were grouped into "Operations" and "Accidents".

It is possible to conclude from the table that:

- Most spills from tankers result from routine operations such as loading, discharging and bunkering, which normally occur in ports or at oil terminals;

- The majority of these operational spills are small, with some 92% involving quantities of less than 7 tonnes;

- Accidents involving collisions and groundings generally give rise to much larger spills, with a fifth involving quantities in excess of 700 tonnes.

Table 2.3 - Incidence of spills by cause - 1974 - 1997 (source: ITOPF, 1998)

	< 7 tonnes	7-700 tonnes	> 700 tonnes	Total
OPERATIONS				
Loading/Discharging	2757	288	15	3060
Bunkering	541	24		565
Other Operations	1162	47	0	1209
ACCIDENTS				
Collisions	144	225	85	454
Groundings	217	186	101	504
Hull Failures	547	67	39	653
Fire & Explosions	149	16	20	185
OTHER	2213	157	34	2404
Total	7730	1010	294	9034

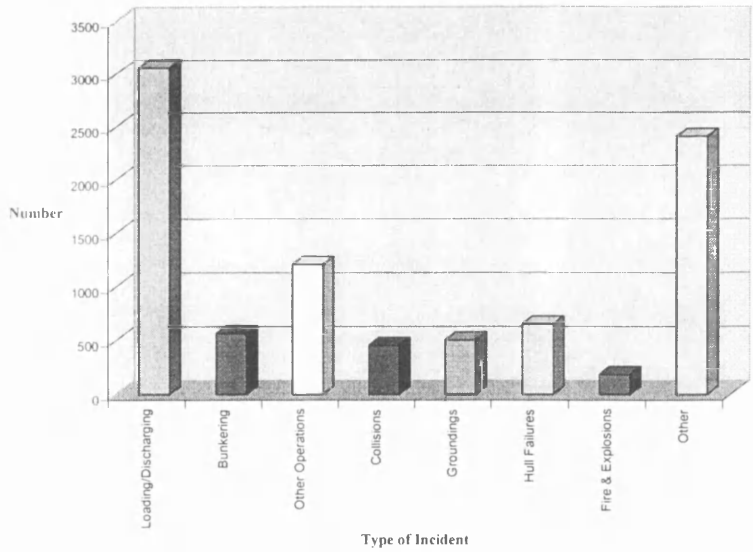


Figure 2.9. - Number of accidents by incident type - 1974 - 1997 (source: ITOPF, 1998)

From Figures 2.9 and 2.10 and Table 2.4 it is clear that groundings and collisions are generally the dominating causes of tanker accidents with large oil spills. For small spills, the causes are most frequently attributed to cargo handling operations. Consequently, both large and small spills mostly occur near the ports or in coastal area with limited depth or/and dense traffic.

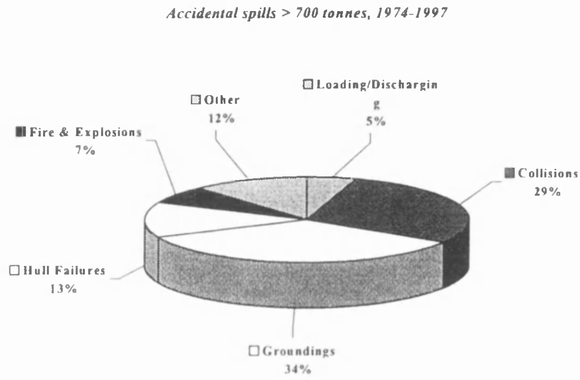


Figure 2.10. - Accidental spills > 700 tonnes, 1974-1997 - (source: ITOPF, International Tanker Owners Pollution Federation Ltd., 1998)

2.4 Development of Regulations for Control of Oil Pollution

Oil pollution from ships was first recognised as a problem during World War I. However, it was only in 1954 that the first treaty to prevent oil pollution of the seas from ships took place. This conference dealt only with operational oil pollution from merchant ships, not taking into discussion any aspects regarding accidental pollution. Nevertheless, it was a first step towards the improvement of ship environmental safety.

The introduction of the first construction measures to reduce the amount of oil released to the sea from tankers after an accident, was made in the 1954 Convention of the Pollution of Sea by Oil (OILPOL).

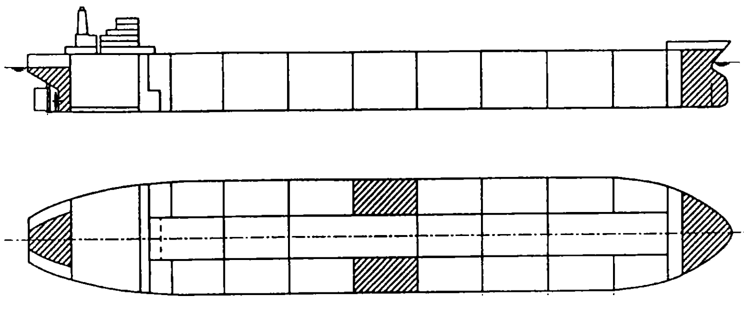


Figure 2.11. - Non-Segregated Ballast Tanker.

In this Convention a series of zones, where discharge of oily wastes was prohibited, has been established. There also introduced the requirement that ports should have facilities for the reception of waste oils from non-tankers. However, for tankers, which produce far greater quantities of oil, no provisions were established.

By the 1960s there was evidence that oil pollution from ships was becoming more of a threat: the amount of oil being moved by sea was increasing, as were the number and size of tankers. The appearance of VLCCs in the 60's gave rise to a growth in the concern about the risk of disastrous oil spills as a result of maritime accidents. This was even more accentuated when in 1967 the Torrey Canyon grounded spilling over 119000 tonnes of oil into the sea.

There was also growing evidence that the 1954 OILPOL Convention was not as effective as some had hoped. Studies by IMO showed that facilities for receiving waste oils in ports were inadequate and the very fact that reception facilities would have to be provided had deterred some countries from ratifying the Convention at all. It was also proving virtually impossible to prosecute those who discharged oil in zones where it was forbidden.

In 1962 IMO called a conference to amend the Convention. The amendments entered into force in May 1967, but by then international attitudes to oil pollution had changed forever by one dramatic event: the sinking of the tanker Torrey Canyon in March of the same year.

The grounding of the Torrey Canyon was the largest marine pollution disaster in history at the time and it was to have profound consequences. It was agreed, that something would have to be done - and it would have to be done at an international level. That meant it would have to be done through IMO.

In 1973 the Oil Pollution Convention was superseded by the International Convention for the Prevention of Pollution from Ships, (MARPOL '73). At this time, it was generally accepted that although vessel accidents receive sensational publicity and cause severe local pollution, the quantity of oil discharged annually from tankers was far greater than the amount of oil lost as a result of vessel casualties. As far as the prevention of oil pollution was concerned the main provision of MARPOL '73 required that every new tanker of 70000 tonnes deadweight and above be provided with **segregated ballast tanks** (SBT). This measure was primarily a means of reducing operational oil pollution and discharge at sea of oil/water mixtures resulting from ballasting cargo tanks. The capacity of the segregated ballast tanks is determined so that the ship can operate safely on ballast voyages without having to recourse to the normal use of oil tanks for water ballast. The vessel must meet certain minimum drafts forward and aft, which enable normal, safe navigation.

In addition to the measures intended to minimise operational discharges, MARPOL '73 contained limited provisions for the minimisation of accidental discharges. These regulations essentially incorporated the amendments to OILPOL '54 in establishing requirements relating to cargo tank arrangements and limitation to tank size in oil tankers, and were based on specified damage assumptions and methods of calculation of the hypothetical oil outflow. Basically, cargo tanks of oil tankers must be of such size and arrangement that the calculated hypothetical oil outflow anywhere in the length of the ship does not exceed 30,000 m^3 or $400.\sqrt[3]{\text{Deadweight}}$, whichever is greater, subject to a maximum of 40,000 m^3.

To protect further the marine environment in the event of damage to oil tankers, provisions were adopted in the Convention specifying bottom and side damage assumptions which tankers in the fully or partially loaded condition must be capable of surviving.

Following a series of tanker accidents in U.S. waters during the winter of 1976/77 growing public concern in the United States over the risk associated with the marine transportation of oil resulted in the announcement of a diverse but inter-related group of measures intended to reduce such risks. The United States Administration were requested to pursue their objectives internationally at the International Maritime Organisation, which led to the IMO Conference on Tanker Safety and Pollution Prevention in 1978 (TSPP '78).

Initially, the TSPP Conference considered a proposal made by the United States to require double-bottoms of a height at least B/15 or two metres, whichever is less, in all new tankers of 20,000 tonnes deadweight and over. This was seen as a mean to reduce oil outflow and the resulting pollution in the event of a grounding. It also considered a US proposal to require all new and existing tankers of 20,000 tonnes deadweight and over to have segregated ballast tanks as a means to reduce oil outflow and the resulting pollution in the event of collision.

As in the MARPOL '73 a majority of nations were strongly opposed to mandatory double-bottoms and a compromise solution was agreed that for new tankers the **protective location** (PL) of segregated ballast tanks was a viable alternative to the fitting of double-bottom tanks.

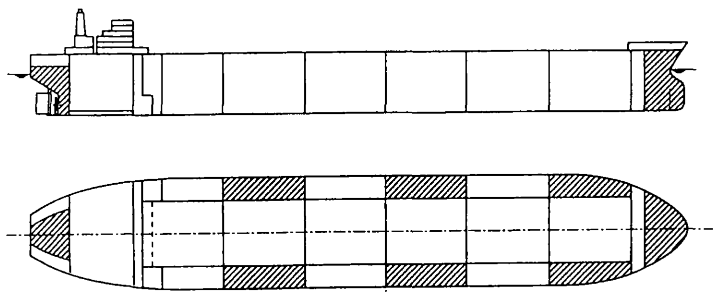


Figure 2.12. - Protective Located Segregated Ballast Tanker.

Protective location is the requirement that SBT should be arranged in such locations so as to provide protection of cargo tanks against rupture in the event of a grounding or collision.

The new requirements for the protective location of segregated ballast tanks formed part of the 1978 Protocol modifying Annex I of MARPOL '73, which has subsequently become known as MARPOL '73/78.

The great majority of international and domestic regulations related to ship design are prescriptive in nature, performance standards would allow greater design flexibility.

Current international regulations for oil tankers, intended to minimize pollution from accidental side and bottom damage, are one example of a prescriptive standard. Although such standards are relatively straightforward in their application, new oil outflow calculation techniques have demonstrated (IMO, 1995a) that these regulations need to be assessed and revised.

The computation of oil outflow from a tanker, that has suffered an accident, is based essentially upon applying an assumed extent of damage and calculating the oil outflow based on physical hydrostatic and "quasi-hydrodynamic" principles.

The International Maritime Organisation has developed guidelines for approving alternatives to the new tanker construction requirements (IMO, 1995b). These guidelines contain a rigorous methodology to compute the oil outflow in accidental groundings and collisions and provide for the development of a "Pollution Prevention Index" for comparison with a series of "reference" double hulls. This index includes three characteristics of the oil outflow performance of any tanker:

- probability of zero outflow;
- mean outflow;
- and extreme outflow,

which will be discussed later in detail. The relative importance of these parameters was determined in an arbitrary manner, although their importance was realised.

Despite the importance of this move, there is a problem with the statistical data used as basis for the probability density functions:

"*The data compiled by the Classification Societies (LR, ABS, DnV, ClassNK, and RI) at IMO's request, is based upon data compiled from collision and grounding incidents including only single-hull tankers, of 30,000 DWT and over, through the period between 1980 to 1990*". (NRC, 1991)

2.4.1 Preventing Operational Oil Pollution

One of the problems involving operational oil pollution from tankers was the ballasting process, once oil was discharged from inside the tanks some of them had to be filled with water, to keep the ship's propeller properly immersed and to maintain sea-keeping and directional stability characteristics.

In the early days of oil tanker operations one of the most important causes of operational oil tanker pollution was the cleaning of tanks with jets spraying seawater, resulting in a mixture of oil and water, which was then pumped overboard.

During the 1960's, technical advances improved some of these procedures. One of the most important innovations being **load on top** that was introduced in 1969 as an amendment to OILPOL '54. This technique introduced two main benefits:

- the owner can recover this oil;
- it is not discharged to the environment as a mixture with water.

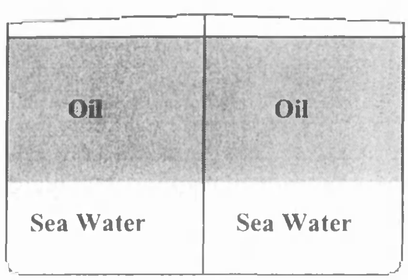


Figure 2.13. - Load-on-top technique.

Recognising that oil was the major threat to the marine environment, in 1973, IMO adopted the International Convention for the Prevention of Pollution from Ships, which covers pollution by chemicals, packed goods, sewage and garbage as well as oil. This Convention was modified by a protocol in 1978 and is now usually known as MARPOL 73/78.

MARPOL '73 regulations are a comprehensive set of regulations dealing with:

- provisions requiring the use of dedicated segregated ballast tanks;
- specific requirements for hypothetical oil outflow;

➢ limitations on the volumes and dimensions of cargo tanks.

The Protocol '78 regulations added requirements for a **Protective Location of Segregated Ballast Tanks**. It also limits or bans the amount of oil that may be discharged into the sea during routine operations.

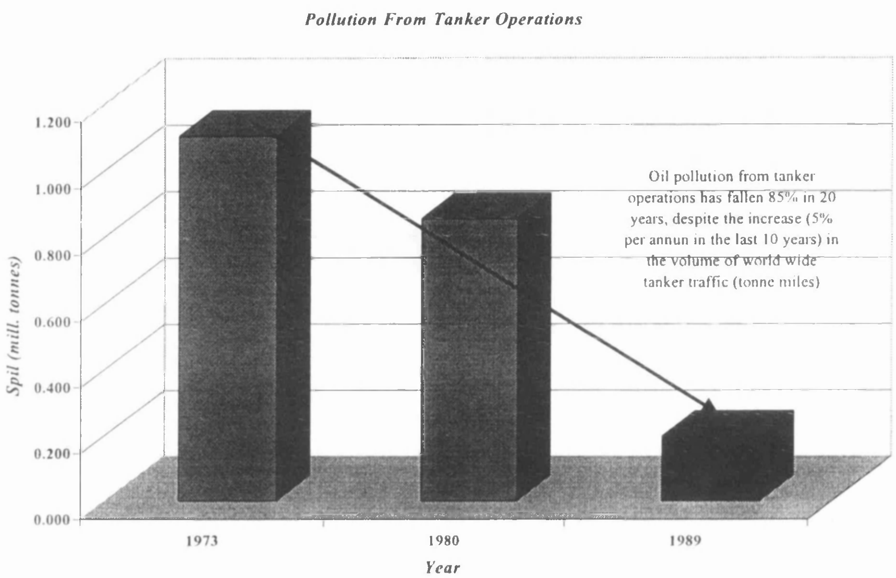


Figure 2.14. - Pollution from Tanker Operations (Source: U.S. National Academy of Sciences, 1990).

2.4.2 Preventing Accidental Pollution

The most important of all conventions adopted by IMO is the International Convention for the Safety of Life at Sea (SOLAS), 1974, which includes special requirements for tankers. Fire safety provisions, for example, are much more stringent for tankers than for ordinary dry cargo ships, since the danger of fire on board ships carrying oil and refined products is much greater.

To provide a safe atmospheric environment inside tanks, the space in empty tanks or the space left above the oil must be filled with inert (non-explosive) gas from the ship's boiler exhausts. An inert gas system is required on all-new tankers and most existing tankers of 20 000 DWT and above.

IMO has introduced several measures over the years, which are designed to ensure that, in the event of mechanical failure, the ship can still be controlled:

- it is necessary that essential parts of the steering gear of tankers to be duplicated;
- the navigational equipment of tankers must also be duplicated;
- the possible duplication of propulsion to provide power in the event of emergencies should be considered.

With the expectations of being able to eliminate sub-standard ships, since 1995 all tankers and bulk carriers aged five years and over have been subjected to a specially enhanced inspection program. The main aim of this measure is to insure the detection of any deficiencies at an early stage (corrosion, wear and tear).

The International Regulations for the Prevention of Collisions at Sea, 1972 is another convention, which is particularly relevant to tanker safety. These regulations contain special provisions for tankers, which have a reduced ability to manoeuvre, by virtue of their draught, It also contains the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978, several of whose requirements are designed specifically for those working on tankers.

This Convention was completely re-written in 1995 and the amendments became effective in 1996. For the first time it gave IMO the right to check on the administrative, training and certification procedures of Governments to ensure that the seafarers they produce meet IMO standards.

An International Safety Management Code was adopted in 1994 and became mandatory for tankers in 1998. The delay was needed because the Code imposes very strict standards on shipping companies, which takes time to implement. Although there have been many huge oil spills resulting from tanker accidents, in the open ocean, oil generally disperses naturally, with relatively minor consequences for wildlife. The major disasters have happened when the spill has been near to land and IMO has developed procedures, which are designed to help Governments respond to emergencies as quickly and effectively as possible.

The Intervention Convention of 1969 was designed to enable Governments to take action when the threat occurs near their coastline but outside their territorial waters. Until the adoption of this Convention there were considerable legal difficulties involved in taking such action, since countries have always been prevented from acting against ships of other countries operating on the high seas. It was widely recognised by Governments, however, that it was essential to operate as soon as possible in the event of a major accident threatening pollution and the Convention was designed to enable them to do so.

Salvage operations at sea are normally arranged between the shipowner and a salvage company. Traditionally in the event of an accident the arrangement is based on a Lloyd's Open Form, meaning that the salvor will only receive payment based on the value of the ship and cargo if the operation is successful (a formula known as "no cure, no pay"). In practice this system did not prove suitable for salvage operations involving possible oil pollution since it does not take pollution into account. A salvor could avert a major pollution incident and, because the ship was not completely salvaged, receive no recompense.

In 1989 IMO adopted the International Convention on Salvage, which has entered into force on 14 July 1996. The Convention makes provision for "special compensation" to be paid to salvors when there is a threat to the environment.

To help ensure that salvage operations are successful, since 1 January 1996 all new tankers of 20,000 dwt and above must be fitted with an emergency towing arrangement at either end of the ship. Similar arrangements must be fitted to existing ships at the first dry-docking scheduled after that date but not later than 1 January 1999.

2.4.3 Reducing the Consequences of Accidents

MARPOL 73/78 stipulates that new tankers must meet certain requirements regarding subdivision and stability, which are intended to ensure that, in any loading conditions, the ship can survive after being involved in a collision or stranding.

The 1978 MARPOL Protocol introduced a further element. This is the concept known as **protective location of segregated ballast tanks**. This way the amount of cargo spilled after such an accident will be greatly reduced. The 1983 MARPOL amendments ban the carriage of oil in the forepeak tank - the ship's most vulnerable point in the event of a collision.

In 1992 MARPOL was amended to make it mandatory for tankers of 5,000 dwt and more ordered after 6 July 1993 to be fitted with double hulls, or an alternative design approved by IMO.

Despite the measures introduced by IMO, tanker accidents continue to happen, as the Braer and Sea Empress incidents have shown. IMO is especially concerned about tanker safety because the world fleet of tankers is growing steadily older - and statistics show that there is a correlation between age and the accident rate. The bulk of the world's tankers were built in the 1970s at a time when it was anticipated that demand for oil would continue to rise. But instead dramatic increases in oil prices stopped this from happening. The industry was left with a surplus of tanker tonnage, which has persisted ever since and has restricted the amount of new tonnage ordered.

Figure 2.15. - Braer (source: Internet).

Apart from the fact that old ships tend to have more accidents than new ones, ships built in the 1970s do not have to comply with many of the stricter standards that have been introduced since. The principle that existing ships should be exempt from new regulations that involve major structural changes could be justified at a time when ships were replaced with new tonnage at a comparatively young age. It was felt that owners who built and equipped their ships according to the standards existing at the time should not be forced to modify them every time new requirements were introduced.

But throughout the 1980s and 1990s the average age of ships including tankers has risen steadily and the "safety gap" that has resulted has increased concern about safety and pollution and has resulted in a reversal of the traditional attitude. As a result many of the requirements introduced for new ships have now been extended to existing vessels.

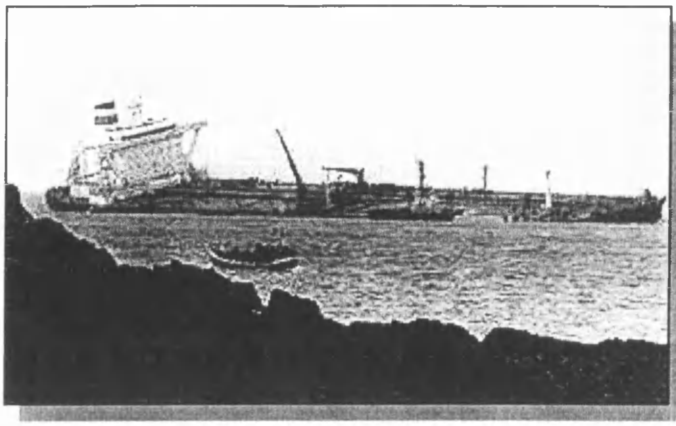


Figure 2.16. - Sea Empress (source: Internet).

The requirement for double hulls that applies to new tankers has been applied to existing ships under a program that began in 1995. All tankers built in the 1970s will have to be converted when they reach the age of 25. Within the next few years, therefore, the bulk of the world's tanker tonnage will have to be fitted with double hulls - or scrapped. This measure is being phased in over a number of years because shipyard capacity is limited and it would not be possible to convert all single hulled tankers to double hulls without causing immense disruption to world trade and industry.

At present only a small amount of the world's 3,500 tankers have double hulls. Calls for single hulled ships to be banned are therefore scarcely practicable from an economic point of view - there are not enough double hulled tankers to carry more than a small fraction of today's world trade in oil and most of those are already committed to fixed trading routes. In any case, it is generally felt that while double hulls can minimise oil spills in certain circumstances - such as a low-speed grounding - they would provide little protection in the event of a high-speed impact or a collision with another ship.

A treaty designed to help Governments combat major oil pollution incidents became international law in May 1995. The treaty is the International

Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC), which was adopted in November 1990.

The Convention is designed to facilitate international co-operation and mutual assistance in preparing for and responding to a major oil pollution incident and to encourage States to develop and maintain an adequate capability to deal with oil pollution emergencies.

2.4.4 Providing Compensation for Pollution

The prevention of marine pollution is IMO's primary concern. However, this Organisation has also taken steps to ensure that adequate compensation is paid to those who suffer when pollution does occur.

The purpose of the 1969 Civil Liability Convention (CLC) is to put the onus of paying compensation on the shipowner. The 1971 Fund Convention extends additional liability to oil importers, who pay into a central fund an amount, which depends upon the amount of oil they import.

The two-tier system works in the following way:

- under the Civil Liability Convention, those affected by oil pollution are able to claim damages from the shipowner whose ship is judged to be responsible for the pollution. But the shipowner is able to limit the amount of compensation payable to about $US 14.6 million or $US 140 per ton of the tanker. This is so that he can obtain insurance cover, if there was no limit on the amount of compensation payable, the shipowner would not be able to insure himself, and a major claim could prove financially disastrous. In the event of the shipowner being forced into bankruptcy there would also be the possibility of claimants not receiving any compensation at all.

But it was recognised that the $US 14.6 million limit could very well prove to be inadequate if the pollution incident were a major one. It was also felt that the oil importers should shoulder their share of the burden. Thanks to the creation of the International Oil Pollution Compensation Fund, victims of oil pollution can claim additional compensation, beyond the $US 14.6 million payable under the Civil Liability Convention, providing total compensation of about $US 90 million. Oil importers pay contributions to the Fund.

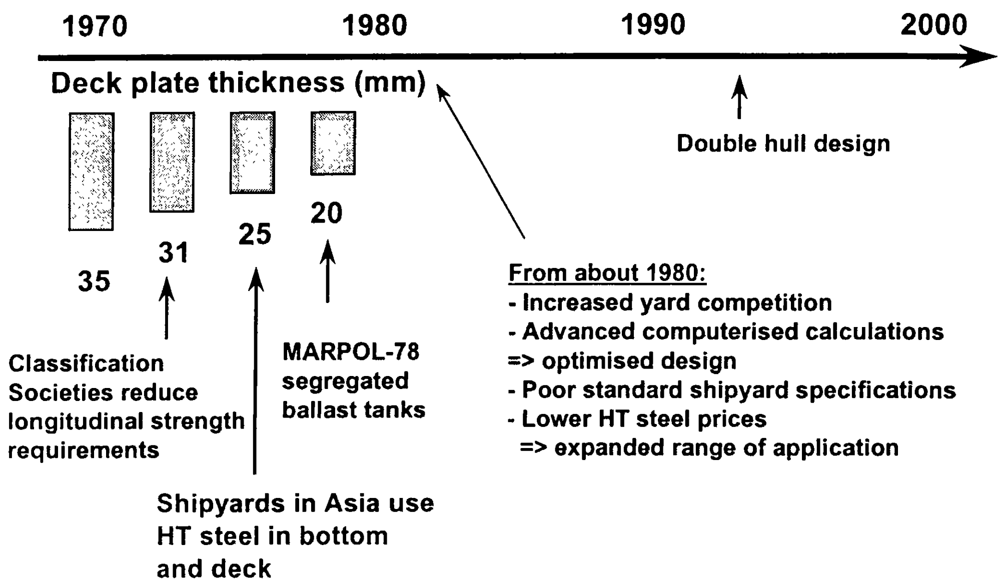


Figure 2.17. - VLCC Historical Background (source: American Petroleum Institute Web Page – Lars Carlsson).

Since the two Conventions were adopted, inflation and other factors have made even these sums inadequate to pay compensation in the event of a major disaster. In 1992 the liability limits in the two Conventions were increased by means of two Protocols. The maximum shipowners' liability limit was increased to $89 million for ships of 140,000 grt and above. When the damage exceeds the limit of the shipowner, the Fund Protocol will provide an additional source of compensation.

The basic coverage (including the liability under the CLC Protocol) will rise to a maximum of $201 million and the procedure for increasing limitation amounts in future has been simplified.

These Protocols entered into force on 30 May 1996.

2.5 Changes in Marine Pollution Regulations Following OPA '90

U.S. legislators in the wake of Exxon Valdez disaster brought in the Oil Pollution Act 1990. It is one of the most important environmental legislation of recent years and affected owners and builders worldwide. It also has important implications for the salvage industry.

In November 1990, the United States submitted a proposal to the thirtieth session of the IMO Marine Environment Protection Committee to establish an international requirement for double-hull tankers. This proposal eventually resulted in the adoption of MARPOL 73/78 Regulations I/13F and I/13G (MARPOL 13F and 13G). These regulations, which became effective in July 1993, apply to the vessels of all nations and are similar to the provisions of Section 4115 of OPA '90.

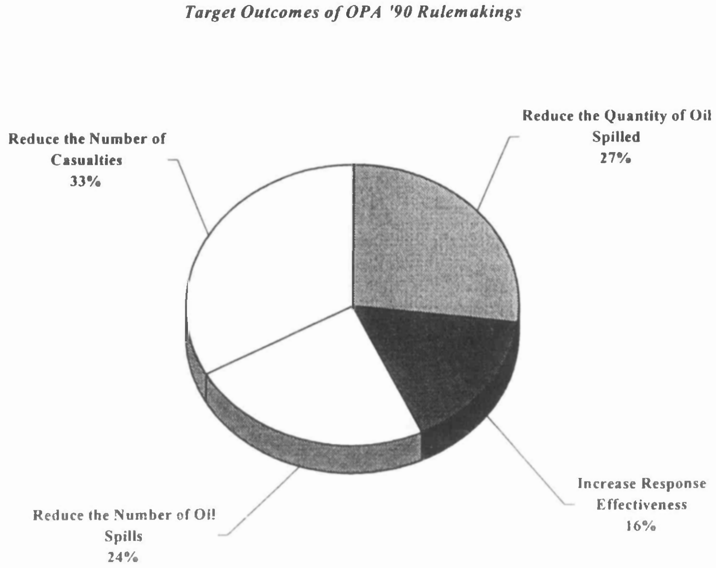


Figure 2.18. -OPA '90 Rulemakings.

2.5.1 New Vessel Requirements

MARPOL 13F specifies the hull configuration requirements for new oil tankers contracted after July 6, 1993, of 600 deadweight ton (DWT) capacity or more. Oil tankers between 600 and 5,000 DWT must be fitted with double bottom or double sides, and the capacity of each cargo tank is specifically restricted. Every oil tanker of more than 5,000 DWT is required to have a double hull (double bottom and double sides), a mid-deck with double sides, or an alternative arrangement specifically approved by IMO as being equivalent to the double hull design. These requirements, along with those of OPA 90, are shown in Table 2.4.

MARPOL 13F specifies that other designs may be accepted as alternatives to double hulls, provided that they give at least the same level of protection against the release of oil in the event of collision or grounding and are approved, in principle, by IMO's Marine Environment Protection Committee.

IMO design guidelines employ a probabilistic outflow methodology for calculating oil outflow and a pollution prevention index to assess the equivalency of alternative designs.

Table 2.4 - Requirements of IMO regulation 13F and OPA '90 for New Vessels (source: National Academy Press).

	Size	Hull Requirements	Enforcement Date
OPA 90 Section 4115	< 5,000 GT	Double-hull or double-containment systems	Building contract placed after June 30, 1990 Delivered after January 1, 1994
	> 5,000 GT	Double-hull	Building contract placed after June 30, 1990 Delivered after January 1, 1994
IMO Regulation 13F	< 600 DWT	Not applicable	
	600 – 5,000 DWT	Double bottom or double sides	Building contract placed after July 6, 1993 New constructions or major renovation begun on or after January 6, 1994 Delivered after July 6, 1994
	> 5,000 DWT	Double hull, mid-deck with double sides, or equivalent	Building contract placed after July 6, 1993 New constructions or major renovation begun on or after January 6, 1994 Delivered after July 6, 1994

Section 4115 of OPA '90 and MARPOL 13F take different paths in addressing the change to double-hull construction. Section 4115 restricts oil trade to the United States by vessels without double-hulls according to a schedule based on vessel age. MARPOL 13F takes a proactive approach requiring all vessels constructed after a certain date to have double-hulls or an approved alternative. MARPOL 13G allows existing vessels to trade for a longer period than that allowed under section 4115 if they are of acceptable design. Table 2.4 shows that Section 4115 is more restrictive in controlling vessels in the international fleet able to serve the United States.

2.5.2 Existing Vessel Requ irements

MARPOL 13G, which pertains to single hull vessels, applies to crude oil tankers of 20,000 DWT or more, and to oil product carriers of 30,000 DWT or more. The regulation specifies a schedule for retrofitting (with double hulls or equivalent hull designs or operational measures) or retiring single-hull tank vessels 25 or 30 years after delivery. The differences between MARPOL 13G and OPA '90 are shown in Table 2.5.

Tankers not fitted with Segregated Ballast Tanks (SBTs), or fitted with SBTs not protectively located, must have designated protectively located double side or double-bottom tanks or spaces when they reach 25 years of age. In appropriate locations, SBT would be acceptable as protectively located spaces.

MARPOL 13G also allows Hydrostatically Balanced Loading (HBL) and other alternatives (operational or structural) to protectively located spaces. Tankers built in compliance with Regulation I (6) of MARPOL 73/78 have protectively located ballast spaces and require no modification until reaching 30 years of age. On reaching 30 years of age, all tankers in the oil trade must be converted to double hulls or an acceptable equivalent according to MARPOL 73/78, Regulation I/13F(5).

Table 2.5 - Requirements of MARPOL 13G and OPA '90 for Existing Vessels (source: National Academy Press).

	Size	Hull Requirements	Enforcement Date
OPA 90 Section 4115	< 5,000 GT	Double-hull or double-containment systems	After January 1, 2015
	> 5,000 GT	Double-hull	Per schedule starting in 1995
		Operational measures	November 27, 1996
IMO Regulation 13F	Crude carriers > 20,000 DWT and product carriers > 30,000 DWT	Double-hull or equivalent	30 years after date of delivery
		PL/DS or PL/DB or PL/SBT or HBL or equivalent	25 years after date of delivery

The United States has reserved its position on the loading and structural provisions of MARPOL 13G applicable to single-hull tankers. The recent rule promulgated by the USCG does not require structural modifications of single-hull vessels before they are phased out. MARPOL 13G also imposes a program of enhanced ship inspections during periodic, intermediate, and annual surveys. This same provision is included in the November 1996 USCG rule in operational measures (Federal Register, 1996).

The fact that the United States has reserved its position on the aforementioned provisions of 13G will have little effect on most vessels calling at U.S. ports and on the resulting protection of U.S. waters. OPA '90 requires most vessels to retire by age 25, and 13G comes into effect only when vessels reach 25 years of age. Thus, most vessels 25 or older - whether in international or coastwise trade - will be excluded from U.S. waters by OPA '90, regardless of the provision of 13G. There is one notable exception to this situation, namely, larger vessels operating to lightering areas and the deepwater port under the OPA '90 exemption.

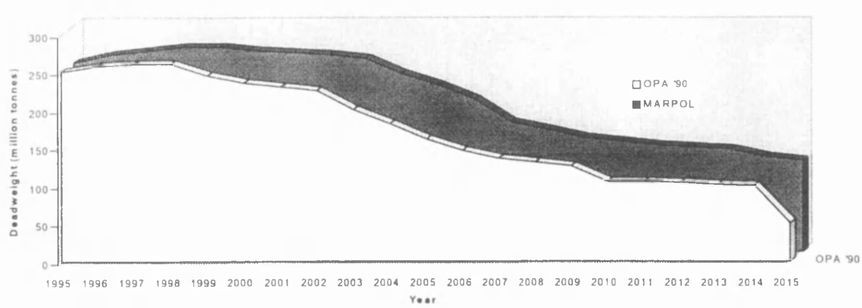


Figure 2.19. - Effect of IMO Regulations 13F and 13G and OPA '90 Section 4115 on eligibility of existing vessels to operate in U.S. waters (source: National Academy Press).

Tankers up to 30 years of age that are in compliance with 13G will be allowed to trade in international waters. These same vessels will be allowed to trade to the United States under OPA '90 exemption, regardless of the U.S. position on 13G.

2.6 New Design Concepts

The Exxon Valdez disaster and the subsequent unilateral legislation by the U.S. (OPA '90), led to a real surge of scientific investigation, engineering work and rule finding activities more or less worldwide. It is of common understanding that they will continue, for some years to come.

The creative unrest among shipbuilders, induced by the above events, yielded various new design and engineering concepts, which had to be proven and compared from an environmental point of view. Regulatory bodies consequently were asked to evaluate and check these concepts.

In February 1991 the Committee on Tank Vessel design on the United States judged, "The Committee did not identify any design superior to the double-hull for all accident scenarios". Furthermore, "The nation deserves designs employing physical barriers, such as double-hulls, over those that continue to employ a single-hull, such as the design with intermediate oil-tight-deck with double sides", i.e. the mid-deck tanker.

Following this judgement, which gave priority to the double-hull, every alternative design that came up had to be compared against this concept, but primarily the double-hull itself had to be optimised from an environmental point of view. In this situation the probabilistic method finally was recognised as the only rational and available tool to perform this considerable task. In Europe, e.g. by Det Norske Veritas (Køhler, 1991), and in the United States

(HEC, 1992) design studies were published, in which the oil outflow for various subdivision modes was compared.

The first group of studies published in 1991 served to demonstrate to the public and to shipbuilders the capability of probabilistic calculations in comparing the oil outflow of various modes of subdivision including double-hulls. Hook (1991) stressed in his investigations, that no correlation exists at all between the ranking of subdivisions which follow the deterministic formula for the protective location of segregated ballast tanks as per MARPOL 73/78, Annex I, regulation 13E and the probabilistic ranking respectively. This refers as well to the probability as to the quantity of the expected outflow itself and means, that a subdivision which according to regulation 13E is optimal, in fact is not necessarily the best, or viceversa. Hence regulation 13E may be due for revision or even cancellation.

In the discussion to papers dealing with the probabilistic concept of damage incidents (see discussions to Abicht, 1977 and Hook, 1991), there are some voices objecting to this approach. It is argued that people partly tend to have a psychological preference for determinism, whether this is adequate and rational or not. There seems to be a barrier against unconventional thinking. It may be that this is a cause of the reluctant acceptance of probability in ship safety and pollution prevention. Another reason could be the extensive computer calculation work, necessary in the early design stage, when the subdivision of a tanker is to be optimised by the probabilistic method.

A second stage of detailed probabilistic investigations on subdivision of tankers began after the rejection of the mid-deck tanker concept by the U.S. Committee on Tank Vessel Design in 1991. The reasons for this rejection were based on the statement that this design and its implementation were unproven. At the same time the Marine Environment Protection Committee (MEPC) of IMO did a contradictory acceptance of the same concept by MARPOL regulation 13F in 1992 (IMO, 1992). This second set of investigations considered various sizes of tankers.

Fortunately the same engineering company performed these investigations, carried out by orders of U.S. Coast Guard and IMO respectively. Therefore, the tools applied for the calculations were identical. U.S. Coast Guard ordered comparative studies for double-hull tankers of 50 000, 150 000, and 270 00 tdw together with four design alternatives for each; these were as follows:

- Mid-deck tanker;
- MARPOL SBT-tanker;
- COULOMBI EGG-tanker (patent);
- POLMIS tanker (proprietary).

The investigation covered various influences on the outflow from grounded tankers, i. e. approach speed, falling tide, current and waves. Furthermore, as applicable, variation of underpressure on top of the oil cargo and influence of rescue tanks were taken into account. The comprehensive results of this careful study, which are based on final flooding and damage stability calculations for all considered damage cases are given in the report of HEC (HEC, 1992).

It has been recognised by all parties for some time that double hulls were not the only answer to reducing pollution from crude carriers. However, the American legislature decided, in the wake of the Exxon Valdez accident, that it was the best solution to their particular problems.

IMO has already recognised that other designs can provide protection equivalent to that of double hulls.

It is now clear that there are two methods of minimising pollution in the event of an accident involving a crude carrier. The first is to prevent the cargo tanks being breached - as double skins are designed to - the second is to minimise the oil escaping from the tanks once the breach has occurred; this later almost invariably involves utilising hydrostatic balance, with or without refinements.

There are strong arguments both for and against double hulls. On the positive side:

- most collisions and groundings involving tankers are low energy accidents which are unlikely to penetrate the inner hull;
- the technology for building double hulls has been around for some time, albeit applied to rather small ships;
- it has, as a design, a proven track record.

The downside lies:

- increased maintenance;
- increased hazards from cargo and explosive gases leaking into the ballast spaces due to the increased boundary between ballast and cargo tanks;
- under certain circumstances, a pollution incident could actually be exacerbated by the double hull rather than reduced.

It is concern with these last points that has led builders and maritime authorities to look for other ways of tackling the problem. The fear before the publication of OPA - that if a particular hull design was prescribed it would strangle innovation - has proved to be unfounded. The door for innovation has been left open by IMO's comparative study on oil tanker design and the possibility that the OPA could be modified at a later date.

Given that double-hulls do not provide all the answers and that other designs may provide equivalent protection, the question arises about how this equivalence is to be judged. The IMO took equivalence to lie in a tanker's "environmental performance (oil outflow in the event of collision or grounding)" but has, however, recognised that there are problems in the application of this criterion to other, potential equivalent, designs. It has setup a sub-committee under the auspices of the Marine Environment Pollution Committee that led to IMO Interim Guidelines (IMO, 1995), applied here in this study.

A number of alternative designs have already been proposed or presented to the maritime community and legislative bodies. The new design concepts found as proposals or already approved as equivalent to double-hulls, during this investigation, are listed below. In this list are also included retro-fitting to existing hulls.

- Mitsubishi Mid-Decker;
- Mid-Deck with rescue tanks (Intertanko);
- POLMIS.
- ECO-bulkhead;
- COULOMBI EGG;
- POLIS;
- SCOL;

The mid-deck tanker from Mitsubishi has been accepted by IMO as an equivalent to double-hulls. This design is characteristic of many of the proposals. It consists of wider side ballast spaces to increase protection against collision. The tank arrangement ensures also a preponderance of upward pressure at the bottom of the hull i.e. that, in the event of a grounding, which ruptures the bottom plating, water will flow in rather than oil flowing out.

The mid-deck or tween-decker uses this principle, having a lower head of cargo in the lower tanks than conventional tanker designs, which will, exert a lower pressure at the bottom of the plating than the upward pressure from the water outside. The position of this horizontal deck is of crucial importance to this design, as both too small and too large pressure differentials would influence performance under certain circumstances. Because there are no ballast tanks in the bottom, the side tanks are wider (6 m) as opposed to approximately 3m for a conventional VLCC.

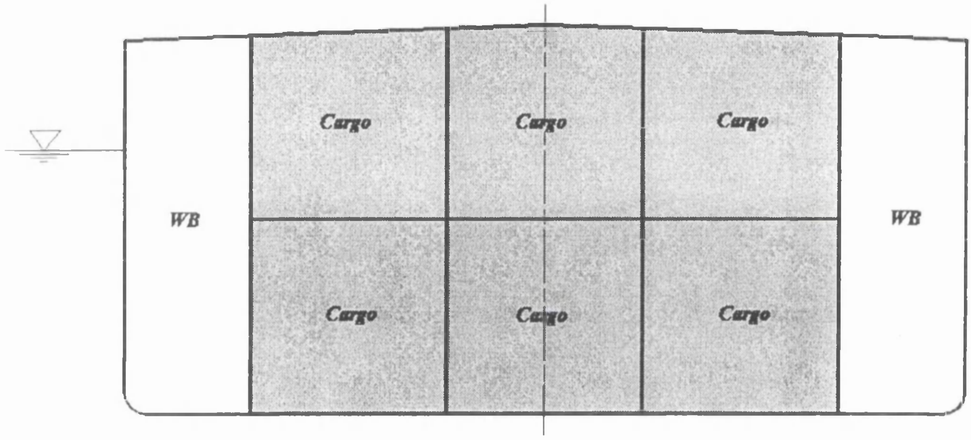


Figure 2.20. - Mitsubishi Mid-Deck Design.

The current consensus of opinion is that these are better than double-hulls in certain circumstances, particularly high-energy accidents. However, there are certain areas where double-hulls out-perform the Mitsubishi design:

- there will be, despite the negative hydrostatic balance of the mid-decker, a small outflow of oil in accidents that would not puncture the inside skin of a double bottomed tanker;

- there are also concerns about gas freeing the bottom tanks and the importance of using the correct loading sequence to avoid capsize.

One criticism that has been levelled at both the double-hulled tanker and the tween-decker is that the oil will stay in the tank and could be subject to "tidal discharge". This is what occurred on the *Exxon Valdez* disaster; after the initial oil outflow, the tide fell and more oil leaked from the damaged tanks. This criticism was answered by a new design that was promoted by Intertanko. Originally proposed by Phillipe Embiricos, this consists of a mid-deck design with a piping network to evacuate the cargo, in the event of an accident, to other, empty, cargo tanks, or to the ballast spaces if there is no room elsewhere. In order to satisfy the MARPOL requirement that the cargo tanks and the ballast spaces are not connected directly there are removable connections above the deck. The piping arrangement should also facilitate refloating in the event of a grounding because it would ease retrimming of a damaged ship.

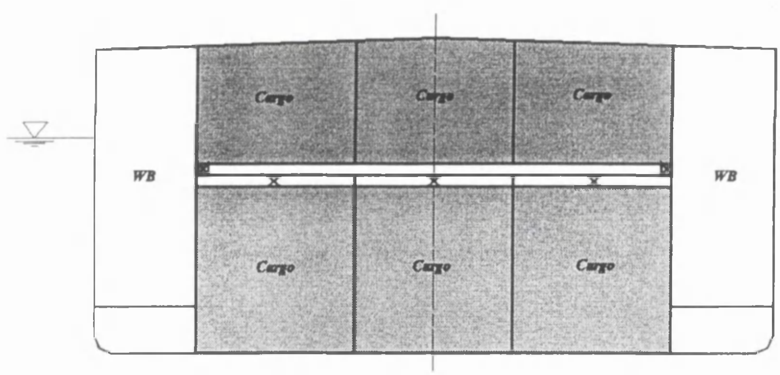


Figure 2.21. - Mid-Decker Design with rescue tanks: promoted by Intertanko.

There are other designs that also promote hydrostatic balance as the answer to reducing pollution. The POLMIS (Pollution Minimisation System) design (Figure 2.22), which has been developed by George Paraskevopoulos, uses Y-shaped divisions inside the main cargo space and features two large rescue tanks in the same Y-format (maintained in vacuum condition) between the cargo tanks. In an emergency, oil can be pumped into these tanks. The large central tank is located in a protected position and the wing tanks are so that they satisfy the criteria for maintaining hydrostatic balance. By maintaining the cargo levels in the wing tanks below that which would create hydrostatic balance, pollution would be minimised. The tanks are also designed to minimise the loss in cargo capacity.

The COULOMBI EGG Mid-Deck Tanker (Figure 2.23) is a proposal of Anders Björkman (Björkman, 1992). It also uses the principle of hydrostatic balance, but avoids the need for double sides. It has a mid-deck with upper wing tanks being used as ballast spaces.

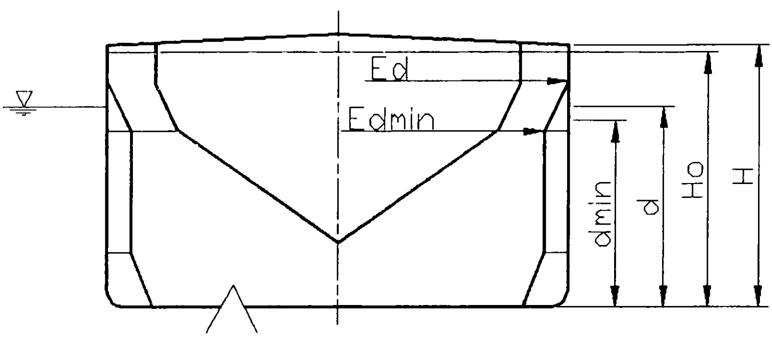


Figure 2.22. - Tank cross-section of POLMIS Concept showing the void spaces at the top of the wings - the potential oil-leak volume is reduced to a minimum between lines H_0 and E_{dmin}.

In the event of collision or grounding, the oil in the damaged tanks would be transferred under hydrostatic pressure via trunk risers to the empty ballast tanks. Provided that the ship is sailing with the horizontal bulkhead below sea level, there should be minimal oil spillage. It is also claimed that the trim of the ship would not change substantially in the event of an accident.

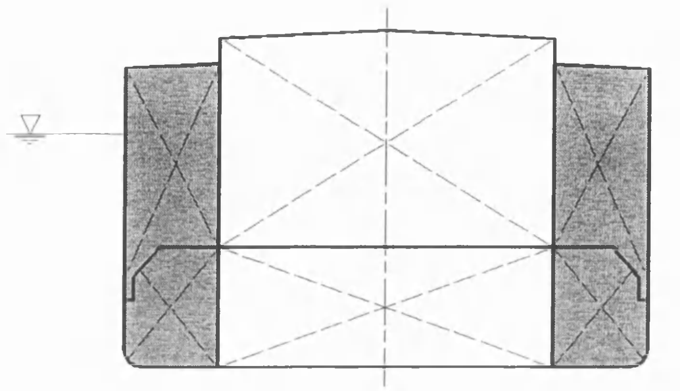


Figure 2.23. - COULOMBI-EGG Mid-Deck Tanker.

The ECO-bulkhead design is an innovative tanker swash bulkhead developed in the Netherlands. This new concept consists of this modified swash bulkhead, having a closed watertight plate structure from deck to bottom except for relatively small holes near the bottom. The authors claim that this specific configuration prevents the outflow of oil from an undamaged part of a tank, by limiting the replacement inflow to the level of the holes near the bottom (Lann, 1995).

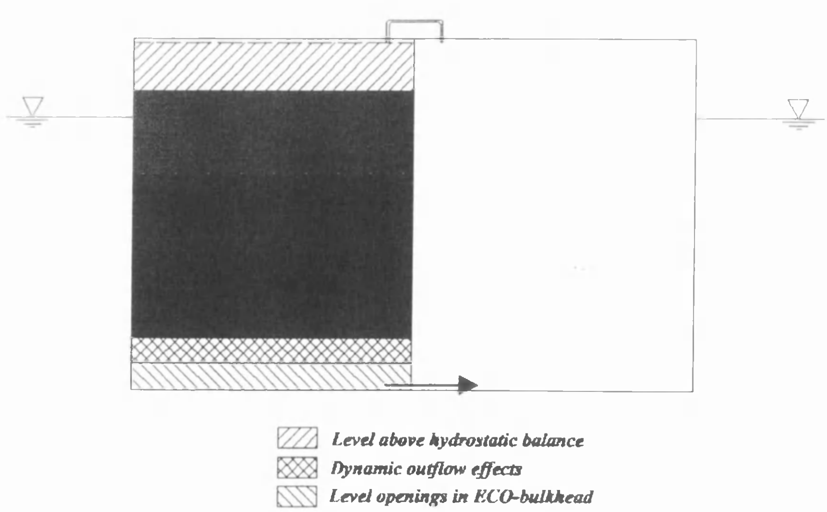


Figure 2.24. - ECO-bulkhead sketch.

The new designs are not only for completely new ship concepts, but also for the retrofitting to existing hulls. George Paskevopoulos, designer of the POLMIS configuration, has also developed a retrofit system called POLIS (Pollution Limitation System).

However the decision to retro-fit or not retro-fit led to a lot of discussion at IMO. They considered the age and configuration of the existing fleet; a large percentage, is more than 15 years old, which means that not only they are starting to reach the end of their originally estimated design life but also that they were built before MARPOL '78. IMO therefore legislated for segregated ballast tanks for new buildings, but did not require their retro-fitting if the cheaper option of a crude oil washing system was fitted.

Various solutions to the pollution problem have been suggested. One of the suggestions that received more attention was one that involved the partial loading of existing tankers to a level where hydrostatic balance is achieved, between the cargo and the sea, coupled to the retro-fitting of a practical level of segregated ballast tanks. This would solve the problem of the remaining life of the vessels, reduce the pressure on the new building yards and avoid a demand-driven price rise.

However this was not the only suggestion. The Energy Transportation Group, of New York promoted THE SCOL system (System for Control of Oil Leakage) (Ship Repair and Conversion Technology, 4^{th} Quarter 1991). It consists of simple mechanism of providing a VLCC with a network of sluice valves and pipe runs, which allow the transfer of oil from a damaged cargo tank to adjacent segregated ballast tanks to limit cargo discharge to the open sea. They claim that this tanker compares favourably with both double-hulls and mid-deck type, but only costs approximately 3% more than a conventional single-hull.

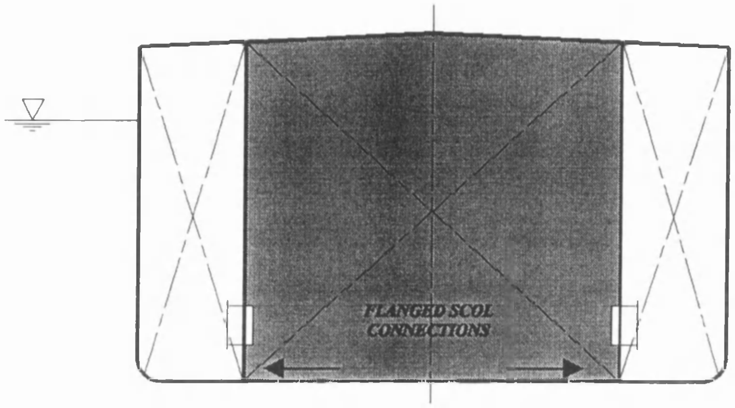
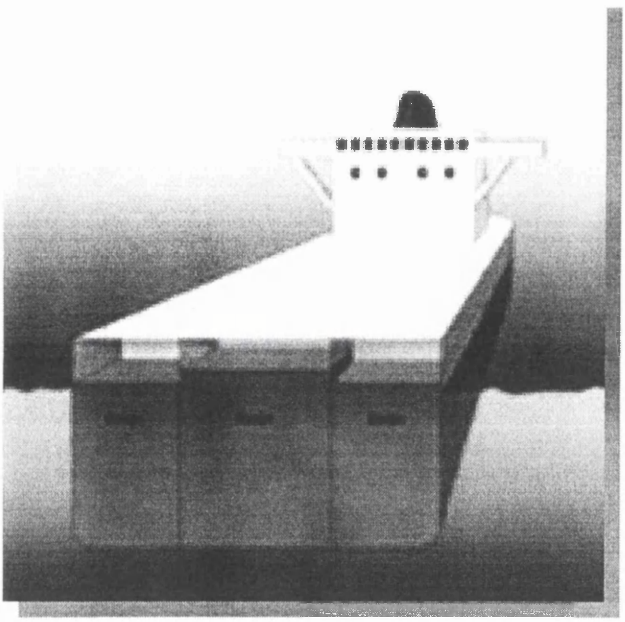


Figure 2.25. - Typical Section Side Tank SCOL.

(see section 2.5, for a better understanding of the changes required for existing vessels and new vessels, under the present regulations.)

CHAPTER 3

THE PROBABILISTIC APPROACH TO SHIP SUBDIVISION



CHAPTER 3 - THE PROBABILISTIC APPROACH TO SHIP SUBDIVISION

3.1 Introduction

The major outcome of the discussion held at meetings of the First Bulkhead Committee was the introduction of the Factorial Method, which lays down a procedure for determining statutory minimum levels of subdivision, which are to be achieved by all sea-going passenger vessels – which meant, in essence, Trans-Atlantic liners.

For the last thirty to forty years IMO members have become increasingly aware of the inherent flaws in the 'Factorial' method as a suitable means of assessing the 'survivability' of a passenger ship. The use of floodable or permissible length curves nowadays is quite rare, since designers appreciate that damage stability requirements invariably over-ride those arising from the subdivision part of SOLAS. Maintaining an adequate level of residual stability is much more important than establishing that there is residual buoyancy available.

The concept of a statutory maximum damage extent is linked with the regulatory minimum residual stability standard to be met. In effect, this implies a minimum length for any compartment before it can be considered as a 'true' compartment in a regulatory sense. Therefore, most present-day designs of passenger ships tend to have compartment lengths only marginally greater than this statutory distance – 0.03L + 3.0m – particularly in the midships region. This preponderance of relatively-closely-spaced bulkheads clearly increases the possibility of a side damage opening up two, or even three, adjacent compartments. When this undesirable situation is linked, in addition, to a freeboard to the bulkhead deck which only achieves marginal compliance with the specified stability criteria, (as it often does), the overall result is a relatively poor standard subdivision.

A ship's subdivision serves primarily to limit flooding due to casualties causing water ingress and its purpose is to conserve floatability and stability. Collisions between ships are perhaps the most common marine accident. They are random events and can be described using the dimensions and locations of the penetrations causing flooding. Those dimensions and locations are random quantities. Whether such accidents can be survived depends on various states, quantities and characteristics whose specific values also occur randomly in the accidents. This whole situation results in the probabilistic concept being the most suitable manner to approach these phenomena.

At the beginning of 1960, Wendel and his associates (Wendel, 1960) introduced the probabilistic approach to evaluate a ship's subdivision, thus making it possible to calculate a numerical value of the attained safety, and also, which is even more important, that of the residual risk. Casualties do occur and they will continue to do so, regardless of the efforts made. Nevertheless, every ship should be able to avoid at least the most serious situations, like too rapid capsizing and foundering that do not allow time to save human lives.

This probabilistic concept has only gradually begun to enter into shipbuilding practice during recent years but at present it is valid only for collision damages of some types of ships. A lot of work remains to be done, to cover all the aspects of flooding, and all other types of floating vessels. The changes, spurred on by the tragic accidents suffered by some Ro-Ro passenger ships, in Resolution MSC 26(60) (IMO, 1992), were made by slight modifications of the well-known Resolution A. 265 (VIII) from 1973 (IMO, 1973).

Very frequent tragic incidents involving even the most modern ships show that they are, unfortunately, much too vulnerable. Contemporary methods of calculations show this convincingly enough to make it necessary to undertake measures to diminish the hazard.

The use of probabilistic concepts is a major change from the outdated deterministic methods of assessment of ship subdivision and damage stability specified by IMO regulations. This method was adopted at IMCO in 1973 in Resolution A. 265 (VIII) as an alternative to the existing subdivision and damage stability requirements for passenger ships based on the one, two or three compartment damage survivability standard. The Dry Cargo Ship Regulations were developed more than fifteen years later than the issue of the Passenger Ship Regulations. The application to dry cargo ships began on 1 February 1992 (IMO, 1992a), and in IMO Resolution (IMO, 1992b) it is expected that the provisions of the Circular (IMO, 1991), to existing Ro-Ro passenger ships will be applied soon.

3.1.1 Mathematical Bases

To begin with, if there is transversal subdivision only, there are two random quantities, which would be sufficient to describe collision casualties resulting in flooding, the longitudinal location and the extent of damage.

They have a random nature and the same holds true for almost all other quantities and conditions on which survival depends. "Random quantities" or "random variables" represent such quantities. Usually some of their ranges of values are more frequent than others.

X may have limiting values. For example, the damage length cannot stretch outside the ship and its value can vary only from zero to not more than the full length of the ship. This is expressed by assigning a unit value to the total probability of damage over the ship length. Outside the length of the ship the probability is zero (see Figure 3.26).

Adopting the symbol p for probability, then the probability of all the values from a range is determined by the area under the curve $f(x)$ in that range. The values $f(x)$ are such that the entire probability, P_m, equals unity:

$$P_m(x_1 < x < x_2) = \int_{x_1}^{x_2} f(x)\,dx = 1. \qquad (4)$$

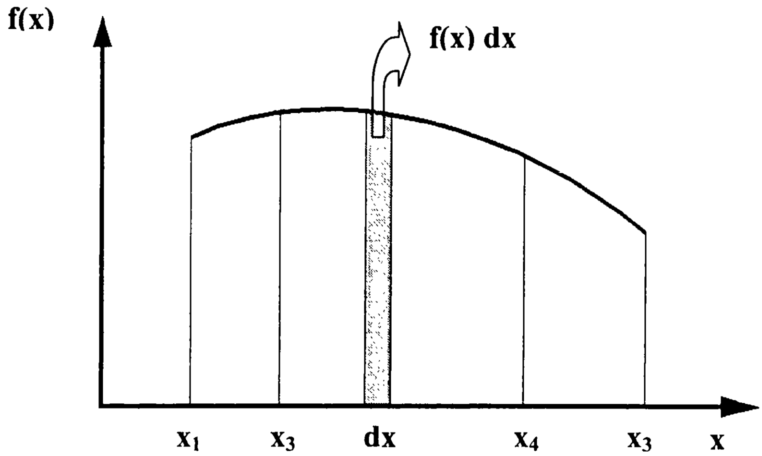


Figure 3.26. - Probability Function.

Although the smallest value, x_1, and the largest, x_2, can also appear, the symbols for equality have been left out of the parentheses $(x_1 \leq x \leq x_2)$ because of the discontinuity of these values.

In general, the probability of a range of values between x_3 and x_4 is smaller than unity:

$$p(x_3 < x < x_4) = \int_{x_3}^{x_4} f(x)\,dx < 1. \qquad (5)$$

Here only one variable, x, was considered and this relates to the marginal or one-dimensional probability distribution.

If a random event, like a casualty, has two qualities with characteristics of random variables then, there is usually a probabilistic link between those quantities also.

In this case it is also necessary to know this interrelation, which is defined by the two-dimensional joint probability density function. Denoting the second random variable as y, the probability density function is $f(x,y)$.

Here the joint event is also called two-dimensional. Instead of surfaces, the probability is now represented by the volume below the spatial surface of the joint probability density function, $f(x,y)$.

If the greatest possible rangs of x and y are from x_1 to x_2, and from y_1 to y_2, then the values of $f(x,y)$ are normalised so that, like before:

$$P_m = \mathrm{p}(x_1 < x < x_2; y_1 < y < y_2) = \int_{x_1}^{x_2}\int_{y_1}^{y_2} f(x,y)dxdy = 1 \qquad (6)$$

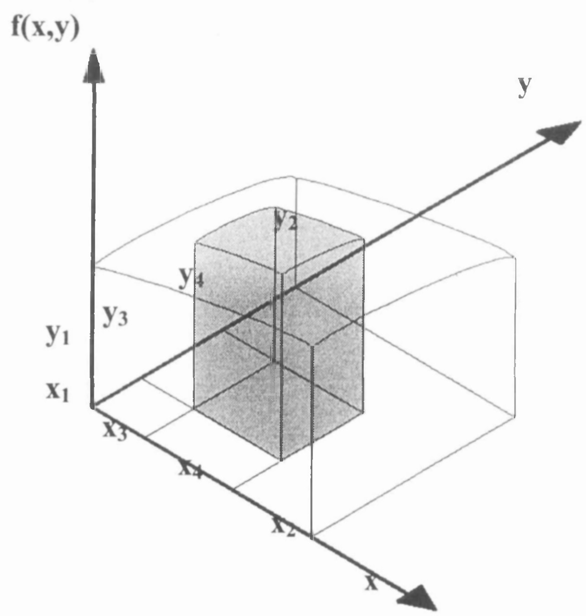


Figure 3.27. - Probability of the two-dimensional event.

The probability of x and y occurring in a partial range, from x_3 to x_4, and between y_3 and y_4, (see Figure 3.26) is:

$$p(x_3 < x < x_4; y_3 < y < y_4) = \int_{x_3}^{x_4}\int_{y_3}^{y_4} f(x,y)\, dx\, dy < 1 \qquad (7)$$

Ships are usually subdivided in all three directions, transversely, longitudinally and horizontally, so that water ingress into one or several adjacent compartments, for example side or wing tanks, involves the following five random variables. These variables are the longitudinal and vertical location of damage as well as its longitudinal, vertical and transversal extent. To calculate the probability that such five events will occur, it is necessary to know the interrelations between the random variables and their joint probability density functions.

If, finally, an occurrence is described by any number of random variables which can have the values $x, y, z,...$, and if the joint probability distribution $f(x, y, z,...)$ is known as well as the interrelations among all quantities then, to calculate the probability of that event occurring it is necessary to know the interval D, of all variables that describe the event. The corresponding probability can then be described by the expression:

$$p = \iiint_D \ldots f(x,y,z,\ldots)\, dx\, dy\, dz \ldots. \qquad (8)$$

Here also the probability of all the possible events has a unit value. Impossible events, whose probability have a zero value, would include any value outside its possible range.

Up to now only one simple event have been considered: the appearance of the casualty itself with collision and water ingress. But the interest was only whether such casualties could be survived. This leads to a joint event, the appearance of the collision with water ingress and its surviving or non-surviving. Here it is necessary to know the interrelations between specific events and then to treat them using the already well-developed rules of statistical theory.

It is possible to conclude immediately that these two occurrences always happen at the same time, because flooding is dependent on an collision, similarly it is possible to conclude that non-survivability is dependent on flooding having occurred.

To find the probability of simultaneous events that do not exclude each other and are independent it is necessary to multiply their corresponding probabilities. Denoting the probability of flooding one single or several adjacent compartments by p_i, and the probability of surviving this casualty s_i, then the probability p of this joint event is:

$$p = p_i . s_i . \tag{9}$$

It is necessary to include all the i possible events to determine the "entire probability". It is easy to conclude that some of them cannot appear simultaneously. For these i interdependent events, that exclude each other, their probability are simply added:

$$P = \sum_{i=1}^{I} p_i . s_i \tag{10}$$

After serious casualties causing water ingress into many adjacent compartments, the ship is usually lost by foundering or capsizing. Then, comes the non-survival term, so:

$$s_i = 0 \tag{11}$$

This leads to the conclusion that there is no point in including in (7) non-surviving combinations of flooding, and therefore the entire probability of survival P never reaches the maximum value, i.e.:

$$P < 1 \tag{12}$$

Where this entire probability *P*, is "the probability of the ship surviving water ingress due to collision", which is the subject here.

The approach has the meaning of so-called "conditional probability" because it pre-supposes the possibility of the casualty occurring, and then goes on to elaborate its characteristics as its first step. It can be described by the expression "... if such a casualty occurs".

The probability of survival of the joint event, *P*, is : "the sum of the products for each compartment or group of compartments of the probability of the simple event, p_i, that a corresponding space is flooded, multiplied by the probability of simple event, s_i, that the ship will not capsize or sink with the considered space flooded". It is expressed by the value of the "attained subdivision index", A.

It has to be compared with the "required subdivision index", *R*, which depends on the subdivision length of the ship, L_s and the following condition should be met:

$$A \geq R \tag{13}$$

R is based on results from a statistical analysis of data from three hundred ships (Dry Cargo and Passenger Ships). The value of *R* does not depend on the ship's type.

If a collision occurs the survival of the struck ship has a random nature therefore that probabilistic approach concerns this ship. The survivability of the striking ship is to a greater extent deterministic, since in the majority of cases the collision bulkhead is not penetrated. The regulations also include requirements concerning the surviving of the striking ships in this way that for all compartments forward of the collision bulkhead, the s-value is to be equal to 1, and the striking ship should be completely safe if it strikes with its bow.

3.1.2 Improvements and Developments in The Probabilistic Concept Formulations

During the last two decades several authors have proposed several different approaches for improvements of ship subdivision probabilistic evaluation. Among them, the more active were Pawlowski (1980, 1993, 1996), whose approach for transversal subdivision is applied in IMO regulations for cargo ships, Abicht (1989, 1990) and Jakic (1989, 1991, 1992, 1993, 1994).

The work carried out by these authors was determinant for the correction of several imprecisions contained in the IMO regulations or even just to point them out.

A very good summary of the work carried out by these authors was done by Jakic (Jakic, 1996), comparing and describing the author's three approaches, IMCO's (IMCO, 1973), IMO's (IMO, 1991, 1992), Pawlowski's (Pawlowski, 1993) and Abicht's (Abicht, 1990) approaches.

However, these formulations were only developed for cargo ships then, using different statistical accidents databases from the ones used in this work, not being possible, this way, to use this formulations applied to tankers.

3.2 Mathematical Model

3.2.1 General

The numerical model developed and implemented for the work realised in this thesis, uses the probabilistic concept to assess the oil outflow from a tanker design. The application is capable of computing the probability and quantity oil outflow for all the possible unique damage groupings of adjacent compartments, given a specific internal tank arrangement.

The mathematical model developed is based upon the IMO "Interim Guidelines for the Approval of Alternative Methods of Design and Construction of Oil Tankers Under Regulation 13F(5) of Annex I of MARPOL 73/78" (IMO, 1995b). These guidelines for evaluating alternatives to double-hull tankers were used to assess the relative oil outflow of different designs. Although intended for evaluating the outflow performance of alternative arrangements to the double-hull concept, these guidelines are also well suited for comparing the outflow performance of different tanker design types. The guidelines take a probabilistic approach based on historical data from collisions and groundings not including any other sources of oil spillage, such as explosions and operational discharges.

This provides a probabilistic-based procedure for assessing the oil outflow performance of an alternative tanker design. The alternative design is compared to a reference double hull design on the basis of a pollution prevention index. A fully probabilistic evaluation of a specific vessel on a specific route would require development of the following conditional probabilities:

- The probability that the ship will encounter damage;

- The probability of the damage location and extent;

- The expected consequences (i.e. quantity of outflow).

The IMO Guidelines do not specifically deal with the probability of whether the ship will encounter damage. Rather, it is acknowledged that the risk exists, and that in fact, the vessel is assumed to have been involved in a grounding or collision event significant enough to breach the outer hull. The following sections provide an overview of the calculation methodology.

Each of the designs has been evaluated using the conceptual analysis approach (without consideration of survivability) as defined in Interim Guidelines for Approval of Alternative Methods of Design and Construction of Oil Tankers under regulation 13F(5) of Annex I of MARPOL 73/78 (IMO, 1995). An overview of the methodology is described below.

The IMO guidelines account for such factors as varying wing tank widths and double-bottom heights, internal tank subdivision, and the effects of tide.

Casualty statistics collected by classification societies were used to develop the expected distribution of side and bottom damage. The damage distribution functions were derived from about 60 tanker casualties involving primarily single-hull vessels. These distribution functions provide information on the expected penetration and the extent and location of damage from collisions and groundings.

In the case of a single-hull tanker, if the outer hull is penetrated adjacent to a cargo tank, the cargo tank will be breached and oil will flow out. For a double-hull tanker, outflow will occur only if the extent of penetration is sufficient to extend beyond the protective double-bottom or wing tanks, there by piercing the inner hull and penetrating the cargo tank. In the case of mid-deck tankers, the outflow will only occur if the inner hull of the side tank is breached in case of side damage. In the case of bottom damage the oil outflow will occur until hydrostatic equilibrium is reached. The size of the spill is directly related to the number of cargo tanks breached and their size.

The dimension of the double-bottom and wing tanks therefore largely influences the likelihood that a double-hull tanker involved in a collision or grounding will spill oil, as well as the height of the horizontal subdivision in the case of mid-deck tankers. The amount of oil spillage is also impacted by the internal subdivision of the cargo tanks, which dictates tank sizes and the spacing of bulkheads forming tank boundaries. Naturally, larger cargo tanks will spill more oil. On the other hand, more closely spaced bulkheads increase the likelihood that more than one cargo tank will be damaged.

The quantitative results of the outflow analysis should be used with care because of the limited size of the casualty database, the nature of the incidents included, and some simplifications in the calculation procedure. The committee recognises that the probabilistic outflow methodology should ideally reflect the response of specific structural configurations. However, the same damage distributions are currently applied to both single-hull and double-hull vessels. This approach is likely to give conservative results (i.e. overestimates of outflow) when applied to double-hull designs, because recent studies have indicated that double-hull structures reduce the extent of damage from a collision or grounding. In certain cases the inner bottom or longitudinal bulkhead can withstand considerable deformation before being penetrated.

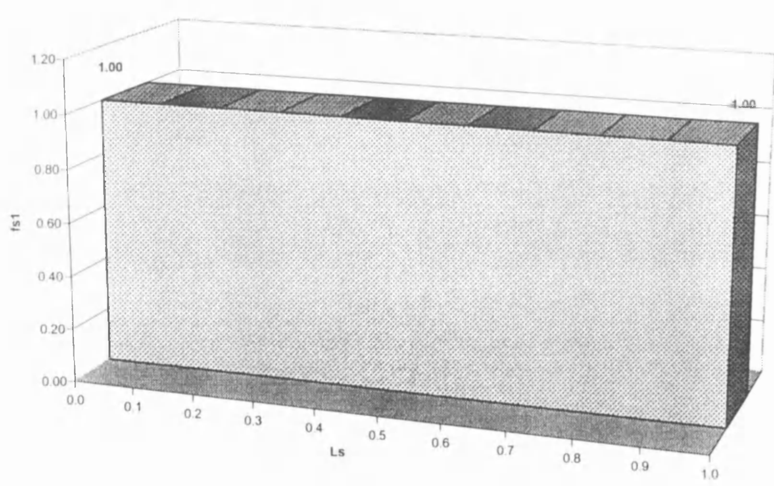


Figure 3.28. - PDF of Longitudinal Location of Damage for Collision Incident

Nonetheless, the IMO methodology provides a rational basis for comparing tanker designs and, in the view of the committee, is currently the best readily available analytical approach.

3.2.2 Methodology for Evaluating Oil Outflow

3.2.2.1 Methodology

The calculation methodology here used is called a *DIRECT* method, as it involves direct application of the IMO probability density distribution functions to the subject design.

The calculation process is established by means of an iterative procedure. This iterative process goes through all the possible locations and extents of damage over the ship length. The probability of the damage location and extent is then computed for each damage condition and if any cargo oil tank breached, the oil outflow from them is also computed.

After this point the uniqueness of this damage is assessed to decide if the computed probability and oil outflow will be merged with an equal damage already computed or if a new damage case was found.

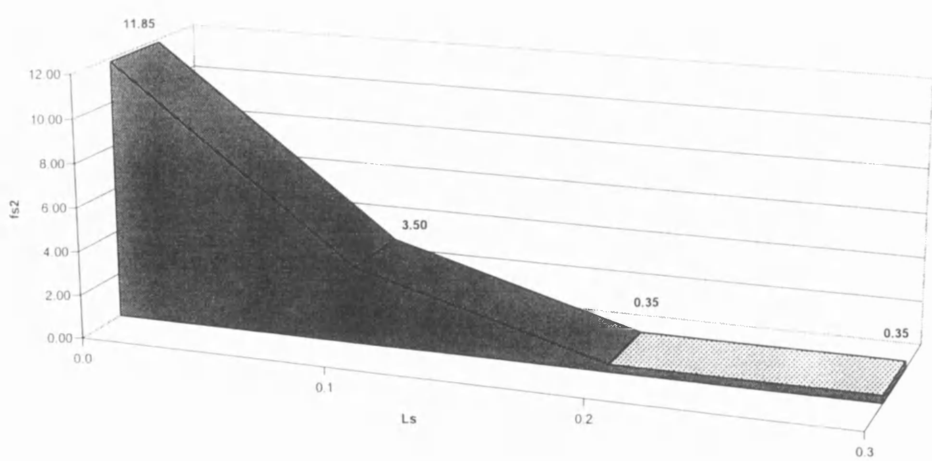


Figure 3.29. - PDF of Longitudinal Extent of Damage for Collision Incident

This process is repeated until all possible combinations are tested. As result of this calculation, at last we have all the possible unique combinations of damage cases, with the correspondent damage probability and oil outflow.

There are four main steps involved when applying the IMO Guidelines:

3.2.2.2 Step 1: Assembling Damage Cases

The IMO Guidelines contain probability density functions (pdfs) describing the location, extent and penetration of side and bottom damage. These functions were derived from historical damage statistics for 52 collisions and 63 groundings of tankers 30,000 metric tons deadweight and above. Side damage pdfs are provided for the probability of the damage longitudinal location, longitudinal extent, transverse penetration, vertical location, and vertical extent (Figures 3.28-3.32).

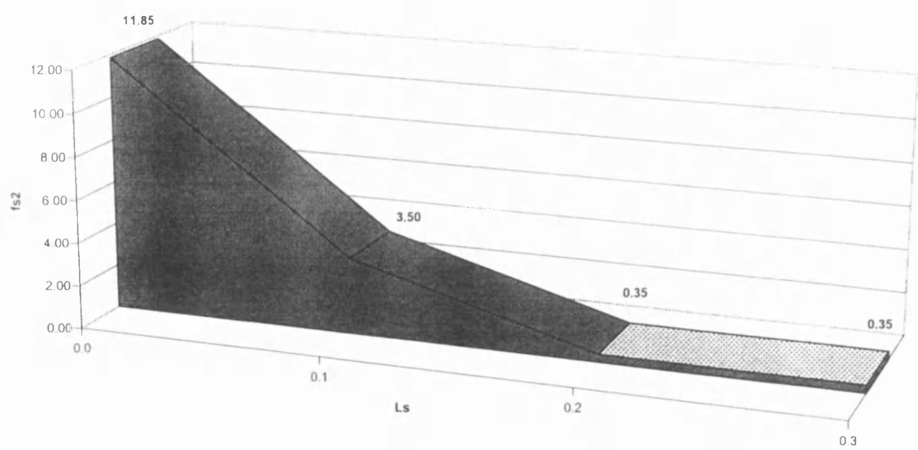


Figure 3.30. - PDF of Transverse Penetration of Damage for Collision Incident

Similarly, bottom damage includes evaluation of the longitudinal location, longitudinal extent, transverse location, transverse extent, and vertical penetration (Figures 3.33 -3.37). The density scales are normalised by the ship length for longitudinal location and extent, by ship breadth for transverse location and extent, and by ship depth for vertical location and extent. The pdf variables are treated independently for the lack of adequate data to define their dependency. The linear plots in Figures 3.28-3.37 represent IMO's piece-wise linear fit to the data of histograms representing statistical data collected by the classification societies (IMO, 1992; DNV, 1993).

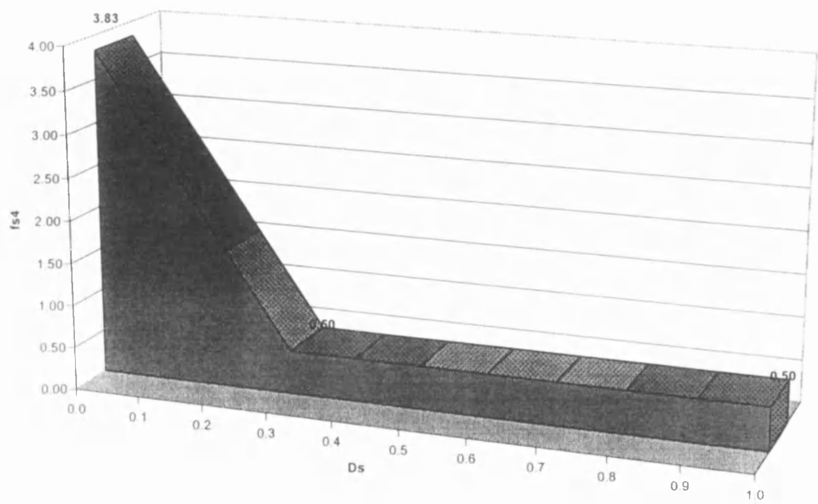


Figure 3.31. - PDF of Vertical Extent of Damage for Collision Incident

The application of the probability density functions to the vessel's compartmentation provides the probability of occurrence for each damage incident. This is done through a stepwise evaluation at a sufficiently fine increment, or a Monte Carlo approach utilising a large number of simulated damage incidents. To reduce computation time, incidents that damage identical sets of compartments are typically combined into groups. The cumulative probability of occurrence of all damage incidents (and similarly, all unique damage groups) is 1.0.

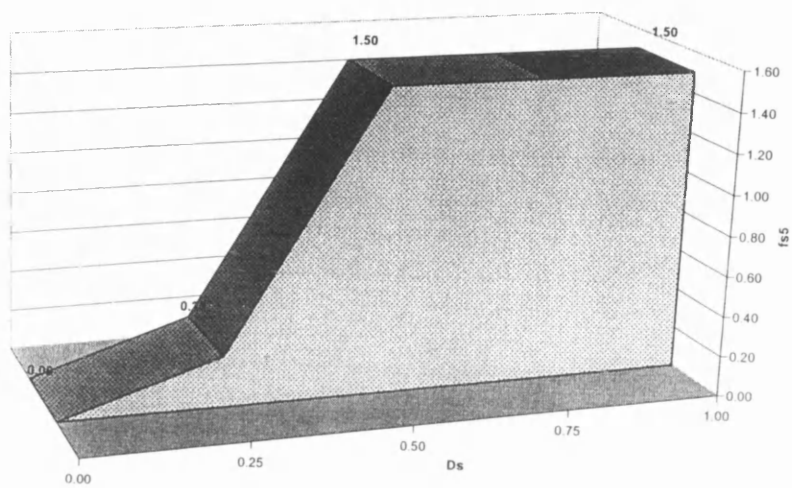


Figure 3.32. - PDF of Vertical Location of Damage for Collision Incident

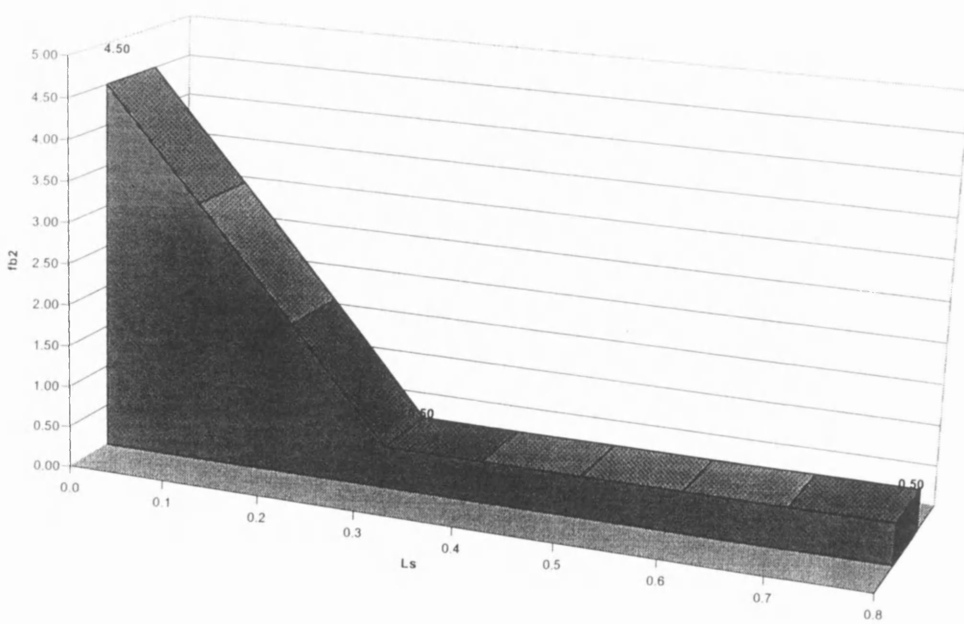


Figure 3.33. - PDF of Longitudinal Extent of Damage for Grounding Incident

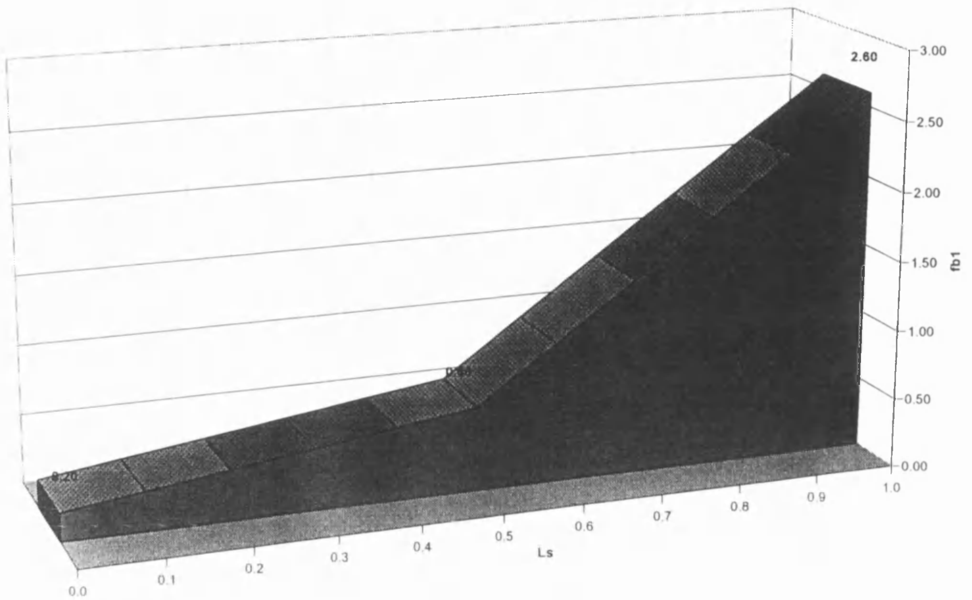


Figure 3.34. - PDF of Longitudinal Location of Damage for Grounding Incident

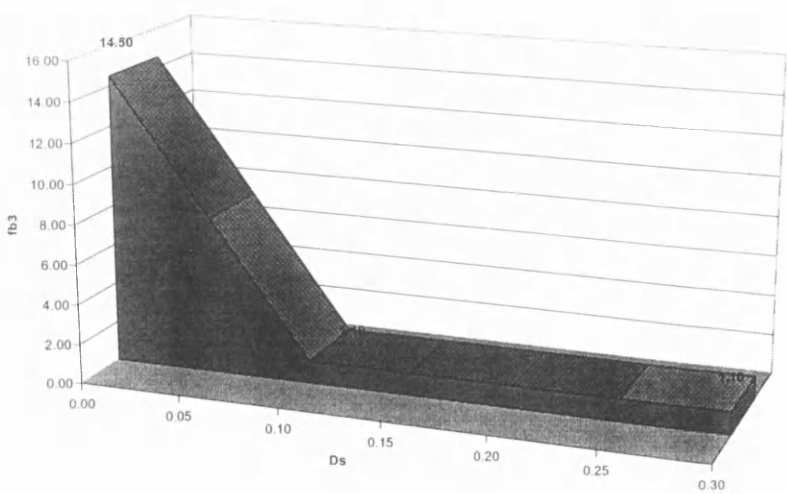


Figure 3.35. - PDF of Vertical Penetration of Damage for Grounding Incident

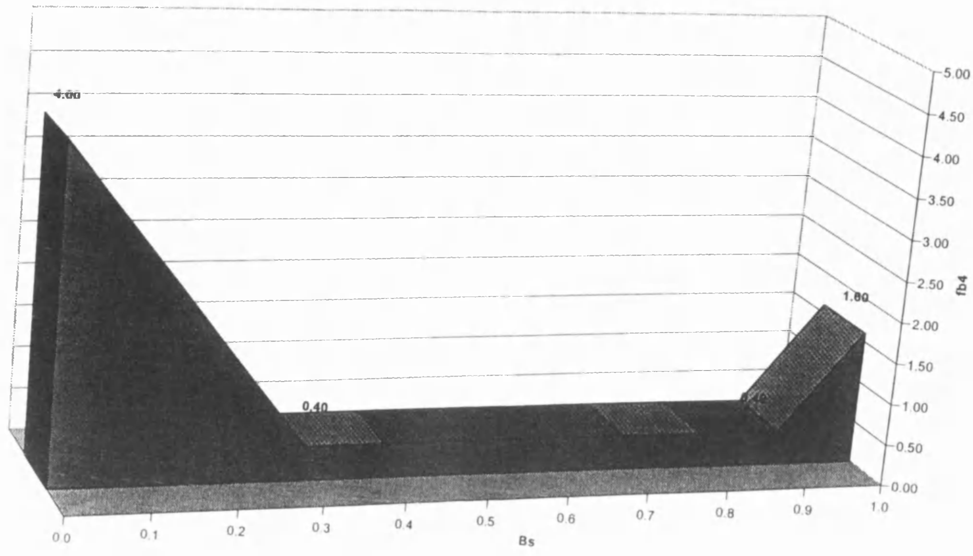


Figure 3.36. - PDF of Transversal Extent of Damage for Grounding Incident.

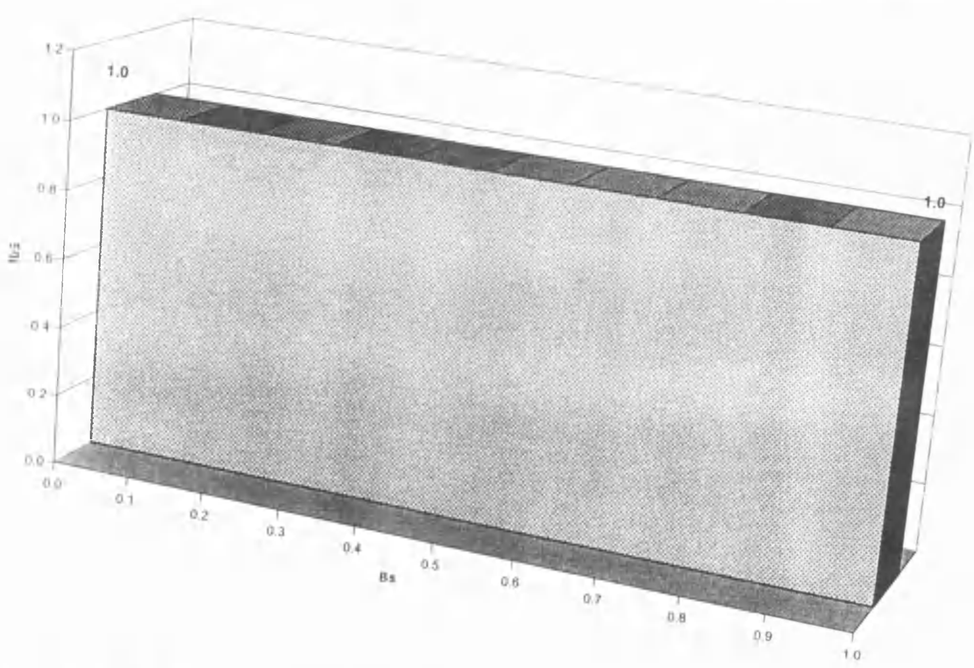


Figure 3.37. - PDF of Transverse Location of Damage for Grounding Incident

3.2.2.3 Step 2: Calculation of Oil Outflow

The next step is to compute the oil outflow associated with each unique side damage and bottom damage case.

For side damage incidents, 100 percent oil loss is assumed for each breached cargo tank. Therefore, if a given damage incident damages only a ballast wing tank, zero outflow occurs. If a damage incident involves breaching of the ballast wing tank and the adjacent cargo oil tank, the full content of the cargo oil tank is assumed to be lost.

For bottom damage, outflow is determined by performing hydrostatic pressure balance calculations. A reduction in tide after the incident of 0.0 metres, 2.0 metres, and 6.0 metres (or one-half the draft, whichever is less) is assumed. Other assumptions applicable to bottom damage calculations are:

- An inert gas pressure of 0.05 bar is applied to all cargo oil tanks. This is a positive pressure and augments the oil outflow; (see Figure 3.38)

- If a double-bottom ballast tank or void space is located immediately below a breached cargo tank, the flooded volume of the double-bottom tank is assumed to be 50:50 mixture of oil and seawater. The oil entrapped in the double-bottom is not included in the assumed spill volume; (see Figure 3.39)

- For breached cargo tanks bounding the bottom shell, an oil outflow equal to 1 percent of the tank volume is assumed as the minimum outflow. In these circumstances, the minimum outflow value accounts for oil losses due to initial impact and the effect of current and waves. For tanks, which are hydrostatically balanced in the intact condition, outflow analysis based on hydrostatic-balance principles will indicate zero outflow for grounding cases not subjected to tidal change.

The IMO Guidelines present two procedures for evaluating the oil outflow. The "conceptual" method, applicable for conceptual design approval, assumes that the ship survives the damage. For bottom damage, the ship is assumed to rest on the ground at its initial intact drafts, with zero trim and heel. The "survivability" method, applicable to final designs, requires damage stability calculations. For damage cases that fail to satisfy the specified survivability criterion, it is assumed that the ship is lost and 100% of all cargo oil onboard outflows to the sea.

3.2.2.4 Step 3: Calculation of Oil Outflow Parameters

The IMO Guidelines call for the calculation of three parameters: the *probability of zero outflow*, *mean outflow*, and *extreme outflow*. The calculation methodology assumes the vessel experiences a collision or grounding, and that the outer hull is breached. The assumed extent of penetration, and therefore the probability that the inner hull of a double-hull tanker will be pierced, are based on the application of probability density functions as described in the following paragraphs.

- The *probability of zero outflow*, P_0, represents the likelihood that no oil will be released into the environment, given a collision or grounding casualty which breaches the outer hull. P_0 equals the cumulative probability of all damage cases with no outflow. This parameter is an indicator of a design's tendency towards avoiding oil spills.

- The *mean outflow parameter*, O_M, is the non-dimensionalized mean or expected outflow. The mean outflow equals the sum of the products of each damage case probability and the associated outflow. O_M equals the mean outflow divided by the total quantity of oil onboard the vessel. The mean outflow is the weighted average of the cumulative oil outflow. This parameter provides an indication of a design's effectiveness in mitigating the amount of oil loss due to collisions and groundings.

• The *extreme outflow parameter*, O_E, is the non-dimensionalized extreme outflow. The extreme outflow is the weighted average of the upper 10% of all casualties (i.e. all damage cases within the cumulative probability range from 0.9 to 1.0). This parameter provides an indication of a design's effectiveness in reducing the number and size of large spills.

The bottom damage outflow parameters for the 0, 2 and 6 meter tides are combined in the ratio of 0.4 : 0.5 : 0.1 respectively. Collision (side damage) and stranding (bottom damage) parameters are then combined in a ratio of 0.4 : 0.6. In this way, overall values for P_0, O_M, and O_E are obtained.

3.2.2.5 Step 4: Computation the Pollution Prevention Index "*E*"

Substituting the outflow parameters for the actual design and the IMO reference double-hull design into the following formula provided in the IMO Guidelines a pollution prevention index is developed. If the Index E is greater than or equal to 1.0, the alternative design is considered at least equivalent to the IMO reference design.

$$E = \frac{0.5P_0}{P_{0R}} + \frac{0.4(0.01 + O_{MR})}{0.01 + O_M} + \frac{0.1(0.025 + O_{ER})}{0.025 + O_E} \qquad (14)$$

where

P_0 = probability of zero outflow for the alternative design

O_M = mean oil outflow parameter for the alternative design = (mean outflow)/C

O_E = extreme oil outflow parameter for the alternative design = (extreme outflow)/C

C = total cargo oil onboard

P_{0R}, O_{MR} and O_{ER} are the corresponding parameters for the reference double-hull design of the same cargo oil capacity.

The IMO reference double hulls are shown in Figures 106 to 109 of Annex B. These reference designs do not represent the minimum subdivision acceptable under current MARPOL regulations. Rather, it was IMO's intent to select designs which "exhibit a favourable oil outflow performance."

The IMO Guidelines specify that *C*, the cargo oil onboard, to be taken at 98 percent of the total cargo tank volume.

All analysis have been carried out in strict conformance with the IMO guidelines, with the exceptions referred to in 3.4.

3.2.3 Principles of Oil Outflow

The following provides a brief description of the fundamental principles affecting oil outflow.

- *Hydrostatic Balance.* In the event of bottom damage, oil outflow will occur until, in the vicinity of the damage, the internal pressure exerted by the entrapped oil and flooded water within a tank, equals the external pressure exerted by the seawater. If the ullage space is under pressurised such that the pressure on the oil surface is less than the atmospheric pressure acting on the seawater, outflow will be reduced. Conversely, higher ullage pressures, as might be introduced by the inert gas system, will result in larger outflows. For groundings, the external pressure is reduced as the tide drops, and outflow will occur until equilibrium is once again attained.

For lightly loaded tanks, the initial pressure head from the cargo oil is less than the external seawater pressure. When bottom damage is sustained, seawater enters the bottom of the tank until equilibrium is achieved. Provided the damage does not extend up the side of the tank and currents or vessel motions do not induce mixing of seawater and oil in the vicinity of the damage, no oil will be lost.

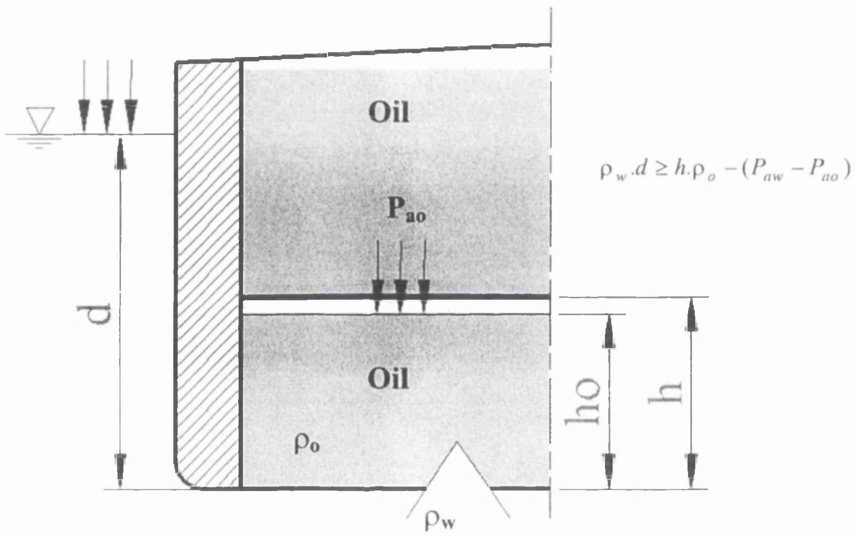


Figure 3.38. - Hydrostatic balance.

- *Oil Entrapment in Double-Hull Tankers.* When a tanker experiences bottom damage through the double-bottom tanks and into the cargo tanks, a certain portion of the oil outflow from the cargo tanks will be entrapped by the double-bottom tanks. This phenomenon was investigated through model testing at the David Taylor Research Centre (DTRC, 1992) and the Tsukuba Institute, Ship & Ocean Foundation (Tsukuba Institute, 1992), and through numerical analysis. These studies indicate that oil entrapment is influenced by many factors, including the size and location of openings, the magnitude of the pressure imbalance, and whether the double-bottom tank is flooded with water at the time the oil tank is ruptured. For conditions in which the double-bottom initially floods and the cargo tank is breached, a viscous jet is formed resulting in minimal retention of oil in the outer hull. The Marine Environment Protection Committee (MEPC) concluded that, "if both outer and inner bottoms are breached simultaneously and the extent of rupture at both bottoms is the same, it is probable that the amount of sea water and oil flowing into the double-hull space would be the same. (IMO, 1995b)" In its regulations, IMO assumes that the double bottoms below oil tanks retain 50:50 ratio of oil to seawater. Where tidal changes introduce a slowly changing pressure differential, higher retention rates can be expected.

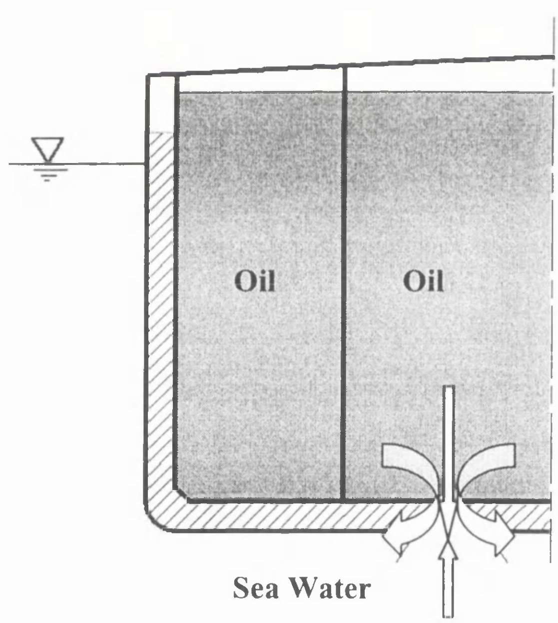


Figure 3.39. - Oil Entrapment.

- *Dynamic Oil Losses.* Oil losses in excess of those predicted by hydrostatic balance calculations may result due to the initial impact when a vessel runs aground, and subsequently, from the effects of current and ship motions.

These losses primarily influence single-hull vessels and alternative designs whose oil tanks contact with the outer hull.

Model tests at David Taylor Research Centre (1992) and the Tsukuba Institute (1992) were carried out to assess the influence of initial impact and current on oil outflow. The speed of the ship, the extent of damage, the magnitude of the current, and the sea state influence dynamic losses. Under extreme weather conditions, losses up to 10 percent of the tank volume can be encountered, although dynamic oil losses of 1 percent to 2 percent are more typical. In its regulations, IMO assumes a minimum outflow of 1 percent of the volume for all breached cargo tanks, which bound the outer hull.

- *Side Damage.* The location and size of the damage openings influence the amount of expected oil outflow from side collisions. If the lower edge of the damage opening lies above the equilibrium waterline (Figure 3.41), the oil level in the tank will drop to the height of the opening and the vessel will heel away from the damage.

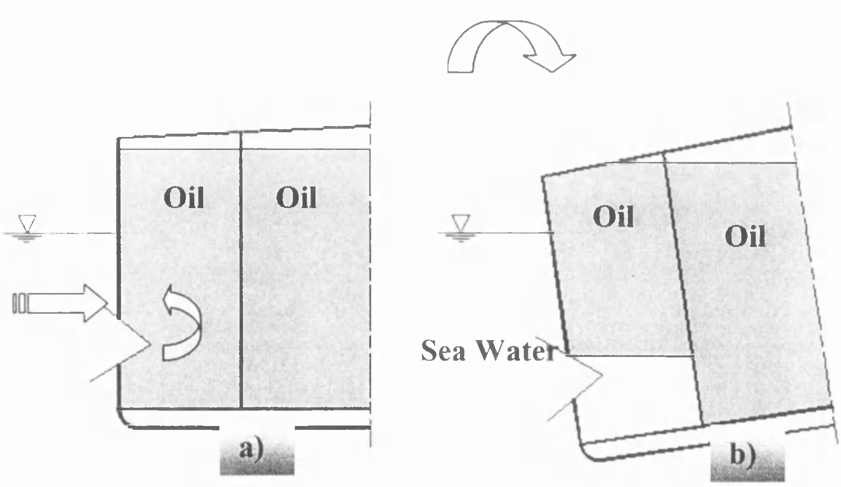


Figure 3.40. - Oil outflow when the damage opening is entirely below the waterline.

When the damage extends below the waterline, outflow of oil will occur until hydrostatic balance is achieved (Figure 3.40). Over time, the denser seawater will replace all oil located below the level of the upper edge of the damage opening. In its regulations, IMO assumes that 100 percent of the oil in breached side tanks is lost (Figure 3.42).

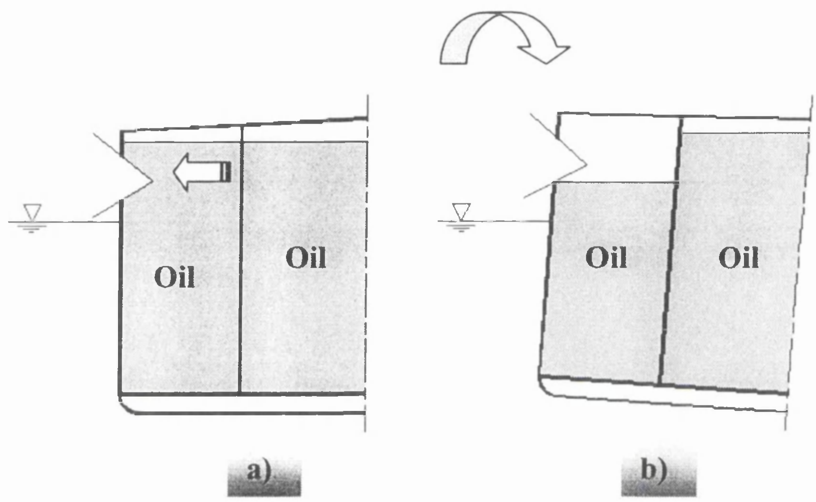


Figure 3.41. - Oil outflow when the damage opening is entirely above the waterline.

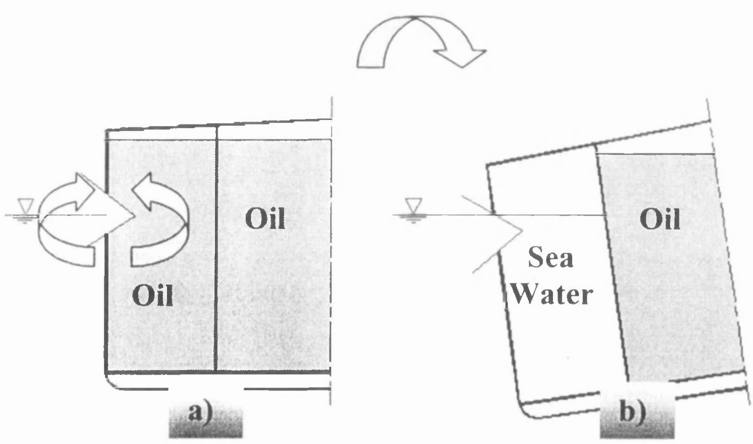


Figure 3.42. - Oil outflow when the damage opening is on the waterline.

3.3 Computational Method

There are several ways available for the assessment of compartment groupings and respective probabilities, which result should be the same for all of them. In this study, the compartment groupings and the use of the probability density functions is applied by a "step-wise" function evaluation method.

This method involves stepping through each damage location and extent at a sufficient fine increment. Then, through the application of an iterative process all different possible combinations of damage in length, width and height of the ship are performed. This is accomplished applying all different combination of values for the three damage variables, in case of collision incidents, and all different combinations of values for the five damage variables, in case of grounding incidents.

Since this method is numerical, all variables are discrete in opposition to the random variables defining the damages, which are continuous. Taking this into consideration, the evaluation is carried out dividing the range of each continuous random variable into defined numbers of equal intervals. The representative value of each interval is taken as being its midpoint. This process enables the approximation of the discrete variable to the continuous variable.

Since the distribution functions are linear the approximation is exact and accurate, without introducing any deviations or errors that could be expected if they were not linear.

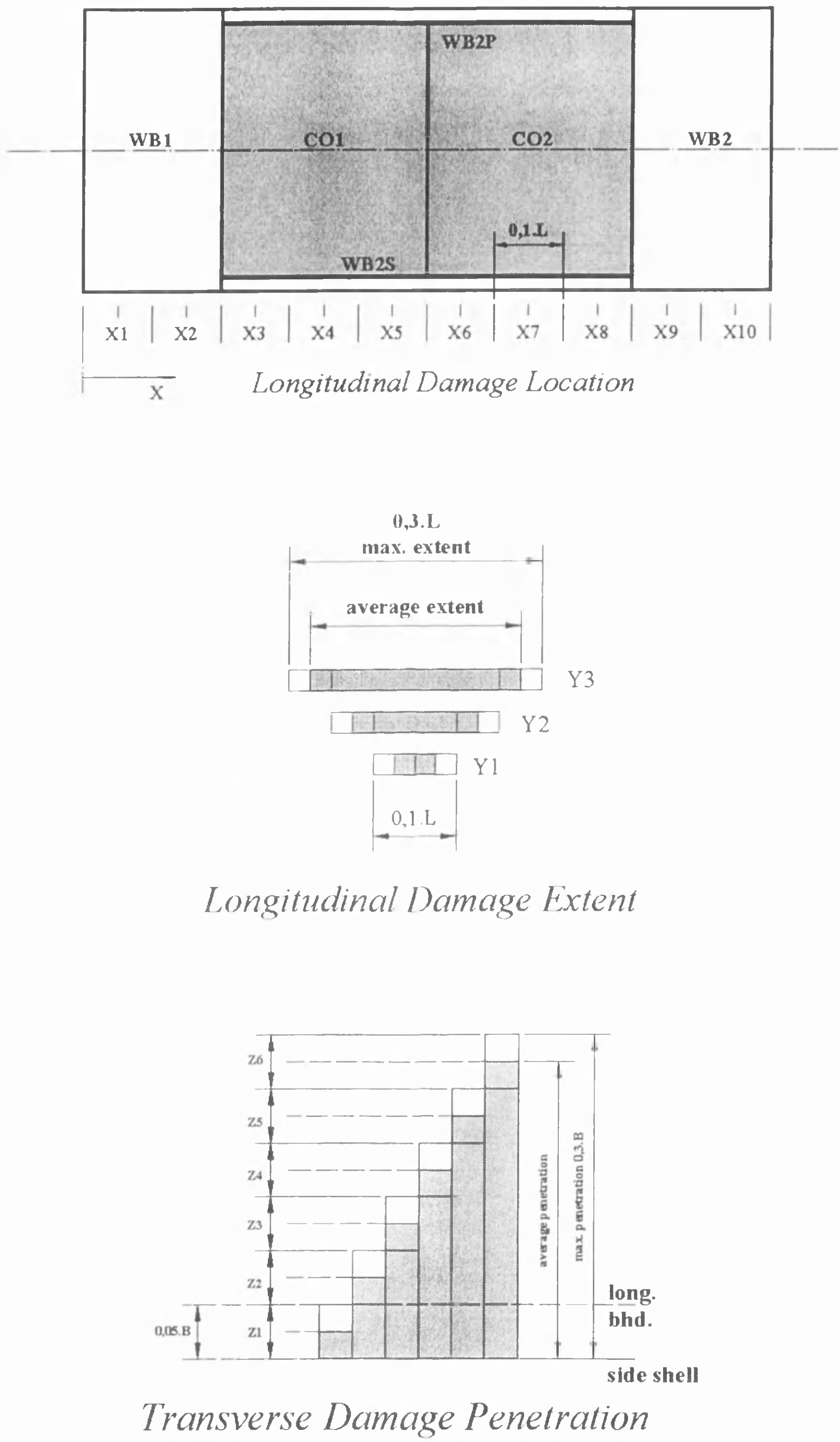


Figure 3.43. - Side Damage Definition (source: 1996 Lloyd's Register of Shipping and International Maritime Organisation).

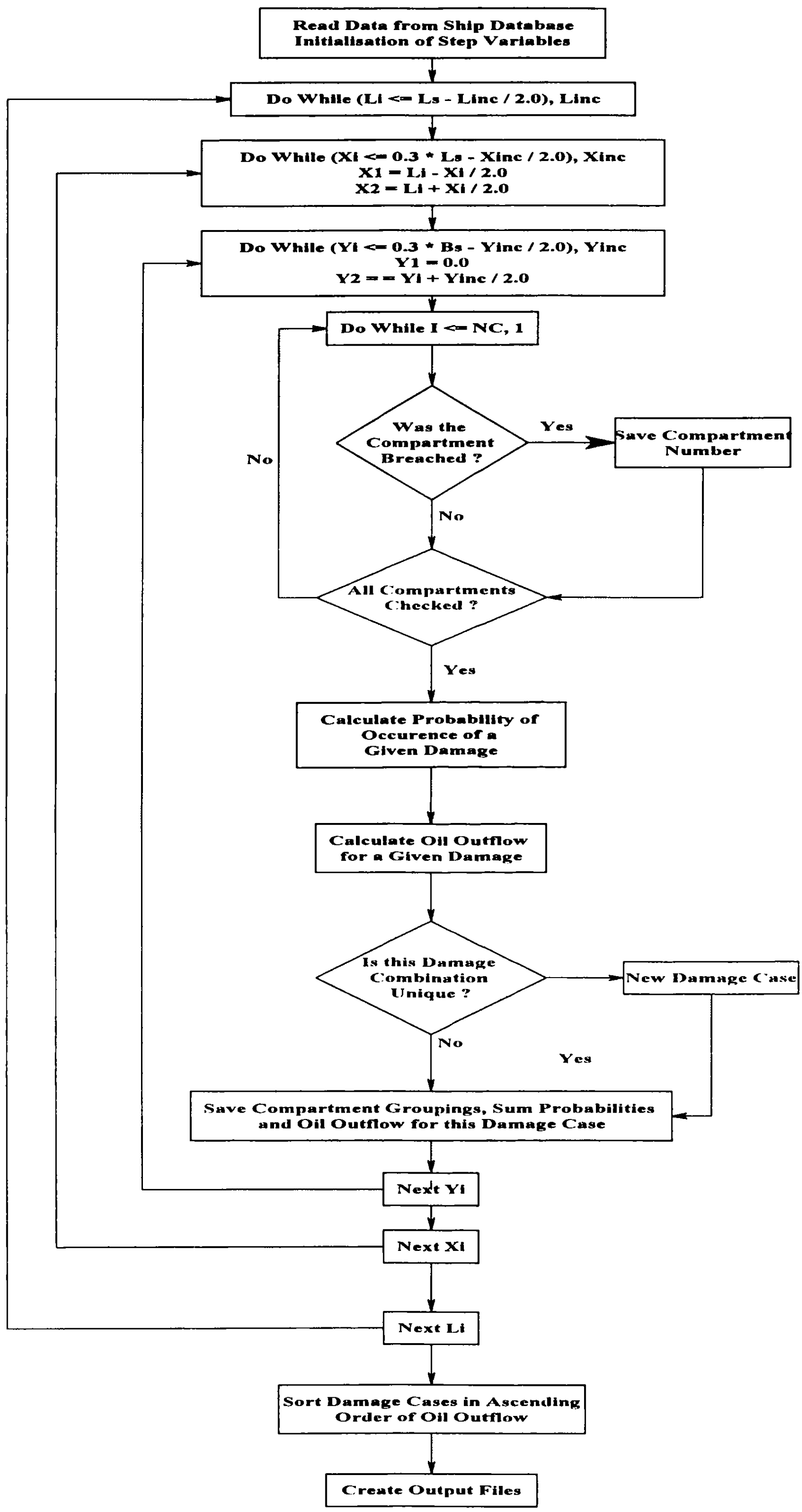


Figure 3.44. - Numerical Model Flowchart for Side Damage Definition (see Appendix E for Bottom Damage Definition).

The application of these step functions to a specific ship must be done with special attention, once is not sure that the step interval of the damage functions can easily coincide with the boundaries of all compartments. The problem arises when this constant increment produces damage extents that do fall short on the compartment boundaries, but the next value intersects one of the boundaries, giving rise to a different grouping of damage compartments.

Thus, if this happens, we are not taking into account the complete probability of damaging only that specific group of compartments. This can lead, in case of cargo compartments, to an overestimation of the expected oil outflow parameters and, to a decrease in the probability of zero outflow, if the boundary is the limit between a ballast and a cargo tank.

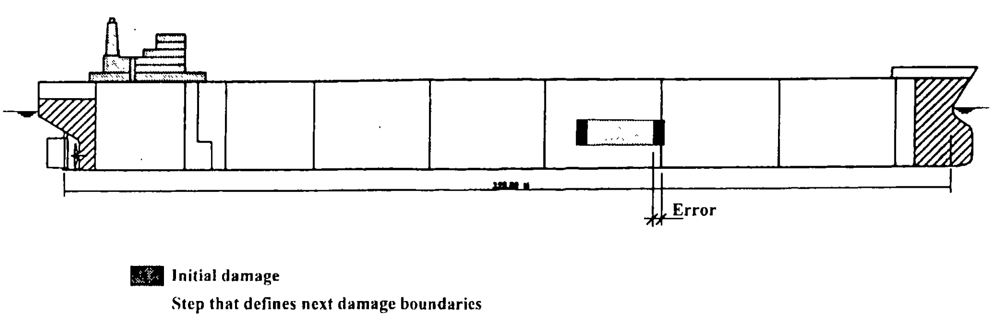


Figure 3.45. - Step interval that introduces errors for the grouping compartments probabilities.

In order to avoid these situations, as much as possible, the mathematical model analyses the internal subdivision geometry, combining it with the maximum damage extents of each variable, suggesting the best value to minimise the errors. As it is possible to imagine, most of the times the step interval suggested is very small and, not suitable for a "reasonably fast" computation of the probabilities and expected oil outflows of the specific ship. Then, it becomes a task of the end user of the model, to find out other step intervals, which are a combination of acceptable time of computation and acceptable probability error. It is clear that the shorter the interval, the lower the error in the damage probability. For instance, taking the example shown in Figure 3.43., and stepping through the functions for side damage:

- longitudinal location = 100 steps;
- longitudinal extent = 100 steps;
- transverse penetration = 100 steps;
- vertical location = 100 steps;
- vertical extent = 100 steps.

it will develop 10^9 damage incidents, which will be reduced to a few hundreds unique groupings of compartments, once some of them are redundant.

Then, it would be correct to reduce the computation time, decreasing the number of step intervals, so that we still have the same compartment groupings as result, respecting the boundaries of each compartment and, still get a sum of the probabilities equal to 1. The suggested values would be:

- longitudinal location = 10 steps, each step of L/10 = 0.1L;
- longitudinal extent = 3 steps, each step 0.3L/3 = 0.1L;
- transverse penetration = 6 steps, each step 0.3B/6 = 0.05B;

3.4 Assumptions and Limitations on this Study

It is important to recognise that, due to both technical and practical limitations, there are many simplifications inherent in the performed calculations. The quantities of oil outflow do not represent a quantitatively accurate estimate of oil outflow. Rather, these calculations provide a rational comparative measure of merit.

Some of the assumptions and simplifications in the development of damage case probabilities are:

- The IMO statistical database (Lloyd's, 1991) used for developing the probability density functions is based on 50 to 60 incidents involving tankers above 30 000 DWT.
- The probability density functions are "marginal" distributions. Locations, extents and penetrations are treated independently. Although, some degree of correlation is expected, the correlated statistics are not currently available. It is believed that this approach is conservative in the sense that it tends to over-predict the amount of expected outflow.
- The historical casualty data primarily involve older, single-hull vessels. It is expected that extents of damage will be somewhat less for double-hull vessels.

Efforts were made to select representative vessels for the study carried out. However, there are some double-hull vessels built for specific trades, which have quite different characteristics as compared to these representative vessels.

A nominal cargo oil density of 0.855 t/m3 is assumed for all designs. The assumed summer load line draft for each baseline design corresponds to a condition with cargo tanks and slop tanks loaded to 98% capacity plus 50% consumables.

The other designs in a given size are extrapolated from the baseline design. The cargo block outer boundaries are assumed constant, and therefore the cargo volume remains unchanged. The beam and depth is reduced or increased as required to accommodate changes in double hull dimensions. The LBP is held constant. The block coefficient is adjusted to maintain constant draft.

The increased wing tank clearances tend to improve environmental performance, i.e. reduce mean outflow and increase the probability of zero outflow. Because these increased clearances are somewhat arbitrary and subject to a yard's practice, outflow calculations in this study assume the nominal double bottom and wing tank clearances are exactly maintained throughout the cargo block. When calculating the probabilities of breaching the cargo tanks, a simplified prismatic hull shape was assumed (Figure 3.46).

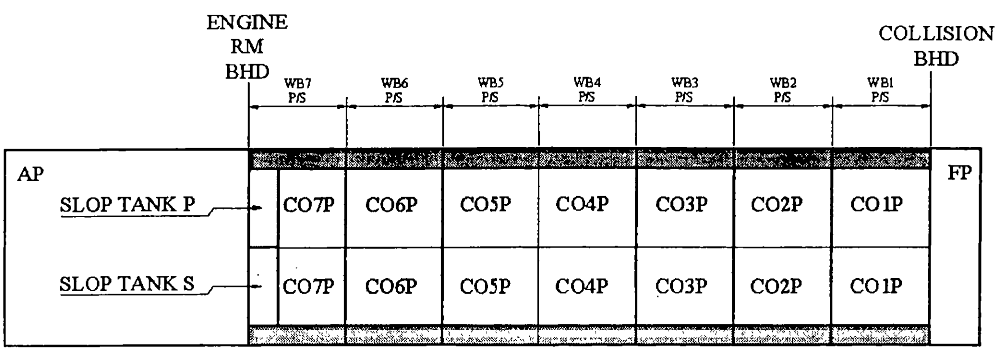


Figure 3.46. - Simplified Prismatic Hull Shape.

For comparison purposes it is assumed that for tanks which are hydrostatically balanced in the intact condition, outflow analysis based on hydrostatic principles will indicate zero outflow for grounding cases not subjected to tidal change. However in real cases some oil outflow is expected due to initial impact and the effect of current and waves. (see 3.2.3)

The IMO Guidelines suggests that in bottom damage calculations it should be assumed that damage extend from port to starboard. In the implemented model this was not followed, once this assumption would make impossible the evaluation of the influence of longitudinal bulkheads on the oil outflow from bottom damage. It would also be a problem to quantify properly the entrapped oil when longitudinal subdivision of bottom tanks exists.

In the present study, survivability is not taken into consideration. Thus, in the final result there is no verification if, for the specific damage calculations performed, there is the possibility that 100% of the cargo is lost due to fail of meeting damage stability requirements.

3.5 Model Architecture and Interfaces

The program runs in a Windows environment, making use of all capacities of this operating system and having interfaces as shown in Figure 3.47.

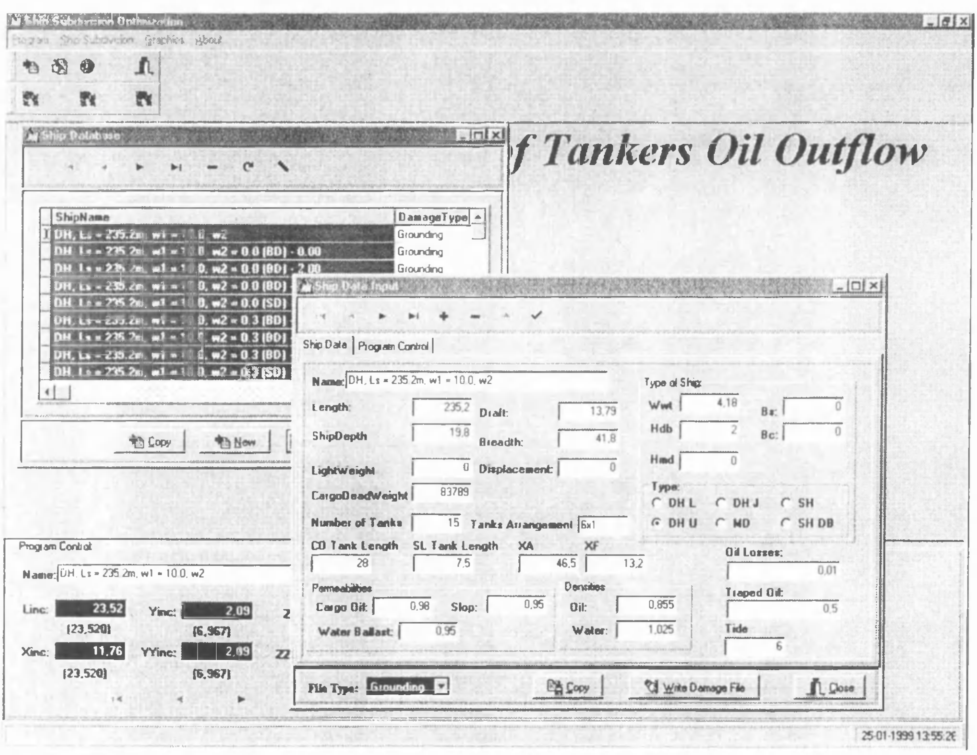


Figure 3.47. - An image of program PATOO.

The description of each tanker is stored on a database, being the model description as follows:

- geometric information comprising the description of the tank arrangement;
- principal dimensions of the ship;
- information concerning the type and characteristics of the fluid cargo;
- analysis parameters describing the initial conditions of the model:
    - ♦ initial draught;
    - ♦ initial and secondary outflow factors (oil losses, trapped oil);
- control of the damage:
    - ♦ maximum extents of damage;
    - ♦ integration step.

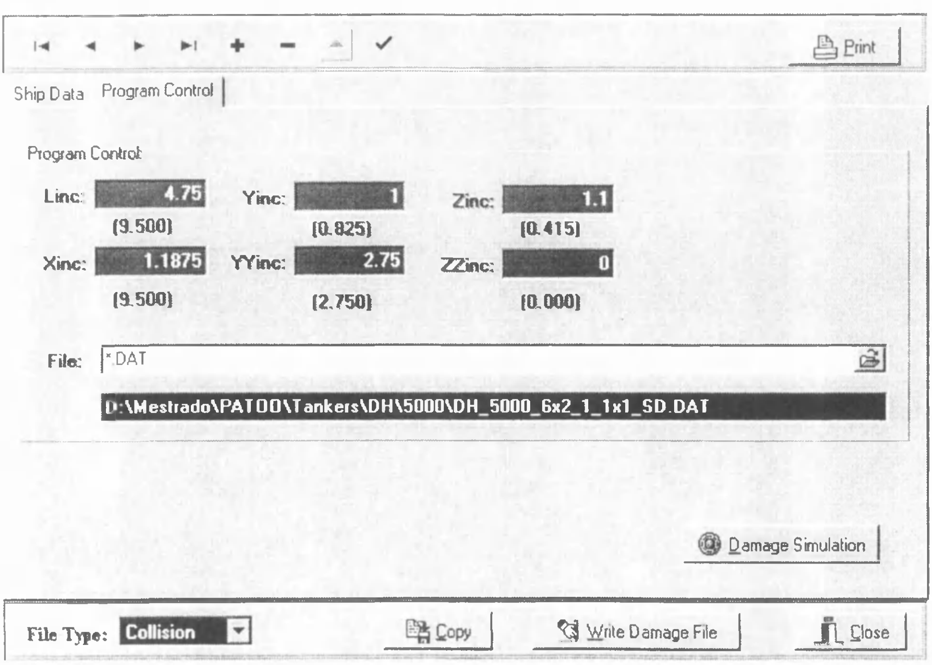


Figure 3.48. - Damage Control Window

The calculation process is established by means of an iterative procedure, which goes through all possible locations and extents of damage over the ship length. The probability of the damage location and extent is then computed for each damage condition and if any cargo oil tank is breached, the oil outflow from it is also computed.

After this point the uniqueness of this damage is assessed to decide if the computed probability and oil outflow will be merged with an equal damage already computed or if a new damage case was found.

This process is repeated until all possible combinations are tested. As a result of this calculation, at last it possible to have all the possible unique combinations of damage cases, with the corresponding damage probability and oil outflow.

A group of tables is produced during this process:

- unique damage compartment groupings and their damage probability, ordered by occurrence in the calculation process (separately for collision, grounding and both incidents);

- unique damage compartment groupings, damage probability and oil outflow ordered in ascending order of oil outflow (separately for collision, grounding and both incidents);

- Summary of oil outflow parameters (separately for collision, grounding and both incidents).

All these results can be exported to Excel for further analysis. The application is also able of producing is own charts from the results produced as shown in Figures 3.49-3.51.

The chart representation is handled through the use of a toolbar, where several options of different chart types are available.

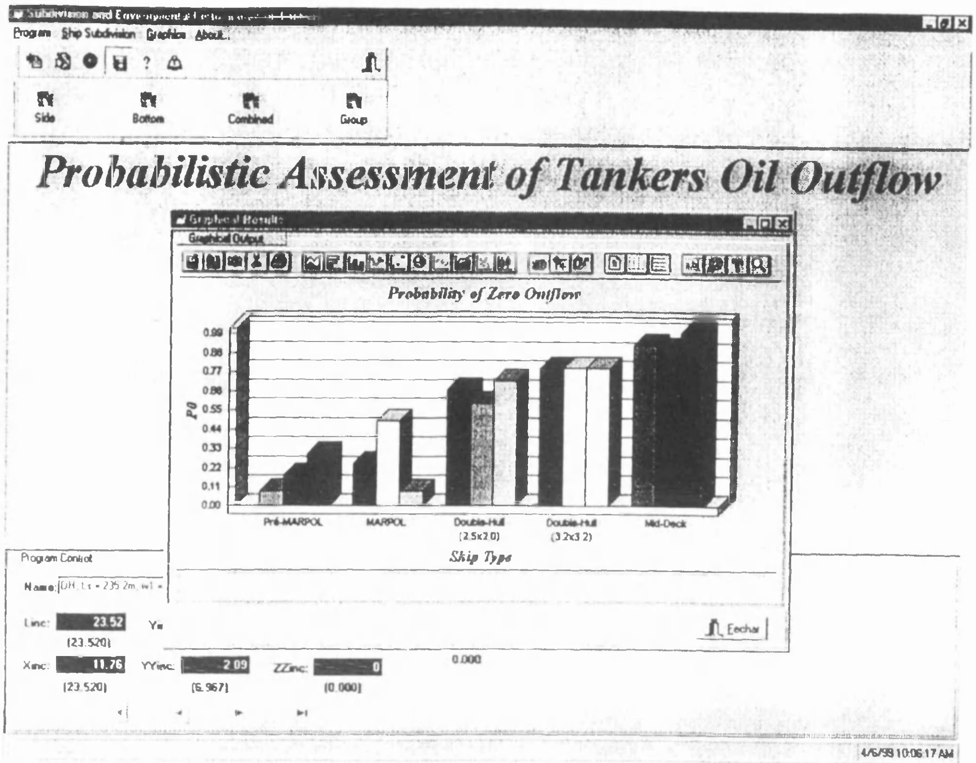


Figure 3.49. - Results Chart Representation I.

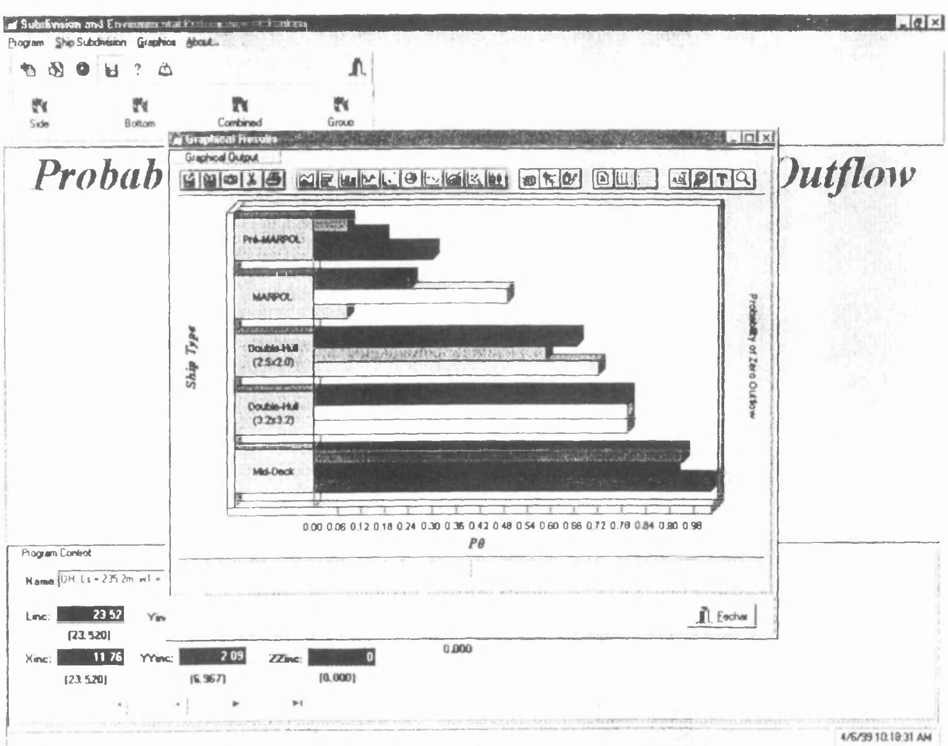


Figure 3.50. - Results Chart Representation II.

The data representation can also be edited during this process and both colours and patterns can be changed in a way to allow a better understanding of the results.

The graphical outputs are also extendable, so that the user can adapt the chart to the available area of the window. This representation can also be tridimensional or bidemensional.

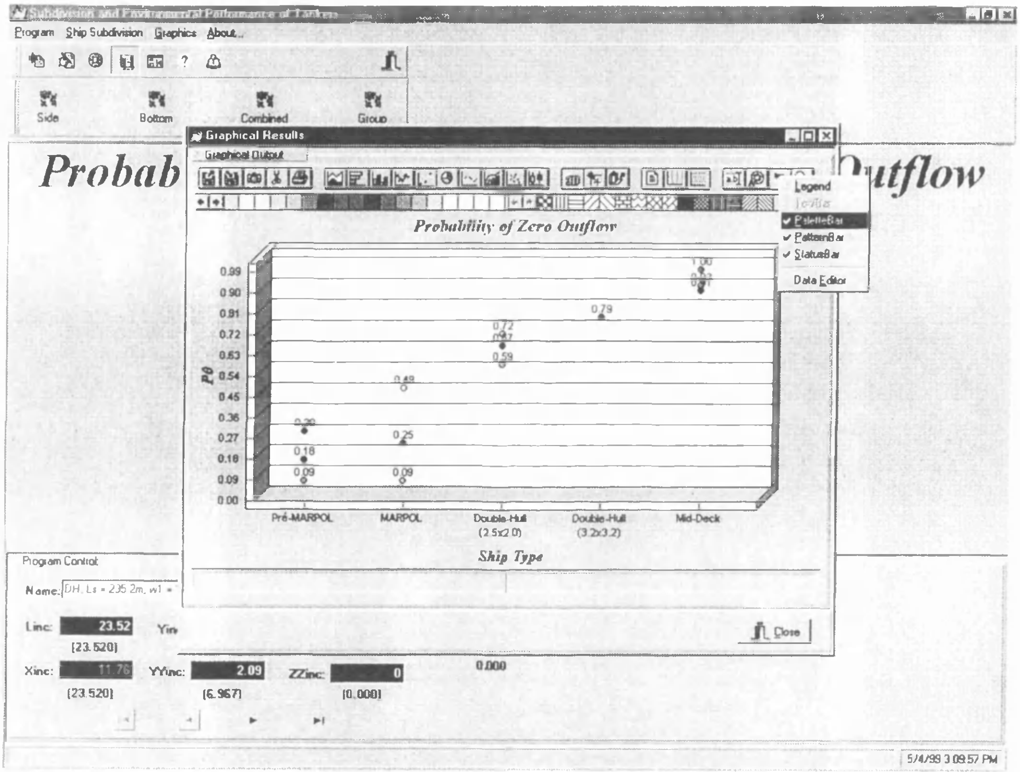


Figure 3.51. - Results Chart Representation III.

The charts can also be saved, as CHF files and recovered later. The chart representation can be printed directly to a printer or they can be copied to the clipboard and used in another Windows application, e.g., Microsoft Word.

The software provides also a help feature, where the user can easily find an explanation and guidance on the use of all the tools available in the application.

Inside this "help" there is also a small introduction and explanation to the probabilistic concept, and how it was applied to implement this software application. The "help" is fulfilled with graphical representations of all the steps involved when performing standard operations. This characteristic enables an easy understanding of how to use it and speeds up the process of getting first results.

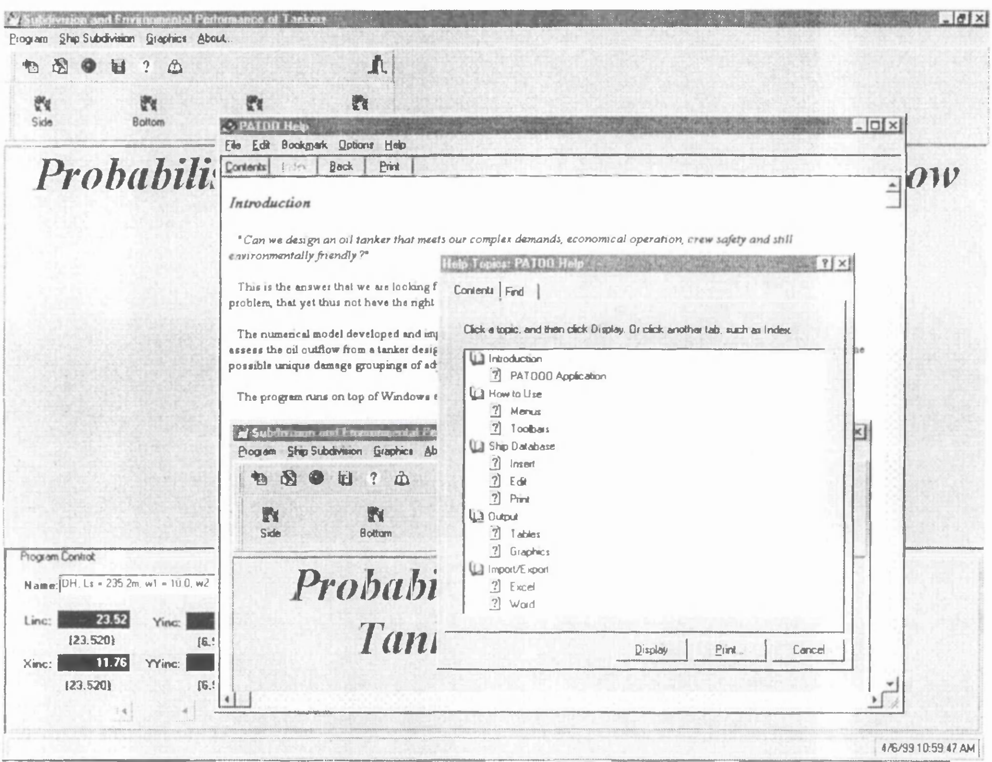


Figure 3.52. - PATOO Help.

As graphically represented in Figure 3.53., the application architecture is structured in a way that it can be installed in a network, where several users can access the same databases. These databases are the pdf functions, described in IMO Interim Guidelines (IMO, 1995b), which can only be modified by an administrator of the system, and a ship database, which can be accessed and modified by all the users that have access to the software.

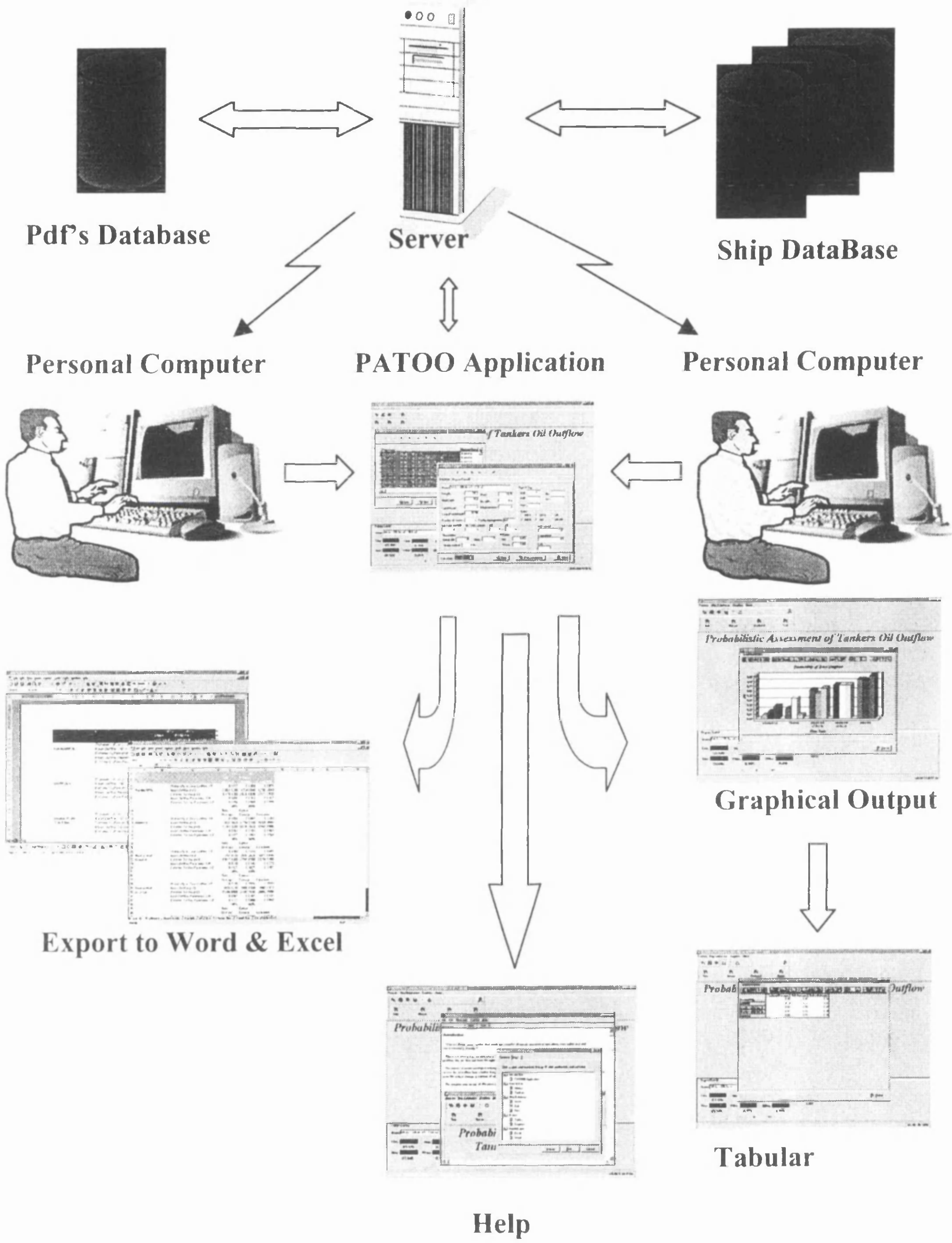


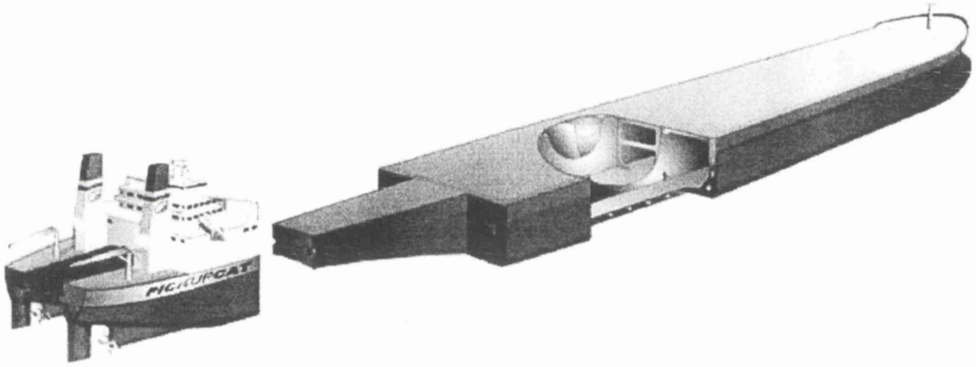
Figure 3.53. - Application Environment Description.

This structure enables the possibility of any new user to the application to have access to an already created ship database. This allows the user to select a set of ships to analyse, or to create new ones and update the existing ship database.

The idea of having a separate database for the pdf functions came from the future necessity of updating the functions describing the different probability distributions. This way, the main mathematical model is always valid being able to use any pdf functions.

CHAPTER 4

EVALUATION OF TANKER DESIGNS



CHAPTER 4 - EVALUATION OF TANKER DESIGNS

After OPA'90, designers and operators of double-hull tankers found themselves confronted with a new set of issues to consider. Design, construction, and operational experience of double-hull tankers was limited primarily to product and parcel tankers under 40,000 tons deadweight, and before this date, most crude oil carriers were built with single hulls. The differences between double-hull oil carriers and single-hull tankers and product carriers are considerable, in terms of stability and strength, giving rise to a new set of problems not yet analysed and solved.

In this study, one of the areas in which double-hull tankers perform differently, compared to single-hull tankers, has been identified and investigated. This is environmental performance with regard to oil outflow from collisions and grounding.

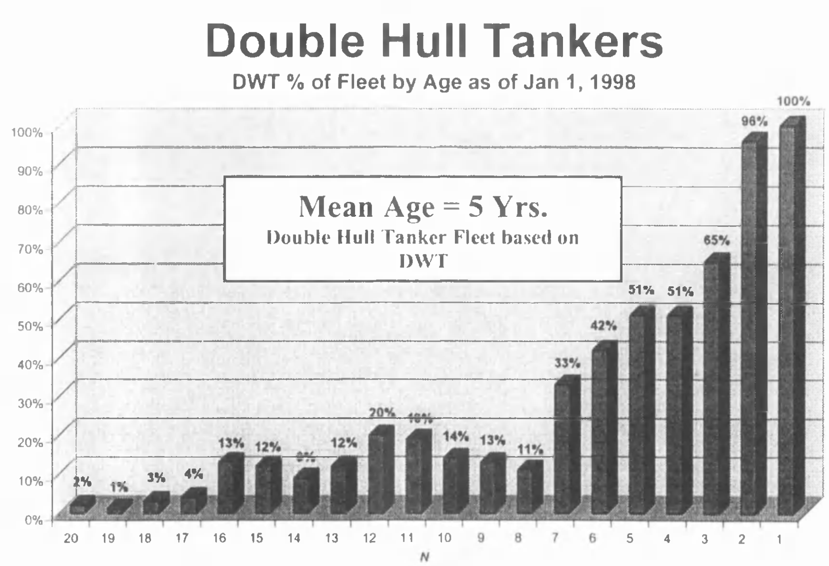


Figure 4.54. - Double-hull tanker fleet based on DWT and Age (N years).

For comparative purposes, both single-hull and double-hull configurations have been investigated. Double-hull ships are selected to be representative of the tankage arrangements and proportions typically built since 1990. In addition, mid-deck tankers were also introduced in to the comparison, to evaluate their environmental performance, when compared with the former ships.

4.1 Subdivision Nomenclature

The following terms are used to describe the ship's subdivision:

- *Cargo block*: the cargo block is the portion of the ship extending from the forward boundary of the forward-most cargo tank to the aft boundary of the aft-most cargo tank. OPA '90 as well as the 1992 Amendments to Annex I MARPOL 73/78 require that all oil tanks within this space be segregated from the side and bottom shell.

- *Cargo tanks*: all tanks arranged for the carriage of cargo oil. Unless noted otherwise, the term "cargo tanks" shall be assumed to include the slop tanks.

- *Slop tanks*: slop tanks are provided for storage of dirty ballast residue and tank washings from the cargo tanks. Annex I of MARPOL 73/78 requires that tankers be arranged with slop tanks.

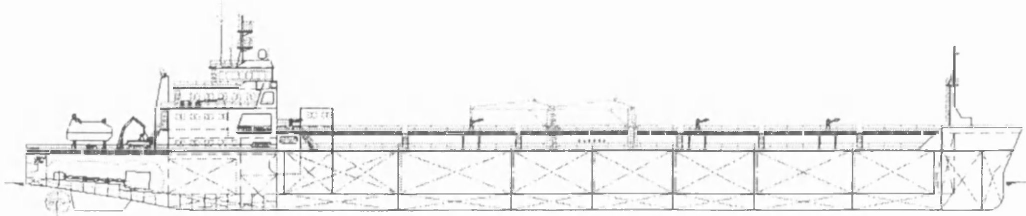


Figure 4.55. - Longitudinal view of a tanker arrangement with double-bottom.

- *Cargo tank arrangements*: Figure 4.60 shows cross-sections of typical cargo tank arrangements for double-hull tankers. The "STA" or single-tank-across arrangement has a single centre cargo tank spanning between wing tanks. This design is frequently arranged with upper hopper tanks in way of the outboard wings, in order to reduce the free surface when the cargo tanks are nearly full. The two-tanks-across arrangement has centreline bulkhead and port and starboard cargo tanks. Vessels under 160 000 DWT are typically arranged as single-tank-across, two-tanks-across, or a combination thereof (see Figure 4.60). The majority of larger tankers are arranged with three-tanks-across, as required to satisfy the MARPOL requirements for tank size and damage stability.

- *Ballast tank arrangements*

➢ "L" tanks are the most commonly used configuration. L tanks are usually aligned with the cargo tanks, although they will occasionally extend longitudinally over two cargo tanks.

➢ "U" tanks reduce asymmetrical flooding, and are generally used when L tank arrangements fail to meet damage stability requirements. U tanks extend over the full breadth of the ship, and have a significantly higher free surface as compared to a pair of L tanks.

➢ "S" or side tanks are located entirely in the wing tanks. S tanks improve the survivability characteristics of a vessel, as they normally will not be penetrated when bottom damage is incurred.

(see Figure 4.61)

4.2 Single-Hull Tankers

The design problems with single-hull tankers are first and foremost their hull design. The single-hulls of MARPOL tankers are configured in such a way that oil (cargo) and seawater sit on either side of a common barrier. This barrier is typically a 35mm steel plate (part of the hull), but in newer tankers it can be as thin as 20mm. This configuration poses some serious problems if one thinks of a grounding that breaches its hull. There is only this single barrier keeping oil from spilling out into the ocean.

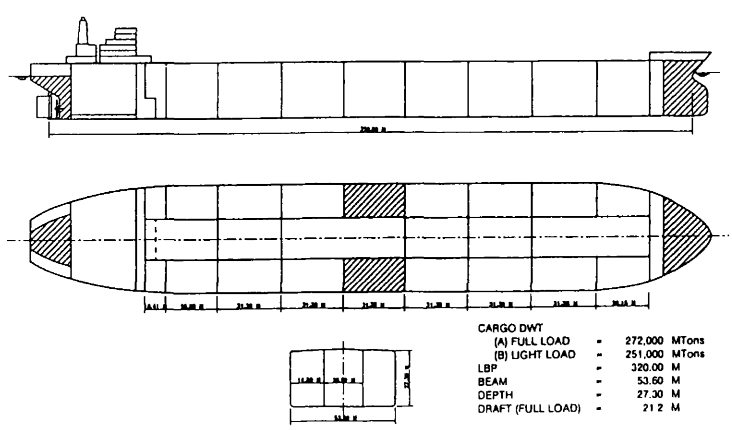


Figure 4.56. - Single-Hull Pre-MARPOL Tanker.

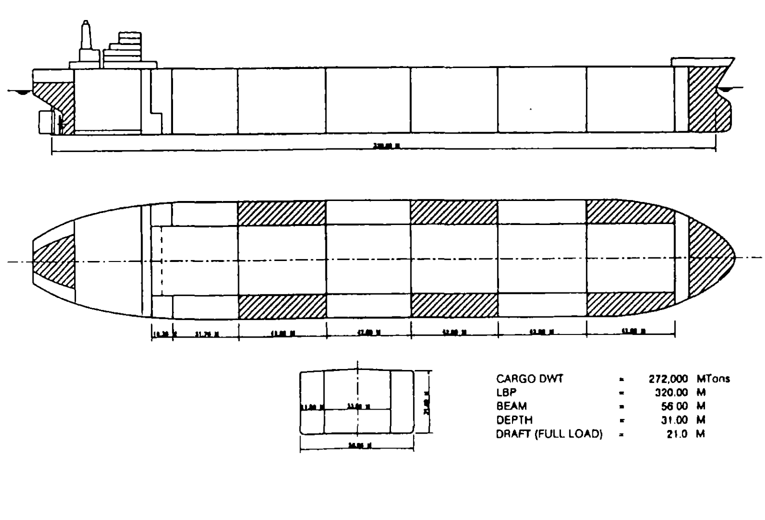


Figure 4.57. - Single-Hull MARPOL Tanker.

4.3 Double-Hull Tankers

The basic concept of double hull tankers is as follows:

- By utilising a protective inner hull, the cargo carrying is separated from the outer hull by means of "U", "S" or "L" shaped ballast wing and bottom tanks. This configuration not only satisfies the necessary segregated ballast capacity requirements, but also provides all-around protection against relatively low-energy impacts which in turn help to reduce the frequency of oil pollution incidents;
- In collisions and groundings which result in the breach of the outer shell plating only, no oil outflow will occur;
- In collisions and groundings, which result in the breach of both the outer and the inner shell plating, the quantity of oil outflow will depend on particular cargo tank arrangement and the amount of oil retention in the double ballast spaces.

4.3.1 Design of Double-Hull Tank Vessels

4.3.1.1 Design Standards

The regulations governing tanker design were developed primarily with single-hull vessels in mind, although the stability and strength characteristics of double-hull vessels are quite different from those of the traditional single-hull tanker. Existing and proposed regulations pertaining to oil outflows, intact stability, and survivability of double-hull tankers are summarised in Table 4.6.

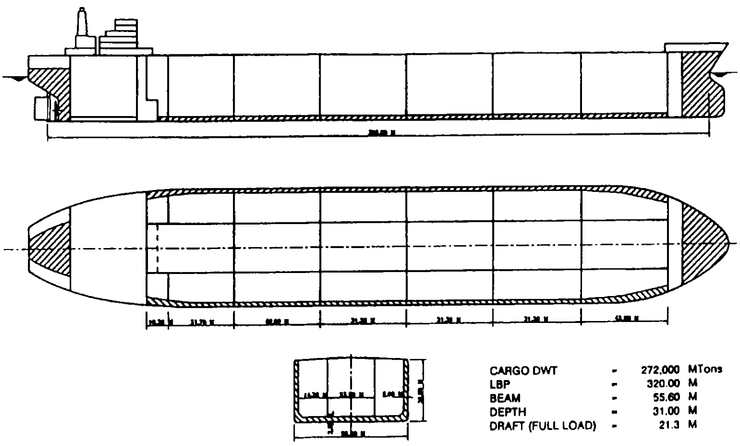


Figure 4.58. - Double-Hull Tanker.

As demonstrated by the comparative study described here, present regulations do not ensure consistent high levels of environmental performance by double-hull tankers. Where practical, IMO is committed to replacing the current deterministic regulations[1] with probabilistic based regulations. Work is under way at IMO to develop a performance-based regulation for evaluating tanker outflow. IMO is also harmonising its damage stability criteria for all types of ships based on a probabilistic methodology that will eventually include tank vessels and chemical carriers.

Performance-based criteria establish a minimum level of performance but do not specify the means of attaining this minimum. Such criteria generally take a probabilistic approach, so that the influence of a given incident on overall design is proportional to its likelihood of occurrence and to its severity and repercussions.

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[1] An example of a deterministic criterion is the IMO ranking bottom damage regulations. This is a damage stability criterion that assumes extensive damage to the bottom shell while the double bottom remains intact. For tankers greater than 75 000 DWT, damage is assumed to begin at the bow and extend aft over 60 percent of the vessel's length. This type of criterion encourages designers to place bulkheads immediately beyond the specified damage extent but does not necessarily lead to optimum designs.

Table 4.6 - Existing and Proposed Regulations Relating to Oil Outflow, Intact Stability, and Survivability Performance of Double-Hull Tankers (source: National Academy Press).

Regulation	Requirements, Scope, Status
Oil outflow from collisions and groundings	
MARPOL 13F	Establishes minimum dimensions for wing and double-bottom tanks comprising outer hull. Consistent with USCG requirements established in response to OPA '90.
Regulations 22-24, Annex I to MARPOL 73/78	Define hypothetical outflow and tank length requirements governing extent of cargo tank subdivisions. Regulations 22-24 being revised in light of probabilistic methodology for oil outflow analysis.
Intact Stability of tankers	
None at present	Intact stability to meet criteria recommended by IMO (Resolution A.749(18), 3.1.2.10)[2] normally exceeded by double-hull tankers through design. Two possible approaches: (1) through design only, and (2) through combination of design and operational procedures. Maritime Safety Committee of IMO addressing issue of intact stability for double-hull tankers. MARPOL Draft Regulation I725A calls for assurance of positive intact stability, both in port and at sea, through design only.
Survivability of tankers	
Regulation 25, Annex I to MARPOL 73/78	Specifies extent of damage tanker must be able to survive
MARPOL 13F	Defines raking bottom damage criterion that supplements Regulation 25. Damage stability criteria for all types of ships being harmonised by IMO based on probabilistic methodology.

For example, current regulations specify minimum wing tank and double-bottom clearances. A performance-based criterion might establish a minimum value for "probability of zero outflow". Rather than a uniform double-hull, a more effective design might have a deeper double-bottom located below the

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[2] IMO instruments cover IMO code on intact stability for all types of ships.

forward cargo tank and narrower wing tanks located outboard of the aft cargo tanks.

Performance-based criteria are more difficult to develop than the traditional deterministic criteria and are generally more complicated in their application. An assessment is required of both the relative probability of each possible event and the associated risks to the vessel's safety and to the marine environment. Thus, the costs and benefits of ship safety and spill mitigation measures must be understood before effective performance-based criteria can be developed.

Nonetheless, properly developed performance-based criteria have many advantages. They give the designer the freedom to optimise a design for minimum construction costs while ensuring that safety and environmental performance standards are met. They are also more adaptable to new concepts. For instance, a performance-based probabilistic outflow criterion would have predicted the poor outflow performance of many of the single-tank-across double-hull tankers. The methodology used to develop performance-based criteria is independent of the required index of performance level, thereby allowing the required level of vessel performance to the readily revised in the light of experience or in response to changes in cost-benefit scenarios.

In the years after the promulgation of OPA '90, co-ordinated research on the performance of double-hull tankers has been pursued at several centres in the United States, Japan, the Netherlands, Denmark, and Norway. Structural research is proving beneficial in providing improved design tools to incorporate fatigue and structural performance in accident scenarios into double-hull tanker design.

4.3.1.2 Tank Arrangements

The performance of double-hull tankers with respect to such matters as structural integrity, safety, and prevention of oil spills in the event of accidents has been the subject of investigation for more than 20 years.

Because few large double-hull tankers had been built before 1990, the promulgation of OPA '90 and MARPOL Regulations 13F and 13G confronted Naval Architects with new design issues. The existing national and international design regulations had been developed with single hull tankers in mind. This new challenge stimulated creativity in the design process, as illustrated by the varied hull arrangements of the double-hull tankers constructed since the passage of OPA '90. Some of these designs however, do not provide the high levels of environmental protection that can be achieved with double-hull vessels.

The arrangement of tank vessel cargo tanks and ballast tanks has a major influence on a vessel's effectiveness in reducing oil outflow after an accident as well as its damage and intact stability. In particular, the subdivision of cargo and ballast tanks by centreline bulkheads can have important implications for oil outflow in the event of a collision or grounding.

Figure 4.60 shows the three most common cargo tank arrangements in double-hull design. Nearly, all double-hull tankers exceeding 200 000 deadweight tons (DWT) – very large crude carriers (VLCCs) – built to date have cargo tanks arranged three-tanks-across. The cargo tanks on double-hull tankers less than 160 000 DWT are usually arranged in "single-tank–across" and "two-tanks-across" configurations. Approximately 60 percent of these vessels have single-tank-across cargo tanks in all or part of the cargo block[3]. All tankers exceeding 120 000 DWT delivered in the last three years have oiltight longitudinal bulkheads subdividing the cargo tanks. This is partly because of concerns regarding the outflow and stability characteristics of single-tank-across tankers and partly because of economic considerations. Suezmax tankers (about 150 000 DWT) that do not have oiltight centreline bulkheads require a large number of transverse bulkheads to satisfy MARPOL regulations for tank size and hypothetical outflow. As a result, construction costs for single-tank-across and two-tank-across double-hull tankers of approximately 150 000 DWT are comparable. In contrast, many Aframax and Panamax tankers continue to be built with single-tank-across cargo tank arrangements. For tankers of less than 110 000 DWT, fewer transverse bulkheads are required within the cargo block, and the cost savings realised with the single-tank-across arrangement are more significant.

Figure 4.61 shows typical ballast tank arrangements for double-hull tankers. The L tank is by far the most common configuration: it is found in 88 percent of double-hull tankers (see Figure 4.59). Ten percent of the tankers have a combination of U, L and S types, and 2 percent have a U design only.

Most oil tankers of modern design have similar features. The tankers developed for the comparison study presented here are arranged with a raised forecastle, and the accommodation, engine room and navigating bridge located aft and a transom stern. Main propulsion is provided by a slow speed diesel engine directly connected to a single fixed-pitch propeller; a single semi-balanced rudder provides steering. Fuel oil storage capacity is provided in tank and

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[3] Data on cargo and ballast tank arrangements are from a compilation by Exxon Company International (Exxon, 1997) of configurations for 327 double-hull tankers comprising more than 95 percent of the world double-hull tanker fleet greater than 5 000 GT (gross tons). The compilation was derived from the Oil Companies International Marine Forum ship information questionnaires provided by ship owners and from Exxon's internal inspection records.

engine room. Ballast is carried in the fore and aft peak tanks and segregated ballast tanks (SBT) in the double-hull in the way of the cargo oil length. In all cases, ballast capacity is sufficient to meet MARPOL segregated ballast tank requirements.

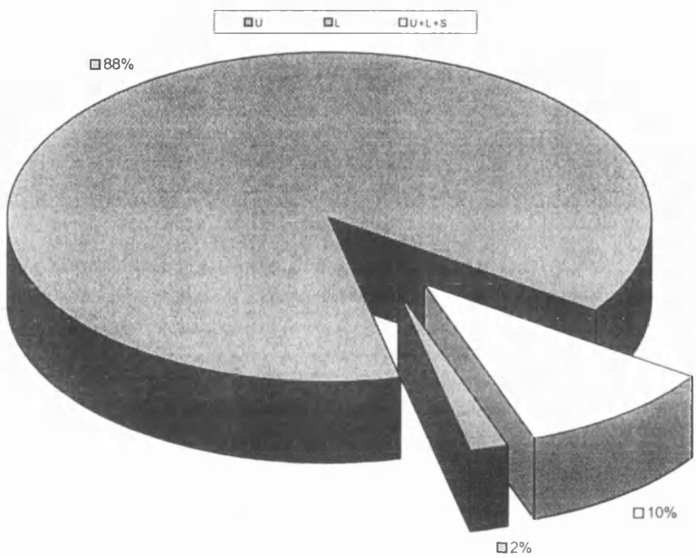


Figure 4.59. - Typical ballast tank arrangements distribution for double-hull tankers (source: National Academy Press).

The minimum dimensions of the double hull tentatively have been agreed at the MEPC meeting July 1991 (31st Session):

$$b_{DS}(\text{meters}) > \min(0.5 + DWT / 20000 ; 2.0) \quad (15)$$

$$h_{DB}(\text{meters}) > \min(B / 15 ; 2.0) \quad (16)$$

where b_{DS} is determined at a normal to the side shell and h_{DB} is measured from the baseline.

The arrangements of the cargo oil tanks are subject to limitations of regulation 24 of MARPOL 73/78 Annex I. While regulation 13 gives the ballast capacity requirements, limitations on the location of the segregated ballast tanks are given in regulation 13E. However, because of the requirements of the regulation 13F, tankers over 30000 DWT will have 100 percent protected area coverage. Crude oil tankers over 20000 DWT and under 30000 DWT with minimum double side dimensions will be required to have a moulded depth, which is at least 53 percent of the moulded breadth.

The arrangements of the double-hull SBT spaces have to be arranged to provide satisfactory intact and damage stability characteristics, inspection, maintenance and ventilation.

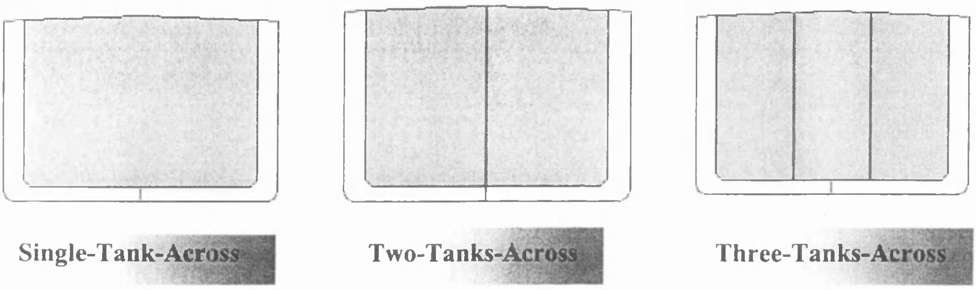


Figure 4.60. - Cargo Tank Arrangements.

Several options are available to arrange the double-hull SBT tanks. These options employ a variety of transverse, longitudinal and horizontal subdivision. Some previous papers (NRC, 1991; ARCO marine, Inc., 1990; Peters, 1991) have investigated some of these options. The types of double-hull SBT tanks that may be employed are:

1 "U" tanks, which extend between transverse bulkheads and do not have longitudinal or transverse subdivision;

2 "L" tanks, which extend between transverse bulkheads and from a longitudinal subdivision in the double-bottom to the main deck;

3 Double bottom-tanks, which may have longitudinal subdivision located solely in the double-bottom space,

4 Side tanks, which may have horizontal subdivision in the double side space;

5 Deck tanks, which may be used mostly on product tankers, located only between the main deck and the top of the cargo tanks.

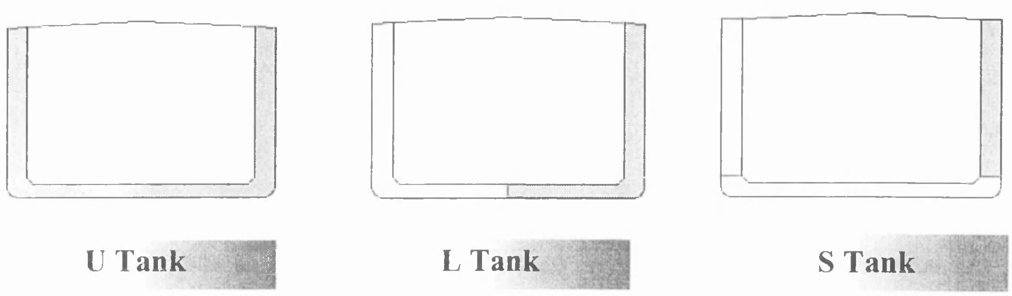


Figure 4.61. - Ballast Tank Arrangements.

These types of SBT tanks in combination are used to subdivide the double-hull space. Examples of these tank types are shown in the Figures 4.61 and 4.62 illustrating typical double-hull sections.

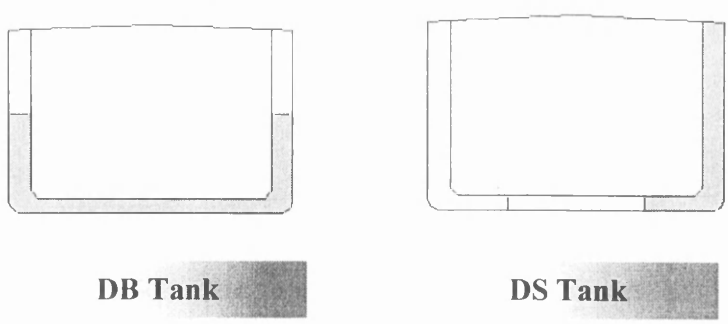


Figure 4.62. - Ballast Tank Arrangements.

4.4 Mid-Deck Tankers

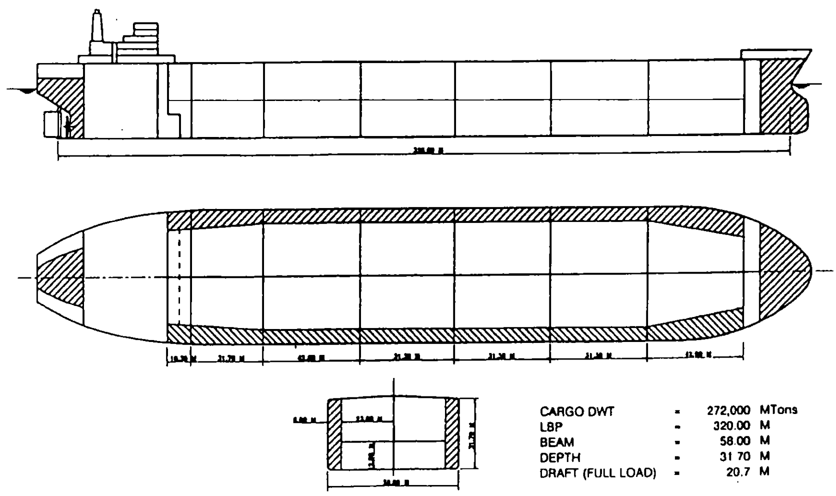


Figure 4.63. - Mid-Deck Tanker.

The basic concept of the mid-deck tanker is as follows:

- In order to satisfy segregated ballast tank capacity requirements and provide improved protection against collision penetration, the width of the wing tank spaces are increased in relation to the conventional double-hull configuration;

- The introduction of a mid-deck between the longitudinal oiltight bulkheads, which form the inner hull, effectively divides the cargo carrying section into upper and lower cargo tanks. The height of the mid-deck is determined by the characteristics and hydrostatic principles encapsulated by each mid-deck design. In the event of a grounding, causing the breach of the keel plating, the intended operational effect of the mid-deck is to reduce the pressure exerted by a column of oil in the lower tank to less than exerted by a column of seawater acting on the tanker's keel, thereby minimising oil outflow.

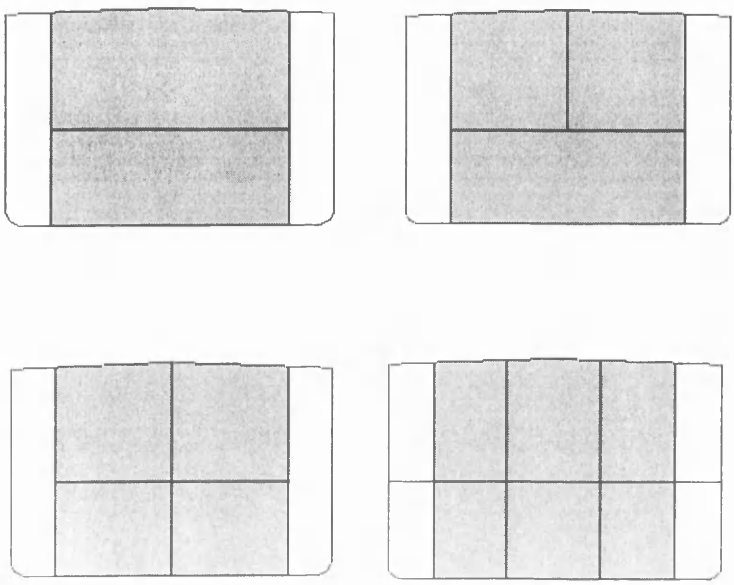


Figure 4.64. - Mid-Deck Tanker Arrangements.

4.5 Evaluating Oil Outflow

4.5.1 Introduction

Oil outflow evaluations have been carried out for 107 tankers. All calculations have been done using PATOO (Sérgio Ferreira, 1998) software. The calculation methodology and assumptions are described in the previous chapter.

The International Maritime Organisation (IMO) guidelines (IMO, 1995b) for evaluation alternatives to double-hull tankers have been applied in this work for assessing oil outflow performance. Although originally intended for evaluating alternatives to the double-hull concept, these guidelines are also well suited for comparing the outflow performance of single-hull, double-hull tankers and other design types like the mid-deck tanker concept. The guidelines use a probabilistic approach based on historical statistical data, and provide a methodology for assessing both the likelihood of a spill and the expected outflow. The IMO guidelines account for factors such as varying wing tank widths and double-bottom heights, the influence of internal subdivision, the effects of tide, and the influence of dynamic effects on outflow.

4.5.2 Case Studies

The importance of the different outflow characteristics can be assessed if one thinks about a ship that does not have any internal subdivision. In this case only one of two situations can happen: no outflow occurs at all (P_0) or one value of outflow will occur, the total volume of cargo (or effective outflow). If instead, we subdivide the cargo space into several tanks through transverse bulkheads, this would not affect the probability of zero outflow, but reduces significantly the extreme outflow (see Figure 4.82) as well the mean outflow (see Figure 4.75). The introduction of longitudinal bulkheads confirms the former relation, proving the importance of these outflow characteristics when evaluating the ability of the ship to resist oil spillage (see Figure 4.70).

The subdivision of tankers and the type of subdivision have significant effect on the prevention of accidental pollution. In order to assess the effect of this on the different measures of merit, three different types of subdivision were investigated:

- Double-hull tankers (DH);
- Mid-deck tankers (MD);
- Single-hull tankers (SH).

In addition, parametric studies were conducted within each type to evaluate the environmental performance of each ship when several parameters were changed, like the width of double sides, double bottom heights and height of horizontal bulkheads. In the case of double-hull tankers, the influence on the mitigation of oil outflow of different configurations of ballast tank arrangements was also investigated.

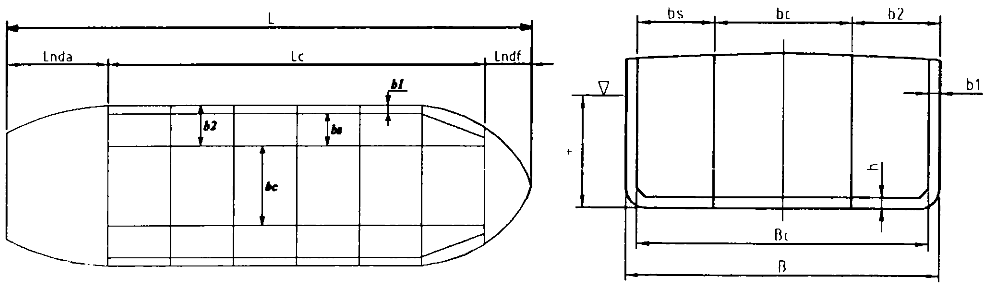


Figure 4.65. - Nomenclature related to the parametric study conducted.

4.5.3 Structural Design Measures

Double sides have been effectively utilised in numerous ship designs. Under the new regulation guidance, double sides would be utilised for ballast and provide low energy collision protection. One aspect of double sides' design, which has presented some concern, is damage stability and survivability (Peters, 1991). In general, the opinion is that existing single-hull tankers can be properly designed with double sides to meet current damage stability regulations. Economic viability must be checked on a case-by-case basis, and therefore, will be a difficult issue to address in rulemaking.

In terms of ***double-bottom design***, the most significant advantage is its ability to protect the cargo block from rupture during groundings. For all but high-energy groundings, a double bottom will resist penetration of the inner hull. The amount of protection offered is dependent upon the height, and structural design, of the double bottom, as well as the amount of energy to be absorbed (Wierzbicki, 1990; DnV, 1990). Typically, if a pre-MARPOL tanker is retrofitted with a double-bottom meeting the current height guidelines, and is to meet current MARPOL ballast requirements, additional tankage will be required. Consequently, a deeper double-bottom will be required. This additional tankage also can be located in double side tanks. However, the overall effect is the same; the centre of gravity of the cargo is raised with a corresponding increase in the hydrostatic head of the cargo oil. For certain damages these increase results in greater oil outflow. The specific configuration of the double bottom is the subject of continuing international debate.

Most oil tankers built after 1979 are required to have ***segregated ballast***, to reduce operational oil pollution. However, it is estimated that roughly 65% of the existing world fleet over 10 000 DWT does not have segregated ballast tanks. SBT does have a negative impact resulting in an increase in oil outflow in certain accident scenarios, particularly if the ballast is placed in the double-bottom. However, operational pollution accounts for approximately half the input of oil into the marine environment.

Protectively Located Ballast Tanks (PL/SBT) were first required by MARPOL regulations (MARPOL 73/78). To meet the MARPOL requirements, the PL/SBT must be arranged to cover between 30 to 45 percent of the total area of the bottom and side shells. The actual percentage is related to the size of the ship. This allows the PL/SBT to provide a measure of protection against oil outflow in case of a grounding or collision. Each wing tank or double-bottom tank also must meet certain minimum width or depth requirements, respectively (generally two meters). The requirements for either SBT or PL/SBT have never been required for existing ships, even though the 1978 conference for the MARPOL convention recommended that the IMO set a date.

The ***Mid-Deck Tanker*** concept has been debated extensively in the recent years. Retrofitting a mid-deck concept to an existing tanker will require extensive modifications to the cargo piping systems, cargo ventilation system, cargo cleaning system, and inert gas system, if required.

Smaller Tanks would limit the potential oil outflow for a given type of damage since there would be a smaller volume of cargo in each tank. From a damage stability point of view, smaller tanks are generally more acceptable by limiting the amount of lost buoyancy after damage. However, from a cost standpoint, smaller tanks require additional capital cost to install, and additional cost associated with maintenance and inspection. Additional study is required to determine whether this measure will adversely affect cargo operations and profit revenue.

There are a number of patented designs currently in existence that implement the concept of ***Rescue tanks/Emergency Transfer Systems.*** This concept are technologically feasible, and therefore warrant consideration. For a system to be successful in time of need, it must be of passive type, i.e., it must be activated independent of crew intervention. However, it also must not place the tanker in a more dangerous situation, especially with rgards to stability. In addition, it must be designed to prohibit the transfer of oil products into ballast tanks during normal operations to comply with regulations.

4.5.4 Outflow Parameters

A vessel's ability to resist oil spillage can usually be best described by the cumulative distribution of oil outflow. This oil outflow can be easily obtained. Once all possible damages have been evaluated, the damage cases are placed in ascending order as a function of the amount of oil outflow. A running sum of probabilities is computed, beginning at the minimum outflow damage case.

This cumulative probability can be plotted against oil outflow as a step-wise function, as shown in Figures 4.66-4.67.

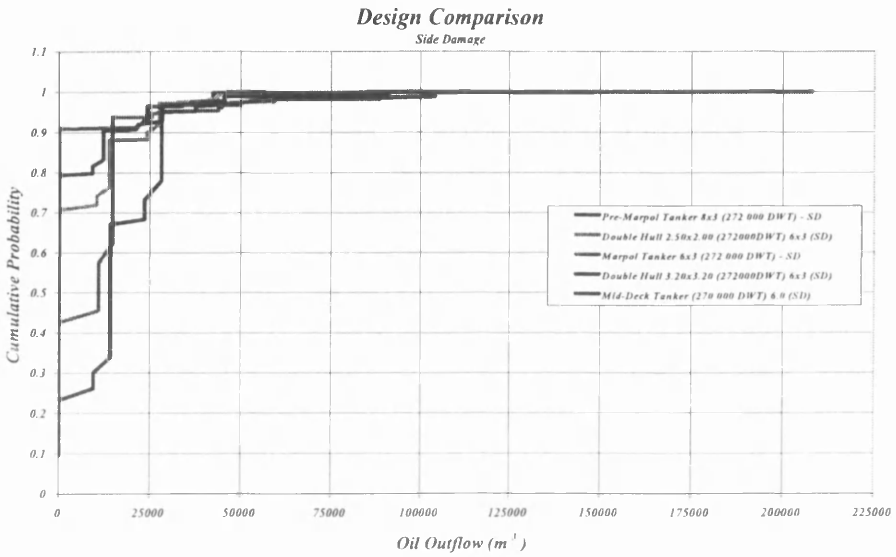


Figure 4.66. - Cumulative Distribution Function of Oil Outflow from Tankers – Side Damage

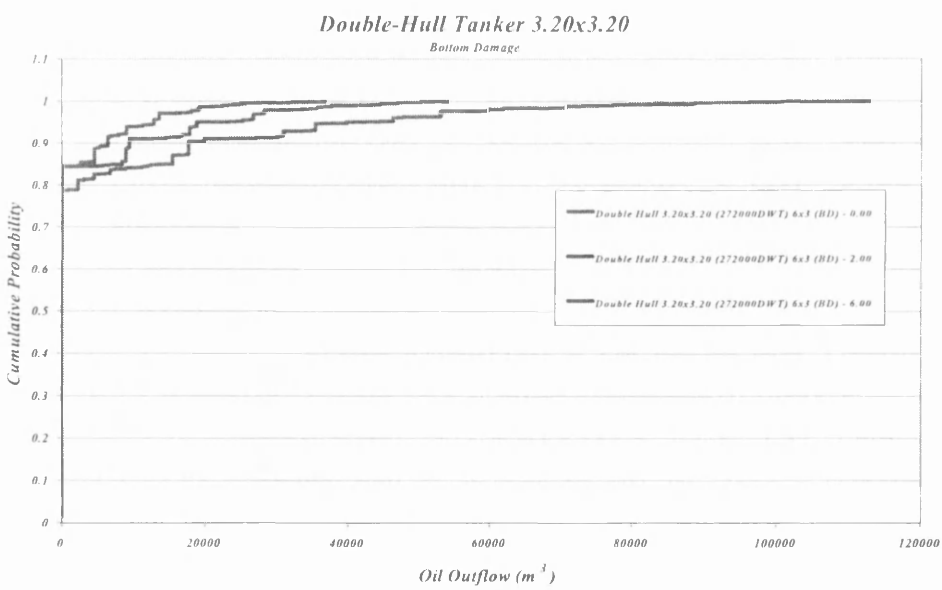


Figure 4.67. - Cumulative Distribution Function of Oil Outflow from a Double-Hull Tanker – Bottom Damage

The oil outflow plots provides a good picture of a vessel's overall ability to resist oil spillage when damaged. It is particularly useful when there is a large number of different values of outflow, which is not always the case.

Analysing the oil outflow plot from Figure 4.66 is possible to note the existence of corners and lines with slope. The vertical jumps between corners represent that several casualties are being calculated, without breaching anymore cargo oil compartments, i.e the cumulative probability is increasing but no oil outflow is added. The slope of lines represent that the consecutive damage casualties experienced by the ship are adding some oil outflow through out time. If the line is almost horizontal, this means that we breached another cargo oil tank, adding a large amount to the oil spilled value. It gives also the information that we were in the vicinity or boundary of two or more cargo oil tanks, damaging the bulkhead that was separating them.

On the sample plot, the oil outflow of a double-hull tanker (3,20x3,20) corresponding to a cumulative probability of 0.8 is 9,100 m^3. This means that in 80% of all collisions, the oil outflow will not exceed 9,100 m^3. It therefore follows that 20% of all collision incidents will have outflows in excess of 9,100 m^3.

The oil outflow graph contains a number of pieces of information, attributed to the concept of distribution function, which are useful when assessing the overall performance of a ship, including:

- probability of zero outflow;
- mean outflow;
- effective outflow;
- hypothetical outflow;
- median outflow;

- significant outflow;
- and extreme outflow.

(see Annex A for a short description of such parameters).

Note that not all these parameters are used by the IMO Interim Guidelines to assess the overall performance of a specific ship design (see section 3.2.2.4), because as stated previously, the three ones choosen are the ones that better characterise the ship in terms of its ability to resist oil spillage.

4.5.4.1 Zero Outflow

Figures 4.68 to 4.72 show the *Probability of Zero Outflow* values for a set of tankers evaluated in the study. It is important to note that P_0 is independent of the subdivision of cargo space of the ship, as shown by Figures 4.68 and 4.69. As a result of this, if different ships have the same cargo capacity, this characteristic will be only affected by the width of double sides, i. e., the spaces that do not carry cargo. Then, it is obvious that it would be appropriate to establish a minimum value for the *Probability of Zero Outflow*, P_0, instead of imposing dimensions regarding the double hull or the protective location of segregated ballast tanks. Hook (1991) showed the flaws in this type of prescriptive regulation.

This parametric study revealed some interesting characteristics as follows. There was a clear intention to evaluate a set of ship lengths with variation of breadth of double sides within each length:

- the effect of double sides on P_0 is significant. The data shows an obvious increase with ship length (Figure 4.70);

- for the same value of P_0, smaller ships have relatively wider double sides than larger ships;

- the increase in P_0 is much more significant between 0% and 5% breadth of double sides. (see Figures 4.69 and 4.70)

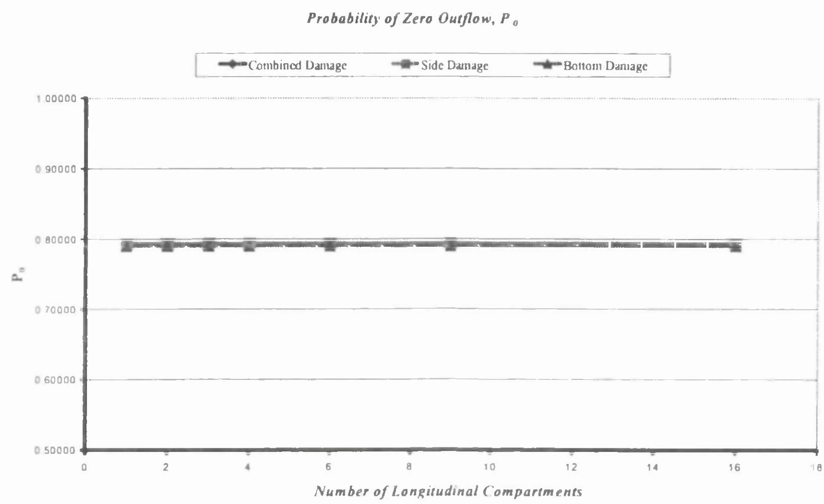


Figure 4.68. - Values of P_0 versus Number of Longitudinal Compartments.

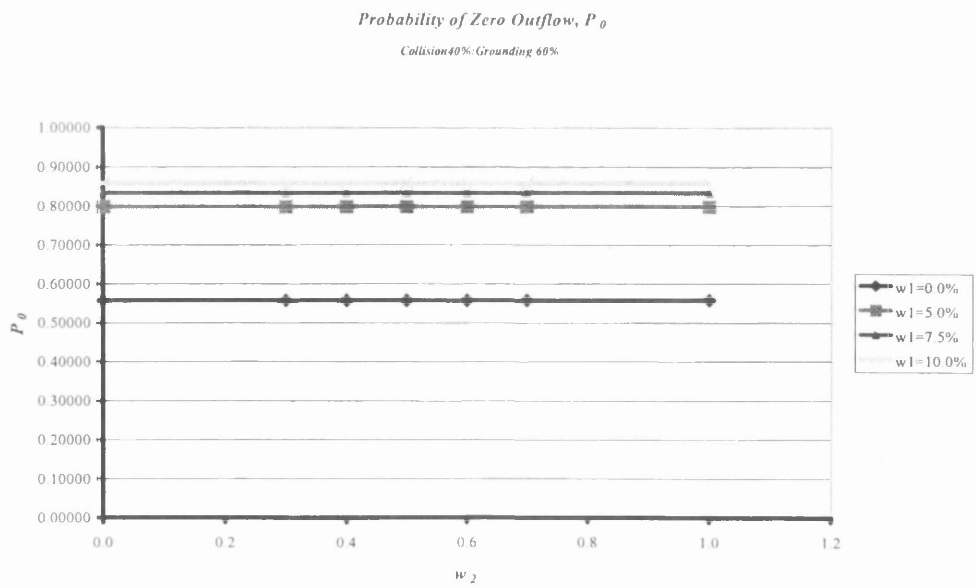


Figure 4.69. - Influence of Internal Cargo Block Subdivision $\left(w_2 = \dfrac{b_2}{B}\right)$ *and Wing Tank Width* $\left(w_1 = \dfrac{b_1}{B}\right)$ *on the Probability of zero Outflow* P_0.

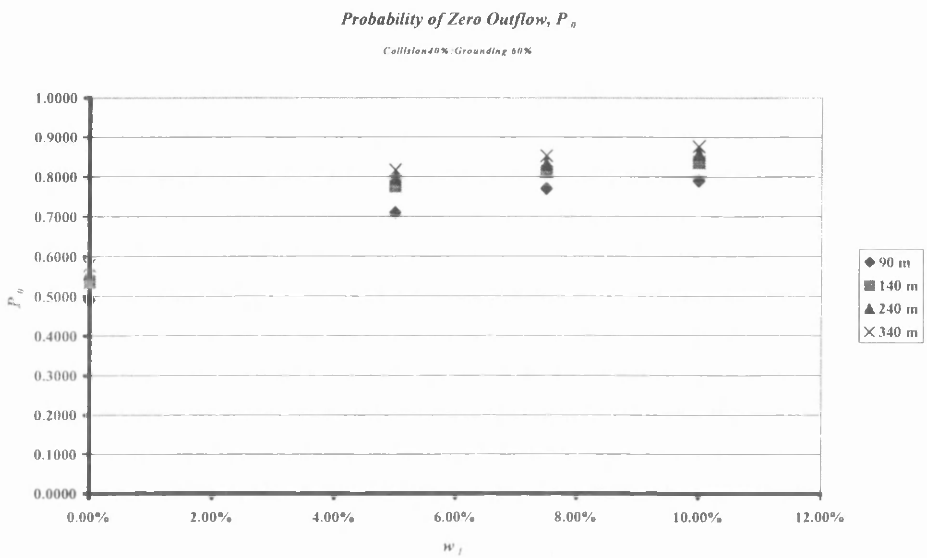


Figure 4.70. - Values of P_0 *versus the non-dimensional breadth of double sides* $w_1 = \dfrac{b_1}{B}$ *and ship's length* L_s *in metres.*

Figure 4.71. and 4.72 show values for P_0 comparing different ship types. The calculations indicated that the probability of zero outflow is four to six times higher for double-hull than for single-hull tankers. In other words, the projected number of spills for double-hull tankers is one-fourth to one-sixth the number of spills projected for single-hull tankers. It is important to state that, this comparison between different ship was made selecting a set of ships similar in cargo oil capacity and ballast cargo capacity, so that the results could be valid for an overall evaluation.

When considering bottom damage alone, double-hull tankers offer a significant improvement over the single bottom configurations. For a double-hull design with a 3.2m double-bottom, more than 75% of the bottom damages will result in no oil outflow and for a 2.5m height of double bottom more than 70%. The mid-deck tanker is by far the best design in terms of bottom damage alone with almost a null probability of oil spillage.

Figure 4.71. - Probability of Zero Outflow, P_0, for different ship types.

When considering side damage alone, the double-hull with 3.2m and the mid-deck tanker designs offer a considerable improvement over the other configurations due to their wing tank arrangements.

Weighting of side versus bottom damage indicates the overwhelming superiority of the mid-deck tankers and also double hulls to reduce the likelihood of an oil spill.

Summing up the obtained results it is possible to say that ballast tanks or other non-oil spaces protect all cargo oil tanks on a double-hull tanker built to OPA '90 requirements. They have the same effect in the mid-deck tanker, with the advantage of being wider wing tanks protecting the cargo. Thus, many scenarios that would culminate in oil spillage from single-hull tankers do not result in penetration of the double-bottom and wing tank dimensions in the case of double-hulls and mid-deck tankers. It is also evident that this measure is not affected by internal subdivision within the cargo tanks. In other words, centreline or other longitudinal bulkheads within the cargo spaces or ballast tanks have no influence on the probability of zero outflow.

Note that the probability of zero outflow in bottom damage incidents with mid-deck tankers, even hydrostatically balanced, the value is not really zero because there are always oil losses due to initial impact and due to dynamic oil losses. However, as stated before, for this specific parameter calculation and comparison purposes they have not been included when evaluating bottom damage incidents with mid-deck tankers. The main reason for this comes from the fact that mid-deck-tankers do not have any bottom internal protecting space between water and cargo oil spaces. Then, all possible damages breaching the hull, breach immediately a cargo oil tank giving origin to oil losses. If theses oil losses are taken into account, the probability of zero outflow would be zero in bottom damages for mid-deck tankers.

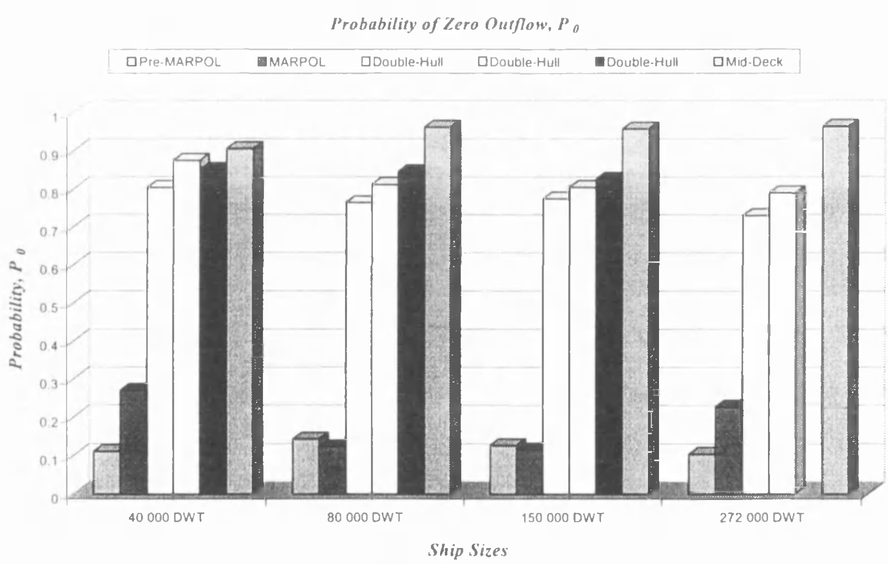


Figure 4.72. - Probability of Zero Outflow, P_0, for different ship types and sizes.

Then, even such a small amount of oil lost would give a wrong idea about the performance of this kind of tanker in terms of probability of zero outflow, when comparing them with other types that have double-bottom spaces.

4.5.4.2 Mean Outflow

As regards the mean outflow, it is again clear from the results that this characteristic value is the one that most naturally reflects the effect of compartimentation on the mitigation of oil outflow. Thus, the ratio O_M/V_c, the non-dimensional mean outflow parameter, shows directly this effect.

The parametric study revealed again some interesting results, from which is possible to highlight that:

- the mean outflow (m^3) is in proportion to the volume of cargo carried out by the ship. Then, the hazard to the environment increases with bigger ships. This means, that if the regulations were to impose a limit on the absolute value of the mean outflow, such a requirement would indirectly impose a restriction on the maximum size of tankers (Pawlowski, 1996); however, in relative terms the opposite is true, i.e. the mean outflow parameter, *MO/C*, where *C* is the cargo capacity in tonnes, is lower for larger ships;

- the idea of increasing the number of compartments to reduce oil outflow quantities revealed to be a very ineffective way of doing it; only until a certain level is possible to get better results(see Figures 4.73-4.75);

- if we talk in relative terms, smaller ships must have relatively wider double sides than bigger ships, for the same level of protection of the environment.

The mean outflow values for tankers evaluated in the comparative study are plotted in Figures 4.76 and 4.78. The mean outflow values for double-hull vessels are one-third to one-fourth the single-hull values, but mean outflow varies significantly even among double-hull tankers of the same size. Once again mid-deck tankers represent the best design, offering the lowest mean outflow values in the comparison of present designs.

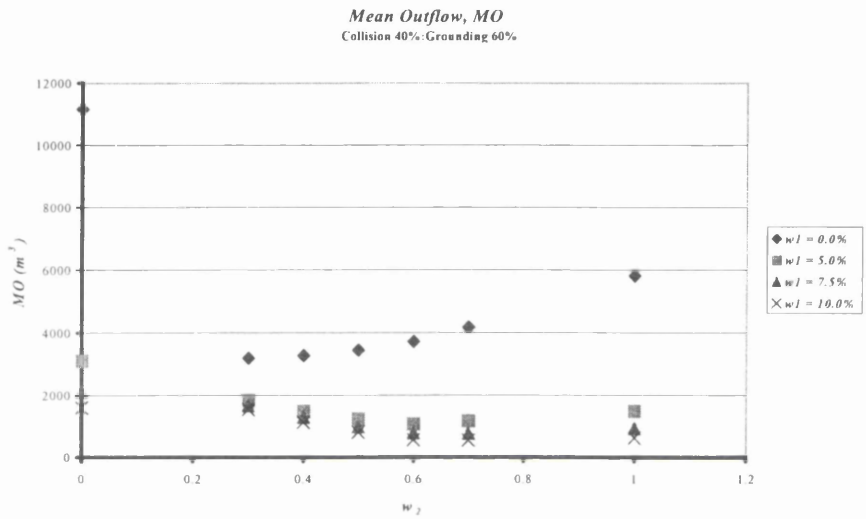


Figure 4.73. - Influence of Internal Subdivision of Cargo Block (w_2) and Width of Wing Tanks (w_1) on Mean Outflow, MO.

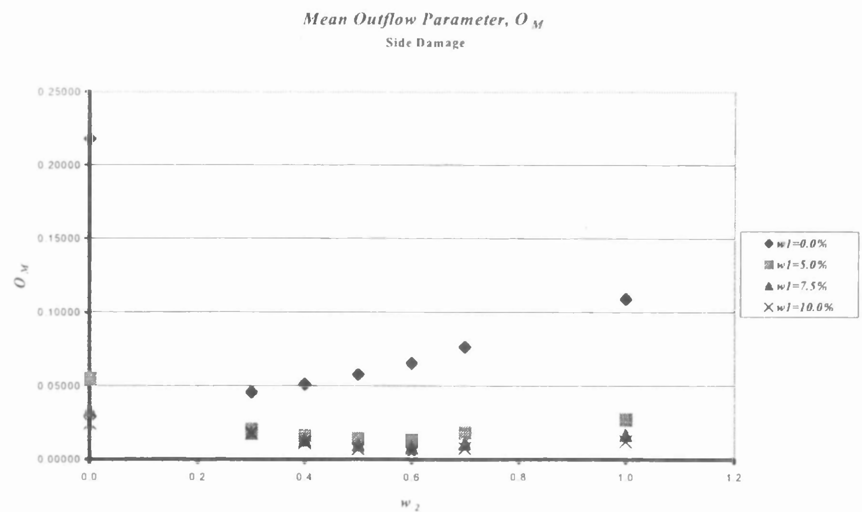


Figure 4.74. - Influence of Internal Subdivision of Cargo Block (w_2) and Width of Wing Tanks(w_1) on Mean Outflow Parameter, O_M.

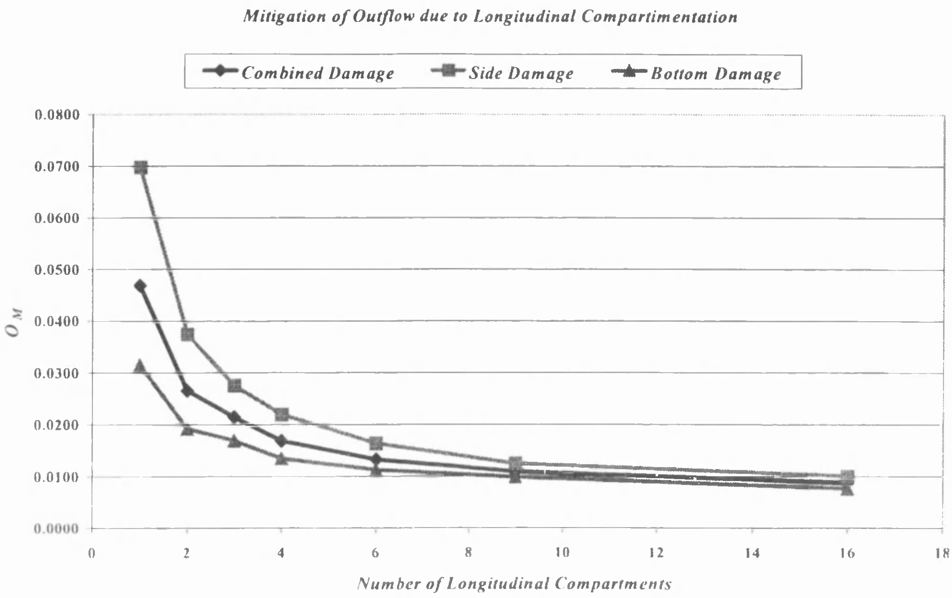


Figure 4.75. - Mean Outflow, O_M, vs. Number of Transverse Compartments.

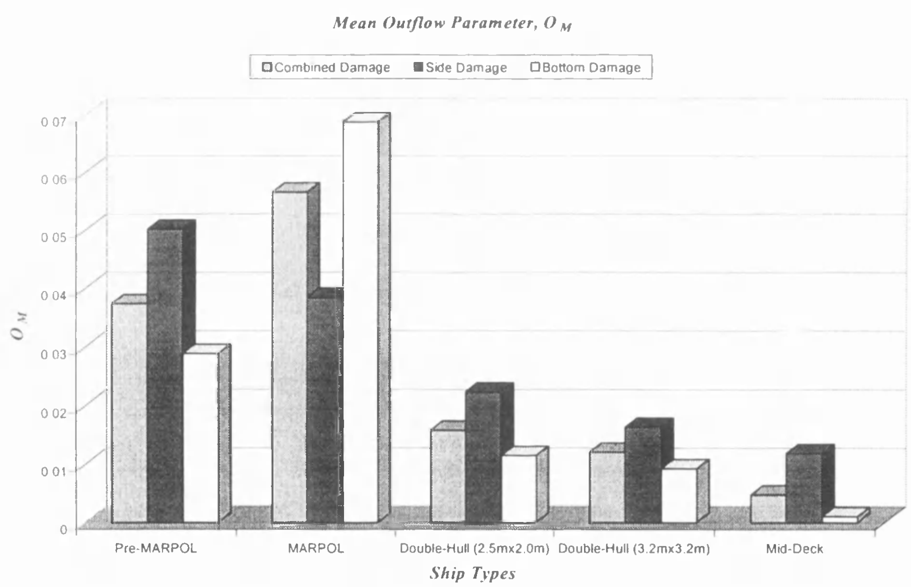


Figure 4.76. - Mean Outflow, O_M, for different ship types.

The double-hull dimensions as well as the extent of external subdivision influence mean outflow. Wider wing tanks and deeper double bottoms tend to reduce the likelihood of a spill, thereby increasing the number of collisions and groundings with no spillage. Hence, an increase in wing tank width and double-bottom depth reduces the mean spill value. Greater internal subdivision also tends to reduce the quantity of oil spilled, as demonstrated in Figure 4.75, but its effectiveness is only felt until a certain level.

The variability in mean outflow values for double-hull tankers is primarily a result of differences in subdivision within the cargo block (see Figures 4.77 and 4.78). Double-hull tankers without centreline bulkheads have approximately twice the expected outflow of designs with oiltight centreline bulkheads in way of all cargo tanks (see Figure 4.74). The same ~~was~~ results were obtained for single-hull tankers.

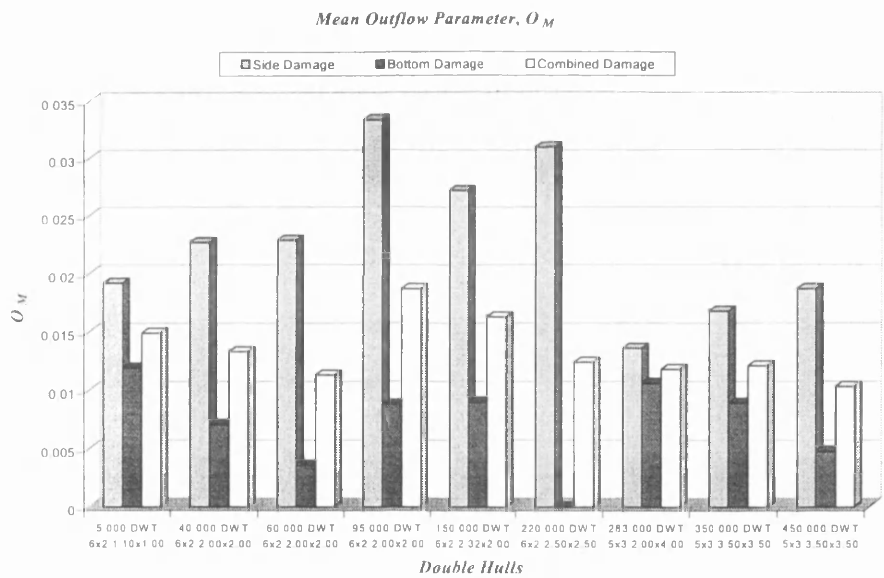


Figure 4.77. - Mean Outflow, O_M, for a set of Double-Hulls.

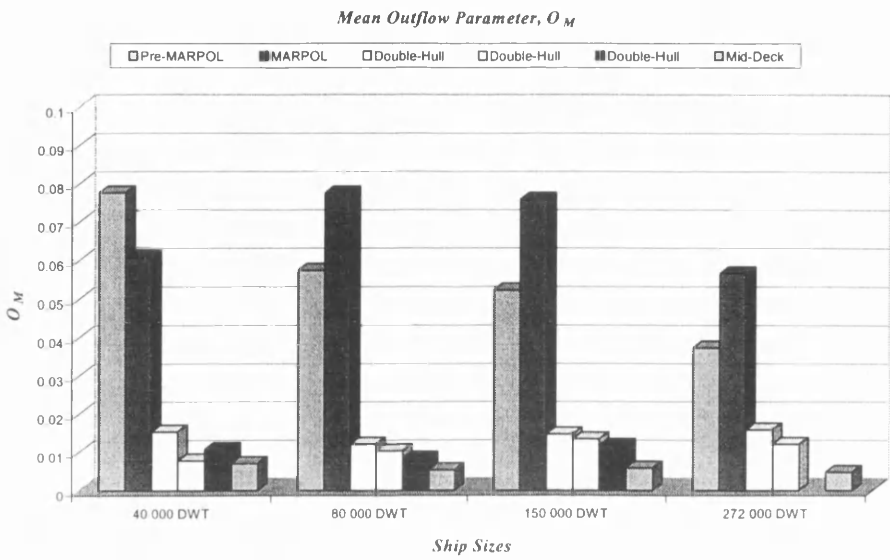


Figure 4.78. - Mean Outflow, O_M, for different Ship Types and Sizes.

Single-tank-across design performed less effectively when the vessel was subjected to side damage than when subjected to bottom damage. The closer spacing of transverse bulkheads in these designs increase the probability that multiple cargo tanks will be breached. Once a single-tank-across tank is breached, oil located all across the cargo compartment will flow out through the damaged side. Oil outflow is no longer limited to the oil being carried on one side of the vessel (see Figure 4.79).

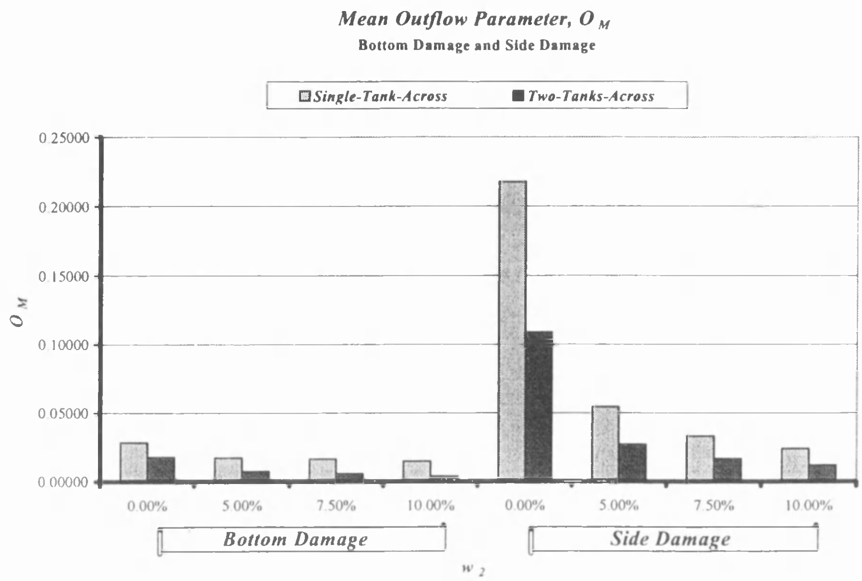


Figure 4.79. - Mean Outflow, O_M, for Single-Tank-Across and Two-Tank Across designs.

When considering bottom damage alone, the hydrostatically balanced design Mid-Deck tanker offers the best overall performance. The MARPOL ship is the worst performer with mean outflows significantly higher than the double-hulls and virtually double the outflow from the Pre-MARPOL ship (see Figure 4.76).

When considering side damage alone, the double-hull and mid-deck designs offer the lowest mean outflow. Mean outflow for the mid-deck design is only slightly lower. The inferiority of the single hull ships in minimising mean outflow from side damage is readily apparent.

Weighting of side versus bottom damage indicates a fairly equivalent performance for all of the proposed improvements to the Pre-MARPOL and MARPOL ships. The conventional single-hull vessels yield the highest levels of mean oil outflow.

4.5.4.3 Extreme outflow

Extreme outflow parameters are shown in Figures 4.80-4.84. There is considerable scatter in the data points, indicating that such characteristics as internal subdivision and draft-to-depth ratio have a significant impact on extreme outflow. Although the comparative analysis indicated that double hulls are very effective in reducing both the number of spills and the mean outflow values, their effectiveness in preventing large spills is less pronounced.

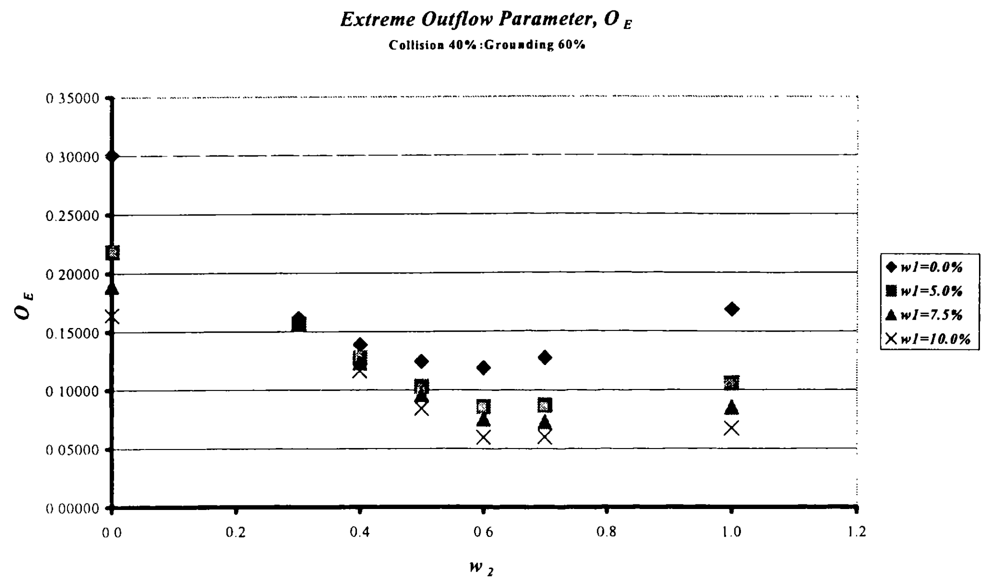


Figure 4.80. - Influence of Internal Subdivision of the Cargo Block (w_2) and Width of Wing Tank (w_1) on Extreme Outflow Parameter, O_E.

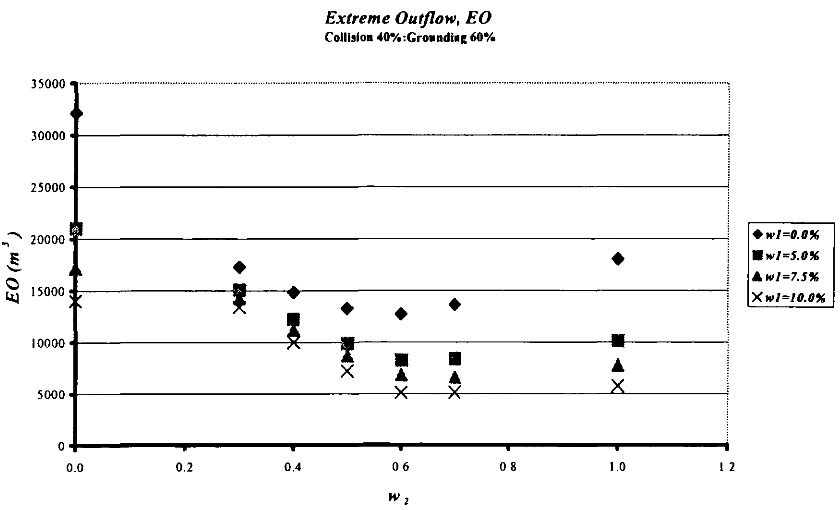


Figure 4.81. - Influence of Internal Subdivision of the Cargo Block (w_2) and Width of Wing Tank (w_1) on Extreme Outflow, EO.

When considering bottom damage alone, the hydrostatically balanced design Mid-Deck tanker offer substantially superior performance regarding extreme oil spills. The MARPOL design is inferior to all other designs in this respect. The double-hull designs offer no improvement over the conventional Pre-MARPOL configuration (see Figure 4.83).

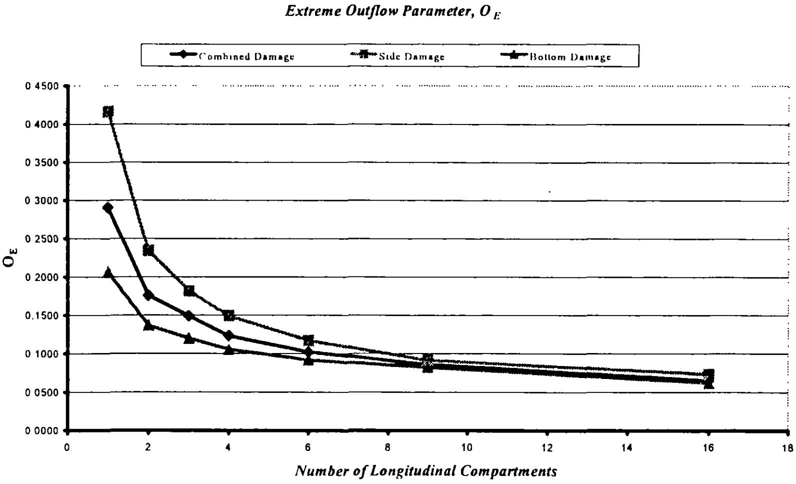


Figure 4.82. - Extreme Outflow Parameter, O_E, for both side, bottom and combined damage vs. Number of Longitudinal Compartments.

When considering side damage alone, the MARPOL design once again is the worst performer. The mid-deck design results in the lowest extreme outflow.

Weighting of side versus bottom damage indicates the superiority of mid-deck design when subjected to extreme damage scenarios. The double-hull ships offer essentially equivalent performance to the existing Pre-MARPOL designs.

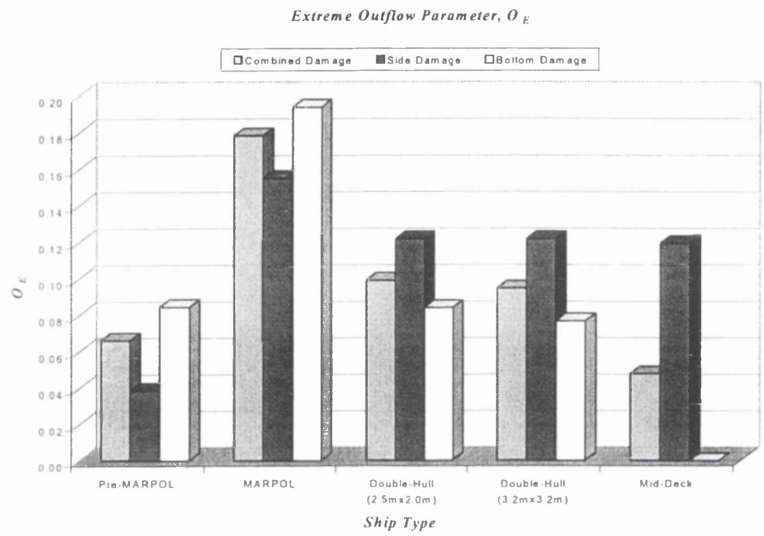


Figure 4.83. - Extreme Outflow, O_E, for different ship types.

When comparing different ship types in size categories, the same conclusions are extracted, with exception made to the Pre-MARPOL 40 000 DWT tanker. In this case, it is the worst performer, mainly due to its high number of longitudinal compartments, giving origin to a high probability of damaging multiple cargo tanks, increasing this way the extreme oil outflow parameter.

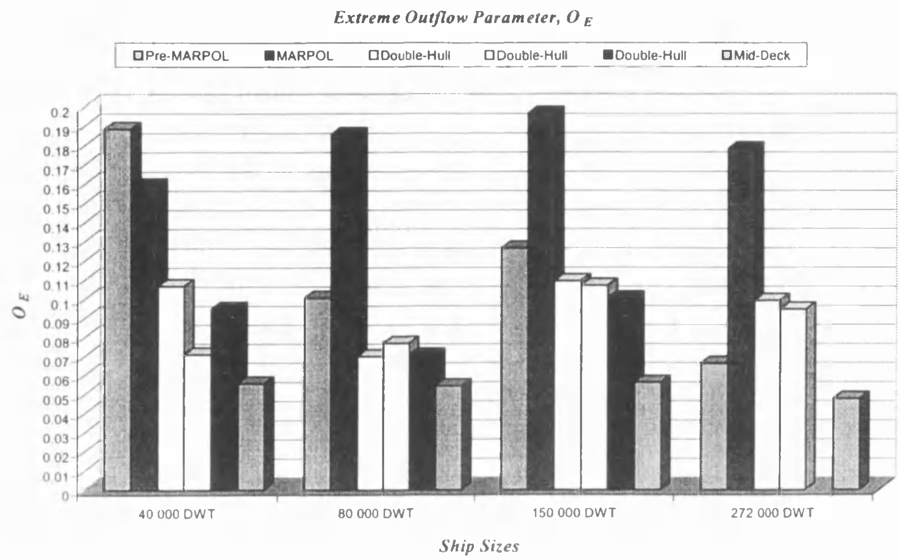


Figure 4.84. - Extreme Outflow, O_E, for different Ship Types and Sizes.

4.5.4.4 Pollution Prevention Index

The IMO Pollution Prevention Index E provides an overall picture of outflow performance. The three outflow parameters for a given design are combined, using weight factors, and then compared to the outflow parameters for an IMO reference ship of similar size[4]. An index greater than or equal to 1.0 indicates equivalence to IMO's reference designs.

[4] Sketches of the IMO ships are provided in Appendix B. These reference designs do not incorporate the minimum subdivision acceptable under current MARPOL regulations. They were selected because they exhibit a favourable oil outflow performance.

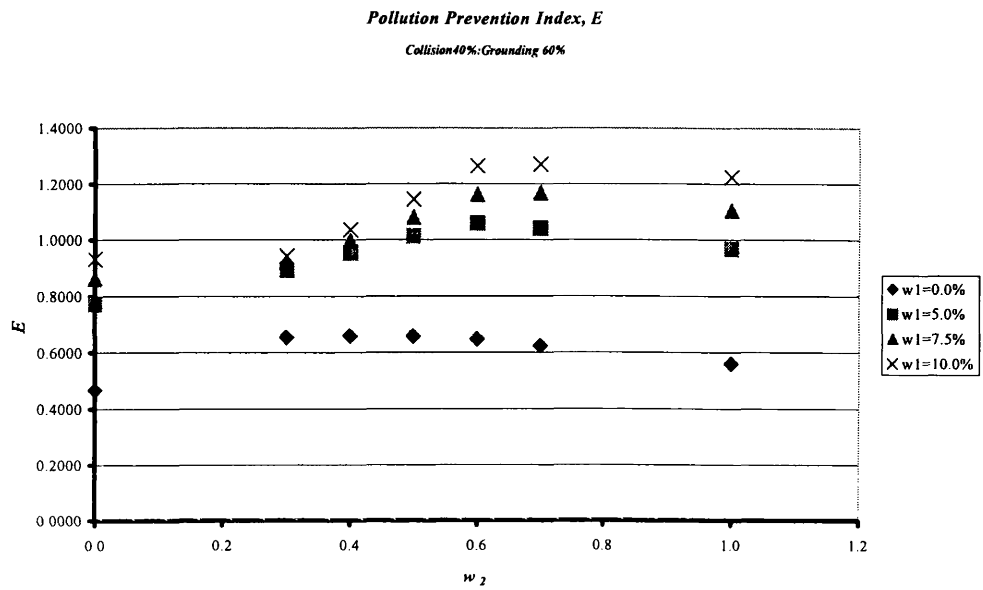


Figure 4.85. - Influence of Internal Subdivision on IMO Pollution Prevention Index, E.

The study of the influence of different double side dimensions, number and location of longitudinal members in the Pollution Prevention Index is shown in Figure 4.85. For the ships evaluated, all the single-hull tankers, even with longitudinal bulkheads, perform poorly when compared with IMO double-hull tankers, with the best values slightly over 65%. When taking different internal configurations for double-hull tankers, the reduction of the centre cargo tank shows the best results, with values over 120% for a double-hull with two longitudinal bulkheads at a distance of 30% breadth and a double side of 10% breadth. Only one of the double-hulls with a central longitudinal bulkhead does not present a Pollution Prevention Index higher than the IMO Double-Hull reference designs, showing typical values between 0.98 an 1.22.

Figure 4.86 shows the Index E for single-hull, double-hull and mid-deck tankers evaluated in the comparative study. Single-hull tanker values generally fall between 0.3 and 0.4, whereas double-hull tanker values lie between 0.9 and 1.1. Sixty nine percent of the double-hull designs evaluated in the study have indices greater than 1.0, indicating equivalency to IMO reference ships. In general, ships with longitudinal oiltight bulkheads in the cargo holds have highest indices (see Figures 4.85-4.89). Among these last, narrower centre tanks lead also to highest indices.

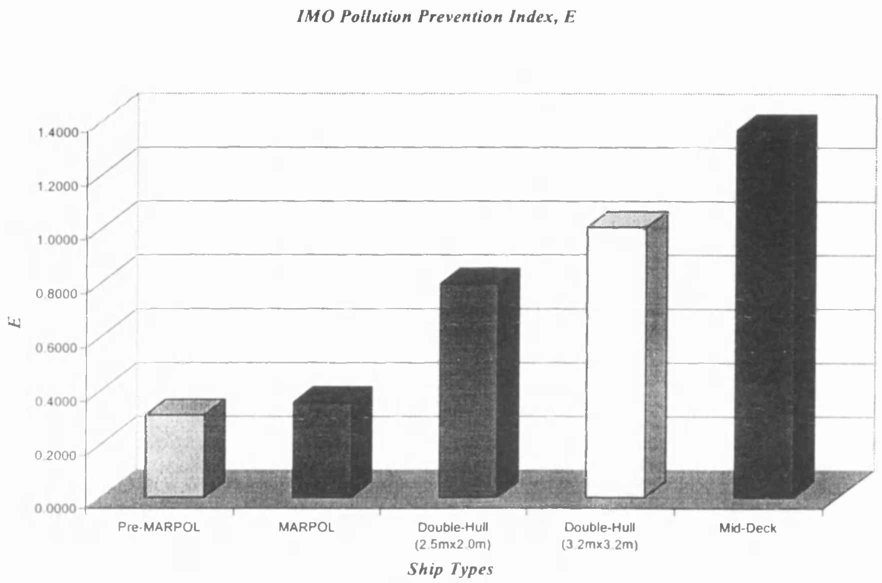


Figure 4.86. - IMO Pollution Prevention Index, E, for different Ship Types.

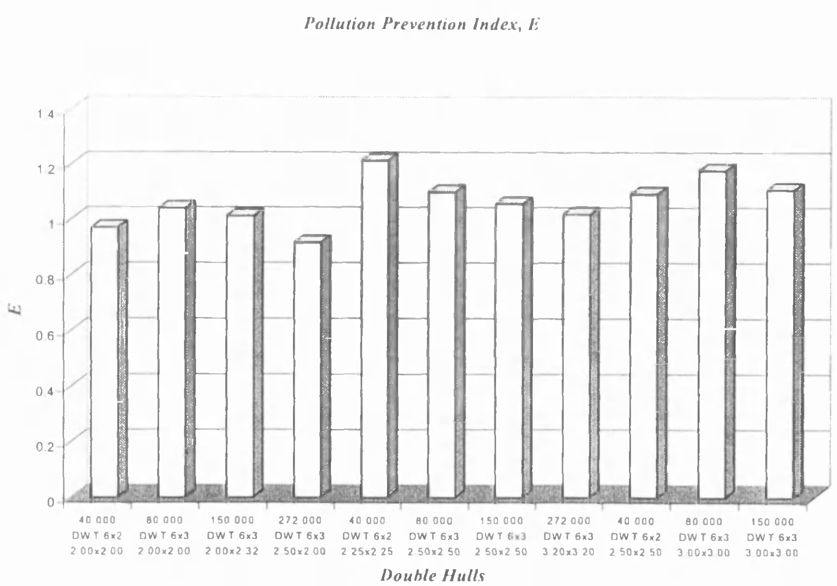


Figure 4.87. - IMO Pollution Prevention Index, E, for a set of Double-Hulls - I.

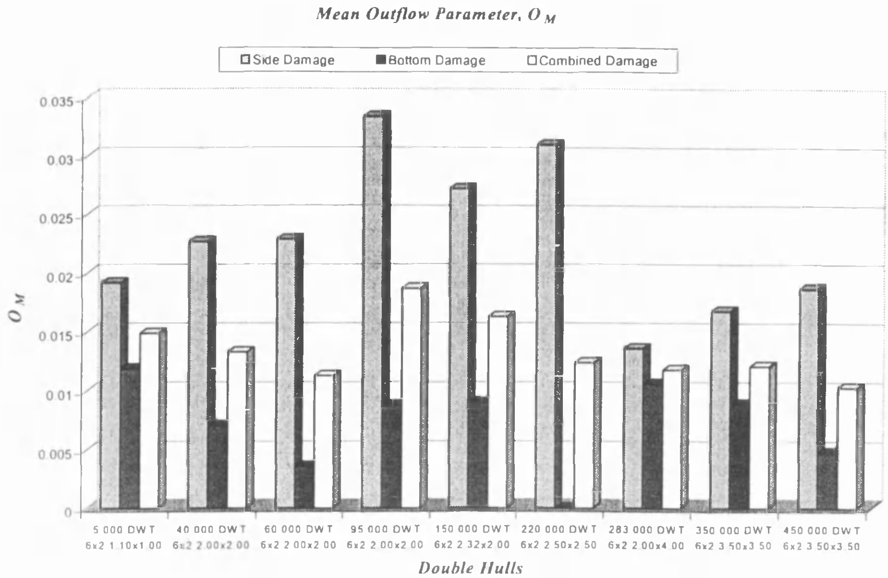


Figure 4.91. - Mean Outflow Parameter, 0_M, for a range of different sizes of Double-Hull Tankers.

4.5.4.6 Longitudinal Bulkheads Arrangement

The arrangement of longitudinal bulkheads is of great importance because collision spills are of greatest importance (see Figure 4.91).

A longitudinal bulkhead may be necessary for tankers over 60,000 DWT. At present there are Panamax, Aframax and Suezmax designs without centre bulkhead. Apart from stability problems during loading and unloading operations, the level of mean outflow must be reduced using a longitudinal bulkhead in these types of tankers.

A VLCC must be provided with two longitudinal bulkheads. The theoretical arrangement of longitudinal bulkheads has been analysed in the study and leads to some important conclusions:

- the optimum position is almost independent of double side dimension (see Figure 4.74). The differences are minimum in Mean Oil outflow Parameter for different sizes of double sides in the Double-Hull tankers investigated (w_2 = 2.5%-10%);

- if we consider both collision and grounding outflows, the optimum position of the longitudinal bulkheads varies towards a narrower dimension of centre cargo tank (also found in the study "Oil tanker concept-design against accidental pollution", DnV, 1992), However, it is important to note that the optimum value always varies between w_2=0.5 and w_2 = 0.7 (see Figure 4.92).

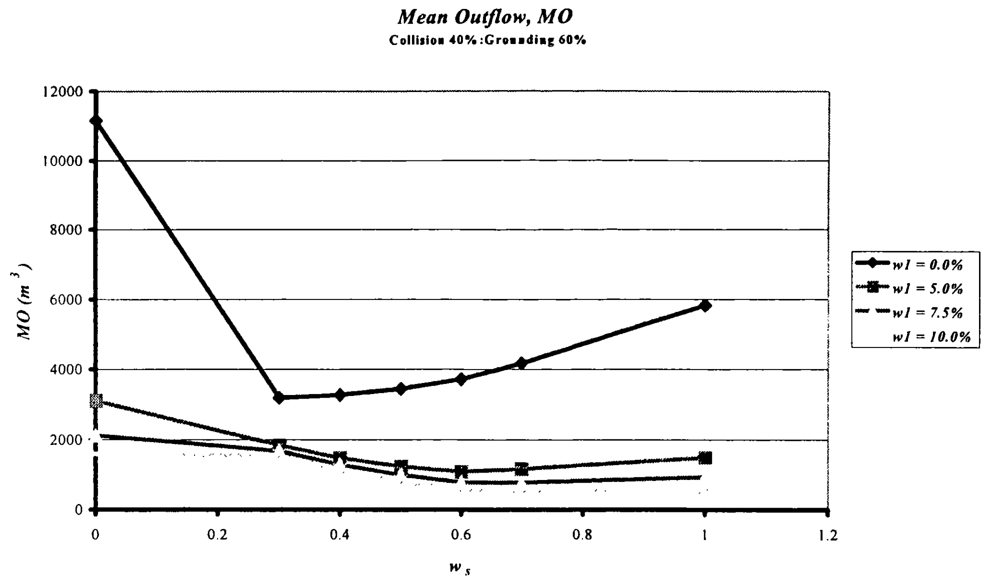


Figure 4.92. - Optimal Position for Longitudinal Bulkheads – Mean Outflow Parameter.

4.5.4.7 Transverse Bulkheads Arrangement

Transverse bulkheads are also important when considering the distribution of damage through the whole length of the ship. Also it is vary important if it is not possible to keep the same dimension of double hull due to hull forms. In some cases this differences in protection may lead to a shortening of cargo dimensions or adjustment of longitudinal bulkheads to optimise the total result for a given number of longitudinal and transverse bulkheads. As a consequence, it is advisable to analyse the combined effect of longitudinal and transverse bulkhead arrangement, even if both effects may be analysed independently (Pawlowsky, 1996).

Usually the mean outflow produced by grounding is less than one half or one third of a collision outflow, but considering the effect of tides both outflows are similar. This is one of the reasons why it is a better solution to apply the same probabilistic method both for collision and for grounding, instead of applying the probabilistic method for the assessment of oil outflow for collisions and the deterministic method for grounding incidents as some authors propose (Pawlowski, 1996).

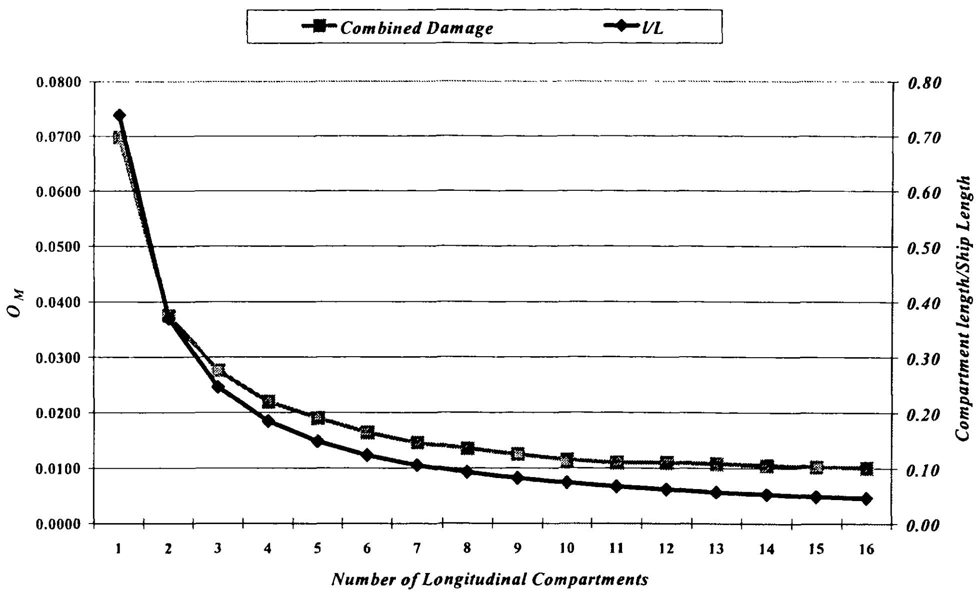


Figure 4.93. - Optimum position for transverse bulkheads.

The maximum number of transverse bulkheads is closely related to the extent of damage considered (Pawlowski, 1996). This means that the required damage length is contributing to determining the longitudinal compartment length of the vessel. As well the maximum length accepted by MARPOL and the convenience of avoiding swash bulkheads or expensive antisloshing reinforcement, this defines the minimum transverse bulkheads. For these reasons there are not too many possibilities concerning the number of transverse bulkheads, but it is possible to provide a shorter length in extreme tanks to reduce potential outflows in areas with a higher probability of damage and sloshing effects.

From the calculation performed, the optimum outflow corresponds approximately to a transverse bulkheads arrangement of l/L = 0.1 (see Figure 4.93).

4.5.4.8 Ballast Tank Arrangements

The improvement of the arrangement of ballast tanks to act as cargo containment spaces in case of grounding is one of the important questions that came out from this study. Another important result is that the introduction of double bottom longitudinal members and the improvement of their location can reduce the extent of damage in case of grounding. This is another feature that gives better protection to the ship.

The results also confirm that by moving ballast capacity from sides to bottom spaces, the probability of outflow and expected outflow will increase for collisions and reduce for groundings (see Figure 4.94).

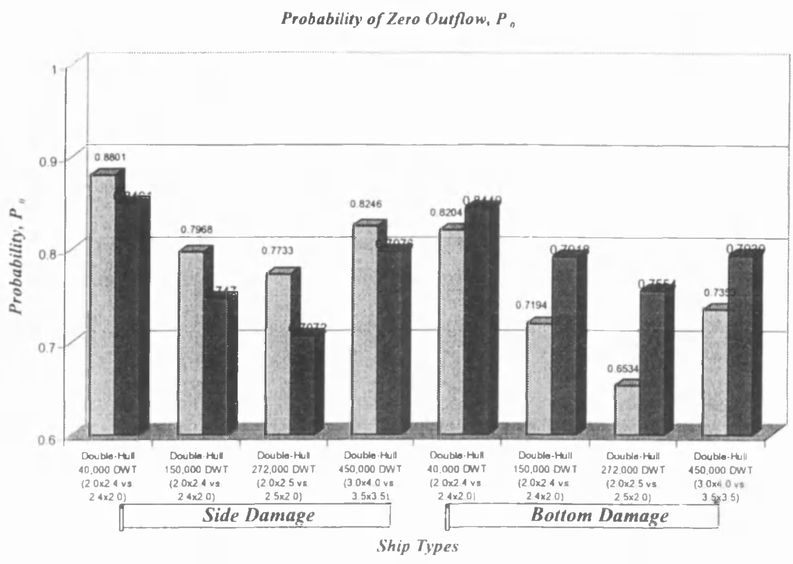


Figure 4.94. - Outflow parameters for different arrangements of ballast tanks.

The results also seem to put in evidence that that by moving ballast capacity from sides to bottom spaces, the environmental performance of double-hull tankers is improved in all size ranges (see Figures 4.95-4.97).

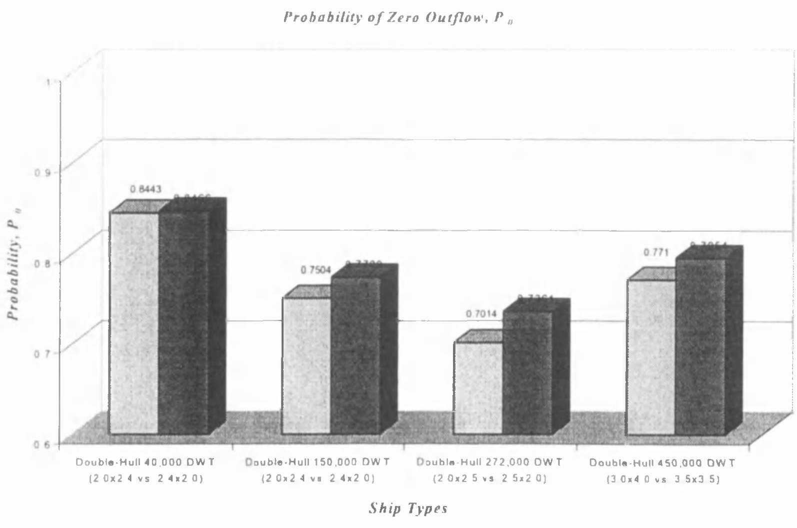


Figure 4.95. - Influence on the Probability of Zero Outflow When Moving Ballast Capacity from Side to Bottom.

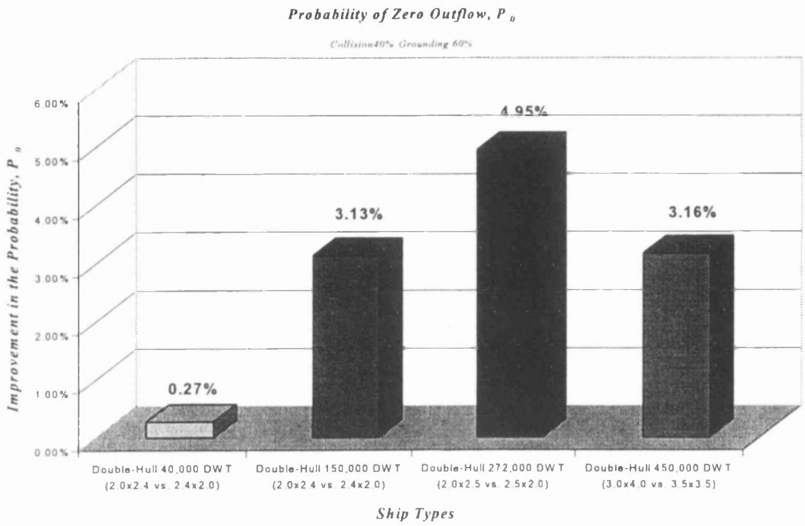


Figure 4.96. - Improvement of Environmental Performance of Tankers, Moving Ballast Capacity from Side to Bottom Spaces .

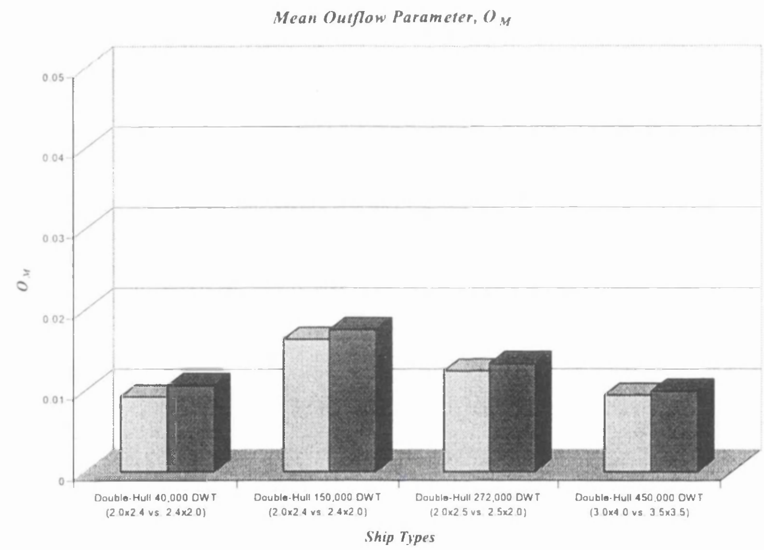


Figure 4.97. - Environmental Performance of Tankers, Moving Ballast Capacity from Side to Bottom Spaces – Mean Oil Outflow Parameter.

However, this is only true if we are talking about the ability of the ship to resist oil spillage. Comparing the same ships in terms of mean oil outflow and extreme oil outflow parameters, is possible to note that both values increase, when moving ballast capacity from sides to bottom. This can be explained mainly by the fact that, oil outflow from collision is always two to three times higher than for groundings. Then, reducing the barrier between oil and water, i.e, the width of double sides, the probability of breaching by collision the oil cargo tanks is increased as well as the amount of oil spilled into the environment. This way is not possible to say that, in overall terms, which is the best solution. In low energy accidents, the solution of increasing bottom ballast capacity is the best solution, but if we are talking about high energy accidents, with breaching of internal subdivisions, the same is not true.

The Figures 4.98-4.102 show different cargo and ballast tank arrangements. From the analysis and evaluation of different grounding situations, it is possible to decide about the best type of ballast tank arrangement, in terms of environmental performance. Taking this into consideration and the possibility of using ballast tanks as cargo containment spaces (IMO, 1995b) in case of grounding, the study of the best solution is an important issue.

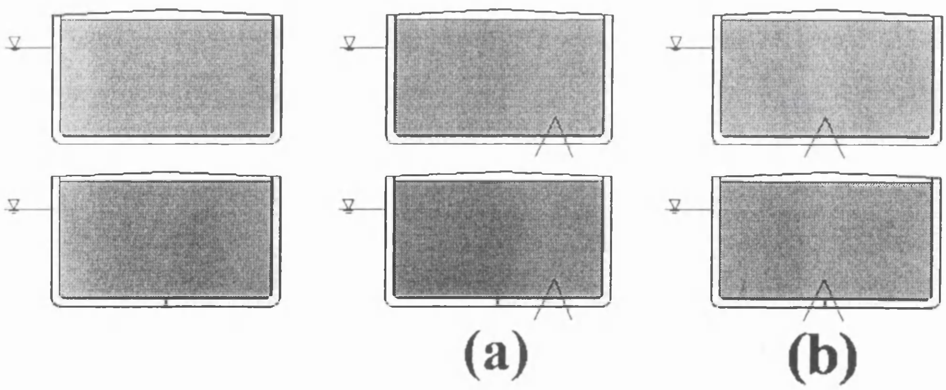


Figure 4.98. - Double-Hull, Single-Tank-Across Arrangement vs. U Ballast Tanks and L Ballast Tanks Arrangements.

In what respects Single-Tank-Across arrangements (Figure 4.98), two different situations can be expected with L and U shape ballast tank arrangements. In the first case, is clear that the U-shape is the best solution, once a larger volume is available as a containment space. In the second, case, where the longitudinal element is damaged, both solutions are equivalent.

If we take also damage stability considerations, is again the U-shape, the best solution, once the heel angle is substantially reduced, when compared with the L-shape, where a asymmetrical flooding takes place (Peters, 1991).

The same can be said for Two-Tanks-Across Arrangements (Figure 4.99), when analysed both with U-shape and L-shape ballast tanks configurations. The situation (a) has again advantage for the U-shape, for the same reasons stated above.

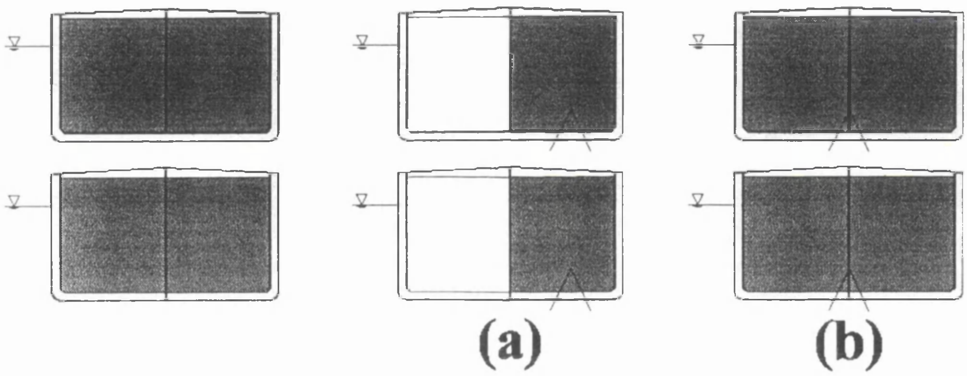


Figure 4.99. - Double-Hull, Two-Tanks-Across Arrangement vs. U Ballast Tanks and L Ballast Tanks Arrangements.

The analysis of Three-Tanks-Across arrangements (Figures 4.100-4.102) is not so direct and obvious as the previous ones. We have now U, L and J ballast tank configurations. For situation (a) the best solution is the U-shape, in terms of environmental performance. The J-shape is the worst solution, once a a smaller volume is availabe as cointaiment space. From the damage stability point of view, both L and J configurations produce asymmetrical flooding, being worst solutions again than the U-shape.

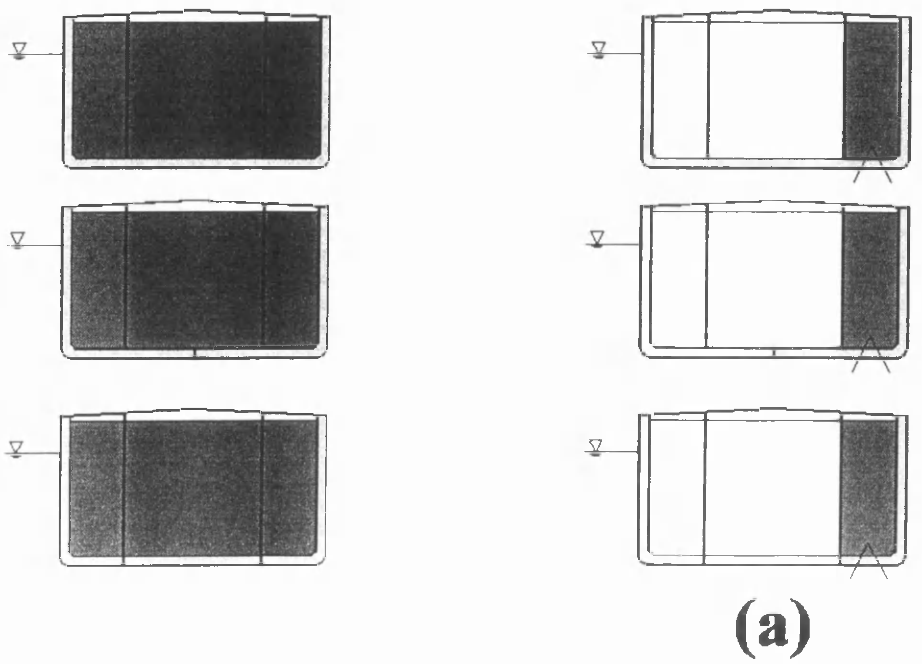


Figure 4.100. - Double-Hull, Three-Tanks-Across Arrangement vs. U Ballast Tanks, L Ballast Tanks and J Ballast Tanks Arrangements - I.

Situation (b) is a grounding situation where only the central cargo tank is breached, but no longitudinal element is damaged. The U-shape presents the largest amount of oil entrapment and the J configuration the lowest amount, once only the bottom ballast tank is also damage, being limited in both extremes by longitudinal elements that limit the flooding and the oil-water mixture. From the damage stability point of view both U-shape and J-shape are the best solution, once the flooding is symetric, reducing this way the heeling angles that may be produced by situations like this.

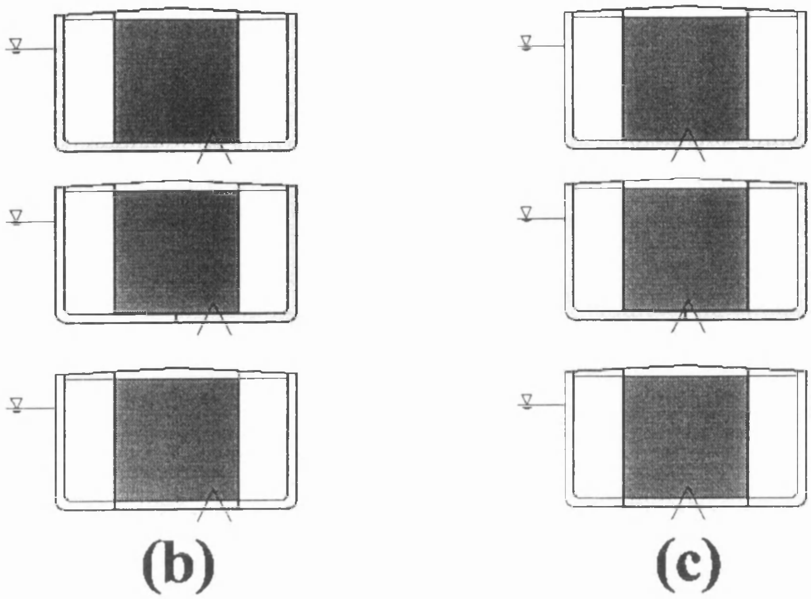


Figure 4.101. - Double-Hull, Three-Tanks-Across Arrangement vs. U Ballast Tanks, L Ballast Tanks and J Ballast Tanks Arrangements - II.

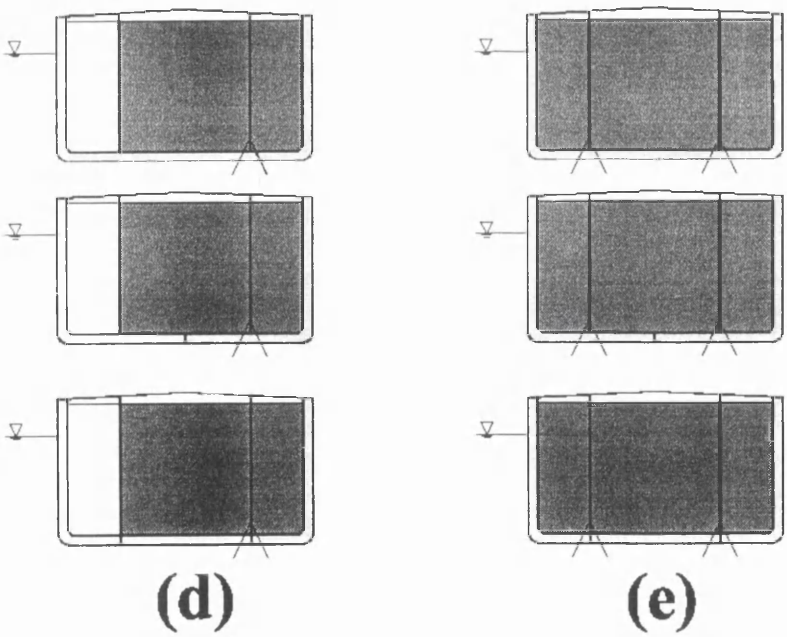


Figure 4.102. - Double-Hull, Three-Tanks-Across Arrangement vs. U Ballast Tanks, L Ballast Tanks and J Ballast Tanks Arrangements - III.

The situation (c), the central ballast tank is breached and the central longitudinal element is also damaged. In this case, both U and L-shape have equivalent containment spaces, being able of containing equal amounts of oil-water mixture. The J-shape presents the worst performance, only with the bottom ballast tank available as containment space. All the configurations present situations symmetrical flooding.

Situation (d) and (e) are the most dangerous ones in terms of environmental threat, once two and three tanks across, respectively are breached simultaneously. The first situation gives again advantage to the U-shape, being the worst case the L-shape, with smallest volume available for entrapment of oil. Both L and J shapes give origin to asymmetrical flooding. Situation (d) presents an equivalent situation for all arrangements, both in environmental and damage stability terms.

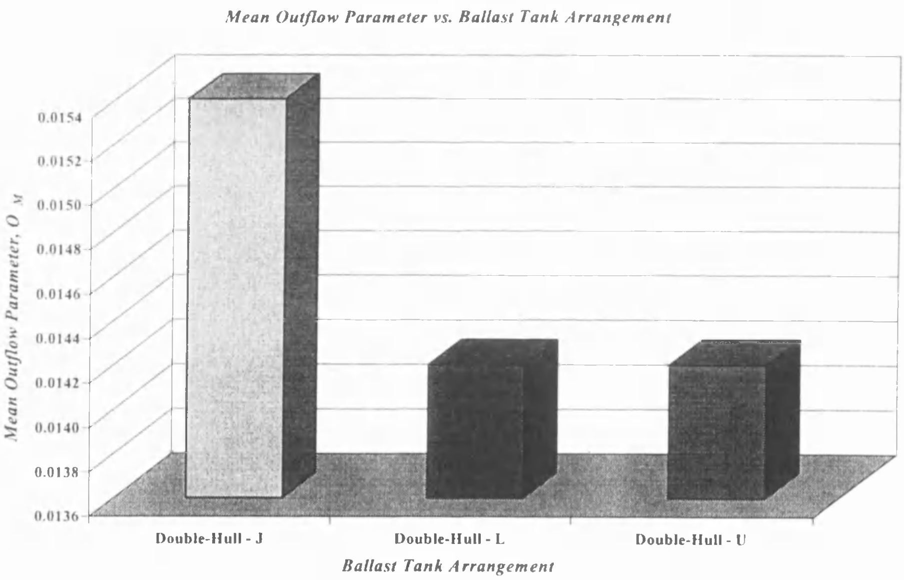


Figure 4.103. - Mean Outflow Parameter vs. Ballast Tank Arrangement.

All these considerations are qualitatively and, taken in separate situations. When gathering this information and computing all possible damage situations, the results do not present such an enormous advantage for the U-shape, when compared with the L-shape, in terms of environmental performance.

The reasons for such small differences between the two configurations may result mainly because the most dangerous situations, involving greater oil outflows have equivalent oil entrapment spaces available. In other cases, the space available is more than enough to accommodate the 50% mixture oil-water, predicted in the regulations.

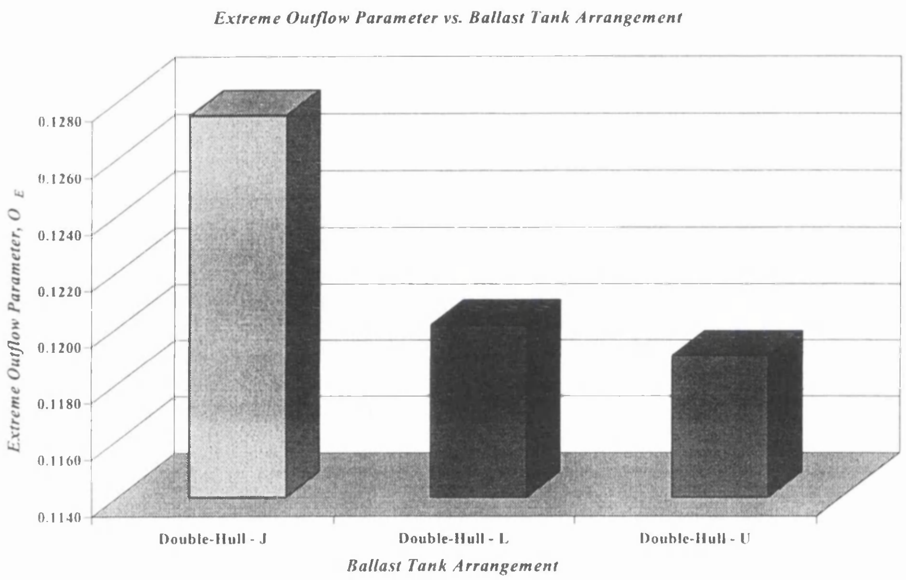


Figure 4.104. - Extreme Outflow Parameter vs. Ballast Tank Arrangement

However, in global terms is not possible to say that the difference between the three arrangements is such that the decision for one or the other should be done only in terms of capacity of oil entrapment. Other important characteristics such damage stability, structural issues, assess to the spaces and ventilation should also be taken into close attention.

In terms of damage stability when different ballast tank arrangements are compared, the study carried out by Peters (Peters, 1991) present a set of interesting conclusions:

- one of the best ways of improving double-hull tanker performance is to incorporate some "U" tanks in way of some of the tanks. However, close attention has to be given to sinkage after damage and surface problems during charging and discharging;
- large J tanks can reduce heel angle substantially in bottom raking damage;
- combination of two or more tank types within the cargo length.

4.5.4.9 Collisions versus Groundings

Since damage statistics will continue to be collected, it is to be expected that the discussion on the distribution of collisions versus groundings will be on-going.

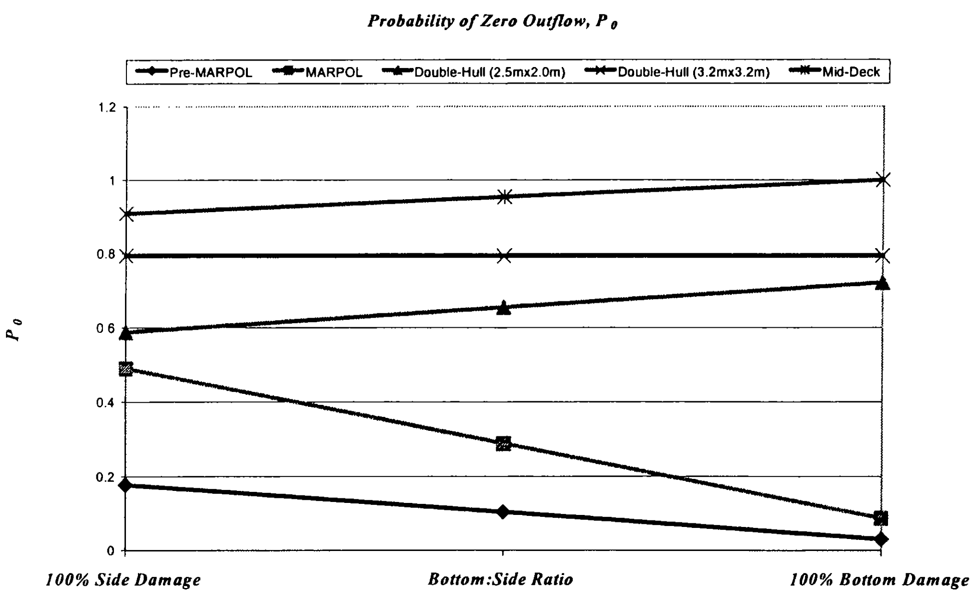


Figure 4.105. - Probability of Zero Outflow, P_0,- Influence of Bottom Damage/Side Damage Ratio.

Abicht (Abicht, 1977), opened the discussion in 1977 with the assumption of 76% collisions versus 24% groundings. This was in line with former IMCO statistics, which in those years were primarily oriented to passenger ships and dry-cargo vessels, but he pointed out, that the available data might be insufficient for ships longer than 200m. Collisions, no doubt, are more frequent for smaller vessels, whereas groundings are more relevant to larger ones. Small ships reach the port via shallow and deep-water approaches, whereas large ships more often meet approaches being relatively shallow for their deep draught.

In statistical data from the U.S.A. (NRC, 1991), these indicate 43% collisions versus 57% groundings. In data from Lloyd's Register the percentage of groundings and collisions are weighted by a sum of products multiplying the number of incidents by the pertinent average dead-weight of the vessels a mix of 49% collisions and 51% groundings can be established (Table 4.7).

Table 4.7 - Probability of collisions and groundings (source: LR data base).

		Incidents				
tdw-class of tankers (10^3)	**tdw-mean (assumed)**	**groundings**	**collisions**	**total**	**tdw-mean x sum of incidents (Millions)**	**probability of groundings**
< 50	27 500	172	244	416	11.44	0.413
50 – 100	75 000	66	57	123	9.23	0.537
> 100	200 000	81	70	151	30.20	0.536
	Total	319	371	690	50.87	0.509

The comparative outflow analysis ordered by U.S. Coast Guard assumes weighting factors of 50% for both side and bottom damages (HEC, 1994), whilst the investigation on behalf of IMO, (IMO, 1994), is based on 40% for side damages and 60% for bottom damages, when calculating the combined probability. In the discussions to (Hook, 1991), Noble has cited statistical data, of accidents in the Baltic, compiled by the Finish Board of Navigation over 25 years. These display a 30%/70% distribution of side damages versus groundings, thus indicating once more that this important feature of damage statistics is strongly related to the draught restrictions or channel widths of certain approaches and the frequency of vessels using them.

Weighting the aforementioned data, the assumption of 40% side damages versus 60% groundings, as stipulated by the MEPC for the Draft Interim Guidelines to regulation 13F (IMO, 1994), is reasonable for the time being.

Since some of the competitive designs investigated (HEC, 1992) show a pronounced gradient of zero outflow probability versus side-bottom damage ratio, this question is of considerable concern. The zero outflow parameter influences the pollution prevention index substantially. Therefore a sound statistical support of the side damage/grounding-ratio is very important for correct evaluation of designs (see Figure 4.105).

4.5.5 Optimising the Double-Hull Tanker

It is stated in the author's summing up of (Hook, 1991), that the double-hull in principle can outperform any other subdivision concept, but the question is raised whether double-hull tankers, which have such very low outflow parameters, are likely to be built. The strong relation between first costs and number of tanks is to be kept in mind. However some design measures can be taken, which will enhance the overall safety of the double-hull tanker.

In some literature consideration is given to the arrangement of U-shaped ballast tanks in the double-hull (Thorpe contribution in (Hook, 1991)). This should be done wherever it is possible with respect to stability and survivability. Any cargo gas, which due to a leakage from the inner hull may be spread in the ballast tanks and of course the inert gas, can be purged more easily from the tanks. This procedure is critical, especially for the huge L-type tanks of a VLCC. This is essential for the overall safety of double-hull tankers including the risk of explosion and fire.

4.5.6 Summary of Main Results

Various types of subdivision differ significantly from the standpoint of protection of the environment. The most efficient in this respect are mid-deck tankers. Double-hull tankers can present more than 50% greater hazard to the environment, whilst single-hull tankers even more than 100%. Larger tankers are safer for the environment (in relative terms), due to smaller relative damage size. There is an optimum position for the longitudinal bulkheads and for the transverse bulkheads that minimises the mean oil outflow.

All cargo oil tanks on a double-hull tanker built to OPA 90 requirements are protectively located. Many of the damage cases that would result in oil spillage on single-hull tankers will not penetrate the cargo tanks of double-hull tankers. As a consequence of this, double-hull tankers will have fewer accidents involving oil spillage. The mean or expected oil outflow from a casualty will usually be less with a double-hull tanker as compared to a single-hull tanker of the same size.

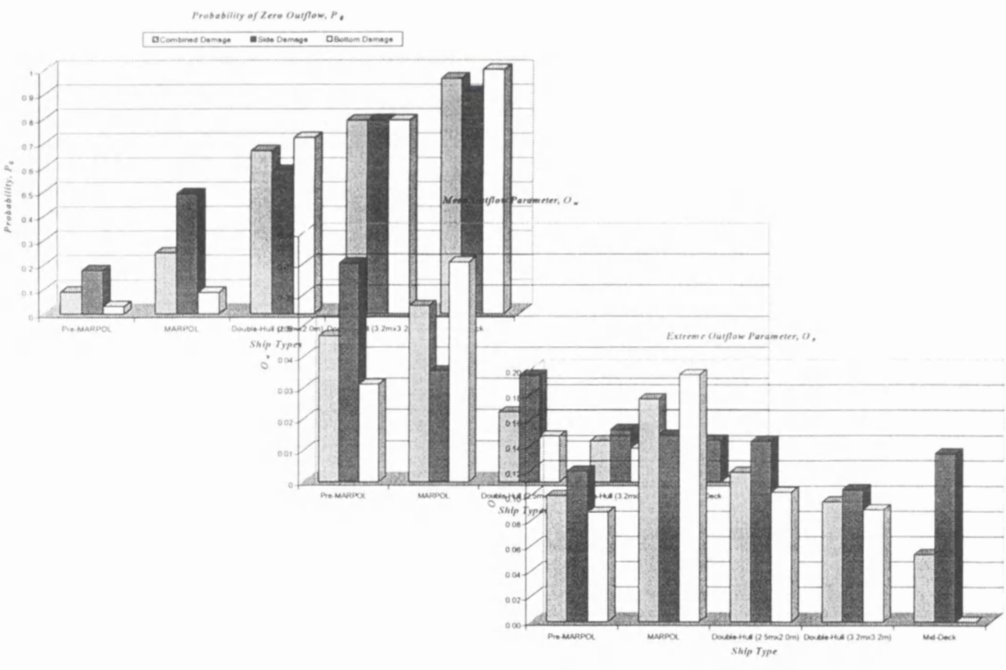
The arrangements of double-hull tankers vary considerably. The vessels proportions, the wing tank and double-bottom dimensions, and the number and location of longitudinal and transverse bulkheads, all influence the outflow performance. As a consequence, the likelihood of oil spillage and the mean or expected oil outflow will vary significantly even among double-hull tankers of the same size.

The results also show that, as expected: by moving ballast capacity from sides to bottom spaces, the probability of outflow and expected outflow will increase for collisions and reduce for groundings.

Since the study is conducted based on the "conditional probability" approach, that is, there is an initial assumption that a casualty has occurred, the results for collisions and groundings should not be taken separately. This ratio of groundings to collisions, needs to be taken into account before an overall comparison of the different designs can be done.

CHAPTER 5

DISCUSSION OF RESULTS



CHAPTER 5 - DISCUSSION OF RESULTS

5.1 General

Even if tanker safety has improved significantly over the past few years, accident risks have not been eliminated continue to be improved. The authorities have adopted proactive principles and the tanker industry is committed to implementing the safety culture onboard and onshore. Also in the present situation with tough competition in the tanker market, safety and environmental aspects become increasingly important competitive factors, and the prospects are good that the sub-standard tanker tonnage will be pushed out of the market.

The safety process for the next generation of tankers starts at the design office and is complemented by a competent management. It involves a wide range of technical, environmental and operational aspects.

The goals should much higher than "designing our ship hull form only to achieve minimum power consumption and just to fulfil IMO's regulations". The keywords in mind when designing the tanker for next century should be: Safety, Economy and Environment.

5.2 Discussion of Results

The probability of zero outflow is a measure of a tanker's ability to avoid oil spills. In this regard, double-hull tankers perform significantly better than single-hull tankers, as the protective double skin reduces the number of casualties with penetration into the cargo tanks. As shown in Figure 4.71, single-hull tankers involved in collision or grounding will be four to six times more likely to spill oil than a double hulled tanker.

The probability of zero outflow is a function of the double-bottom and wing tank dimensions, and is not affected by the internal subdivision within the cargo tanks. Therefore, centreline or other longitudinal bulkheads within the cargo spaces have no influence on the probability of zero outflow.

The mean outflow is a measure of the ability of a design to mitigate the amount of oil outflow. Again, double hulls perform significantly better than single-hull vessels, with double-hull mean outflow values averaging one-third to one-fourth of the single-hull vessels.

The double-side vessels perform reasonably well with respect to collisions, but have higher outflows for bottom damage. These vessels have single-tank-across arrangements for cargo tanks, which significantly increase outflow as compared to the more extensive cargo tank subdivision incorporated into the pre-MARPOL and MARPOL 78 designs.

The double-hull dimensions as well as the extent of internal subdivision within the cargo tanks influence mean outflow. There is little variation in the arrangement of VLCCs, with most single-hull and double-hull designs incorporating a 5x3-cargo tank arrangement. Wing tank and double-bottom dimensions for VLCCs typically fall between 3.0 and 3.5 metres. As a result, mean outflow values for VLCC are relatively consistent. In contrast, there is considerable scatter in the outflow values for tankers under 165 000 DWT. Figure 4.76 shows the side and bottom damage contributions to mean outflow for the 150 000 DWT tankers evaluated in this study.

The projected outflow is consistently lower for the designs, which have an oiltight centreline bulkhead over the length of the cargo block. Designs with all single-tank-across cargo tanks have the highest mean outflow. It is interesting to note that the bottom damage outflow are relatively consistent, but the single-tank-across designs perform less effectively when subjected to side damage. The closer spacing of transverse bulkheads on these designs increases the probability of breaching multiple cargo tanks. Once a cargo tank is breached, oil outflow is no longer limited to one side of the vessel.

Double-hull tankers without centreline bulkheads typically have twice the expected outflow of designs with oiltight longitudinal bulkheads in way of the cargo block.

Extreme outflow is a measure of a design's propensity to spill large volumes of oil in the event of a very severe collision or grounding. The extreme outflow parameters are plotted in Figures 4.82-4.84. Whereas double-hulls were found to be 3 to 6 times more effective in avoiding spills and reducing mean outflow, double-hulls are somewhat less effective in controlling large spills. There is a considerable scatter in the data points, indicating that such parameters as internal subdivision and draft/depth ratio have a significant impact on extreme outflow. With regard to extreme outflow, the double-hull vessels with single-tank-across arrangements performed more poorly than both pre-MARPOL and MARPOL 78 vessels of comparable size.

The study clearly demonstrated that:

- mid-deck tankers are superior to other designs due to the much larger width of double sides, for a given amount of transverse subdivision. This may not be the case if other aspects are taken into account such as the number of tanks, for example;
- the mean outflow is in proportion to the volume of cargo carried by the ship: the bigger the ship, greater the hazard to the environment;
- increasing the number of compartments above a certain value is a very ineffective means of improving outflow qualities of tankers.

5.3 Comparison With Other Studies

The comparison between studies carried out by different people is not always an easy task. One of the main reasons for these difficulties is the difference in purpose of the work carried out. The aim of this work is to encourage the establishment of the guidelines based on assumptions and methods applied through out this study.

The studies by others always had some important differences when compared with the study described here. Some of these differences can be summarised as follows:

- the probability density functions used were not the same;
- different damage assumptions were taken into consideration;
- the set of ships analysed and the internal subdivision arrangements selected were not quite identical;
- the implemented computational method for the application of the probabilistic concept was different (simplified or direct).

The most important studies selected for this comparison were

- Hook, 1991;
- Michel and Tagg, 1991;
- Hart, 1992;
- Michel & al, 1997;
- HEC, 1998.

However, since comparison is always useful, there was a clear intention of keeping similar aspects between this study and the ones selected for comparison.

Taking the work carried out by Michel and Tagg (Michel, 1991), the distribution functions used are completely different from the ones used here, as well the maximum extensions of damage. The methodology used in the calculation procedure is also different. However, the same damage survivability criterion is used. Qualitatively it is possible to compare the results, in terms of the environmental performance of the tankers evaluated. The two studies in agreement revealed:

- the superiority of double-hull design (when compared to single-hull design) to reduce the likelihood of an oil spill;
- the bad performance of single-hull designs in terms of environmental performance – highest levels of mean oil outflow, lowest levels of the probability of zero outflow and the MARPOL design presenting the highest value for the extreme outflow parameter;
- the hydrostatic balanced designs (Mid-Deck) offer the best environmental performance of all the designs in compared[5].

When analysing the studies conducted by Hook (Hook, 1991), once again several differences can be identified. The pdf functions are different, using as Michel (Michel, 1991), the ones defined in the 1973 IMO Passenger Regulations. The calculation methodology differs also from the one used in this study. Hook developed joint probability density functions to perform the damage calculations. Nevertheless some conclusions agreed:

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[5] For a better understanding of the results here mentioned see 4.5.4.

- by moving ballast from the sides to the bottom the probability of outflow and expected outflow will increase for collision and reduce for groundings;
- horizontal subdivision offers the greatest reduction in expected outflow for grounding situations;
- double-hulls with greater longitudinal subdivision of the cargo tanks offers substantial reduction when compared with other designs in terms of expected oil outflow;

The closest study to the one carried out here is the one described in Michel et al (Michel et al., 1997). Since both studies follow the IMO Interim Guidelines (IMO, 1995), both initial assumptions and pdf functions are identical. Comparing both studies the following conclusions were agreed:

- longitudinal subdivision has a significant influence on mean outflow, specially with the introduction of a central bulkhead;
- the addition of a second longitudinal bulkhead does not provide as much additional benefit as that achieved by the introduction of the first central bulkhead;
- the addition of transverse bulkheads decreases mean outflow, but the decrease in outflow diminishes as additional bulkheads are added, leading to the idea of an optimum number of transversal bulkheads;
- double-bottom and wing tank dimensions are determine the decrease of the probability of oil outflow and mean outflow.

The Herbert Engineering Corporation (HEC, 1998), carried out a study of "Oil Outflow Analysis for a Series of Double Hull Tankers", using the "Accidental Oil Outflow" regulations, that will replace the requirements contained in MARPOL Regulation I/22-24. The outflow parameters for the similar designs evaluated are in close agreement to the values calculated here, presenting differences of no more than 2%-5%.

Table 5.8 - Comparison of results for the IMO Reference Double-Hulls.

	Cargo DWT (t)	Cargo Tank Arrangement	WTxDB (m)	Mean Outflow Parameter	Probability of Zero Outflow
Calculated	5000	6x2	1.0 x 1.1	0.015	0.814
HEC				***0.014***	***0.840***
IMO Guidelines				**0.017**	**0.810**
Calculated	60000	6x2	2.0 x 2.0	0.015	0.806
HEC				***0.016***	***0.810***
IMO Guidelines				**0.014**	**0.810**
Calculated	150000	6x2	2.0 x 2.32	0.016	0.750
HEC				***0.018***	***0.770***
IMO Guidelines				**0.016**	**0.790**
Calculated	283000	5x3	4.0 x 2.0	0.012	0.732
HEC				***0.012***	***0.750***
IMO Guidelines				**0.013**	**0.770**

CHAPTER 6

CONCLUSIONS

CHAPTER 6 - CONCLUSIONS

The implementation of the MARPOL regulations has had a major effect on the reduction of operational oil pollution, but the same cannot be said for accidental oil pollution. Although accidental oil spills have reduced significantly from the levels experienced in the 1970's, not as a direct result of MARPOL, they have now started rising again with the increase in activity over the last few years.

The MARPOL rules are minimum requirements for protection against oil spills and for minimising operational oil discharges. The rules do not consider in any depth factors like structural design, production, fabrication, corrosion protection, access, ventilation and general safety. In the end it is the tanker owner, who has to face these questions and the associated, operational difficulties.

As a result of recent highly publicised accidents, the US has legislated to require all vessels trading to its ports to have double hulls. The effectiveness of such arrangements is currently being widely debated. As a response to this the International Maritime Organisation (IMO) introduced guidelines (1995) for the evaluation of alternatives to double-hull tankers (MARPOL 13F, 13G).

A numerical model for the probabilistic estimation of oil spillage from a tanker involved in an accident was developed and implemented in a computer program. Both collision and damage incidents were taken into consideration, when developing the model.

The work carried out here shows that the probabilistic approach represents a superior method when compared to the deterministic approach in predicting effectiveness of various arrangements in mitigating accidental oil spills. This method allows a value to be put on the expected outflow in a similar manner to that used in calculating the "Subdivision Index".

At the suggestion of other authors, the positioning of bulkheads was investigated longitudinally, transversally and horizontally. The "ideal" number of these subdivisions was also investigated in this study, revealing a interesting set of conclusions.

It has been shown that horizontal subdivision can be particularly effective in reducing expected outflow and the new concepts in development based on this design should be fully explored using the probabilistic approach.

The main argument over double bottoms has been that they may be counterproductive because of the loss in buoyancy following a grounding and subsequent break-up causing much greater pollution than may otherwise of occurred. With horizontal subdivision this argument does not apply because there is no loss in buoyancy and cargo could be easily transferred to another vessel from the upper tanks using the ship's own pumps. On the other hand double-bottoms provide an inner space where an oil/water mixture can be trapped, reducing the oil outflow in case of accident and breaching of the inner hull.

This work provides a detailed analysis of probabilistic regulations for tanker subdivision and discusses how they can be used in design. It is argued that these regulations are superior to the deterministic regulations, as they represent a rational framework that is design independent, goal setting and non-prescriptive in nature and is thus unlikely to date with the passage of years. These regulations are therefore capable of accommodating different design solutions as they emerge. They also can be easily updated from time to time if new relevant statistical data become available.

Parametric studies about the influence of different internal subdivision characteristics and dimensions ratios on the environmental performance of tankers were carried out. Calculations of the expected oil outflow for tankers with different design concepts were undertaken for a series of collision and grounding scenarios. Both studies included a sensitivity analysis of both initial oil losses following impact, and oil retention in the double-hull space.

From the preceding analysis, the calculated expected oil outflow from mid-deck tanker designs in collision, grounding and at all likely combined ratios of collision and grounding was, in general, lower than that from corresponding double-hull designs.

In relative terms bigger ships are safer to the environment, but in global terms they present a major threat once they carry much more oil. For the same level of protection, smaller ships must have relatively wider double sides than larger ships. The mid-deck and double-hull tankers presented always an overwhelming superiority to reduce the likelihood of an oil spill.

Wider wing tanks and deeper double bottoms tend to reduce the likelihood of a spill, thereby increasing the number of collisions and groundings with no spillage. The effect of increasing double sides dimension is then determinant in the improvement of environmental performance of tankers. This is much more significant between 0% and 5% breadth of double sides. Greater internal subdivision also tends to reduce the quantity of oil spilled, but its effectiveness is only felt until a certain level.

The effectiveness of double-hull in preventing large spills is less pronounced than expected or desirable, raising some questions about their overall safety in a major accident, involving high energy impacts. However, mid-deck tankers keep the same behaviour, presenting the lowest indices of the compared ship types.

The comparison of the different types, sizes and arrangements of tankers, showed clearly that the mid-deck tankers, in general, present always better performances than the IMO Reference Double-Hull designs; ships with longitudinal bulkheads in the cargo holds have highest indices being improved with narrower centre tanks. Most of double-hull designs with these characteristics have a better performance than the IMO Double-Hull designs. All the single-hull tankers have lower indices when compared with the IMO designs, showing clearly that they have to be retrofitted so that they can comply with the new regulations.

The exchange of ballast capacity from sides to bottom spaces was not conclusive in overall terms about the best solution to choose. It is clear that the probability that no cargo oil will be released into the environment in case of accident is increased when bottom ballast capacity is increased and side capacity reduced. But when evaluating the worst case spill scenarios and the design's effectiveness in mitigating the amount of oil loss due to collisions and groundings it seems better to move ballast capacity from bottom to sides. Since the gain and losses in the three parameters are much equivalent, a deeper study is necessary to assure the best solution, if there is one.

Another important conclusion is the fact that usually the mean outflow produced by a collision is two to three times higher than by a grounding incident.

Since the analysis confirmed that the expected oil outflow is dependent on the specific cargo tank arrangement of each design, there would appear to be scope for optimising tanker designs with a view to minimising the expected oil outflow.

The calculation procedure did not take into consideration any mitigation factors, except for the retention of oil in the ballast spaces of the double-hull configuration. Clearly, vacuum effects, rescue tanks, cargo transfer and other aspects of tanker design and operation could influence the expected oil outflow.

The study showed that tidal changes have a significant effect on oil outflow, and should be evaluated, especially, for vessels trading in waters subject to large tidal variations. This information would prove helpful when developing spill response plans for such areas.

While a number of approximations were made in the methodology to prevent it from becoming unnecessarily complicated, further refinement is possible to reflect additional studies and tests. However, the oil outflow calculation methodology in the guidelines is quite complex, in part because of the necessary rigor required for a careful comparison of alternative tanker designs. For the purpose of comparing alternative designs this method is acceptable. Indeed, due to its importance, IMO maintained review authority in the regulations for considering alternatives. However, for routine regulatory design applications (as opposed to relatively infrequent applications for evaluating regulatory alternatives), a simplified methodology is preferable.

Double-hull tankers and other new designs like the mid-deck tanker, display very low ecological risks in case of damage incidents, when compared with conventional SBT tankers. But there exists a bandwidth of new ships reaching from excellent to still satisfactory performance, all of them fulfilling the actual requirements of MARPOL.

The work carried out is somehow based on the studies carried out by others through the last few years. There was a clear intention of improving and develop what was already done and there are many outcomes confirming the exit of it.

The study is not only a confirmation of the results and solutions already recognised by others, but also puts in evidence some questions that were forgot, like the importance of ballast tank arrangements in the oil entrapment process and the introduction of longitudinal members in double-bottom spaces. This was not possible to evaluate in all the other studies that were compared, once there was an initial assumption that all groundings produced a rupture from port to starboard, what is not true most of the times.

The study is also more consistent, once a large number of different tankers, both in size and internal configurations, were studied giving origin to a large set of results that supported all the established conclusions. Some of the studies compared presented just a small set of ships analised.

6.1 Recommendations for Further Studies

One of the problems faced during the oil outflow assessment, from different ship designs, was the very large amount of data to be processed and the time consuming nature of the process. For these reasons the range of tankers analysed is just a subset of the total number initially prepared for the purpose. However, it was selected in a way that all desirable conclusions and evaluations could be performed, including both the evaluation of collision and grounding incidents. As a result of this aspects it is desirable that a simplified method is used, instead of the direct application of the probabilistic concept. This method, however has the advantage of being able to accommodate any internal subdivision arrangement in its mathematical model, what is not true for the simplified one.

There are many simplifying assumptions inherent in the calculation procedure for the probabilistic analysis of oil outflow from groundings and collisions. Research is required to assess the sensitivity of these assumptions to the final results, and to refine the methodology were appropriate. The probability of experiencing a collision or grounding was applied equally for all designs, although some variation is expected among different services. For instance, a FPSO or a VLCC used for offshore lightering will have a different probability of grounding as compared to a coastal tanker.

The improvement of the mathematical model developed is another area were some future studies can be involved. As stated above, one solution is the development of a simplified method avoiding this way the iteration process involved in the application of the direct method. If the direct method is the chosen solution, than the accuracy of potential oil outflow calculations should be improved in a way that the error introduced by the incompatibility of iteration steps and internal subdivision is avoided. This can be accomplished by varying the step interval whenever that is required by the presence of an internal subdivision.

In respect to the input data, the probability density functions (for the extents of damage) are applied independently. In reality, some correlation is expected. For instance, it is not realistic to assume that the maximum longitudinal extent of damage (generally caused by raking damage) will occur simultaneously with the maximum transverse penetration (generally caused by a "t-bone" collision). There should be provided joint pdfs to improve the calculation method.

The probability density functions were developed from historical data of collisions and groundings, which involved primarily single-hull tankers. The influence of double-hull construction on damage extents needs to be understood.

Another important question raised during the study and, since a large amount of ships was study, there was the possibility of studying different ratio parameters, their variability and their influence in the three merit measures used and proposed by IMO:

- L/B;
- L/D;
- B/D;

- T/D.

The collection of this type of information was started in this study, being possible to present some ranges of values typical for different type of ships (Appendix D) and sizes. However, the systematic calculations and results were not concluded in time so that they could be included in the work.

Nomenclature and Glossary

NOMENCLATURE AND GLOSSARY

Nomenclature

p_i	probability of flooding a single or several adjacent compartments
P_m	total probability of ship survival
v_i	volume of a single or several adjacent compartments
s_i	probability of surviving casualty i
i –	i^{th} casualty
b_s	width of lateral cargo tank
b_c	width of central cargo tank
b_1	width of wing tank
b_2	transversal location of first longitudinal bulkhead in reference to ship side
w_s	$w_s = \frac{b_s}{B}$
w_1	$w_1 = \frac{b_1}{B}$
w_2	$w_2 = \frac{b_2}{B}$
P_0	Probability of Zero Outflow
O_M	Mean Outflow Parameter
O_E	Extreme Outflow Parameter
MO	Mean Outflow (m^3)
EO	Extreme Outflow (m^3)
dm	moulded draft amidships (mathematical average of moulded drafts at forward and aft perpendiculars)
da	draft at aft perpendicular

df	draft at forward perpendicular
LOA	length overall
LBP	length between perpendiculars
L_s	Subdivision length
L_c	Cargo block length
T	draft
Δ	displacement
B	maximum breadth of vessel measured amidships to moulded line of frame
D	moulded depth measured vertically from top of keel plate to top of forward deck beam at side amidships

Acronyms and Glossary

13F	Regulation 13F of Annex I of MARPOL 73/78
13G	Regulation 13G of Annex I of MARPOL 73/78
ABS	American Bureau of Shipping
CBT	dedicated clean ballast tanks
COW	crude oil washing system
DB	double bottom
DnV	Det Norske Veritas
DOT	U.S. Department of Transportation
DS	double sides
DWT	deadweight ton
DWT	displacement at assigned summer load waterline less the light ship displacement.

GRT	gross registered tonnage
GT	gross tons
HBL	hydrostatically balanced loading
IACS	International Association of Classification Societies
ICLL	International Convention on Load Lines
IGS	inert gas system
IMCO	IMO was originally called the Inter-Governmental Maritime Consultative Organization (IMCO). The name was changed in 1982
IMO	International Maritime Organisation; the United Nations agency responsible for maritime safety and environmental protection of the seas.
INTERTANKO	International Association of Independent Tanker Owners
ISM	International Safety Management (code)
MARAD	U.S. Maritime Administration
MARIENV'95	International Conference on Technologies for Marine Environment Preservation, Tokyo, Japan, September 24-29, 1995
MARPOL 73	International Convention for the Prevention of Pollution
MARPOL 73/78	from Ships, adopted in 1973 and amended in 1978
MEPC	Marine Environment Protection Committee of the International Maritime Organisation
NRC	National Research Council (U.S.)
OBO	oil-bulk-ore - Vessel designated for alternative carriage of oil, bulk cargoes, or ore.
OPA '90	Oil Pollution Act of 1990 (P.L. 101-380)
PL/SBT	protectively located segregated-ballast tanks

SBT	segregated-ballast tank designated for ballast only
SNAME	Society of Naval Architects and Marine Engineers
SOLAS	International Convention on Safety of Life At Sea
STCW	Convention for Standards for Training, Certification, and Watchkeeping
ULCC	ultra large crude carrier, refers to vessels of more than 400,000DWT.
USCG	U.S. Coast Guard
VLCC	very large crude carrier, refers to vessels of abou 150,000 and 300,000 DWT

Cargo block is the portion of the ship extending from the forward boundary of the forward-most cargo tank to the aft boundary of the aft-most cargo tank. OPA '90 as well as the 1992 Amendments to Annex I MARPOL 73/78 require that all oil tanks within this space be segregated from the side and bottom shell.

Cargo tanks are all tanks arranged for the carriage of cargo oil. Unless noted otherwise, the term "cargo tanks" shall be assumed to include the slop tanks.

Crude oil washing (COW) system is a tank cleaning procedure that utilises crude oil as the washing medium. Crude oil is discharged through fixed tank washing machines, positioned so that oil is sprayed on internal tank bulkheads and structures to remove the oil residue, which would normally remain after cargo discharge. In this regard, crude oil washing is conducted in the same manner as water washing or "butterworthing", except crude oil is used rather than seawater. The spray action of the crude oil and the subsequent rundown, place the oil residue remaining on the tank surfaces back into suspension, so that the combination of remaining cargo and residue can be collected and discharged ashore through installed piping. Due to the solvent action of the crude oil, the amount of oil and sludge recovered and pumped ashore is increased significantly over that which is removed by other washing techniques.

Deadweight tonnage is a measure of the weight of cargo (plus water, fuel, and stores) that a vessel can carry.

Dedicated clean ballast tanks (CBT) are cargo tanks that are dedicated solely to the carriage of clean ballast and which no longer carry cargo. The associated pumps and piping systems for CBT are allowed to be common with the cargo piping systems and, therefore, require flushing each time prior to the handling of clean ballast.

Existing vessel is a vessel, which has not been designed and constructed in accordance with the new regulations.

Gross tonnage is a measure of a vessel's volume determined according to international convention.

Hydrostatically balanced loading means whereby the level of cargo (e.g., crude oil) is limited to ensure that the hydrostatic pressure at the tank (and ship) bottom is lower than the external sea pressure. Thus, if the tank is breached, seawater will flow in rather oil flowing out.

Inert gas system (IGS) is a system that supplies to the cargo tanks a gas of mixture of gases, which are so deficient in oxygen content that combustion cannot take place within the cargo tanks. The inert gas is either treated flue gas from a tank vessel's boiler or treated gas from an inert gas generator. This gas is pumped into the cargo tanks to displace the air in the tank that has a combustible oxygen content.

Length overall (Loa) is the distance between the extreme points forward and aft measured parallel to the summer (or design) waterline. Forward the point may be on the raked stem or on a bulbous bow.

Light ship – displacement of vessel without cargo, oil fuel, lubricating oil, ballast water, fresh water and feedwater in tanks, consumable stores and any persons and their effects

New vessel is a vessel, which must be designed and constructed in accordance with the new regulations.

Protectively located segregated-ballast tanks (PL/SBT) are segregated ballast tanks as described in the foregoing that are located within the cargo tank length of a tank vessel, outboard of or below the cargo tanks.

Segregated-ballast tanks (SBT) are ballast tanks that are permanently alocated to the carriage of ballast water and are completely separated from cargo oil and fuel oil systems.

Slop tanks are provided for storage of dirty ballast residue and tank washings from the cargo tanks. Annex I of MARPOL 73/78 requires that tankers be arranged with slop tanks.

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APPENDIX A

APPENDIX A - OIL OUTFLOW PARAMETERS (A SHORT DESCRIPTION)

Probability of Zero Outflow (P_0). This parameter represents the probability that no cargo oil will be released into the environment. Since even small spills which occurr in environmentally sensitivity areas can have serious consequences, the significance of this number is intuitively obvious.

$$P_0 = \sum p_{bi}$$

Mean Outflow (O_M). The sum of products of each damage case probability and the computed outflow for that damage case yields the mean (expected value) of oil outflow. This weighted mean is a good indication of the overall effectiveness of a particular design in limiting the oil outflow.

$$O_M = \sum p_i . v_i$$

Effective Outflow (O_{ef}). This is a weighted average of oil outflow in all damage cases resulting in cargo outflows.

$$O_{ef} = \frac{\sum p_i . v_i}{\sum p_i}$$

where the summations are taken over all cases of flooding with outflow of oil.

Hypothetical Outflow (O_h). This is an average outflow calculated disregarding cases with flooding of the fore and aft parts of the ship where there is no cargo oil.

$$O_h = \frac{O_m}{1 - p_a - p_f}$$

p_a – probability of flooding the aft part of the ship that has no cargo oil

p_f – probability of flooding the forward part of the ship that has no cargo oil

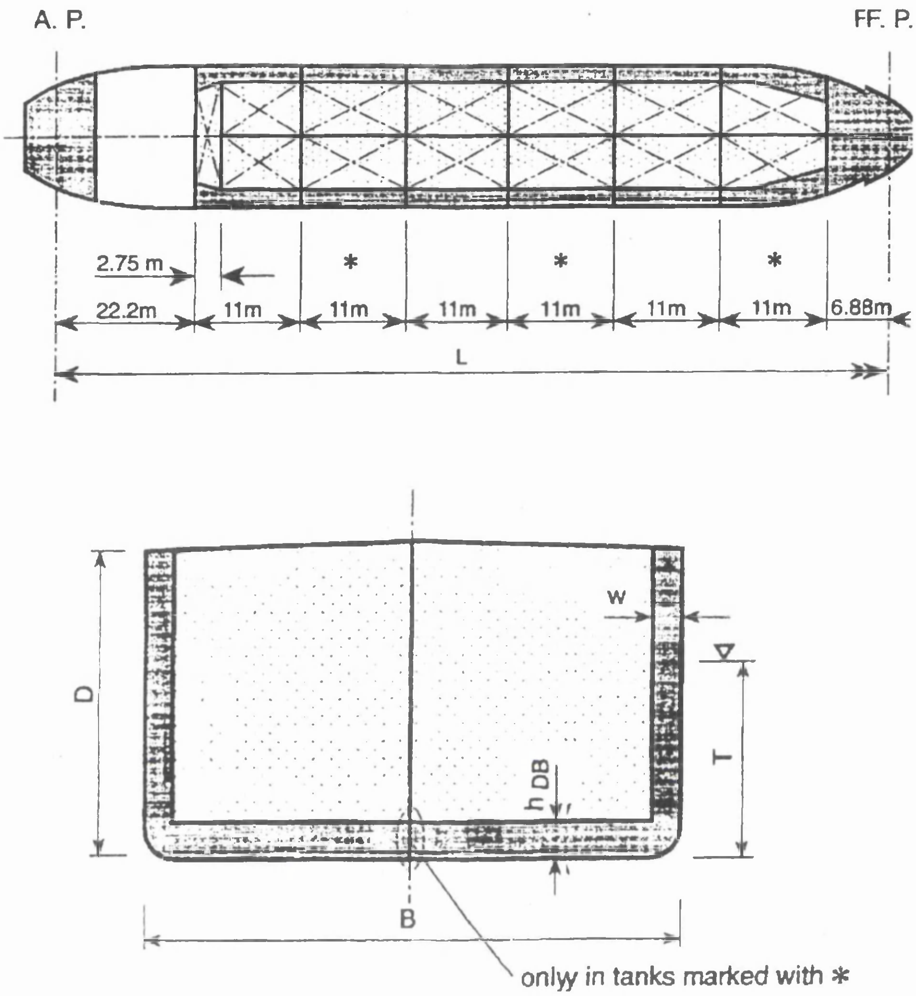
Median Outflow. This is the oil outflow corresponding to a cumulative probability of 0.50. This means that in 50% of all cases of outflow, the outflow will not exceed the above value.

Significant (1/3) Outflow. This is a weighted average of the upper 1/3 of all spill scenarios with the largest outflow and represents the significant value of outflow.

Extreme Outflow (Oe). This value represents the "*worst case*" spill scenario and is a weighted average of the upper 10% of all spill casualties. It provides a characteristic value describing the behaviour of a vessel subjected to extreme damage

APPENDIX B

APPENDIX B - IMO REFERENCE DOUBLE-HULL DESIGNS



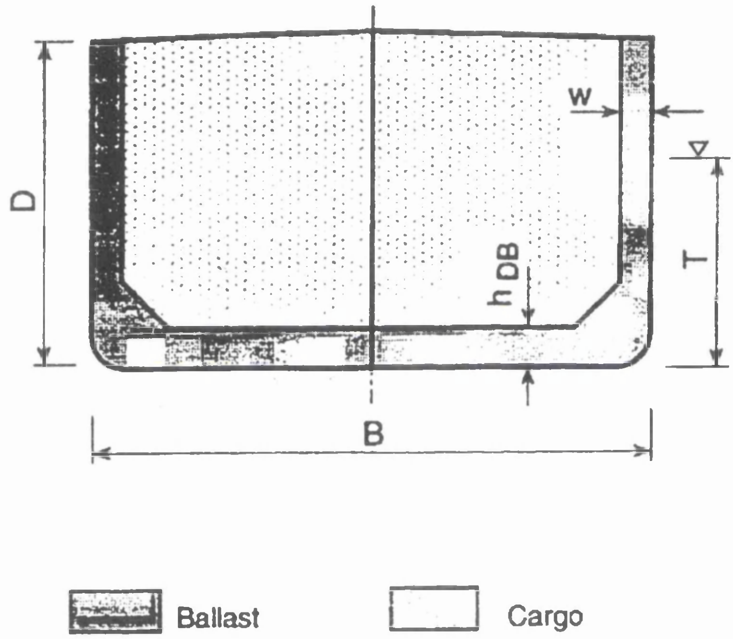
Ballast

Cargo

L = 95.00 m
B = 16.50 m
D = 8.30 m
T = 6.20 m
h_{DB} = 1.10 m
w = 1.00 m

Cargo oil capacity at 98 % tank filling: 6 0661 m^3
Cargo oil density: 0.8225 t/m^3

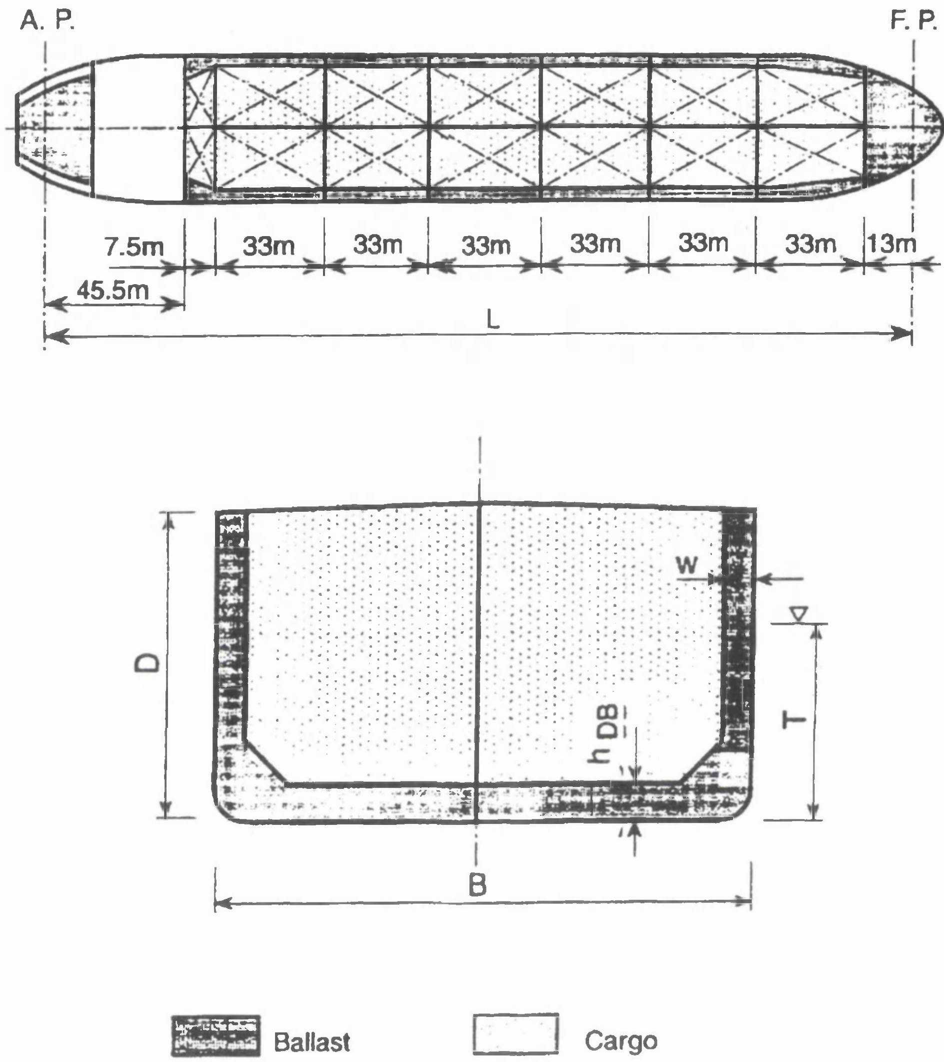
Figure 106. - IMO Reference Double-Hull Design N.º 1 – 5 000 DWT.



L = 203.50 m
B = 36.00 m
D = 18.00 m
T = 13.50 m
h_{DB} = 2.00 m
w = 2.00 m

Cargo oil capacity at 98 % tank filling: 70 175 m^3
Cargo oil density: 0.855 t/ m^3

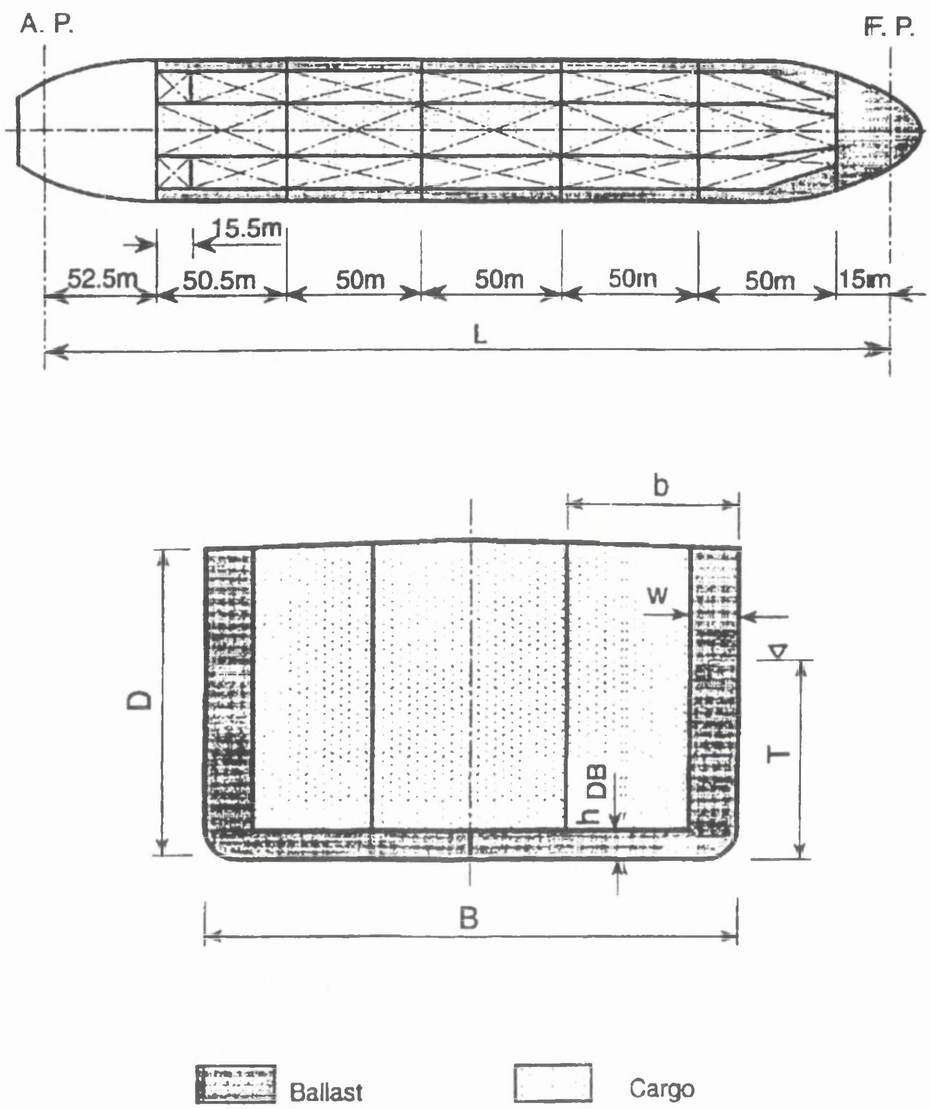
Figure 107. - IMO Reference Double-Hull Design N.° 2 – 60 000 DWT.



L	=	264.00 m
B	=	48.00 m
D	=	24.00 m
T	=	16.80 m
h_{DB}	=	2.32 m
w	=	2.00 m

Cargo oil capacity at 98 % tank filling: 175 439 m^3
Cargo oil density: 0..855 t/ m^3

Figure 108. - IMO Reference Double-Hull Design N.º 3 – 150 000 DWT.



L = 318.00 m
B = 57.00 m
D = 31.00 m
T = 22.00 m
h_{DB} = 2.00 m
w = 4.00 m
b = 18.00 m

Cargo oil capacity at 98 % tank filling: 330 994 m^3
Cargo oil density: 0.855 t/m^3

Figure 109. - IMO Reference Double-Hull Design N.° 4 – 283 000 DWT.

APPENDIX C

APPENDIX C – SHIP DESIGNS EVALUATED

Parametric Studies

CDW (t)	150000
Cargo Tank Arrangement	6x2
Wing Tank Width (m)	2.00
Double Bottom Ht (m)	2.32
LBP (m)	264.00
Beam molded (m)	48.00
Depth molded (m)	24.00
Full Draft molded (m)	16.80
98% Cargo Capacity (m3)	175.439
Cargo Oil density (t/m3)	0.855

	Baseline Vessel 2
Ls (m)	235.00
Breadth (m)	41.80
Depth (m)	19.80
Draught (m)	13.79
Cargo Oil density (t/m^3)	0.855

Design Types Comparison

	Pre-MARPOL	MARPOL	Double-Hull (2m Side Tanks)	Double-Hull (3.2m Side Tanks)	Mid-Deck
CDW (t)	272000	272000	272000	272000	272000
Cargo Tank Arrangement	8 x 3	6 x 3	6 x 3	6 x 3	6 x 2
Wing Tank Width (m)	0.00	0.00	2.00	3.20	6.00
Double Bottom Ht (m)	0.00	0.00	2.50	3.20	0.00
Long. Bulkhead Location from ship side	16.80	11.50	16.30	17.50	29.00
LBP (m)	320.00	320.00	320.00	320.00	320.00
Beam molded (m)	53.60	56.00	55.60	58.00	58.00
Depth molded (m)	27.30	31.00	31.00	31.70	31.70
Full Draft molded (m)	21.20	21.00	21.30	20.80	20.70

Double-Hull Designs - HEC

Baseline Design Particulars

CDW (t)	5000	40000	60000	95000	150000	220000	283000	350000	450000
Cargo Tank Arrangement	6x2	6x2	6x2	6x2	6x2	6x2	5x3	5x3	5x3
Wing Tank Width (m)	1.00	2.00	2.00	2.00	2.00	2.50	4.00	3.50	3.50
Double Bottom Ht (m)	1.10	2.00	2.00	2.00	2.32	2.50	2.00	3.50	3.50
LBP (m)	95.00	170.25	203.50	235.20	264.00	295.50	318.00	342.00	365.00
Beam molded (m)	16.50	30.96	36.00	41.80	48.00	53.50	57.00	63.00	68.00
Depth molded (m)	8.30	17.03	18.00	19.80	24.00	27.50	31.00	32.50	35.00
Full Draft molded (m)	6.20	11.72	12.20	13.79	16.80	19.66	22.00	23.00	25.50
98% Cargo Capacity (m3)	5.848	46.784	70.175	111.111	175.439	257.310	330.994	409.357	526.316
Cargo Oil density (t/m3)	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855

Sizes and Hull Types of Tank Vessel Evaluated

	Single-Hull	Double-Hull	Mid-Deck
35000-50000 DWT tankers	2	3	1
80000-100000 DWT tankers	2	4	1
135000-160000 DWT tankers	3	5	1
265000-30000 DWT tankers	3	3	1
Total	10	15	4

Appendix C

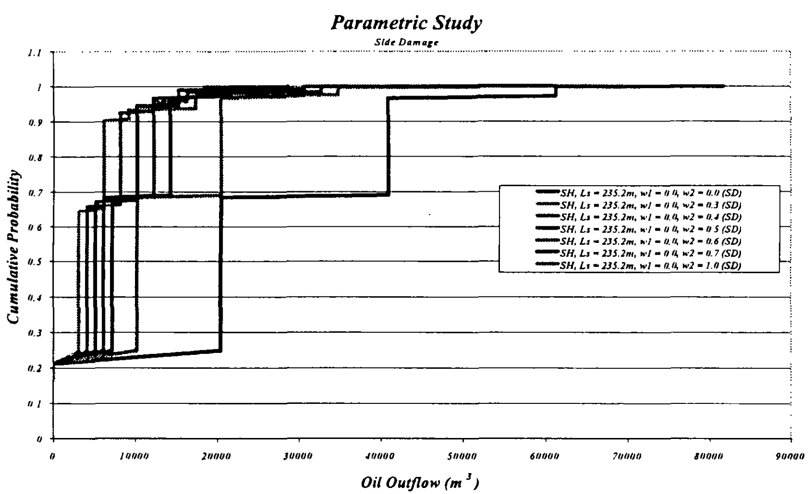
	Cargo Deadweight at 98% Filling (T)								
	5000	40000	**60000**	100000	**150000**	220000	**283000**	350000	450000
Wwt x Hdb	**1.0 x 1.1**	2.0 x 2.0	**2.0 x 2.0**	2.0 x 2.0	**2.0 x 2.32**	2.5 x 2.5	**4.0 x 2.0**	3.0 x 3.0	3.0 x 3.0
	1.25 x 1.25	2.25 x 2.25	2.25 x 2.25	2.5 x 2.5	2.5 x 2.5	3.0 x 3.0	3.0 x 3.0	3.5 x 3.5	3.5 x 3.5
	1.5 x 1.5	2.5 x 2.5	2.5 x 2.5	3.0 x 3.0	3.0 x 3.0	3.5 x 3.5	3.5 x 3.5	4.0 x 4.0	4.0 x 4.0
Cargo Tank Arrangement	5 x 2	5 x 2	5 x 2	5 x 2	5 x 2	6 x 2	**5 x 3**	5 x 3	5 x 3
	6 x 2	6 x 2	**6 x 2**	6 x 2	**6 x 2**	7 x 2	6 x 3	6 x 3	6 x 3
	7 x 2	7 x 2	7 x 2	7 x 2	7 x 2	5 x 3	5 x 4	5 x 4	5 x 4
					5 x 3	6 x 3	5 x 5	5 x 5	5 x 5
No. of designs	9	9	9	9	12	12	12	12	12

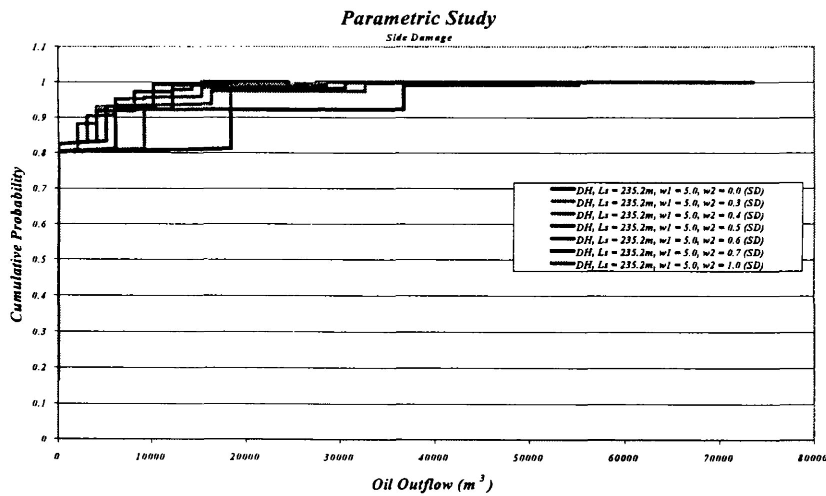
APPENDIX D

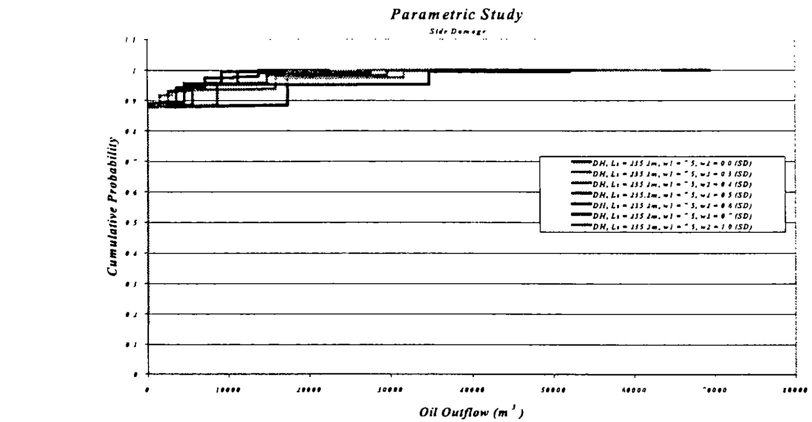
APPENDIX D - GRAPHIC AND TABULAR RESULTS

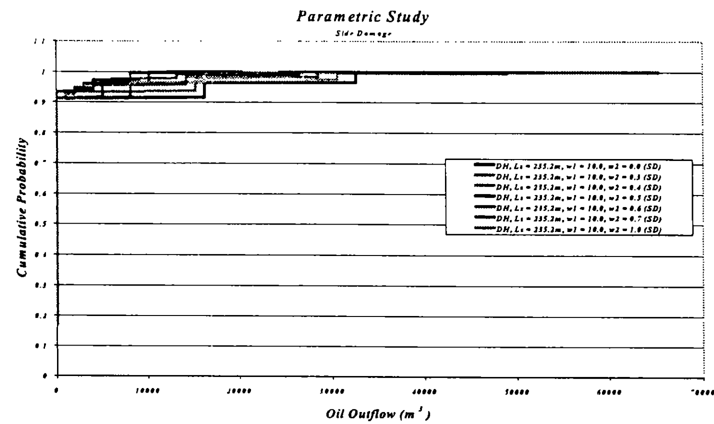
	Ship I
Ls (m)	235.00
Breadth (m)	41.80
Depth (m)	19.80
Draught (m)	13.79
Cargo Oil density (t/m^3)	0.855

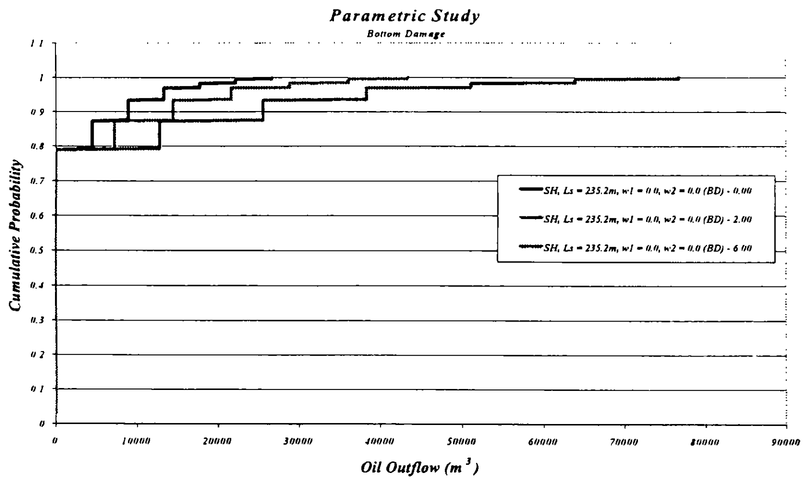
First Set of Ships Analysed							
	Ls = 235.20m						
w1\w2	0.0	0.3	0.4	0.5	0.6	0.7	1.0
0.00%	Single-Hull	Single-Hull	Single-Hull	Single-Hull	Single-Hull	Single-Hull	Single-Hull
5.00%	Double-Hull	Double-Hull	Double-Hull	Double-Hull	Double-Hull	Double-Hull	Double-Hull
7.50%	Double-Hull	Double-Hull	Double-Hull	Double-Hull	Double-Hull	Double-Hull	Double-Hull
10.00%	Double-Hull	Double-Hull	Double-Hull	Double-Hull	Double-Hull	Double-Hull	Double-Hull

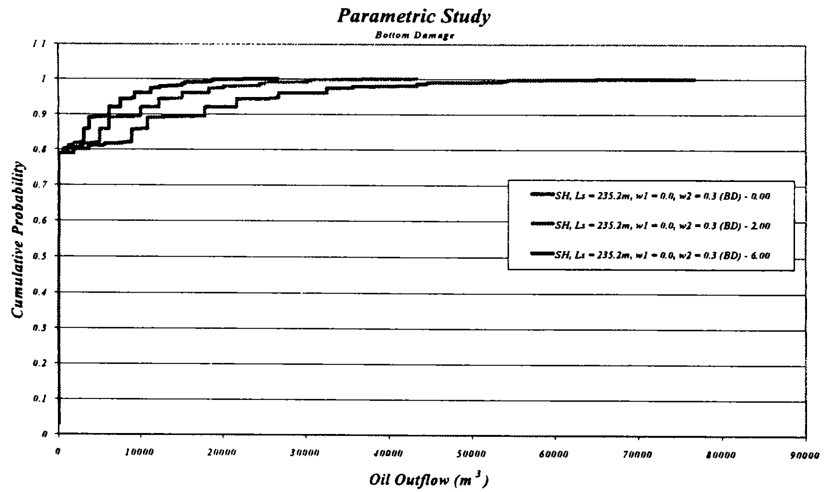


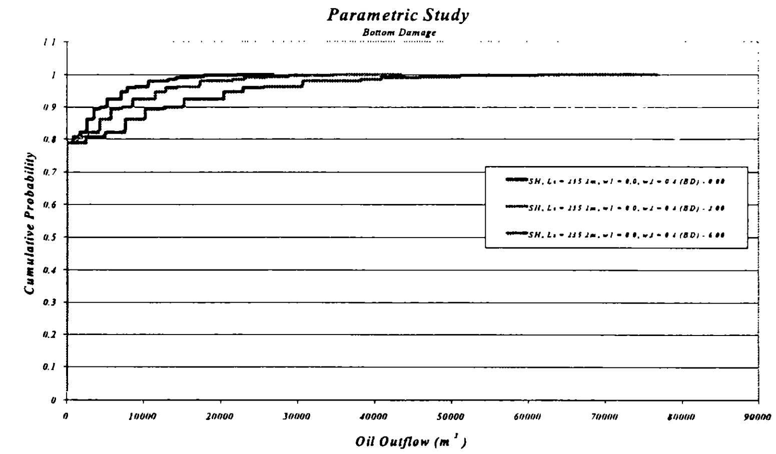


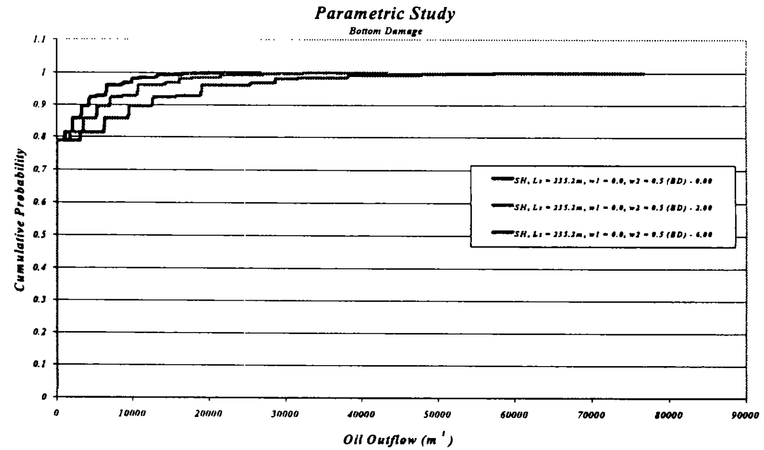

Parametric Study
Side Damage
Cumulative Probability
Oil Outflow (m³)

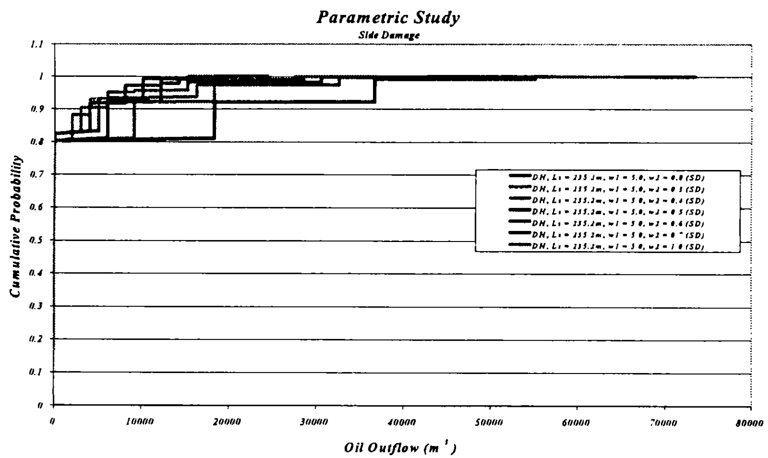

Parametric Study
Side Damage
Cumulative Probability
Oil Outflow (m³)

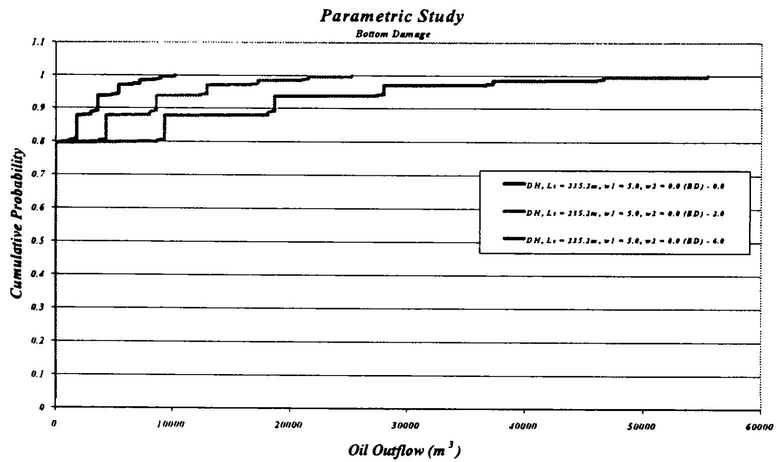

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)
SH, Ls = 235.2m, w1 = 0.0, w2 = 0.0 (BD) - 0.00
SH, Ls = 235.2m, w1 = 0.0, w2 = 0.0 (BD) - 2.00
SH, Ls = 235.2m, w1 = 0.0, w2 = 0.0 (BD) - 6.00

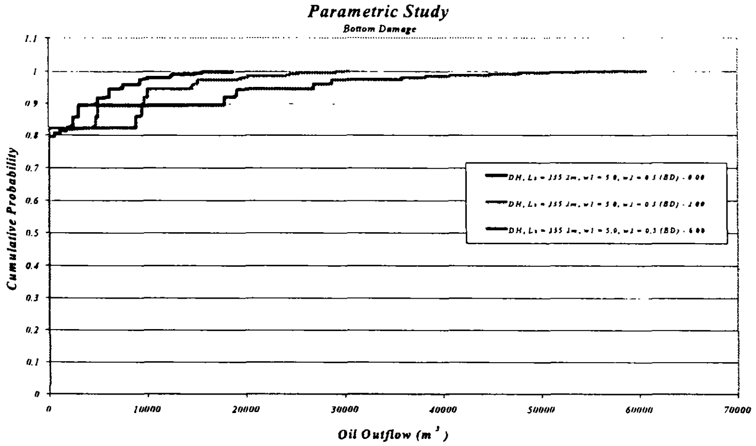

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)
SH, Ls = 235.2m, w1 = 0.0, w2 = 0.3 (BD) - 0.00
SH, Ls = 235.2m, w1 = 0.0, w2 = 0.3 (BD) - 2.00
SH, Ls = 235.2m, w1 = 0.0, w2 = 0.3 (BD) - 6.00

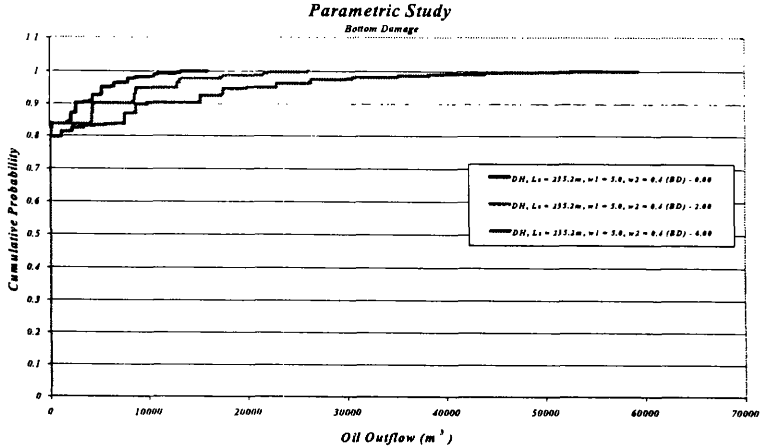

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m^3)

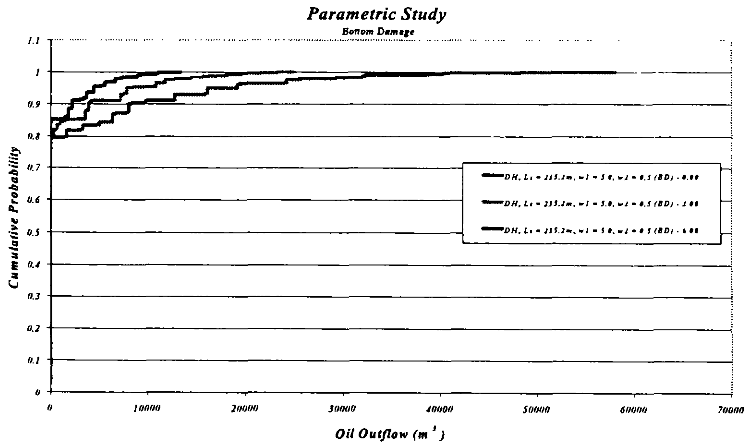

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m^3)

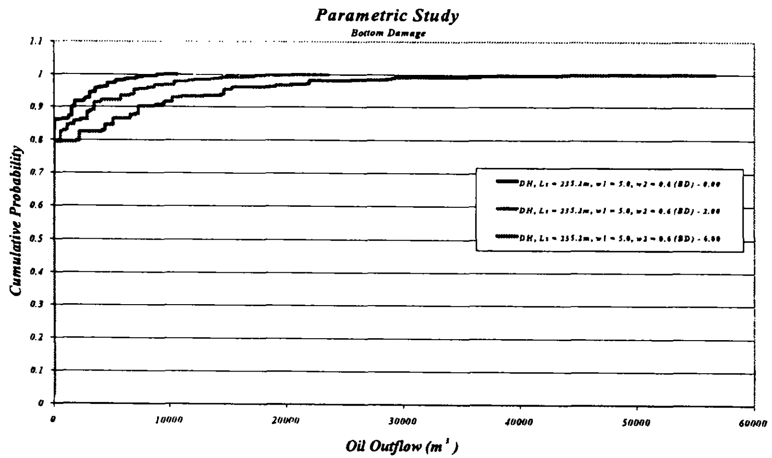

Parametric Study
Side Damage
Cumulative Probability
Oil Outflow (m^3)

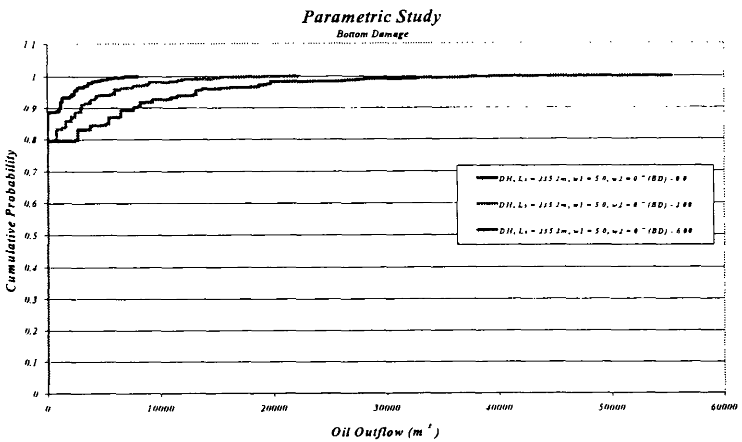

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m^3)

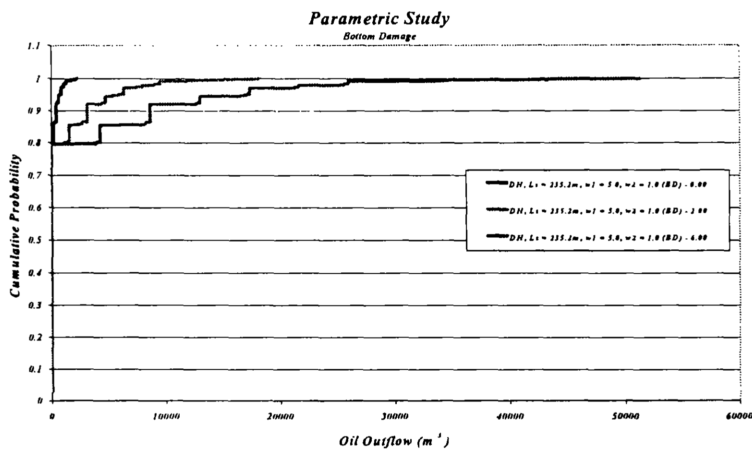

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m^3)
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.3 (BD) - 0.00
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.3 (BD) - 2.00
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.3 (BD) - 6.00

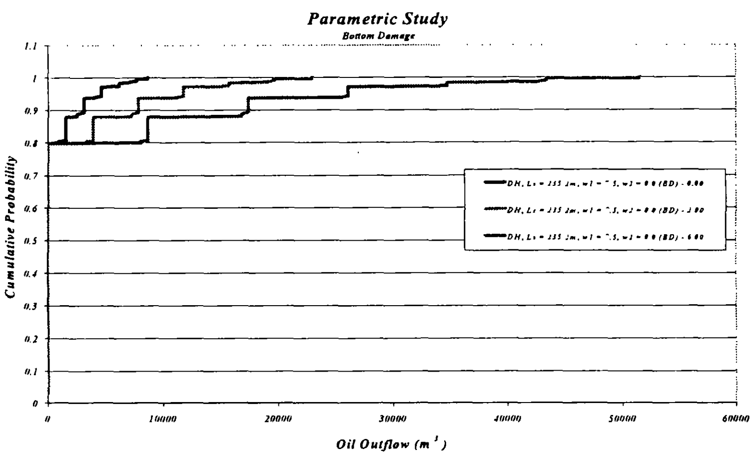

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m^3)
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.4 (BD) - 0.00
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.4 (BD) - 2.00
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.4 (BD) - 6.00

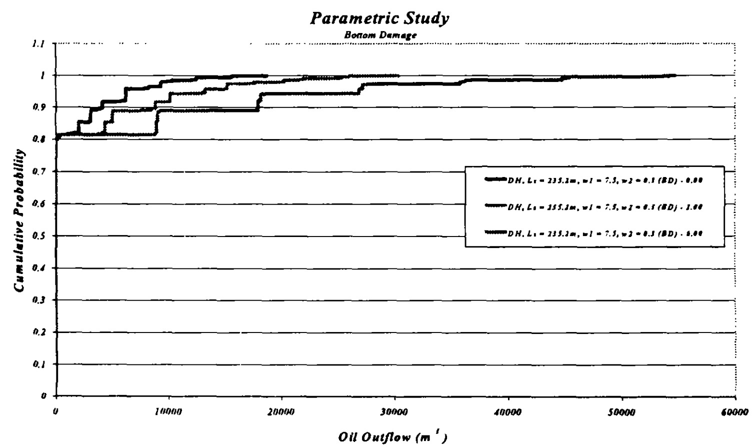

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m^3)
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.5 (BD) - 0.00
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.5 (BD) - 2.00
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.5 (BD) - 6.00

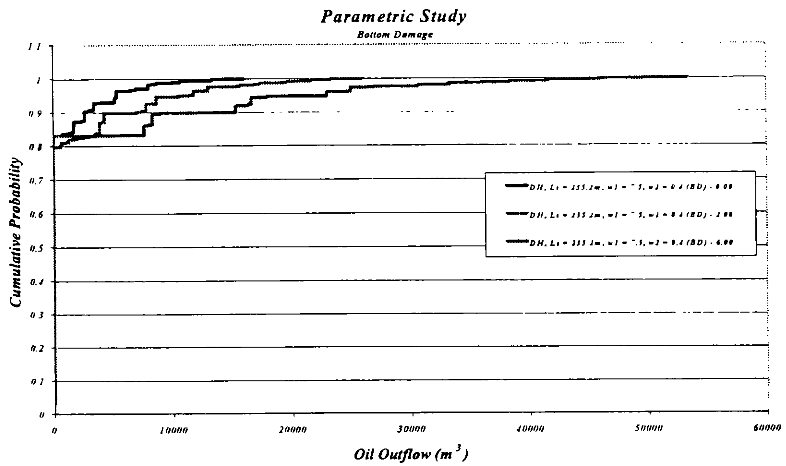

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m^3)
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.6 (BD) - 0.00
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.6 (BD) - 2.00
DH, Ls = 235.2m, w1 = 5.0, w2 = 0.6 (BD) - 6.00

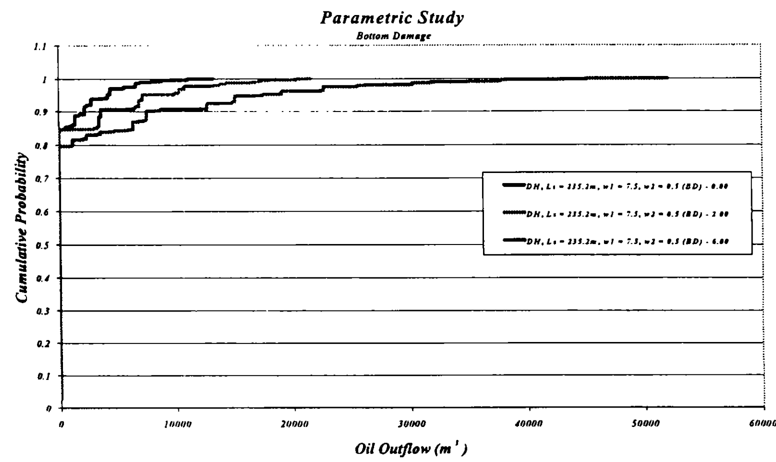

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)

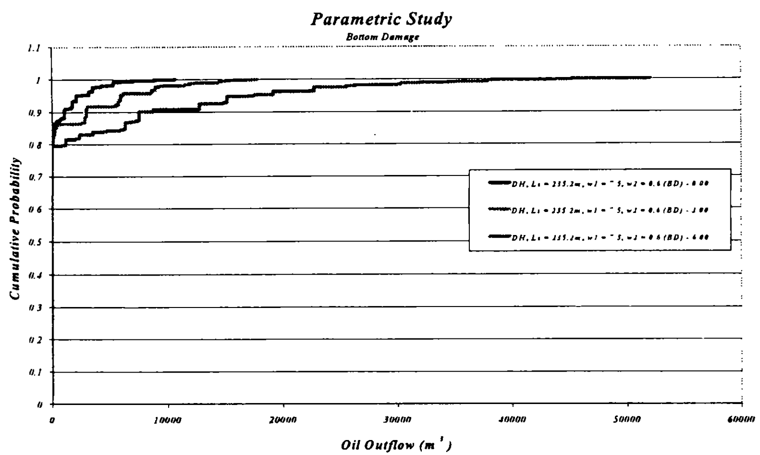

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)

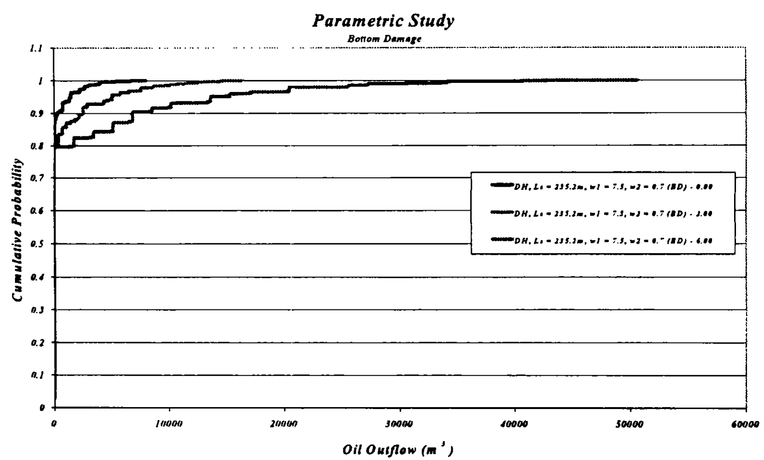

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)

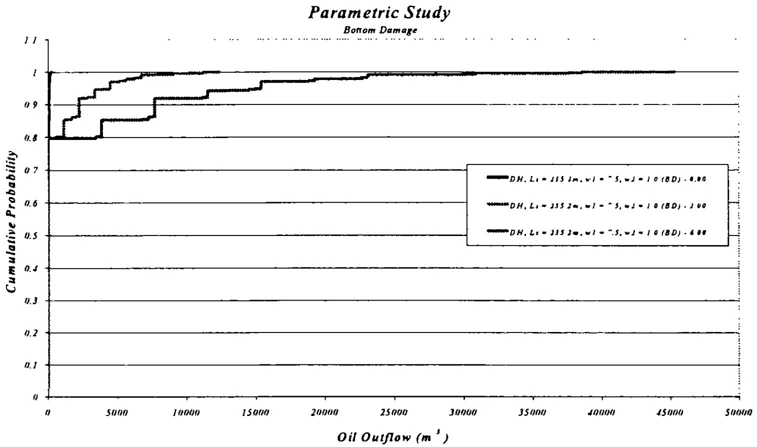

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)

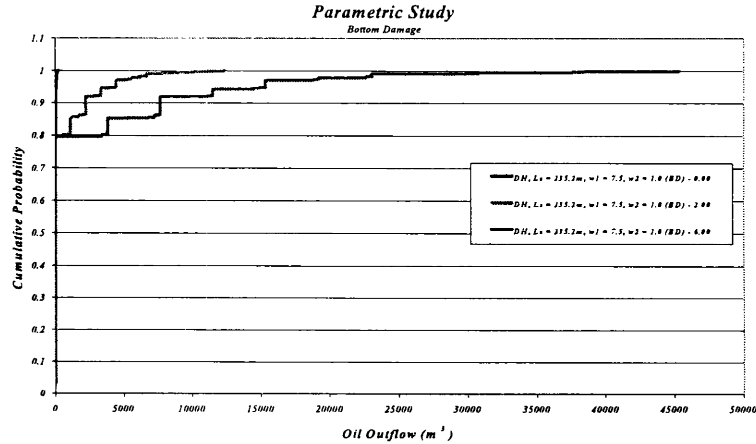

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.4 (BD) - 0.00
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.4 (BD) - 2.00
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.4 (BD) - 4.00

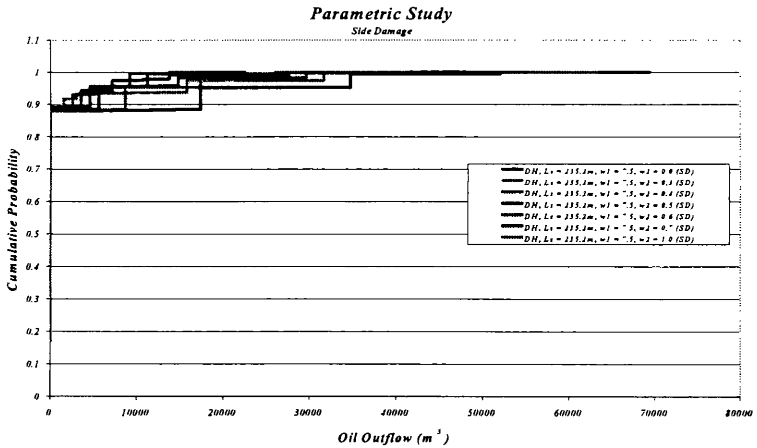

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.5 (BD) - 0.00
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.5 (BD) - 2.00
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.5 (BD) - 4.00

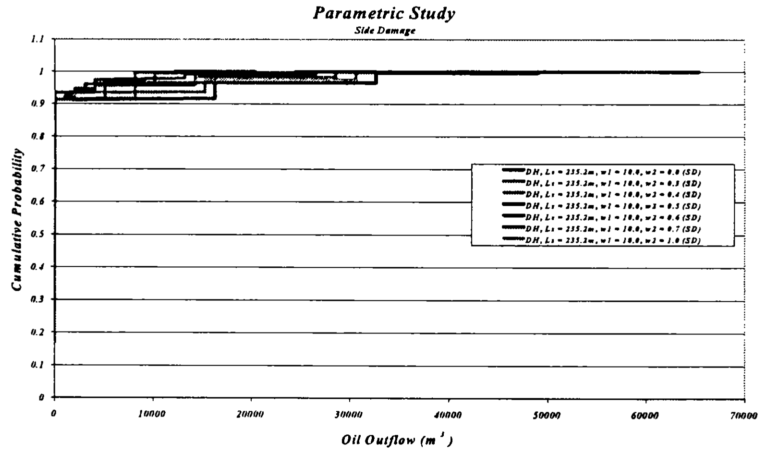

Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.6 (BD) - 0.00
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.6 (BD) - 2.00
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.6 (BD) - 4.00


Parametric Study
Bottom Damage
Cumulative Probability
Oil Outflow (m³)
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.7 (BD) - 0.00
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.7 (BD) - 2.00
DH, Ls = 235.2m, w1 = 7.5, w2 = 0.7 (BD) - 4.00

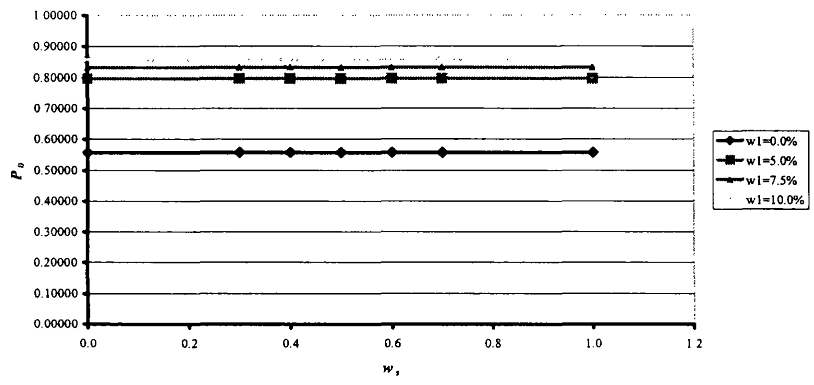

Parametric Study
Bottom Damage
Cumulative Probability
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
DH, L1 = 235.2m, w1 = 7.5, w2 = 1.0 (BD) - 0.00
DH, L1 = 235.2m, w1 = 7.5, w2 = 1.0 (BD) - 2.00
DH, L1 = 235.2m, w1 = 7.5, w2 = 1.0 (BD) - 6.00
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
Oil Outflow (m³)


Parametric Study
Bottom Damage
Cumulative Probability
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
DH, L1 = 235.2m, w1 = 7.5, w2 = 1.0 (BD) - 0.00
DH, L1 = 235.2m, w1 = 7.5, w2 = 1.0 (BD) - 2.00
DH, L1 = 235.2m, w1 = 7.5, w2 = 1.0 (BD) - 6.00
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
Oil Outflow (m³)

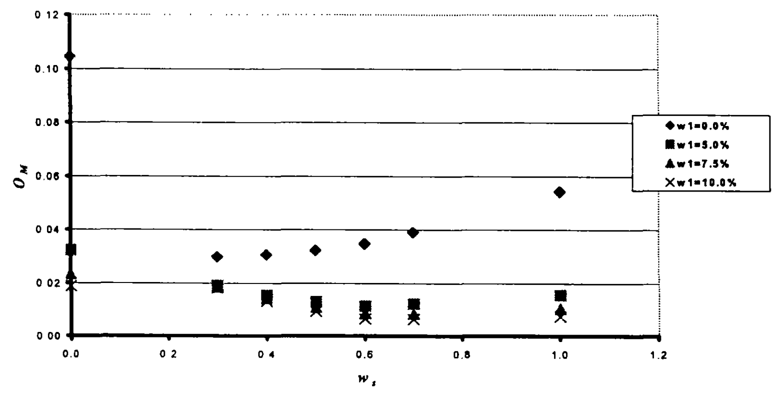

Parametric Study
Side Damage
Cumulative Probability
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
DH, L1 = 235.2m, w1 = 7.5, w2 = 0.0 (SD)
DH, L1 = 235.2m, w1 = 7.5, w2 = 0.3 (SD)
DH, L1 = 235.2m, w1 = 7.5, w2 = 0.4 (SD)
DH, L1 = 235.2m, w1 = 7.5, w2 = 0.5 (SD)
DH, L1 = 235.2m, w1 = 7.5, w2 = 0.6 (SD)
DH, L1 = 235.2m, w1 = 7.5, w2 = 0.7 (SD)
DH, L1 = 235.2m, w1 = 7.5, w2 = 1.0 (SD)
0
10000
20000
30000
40000
50000
60000
70000
80000
Oil Outflow (m³)


Parametric Study
Side Damage
Cumulative Probability
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
DH, L1 = 235.2m, w1 = 10.0, w2 = 0.0 (SD)
DH, L1 = 235.2m, w1 = 10.0, w2 = 0.3 (SD)
DH, L1 = 235.2m, w1 = 10.0, w2 = 0.4 (SD)
DH, L1 = 235.2m, w1 = 10.0, w2 = 0.5 (SD)
DH, L1 = 235.2m, w1 = 10.0, w2 = 0.6 (SD)
DH, L1 = 235.2m, w1 = 10.0, w2 = 0.7 (SD)
DH, L1 = 235.2m, w1 = 10.0, w2 = 1.0 (SD)
0
10000
20000
30000
40000
50000
60000
70000
Oil Outflow (m³)

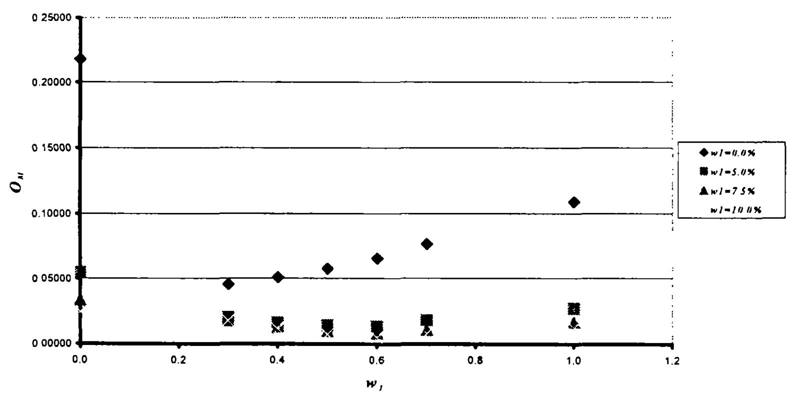
Probability of Zero Outflow, P_0
Collision 40% : Grounding 60%



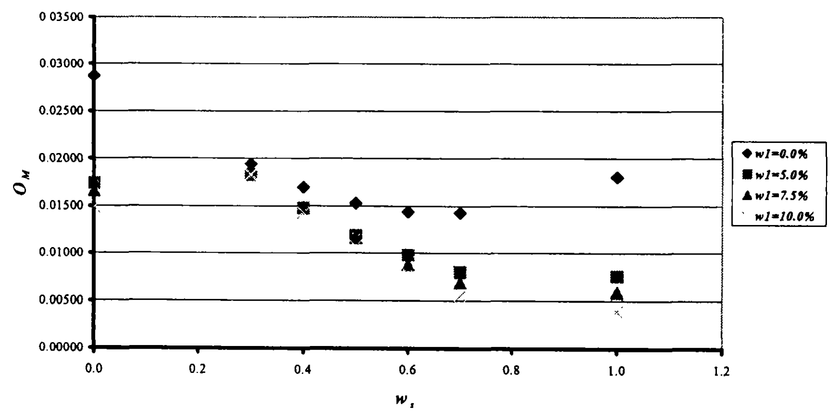
Mean Outflow Parameter, O_M
Collision 40% Grounding 60%

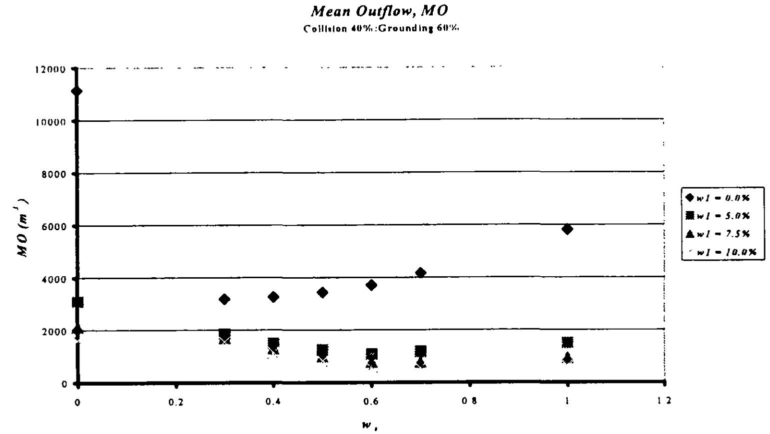


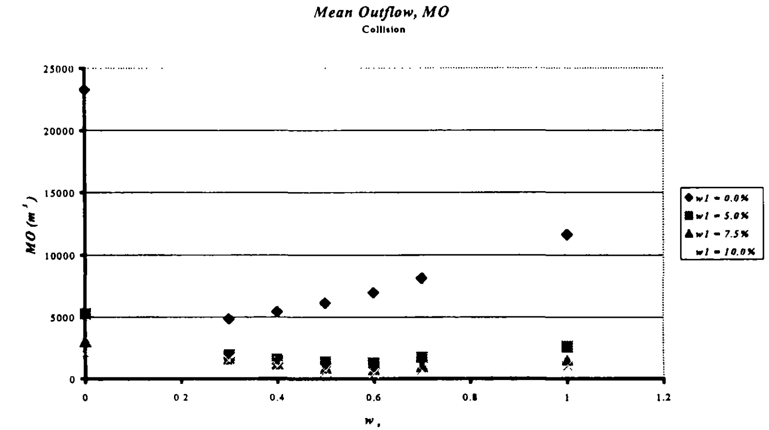
Mean Outflow Parameter, O_M
Side Damage

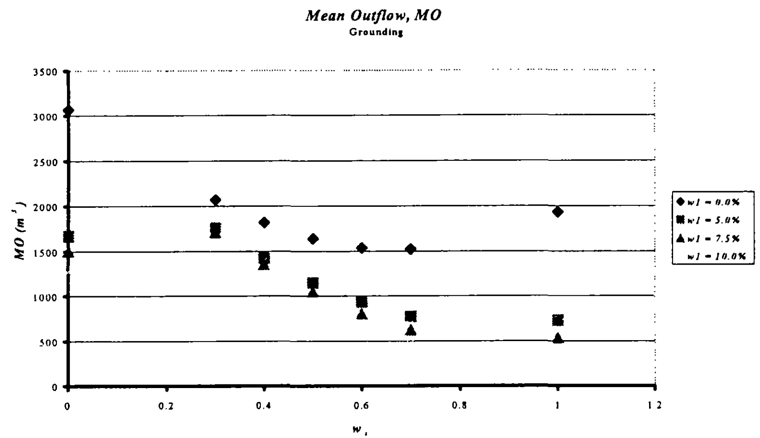


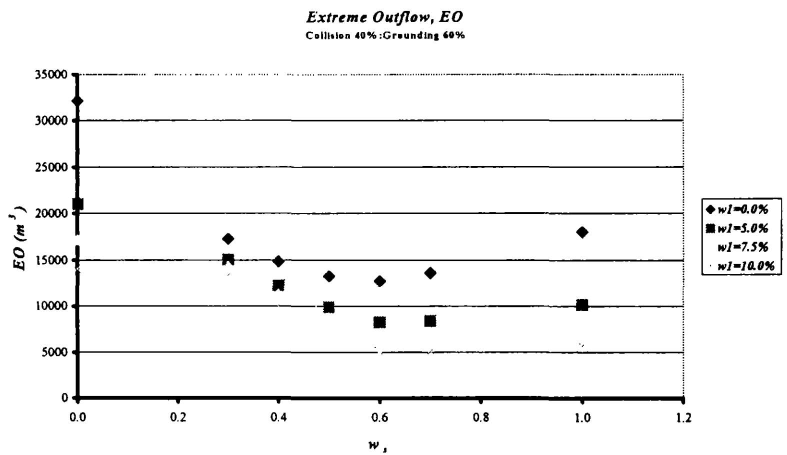
Mean Outflow Parameter, O_M
Bottom Damage

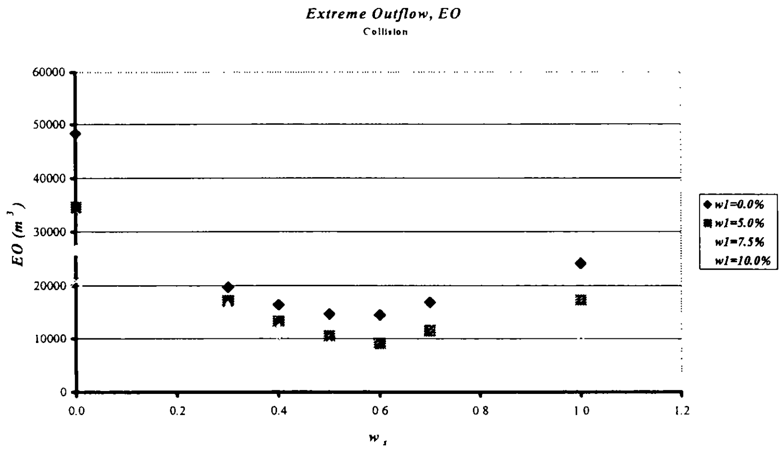


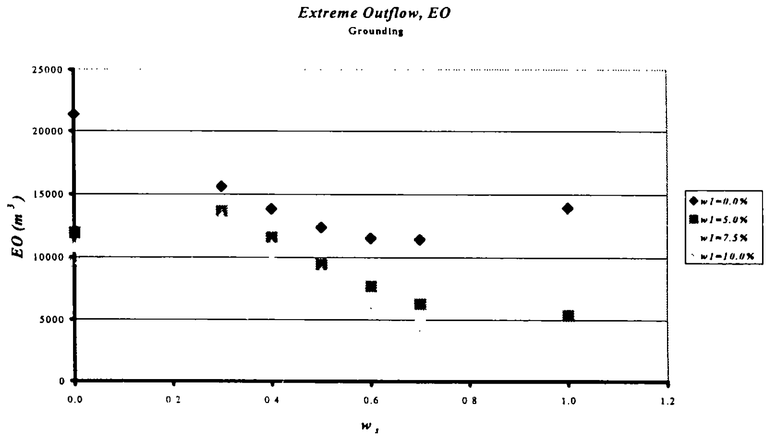

Mean Outflow, MO
Collision 40%:Grounding 60%
MO (m³)
w₁
w1 = 0.0%
w1 = 5.0%
w1 = 7.5%
w1 = 10.0%

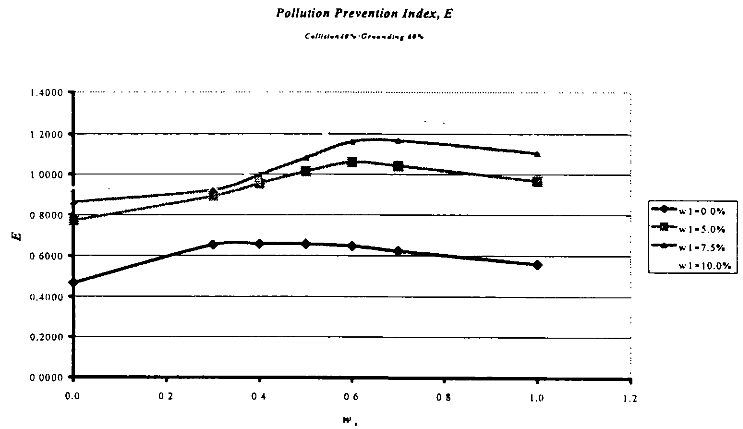

Mean Outflow, MO
Collision
MO (m³)
w₁
w1 = 0.0%
w1 = 5.0%
w1 = 7.5%
w1 = 10.0%


Mean Outflow, MO
Grounding
MO (m³)
w₁
w1 = 0.0%
w1 = 5.0%
w1 = 7.5%
w1 = 10.0%

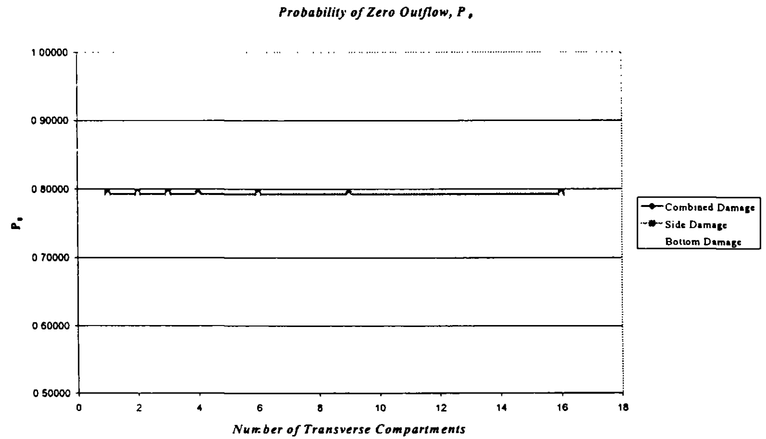

Extreme Outflow, EO
Collision 40%:Grounding 60%
EO (m³)
w₁
w1=0.0%
w1=5.0%
w1=7.5%
w1=10.0%

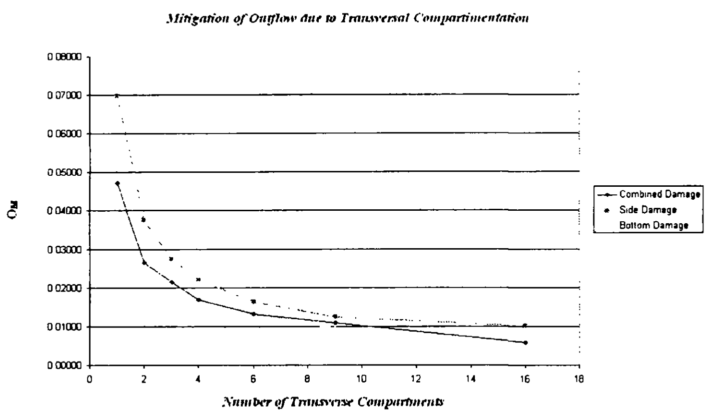

Extreme Outflow, EO
Collision
EO (m³)
60000
50000
40000
30000
20000
10000
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
w1=0.0%
w1=5.0%
w1=7.5%
w1=10.0%

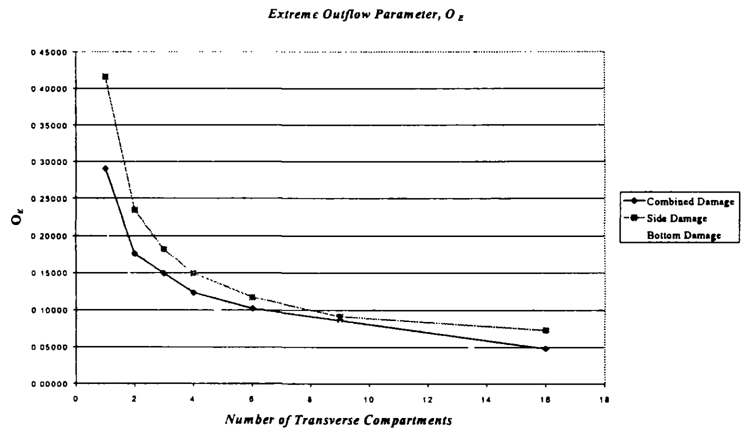

Extreme Outflow, EO
Grounding
EO (m³)
25000
20000
15000
10000
5000
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
w1=0.0%
w1=5.0%
w1=7.5%
w1=10.0%


Pollution Prevention Index, E
E
1.4000
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
0.0
0.2
0.4
0.6
0.8
1.0
1.2
w1=0.0%
w1=5.0%
w1=7.5%
w1=10.0%

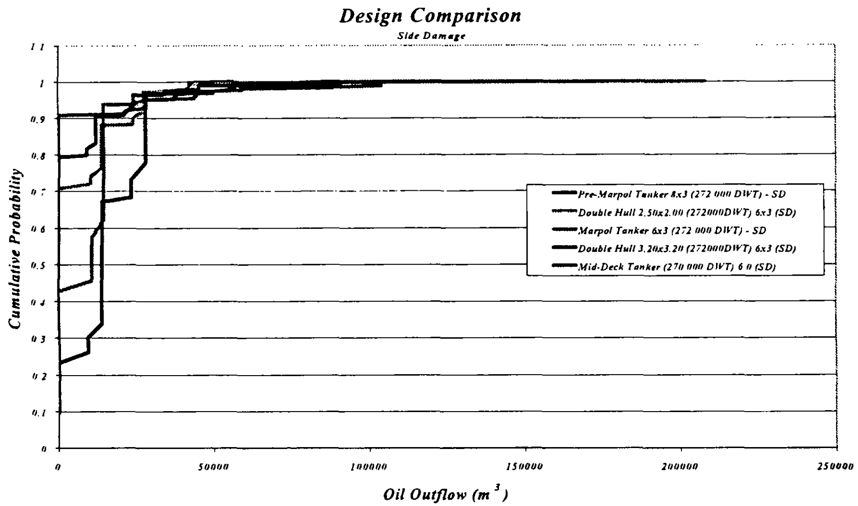
Second Set of Ships Analysed				
	Ls = 264.00m (150000DWT)			
n\w1	0.00%	5.00%	7.50%	10.00%
1	Single-Hull	Double-Hull	Double-Hull	Double-Hull
2	Single-Hull	Double-Hull	Double-Hull	Double-Hull
3	Single-Hull	Double-Hull	Double-Hull	Double-Hull
4	Single-Hull	Double-Hull	Double-Hull	Double-Hull
6	Single-Hull	Double-Hull	Double-Hull	Double-Hull
9	Single-Hull	Double-Hull	Double-Hull	Double-Hull
16	Single-Hull	Double-Hull	Double-Hull	Double-Hull
25	Single-Hull	Double-Hull	Double-Hull	Double-Hull

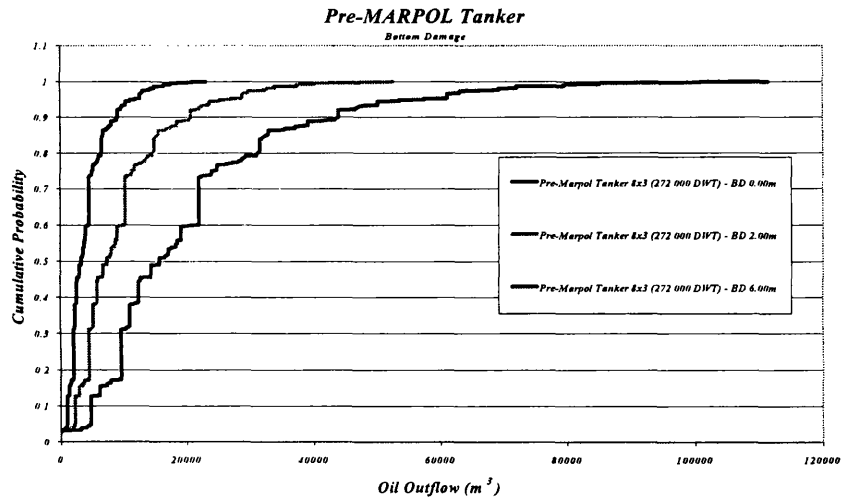


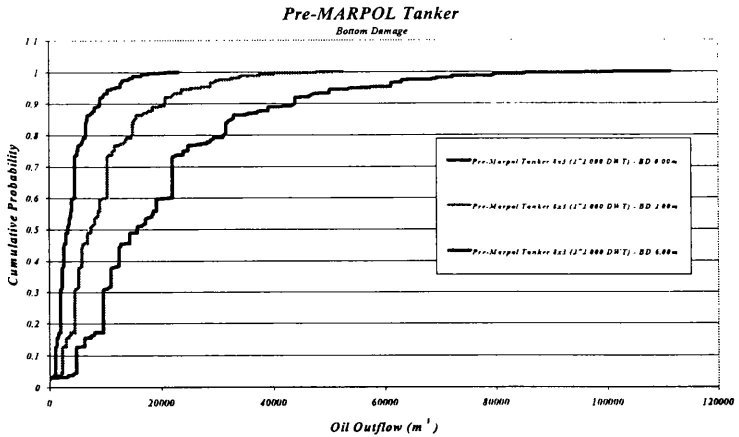


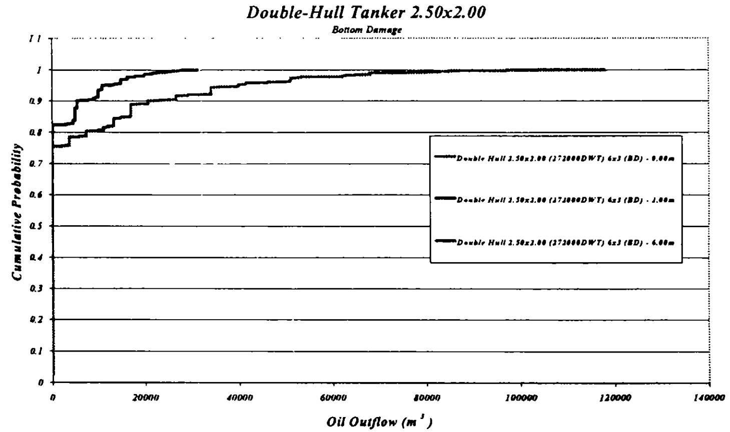


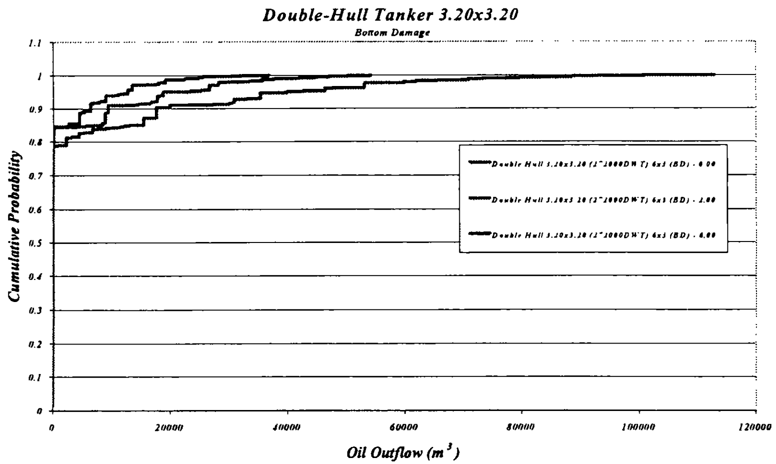
	Pre-MARPOL	MARPOL	Double-Hull (2m Side Tanks)	Double-Hull (3.2m Side Tanks)	Mid-Deck
CDW (t)	272000	272000	272000	272000	272000
Cargo Tank Arrangement	8 x 3	6 x 3	6 x 3	6 x 3	6 x 2
Wing Tank Width (m)	0.00	0.00	2.00	3.20	6.00
Double Bottom Ht (m)	0.00	0.00	2.50	3.20	0.00
Long. Bulkhead Location from ship side	16.80	11.50	16.30	17.50	29.00
LBP (m)	320.00	320.00	320.00	320.00	320.00
Beam molded (m)	53.60	56.00	55.60	58.00	58.00
Depth molded (m)	27.30	31.00	31.00	31.70	31.70
Full Draft molded (m)	21.20	21.00	21.30	20.80	20.70

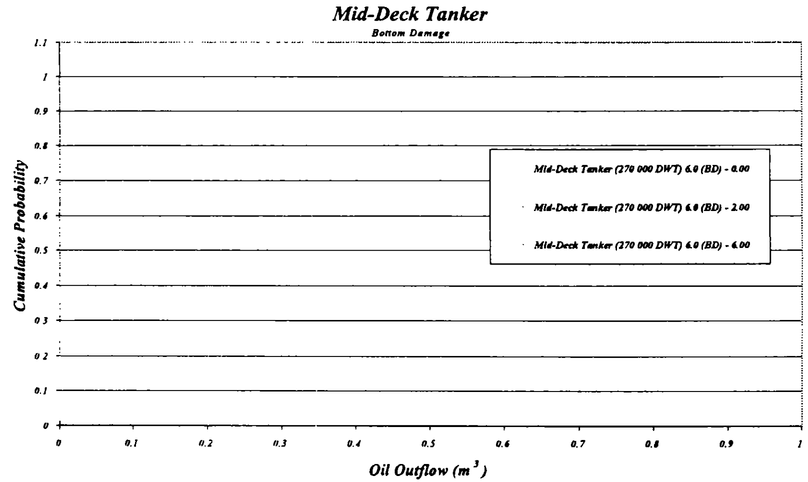


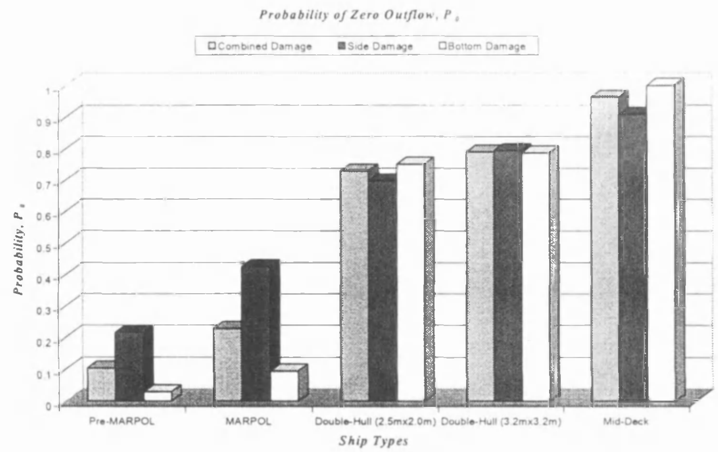


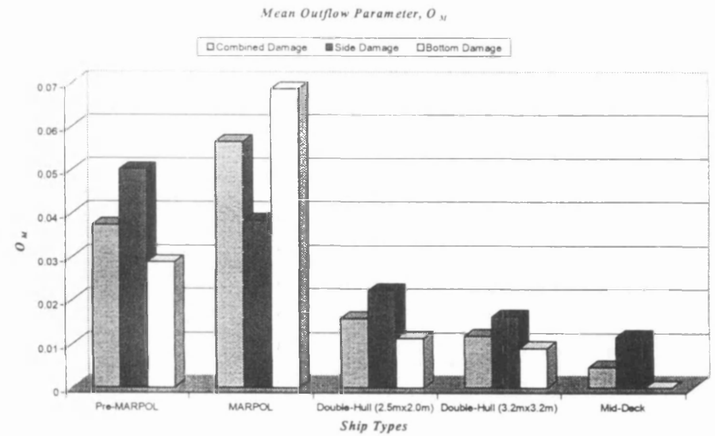

Pre-MARPOL Tanker
Bottom Damage
Cumulative Probability
Oil Outflow (m³)

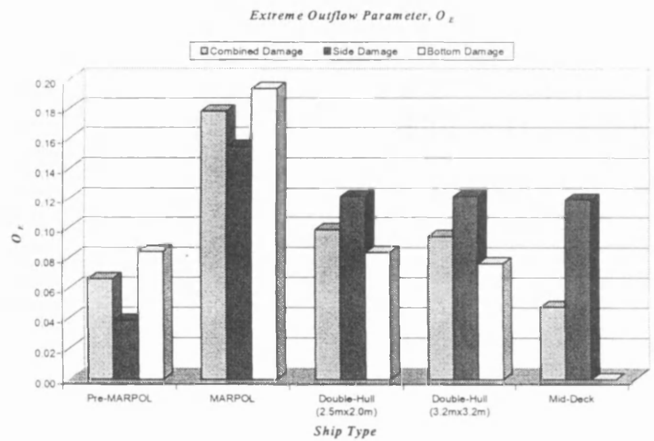

Double-Hull Tanker 2.50x2.00
Bottom Damage
Cumulative Probability
Oil Outflow (m³)

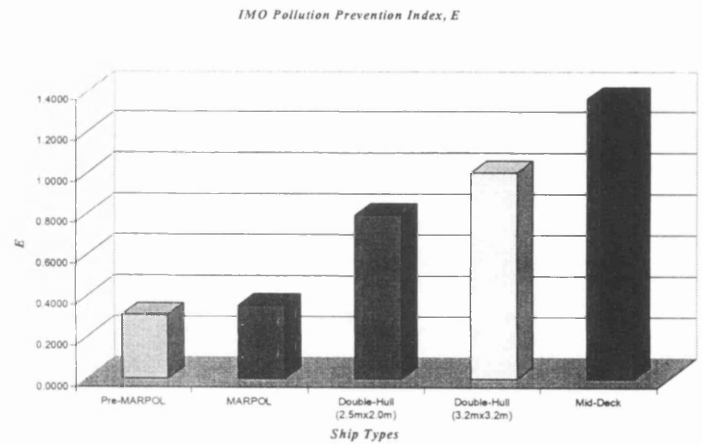

Double-Hull Tanker 3.20x3.20
Bottom Damage
Cumulative Probability
Oil Outflow (m³)

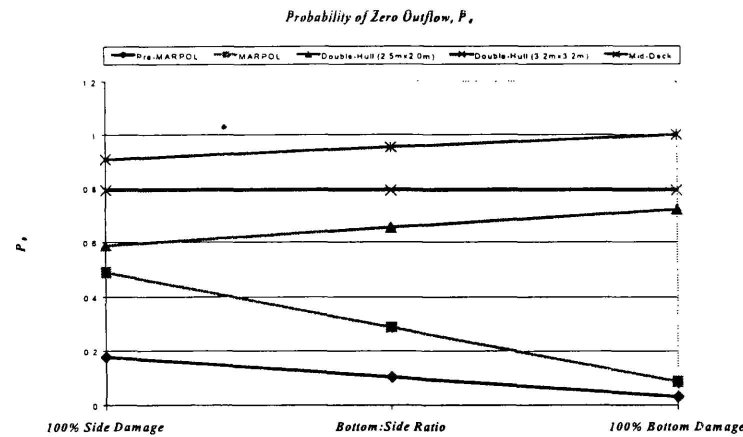

Mid-Deck Tanker
Bottom Damage
Mid-Deck Tanker (270 000 DWT) 6.0 (BD) - 0.00
Mid-Deck Tanker (270 000 DWT) 6.0 (BD) - 2.00
Mid-Deck Tanker (270 000 DWT) 6.0 (BD) - 6.00
Cumulative Probability
Oil Outflow (m³)


Probability of Zero Outflow, P_0
Combined Damage
Side Damage
Bottom Damage
Probability, P_0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre-MARPOL
MARPOL
Double-Hull (2.5mx2.0m)
Double-Hull (3.2mx3.2m)
Mid-Deck
Ship Types


Mean Outflow Parameter, O_M
Combined Damage
Side Damage
Bottom Damage
O_M
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Pre-MARPOL
MARPOL
Double-Hull (2.5mx2.0m)
Double-Hull (3.2mx3.2m)
Mid-Deck
Ship Types


Extreme Outflow Parameter, O_E
Combined Damage
Side Damage
Bottom Damage
O_E
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Pre-MARPOL
MARPOL
Double-Hull (2.5mx2.0m)
Double-Hull (3.2mx3.2m)
Mid-Deck
Ship Type


IMO Pollution Prevention Index, E
E
1.4000
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
Pre-MARPOL
MARPOL
Double-Hull (2.5mx2.0m)
Double-Hull (3.2mx3.2m)
Mid-Deck
Ship Types


Probability of Zero Outflow, P_0
Pre-MARPOL
MARPOL
Double-Hull (2.5m×2.0m)
Double-Hull (3.2m×3.2m)
Mid-Deck
1.2
1
0.8
0.6
0.4
0.2
0
P_0
100% Side Damage
Bottom:Side Ratio
100% Bottom Damage

Principal Particulars for 35 000 DWT - 50 000 DWT Tankers

	40-S1	40-S2	40-DS3	40-D1	40-D2	40-D3
	Pre-MARPOL	MARPOL 78	Double Sides	Double Hull	Double Hull	Double Hull
Longitudinal Bulkhead in Cargo Tanks	All	All	None	None	All	All
Longitudinal bulkhead in Ballast Tanks				Some	All	All
Deadweight (t)	39000	36000	40000	47000	40000	46000
Length/Beam	7.01	5.53	5.72	5.40	6.51	5.41
Length/Depth	12.92	10.37	12.45	9.67	12.50	9.08
Beam/Depth	1.84	1.88	2.18	1.79	1.92	1.68
Loadline Draft/Depth	0.75	0.68	0.66	0.68	0.74	0.64
Number of Longitudinal Bulkheads	2	2	2	2	3	3
Number of Cargo Tanks (excl. slops)	13	15	6	8	16	14
Number of Ballast Tanks	7	6	10	9	22	12
Wing Tank Width/Required Width	-	-	2.240	1.130	1.220	1.000
Wing Tank Width/Beam	-	-	0.139	0.070	0.083	0.062
Double Bottom Height/Required Height	-	-	-	1.000	1.090	1.080
Double Bottom Height/Depth	-	-	-	0.111	0.140	0.112
Cargo Oil at 98% (m3)	44000	44000	47000	52000	43000	54000
Segregated Ballast (t)	11000	13000	20000	23000	22000	20000

Principal Particulars for 80 000 DWT - 100 000 DWT Tankers

	80-S1	80-S2	80-DS3	80-D1	80-D2	80-D3	80-D4
	Pre-MARPOL	MARPOL 78	Double Sides	Double Hull	Double Hull	Double Hull	Double Hull
Longitudinal Bulkhead in Cargo Tanks	All	All	None	None	None	Some	Some
Longitudinal bulkhead in Ballast Tanks				All	All	All	All
Deadweight (t)	97000	81000	85000	97000	94000	96000	96000
Length/Beam	5.75	5.93	5.09	5.57	5.57	5.60	5.57
Length/Depth	11.62	12.46	12.38	11.65	12.00	12.05	11.65
Beam/Depth	2.02	2.10	2.43	2.09	2.15	2.15	2.09
Loadline Draft/Depth	0.75	0.64	0.67	0.68	0.70	0.69	0.69
Number of Longitudinal Bulkheads	2	2	2	2	2	3	3
Number of Cargo Tanks (excl. slops)	12	11	7	7	7	10	12
Number of Ballast Tanks	4	8	10	10	12	13	14
Wing Tank Width/Required Width	-	-	3.000	1.000	1.350	1.450	1.230
Wing Tank Width/Beam	-	-	0.136	0.048	0.064	0.069	0.059
Double Bottom Height/Required Height	-	-	-	1.050	1.050	1.050	1.230
Double Bottom Height/Depth	-	-	-	0.105	0.108	0.108	0.123
Cargo Oil at 98% (m3)	119000	100000	98000	108000	106000	108000	108000
Segregated Ballast (t)	13000	38000	40000	41000	40000	39000	42000

Principal Particulars for 135 000 DWT - 160 000 DWT Tankers

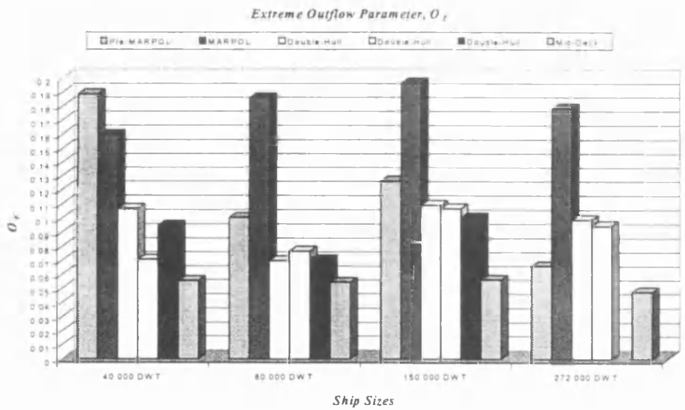
	150-S1	150-S2	150-S3	150-D1	150-D2	150-D3	150-D4	150-D5
	Pre-MARPOL	MARPOL 78	MARPOL 78	Double Hull	Double Hull	Double Hull	Double Hull	Double Hull
Longitudinal Bulkhead in Cargo Tanks	All	All	All	None	Some	All	All	All
Longitudinal bulkhead in Ballast Tanks				All	Some	All	All	Some
Deadweight (t)	156000	149000	155000	151000	136000	150000	150000	157000
Length/Beam	5.00	5.78	5.22	5.50	5.08	5.61	5.52	5.22
Length/Depth	13.40	11.81	10.40	11.48	9.75	10.79	11.58	10.40
Beam/Depth	2.68	2.04	1.99	2.09	1 92	1.92	2.10	1.99
Loadline Draft/Depth	0.77	0.66	0.07	0.70	0.67	0.71	0.70	0.69
Number of Longitudinal Bulkheads	2	2	2	2	3	3	3	3
Number of Cargo Tanks (excl. slops)	12	9	11	9	10	12	12	12
Number of Ballast Tanks	4	8	6	12	16	14	14	15
Wing Tank Width/Required Width	-	-	-	1.150	1.880	1.350	1.280	1.670
Wing Tank Width/Beam	-	-	-	0.048	0.078	0.059	0.053	0.067
Double Bottom Height/Required Height	-	-	-	1.250	1.650	1.400	1.400	1.670
Double Bottom Height/Depth	-	-	-	0.109	0.131	0.117	0.123	0.133
Cargo Oil at 98% (m3)	187000	177000	180000	165000	159000	164000	167000	179000
Segregated Ballast (t)	24000	64000	66000	59000	63000	56000	57000	67000

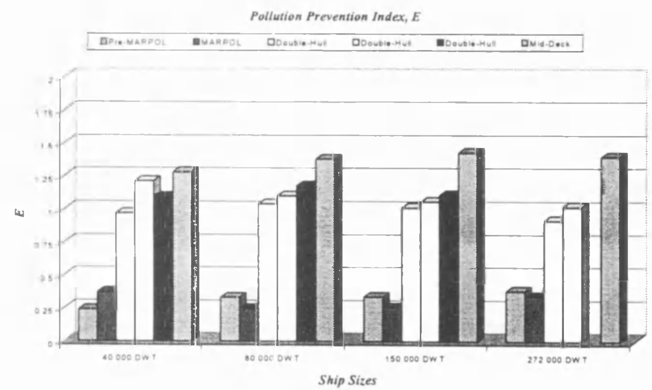
Principal Particulars for 265 000 DWT - 300 000 DWT Tankers

	280-S1	280-S2	280-S3	280-D1	280-D2	280-D3
	Pre-MARPOL	MARPOL 78	MARPOL 78	Double Hull	Double Hull	Double Hull
Longitudinal Bulkhead in Cargo Tanks	All	All	All	All	All	All
Longitudinal bulkhead in Ballast Tanks				All	Some	Some
Deadweight (t)	277000	268000	292000	280000	300000	298000
Length/Beam	5.87	5.97	5.50	5.47	5.52	5.37
Length/Depth	12.31	12.12	10.13	10.10	10.32	10.06
Beam/Depth	2.10	2.03	1.84	1.85	1.87	1.87
Loadline Draft/Depth	0.81	0.78	0.69	0.66	0.71	0.70
Number of Longitudinal Bulkheads	2	2	2	4	4	4
Number of Cargo Tanks (excl. slops)	16	12	13	15	15	15
Number of Ballast Tanks	3	6	6	13	14	17
Wing Tank Width/Required Width	-	-	-	1.970	3.520	3.150
Wing Tank Width/Beam	-	-	-	0.068	0.061	0.053
Double Bottom Height/Required Height	-	-	-	1.550	1.500	1.600
Double Bottom Height/Depth	-	-	-	0.099	0.097	0.101
Cargo Oil at 98% (m3)	309000	314000	338000	343000	338000	244000
Segregated Ballast (t)	37000	41000	114000	108000	102000	111000

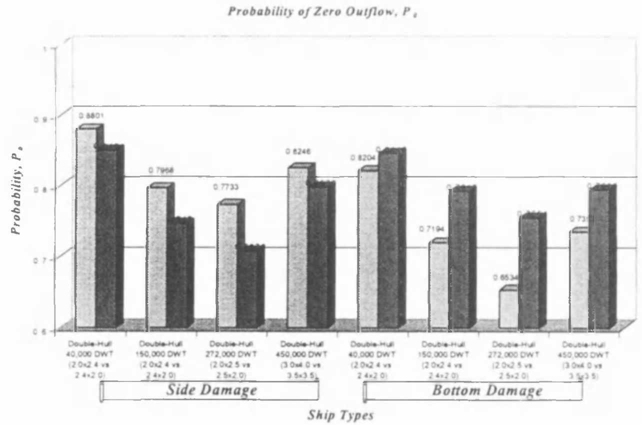

Probability of Zero Outflow, P_0
Pre-MARPOL
MARPOL
Double-Hull
Double-Hull
Double-Hull
Mid-Deck
Probability, P_0
40 000 DWT
80 000 DWT
150 000 DWT
272 000 DWT
Ship Sizes

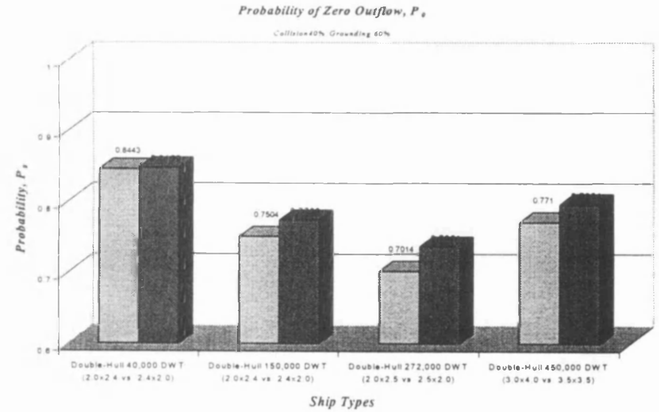

Mean Outflow Parameter, O_M
Pre-MARPOL
MARPOL
Double-Hull
Double-Hull
Double-Hull
Mid-Deck
O_M
40 000 DWT
80 000 DWT
150 000 DWT
272 000 DWT
Ship Sizes

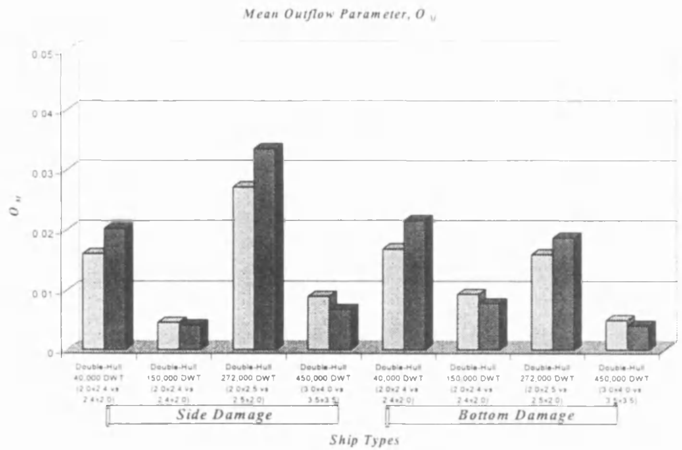

Extreme Outflow Parameter, O_E
Pre-MARPOL
MARPOL
Double-Hull
Double-Hull
Double-Hull
Mid-Deck
O_E
40 000 DWT
80 000 DWT
150 000 DWT
272 000 DWT
Ship Sizes

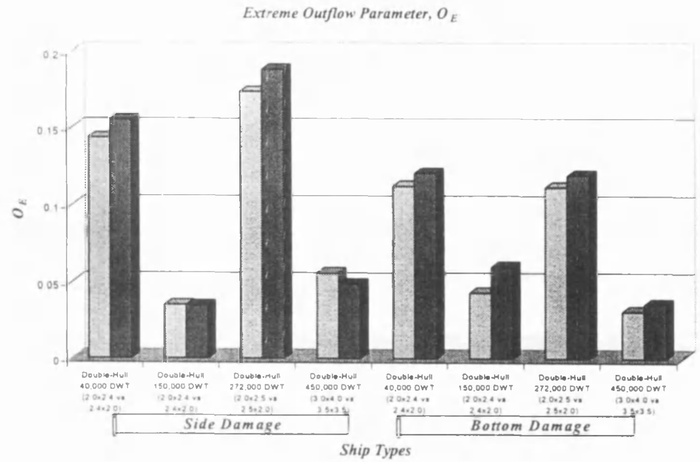

Pollution Prevention Index, E
Pre-MARPOL
MARPOL
Double-Hull
Double-Hull
Double-Hull
Mid-Deck
E
40 000 DWT
80 000 DWT
150 000 DWT
272 000 DWT
Ship Sizes

CDW (t)	40000		150000		272000		450000	
Cargo Tank Arrangement	6x2	6x2	6x2	6x2	6x3	6x3	5x3	5x3
Wing Tank Width (m)	2.00	2.40	2.40	2.00	2.00	2.50	3.50	4.00
Double Bottom Ht (m)	2.40	2.00	2.00	2.40	2.50	2.00	3.50	3.00
LBP (m)	170.25	170.25	264.00	264.00	320.00	320.00	365.00	365.00
Beam molded (m)	30.00	30.00	48.00	48.00	55.60	55.60	68.00	68.00
Depth molded (m)	18.00	18.00	24.00	24.00	31.00	31.00	35.00	35.00
Full Draft molded (m)	11.72	11.72	16.80	16.80	21.30	21.30	25.50	25.50
98% Cargo Capacity (m3)	46784	46784	175439	175439	318129	318129	526316	526316
Cargo Oil density (t/m3)	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855



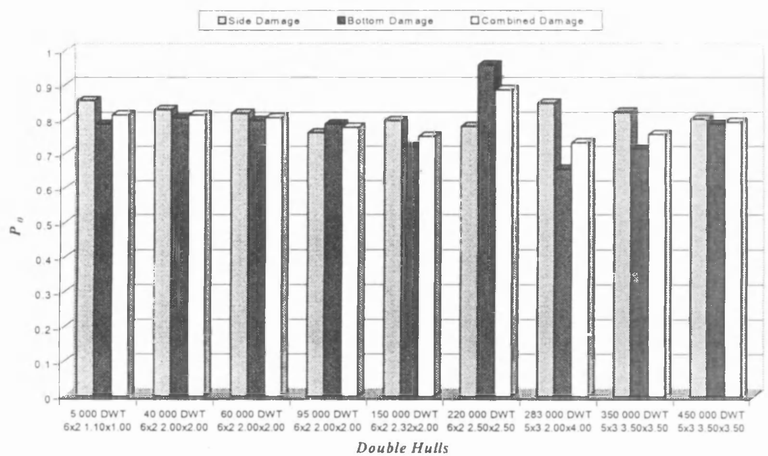



Mean Outflow Parameter, O_M
O_M
Side Damage
Bottom Damage
Ship Types

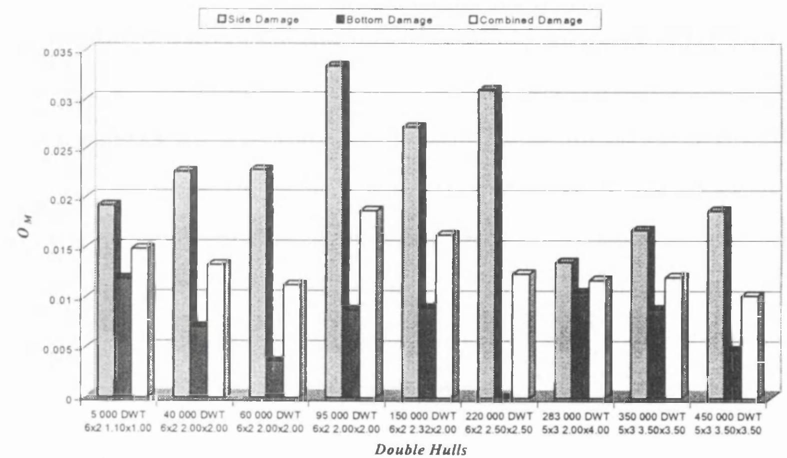

Extreme Outflow Parameter, O_E
O_E
Side Damage
Bottom Damage
Ship Types

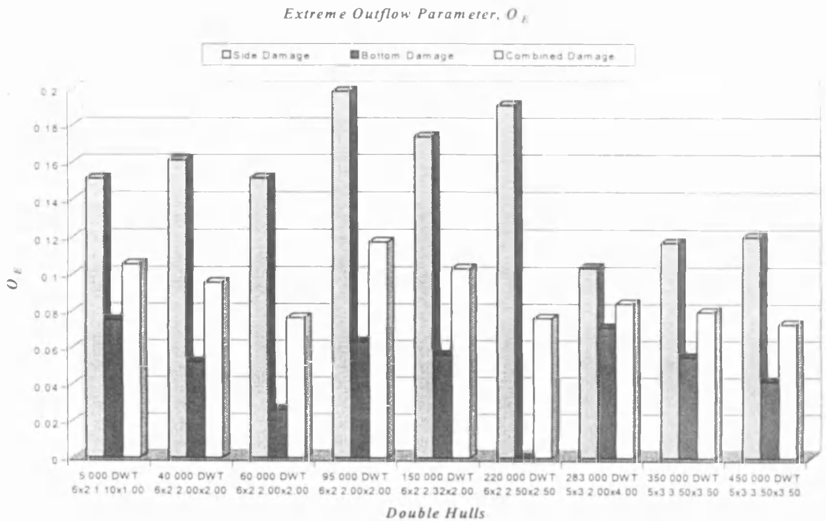
CDW (t)	5000	40000	60000	95000	150000	220000	283000	350000	450000
Cargo Tank Arrangement	6x2	6x2	6x2	6x2	6x2	6x2	5x3	5x3	5x3
Wing Tank Width (m)	1.00	2.00	2.00	2.00	2.00	2.50	4.00	3.50	3.50
Double Bottom Ht (m)	1.10	2.00	2.00	2.00	2.32	2.50	2.00	3.50	3.50
LBP (m)	95.00	170.25	203.50	235.20	264.00	295.50	318.00	342.00	365.00
Beam molded (m)	16.50	30.96	36.00	41.80	48.00	53.50	57.00	63.00	68.00
Depth molded (m)	8.30	17.03	18.00	19.80	24.00	27.50	31.00	32.50	35.00
Full Draft molded (m)	6.20	11.72	12.20	13.79	16.80	19.66	22.00	23.00	25.50
98% Cargo Capacity (m3)	5.848	46.784	70.175	111.111	175.439	257.310	330.994	409.357	526.316
Cargo Oil density (t/m3)	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855

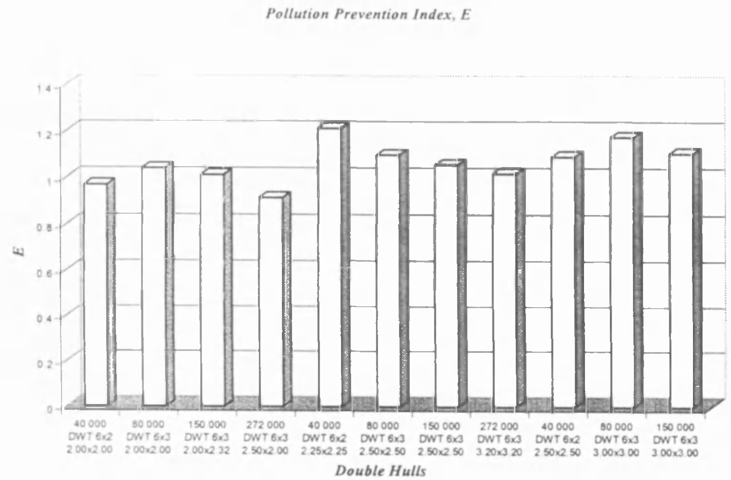
Probability of Zero Outflow, P_0



Mean Outflow Parameter, O_M



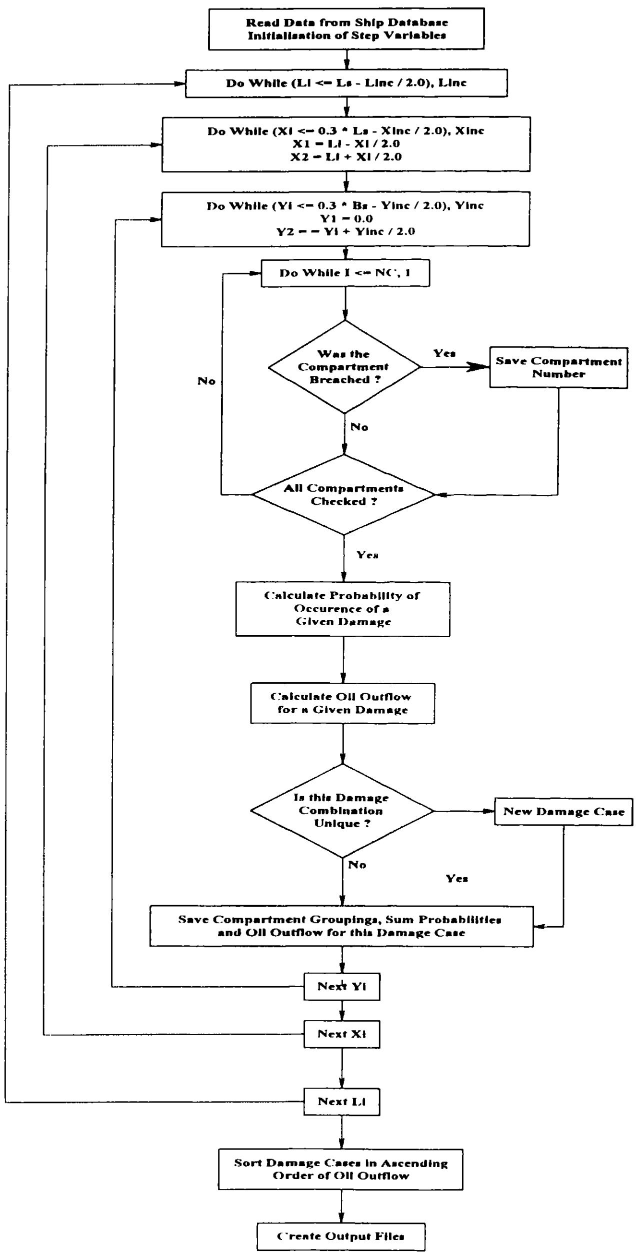

Extreme Outflow Parameter, O_E
Side Damage
Bottom Damage
Combined Damage
O_E
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
5 000 DWT 6x2 1.10x1.00
40 000 DWT 6x2 2.00x2.00
60 000 DWT 6x2 2.00x2.00
95 000 DWT 6x2 2.00x2.00
150 000 DWT 6x2 2.32x2.00
220 000 DWT 6x2 2.50x2.50
283 000 DWT 5x3 2.00x4.00
350 000 DWT 5x3 3.50x3.50
450 000 DWT 5x3 3.50x3.50
Double Hulls


Pollution Prevention Index, E
E
1.4
1.2
1
0.8
0.6
0.4
0.2
0
40 000 DWT 6x2 2.00x2.00
80 000 DWT 6x3 2.00x2.00
150 000 DWT 6x3 2.00x2.32
272 000 DWT 6x3 2.50x2.00
40 000 DWT 6x2 2.25x2.25
80 000 DWT 6x3 2.50x2.50
150 000 DWT 6x3 2.50x2.50
272 000 DWT 6x3 3.20x3.20
40 000 DWT 6x2 2.50x2.50
80 000 DWT 6x3 3.00x3.00
150 000 DWT 6x3 3.00x3.00
Double Hulls

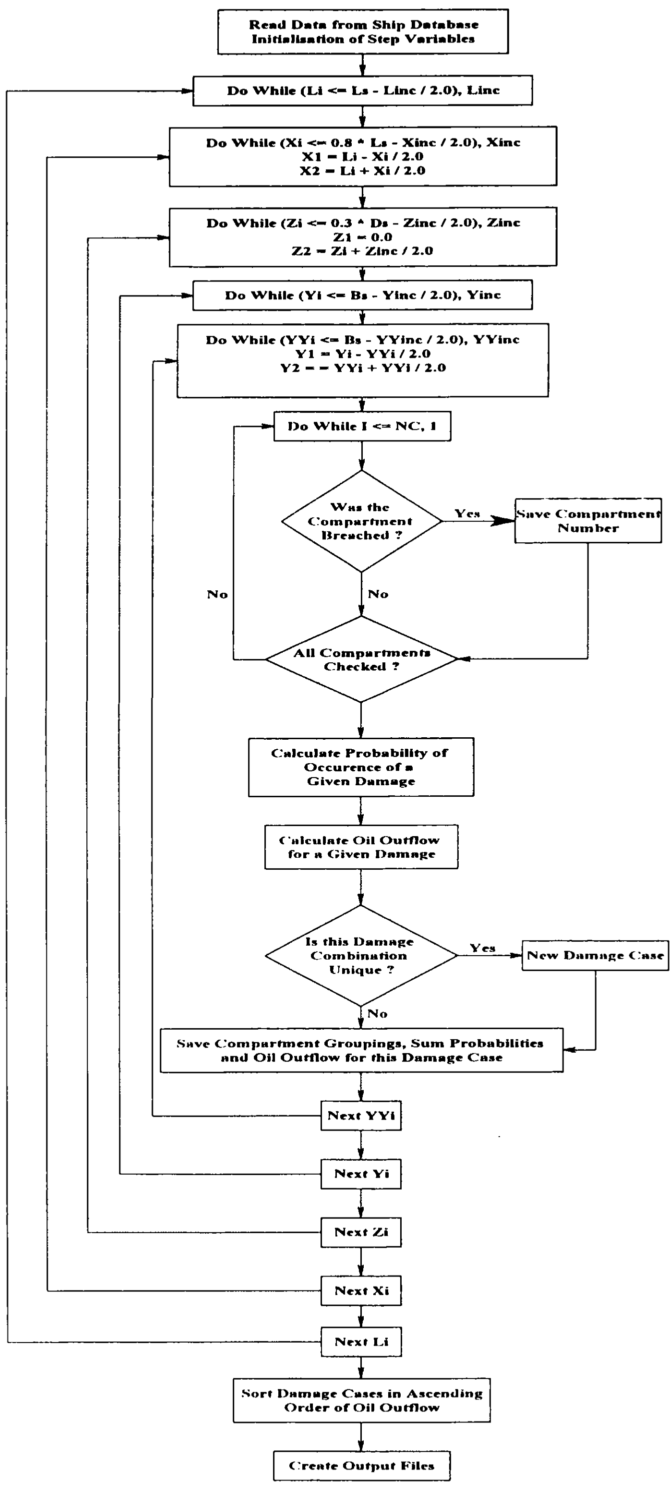
APPENDIX E

APPENDIX E – COMPUTER PROGRAM

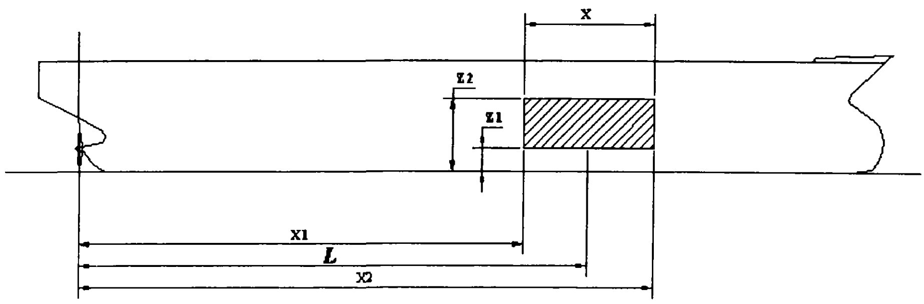
Program Flowchart (Side Damage)

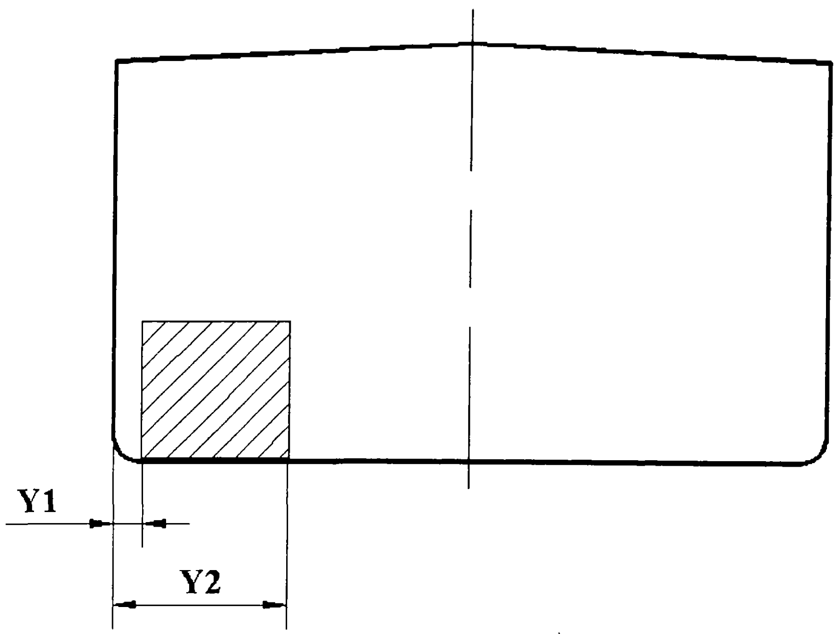


Program Flowchart (Bottom Damage)



Illustration





Definition of Variables

NC – Number of compartments

Li – longitudinal location of damage

Linc – increment for Li

Lprob – probability of longitudinal location

Xi – longitudinal extent of damage

X1 – aft longitudinal boundary of damage

X2 - forward longitudinal boundary of damage

Xinc – increment of Xi

Xprob – probability of longitudinal extent

Yi – transverse location of damage

Y1 – outer transverse boundary of damage

Y2 – inner transverse boundary of damage

Yinc – increment of Yi

Yprob – probability of transverse location

YYi – transverse extent of damage

YYinc – increment of Yyi

YYprob – probability of transverse extent

Zi – vertical location of damage

Z1 – upper boundary of damage

Z2 – lower boundary of damage

Zinc – increment of Zi

Zprob – probability of vertical location

ZZi – vertical extent of damage

ZZinc – increment of ZZi

ZZprob – probability of vertical extent

APPENDIX F

APPENDIX F – OIL SPILL PREVENTION – IMPROVEMENTS, INTERNATIONAL CONVENTIONS AND TREATIES

INTERNATIONAL CONVENTIONS AND TREATIES

The following list contains the IMO Conventions that have been entered into force over the years. Details of each of these can be found in the IMO web page at www.imo.org

Maritime safety

- International Convention for the Safety of Life at Sea (SOLAS), 1960 and 1974
- International Convention on Load Lines (LL), 1966
- Special Trade Passenger Ships Agreement (STP), 1971
- International Regulations for Preventing Collisions at Sea (COLREG), 1972
- International Convention for Safe Containers (CSC), 1972
- Convention on the International Maritime Satellite Organization (INMARSAT), 1976
- The Torremolinos International Convention for the Safety of Fishing Vessels (SFV), 1977
- International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), 1978

- International Convention on Maritime Search and Rescue (SAR), 1979
- International Convention on Standards of Training, Certification and Watchkeeping for Fishing Vessel Personnel (STCW-F), 1995

Marine pollution

- International Convention for the Prevention of Pollution of the Sea by Oil (OILPOL), 1954
- Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LDC), 1972
- International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78)
- International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties (INTERVENTION), 1969
- International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC), 1990

Liability and compensation

- International Convention on Civil Liability for Oil Pollution Damage (CLC), 1969
- International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage (FUND), 1971
- Convention relating to Civil Liability in the Field of Maritime Carriage of Nuclear Materials (NUCLEAR), 1971
- Athens Convention relating to the Carriage of Passengers and their Luggage by Sea (PAL), 1974

- Convention on Limitation of Liability for Maritime Claims (LLMC), 1976

- International Convention on Liability and Compensation for Damage in connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS), 1996

Other subjects

- Convention on Facilitation of International Maritime Traffic (FAL), 1965

- International Convention on Tonnage Measurement of Ships (TONNAGE), 1969

- Convention for the Suppression of Unlawful Acts Against the Safety of Maritime Navigation (SUA), 1988

- Protocol for the Suppression of Unlawful Acts Against the Safety of Fixed Platforms Located on the Continental Shelf (SUAPROT), 1988

- International Convention on Salvage (SALVAGE), 1989

APPENDIX F

Table 14.9 - Grouping of the core improvement by intended outcomes (source: API, 1998)

Intended Outcomes	§ Core Areas of Improvement
Reduce the number of vessel casualties	• Financial Responsibility • License & Merchant Mariners' Documents • Industry Best Practices • Industry Research Initiatives • Operational Measures for Vessels • Port State Control • Port State Control Information Exchange (SCG PSIX) • Tanker Inspections • Vessel Traffic Service systems
Reduce the number of oil spills	• Double Hulls • Financial Responsibility • Industry Best Practices • Industry Research Initiatives • License & Merchant Mariners' Documents • Operational Measures for Vessels • Overfill Devices • Port State Control • Port State Control information exchange (USCG PSIX) • Tanker Inspections • Vessel and Facility Response Plans • Vessel Traffic Service systems
Reduce the quantity of oil spilled	• Double Hulls • Financial Responsibility • License & Merchant Mariners' Documents • Industry Best Practices • Industry Research Initiatives • Operational Measures for Vessels • Port State Control information exchange (USCG PSIX) • Spill Response Equipment and Personnel Requirements • Tanker Inspections • Vessel and Facility Response Plans • Vessel Traffic Service systems
Increase response effectiveness	• Financial Responsibility • Spill Response Equipment • Vessel and Facility Response Plans • Vessel Traffic Service systems • Industry Research Initiatives