INFLUENCE OF OIL TANKER SUBDIVISION ON PROBABILISTIC OIL OUTFLOW FOLLOWING SIDE DAMAGE

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Thesis submitted for the qualification of Master of Science (MSc)

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November 1995

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ABSTRACT

We live in an era of growing environmental concern. In the future no activity will be considered acceptable unless it is reasonably safe for the environment.

Since the late 60's, when growing demand for oil transportation by sea introduced the concept of VLCCs, oil tanker accidents received wide coverage by the media. In 1967 the stranding of the *Torrey Canyon* highlighted the immense threat of massive pollution that could result from accidental discharge of oil in the event of stranding, collision, etc. The *Amoco Cadiz* in 1978 and the *Exxon Valdez* in 1989 are some of the accidents which have since greatly added to the public's concern about that threat.

Measures and tentative solutions to the technical aspect of accidental oil pollution from tankers have been put forward from time to time. The U.S. Oil Pollution Act 1990 (O.P.A.'90) and amendment 13F to Annex I of MARPOL 73/78 are the latest attempts to curb accidental oil spillage, by introducing new requirements for the construction of oil tankers. The requirements prescribe double hull construction as the reference in terms of pollution prevention, with MARPOL leaving the door open to novel design solutions that provide "equivalent protection" against oil pollution.

The controversy that preceded and followed, particularly in the case of the unilateral enforcement of O.P.A.'90, prompted new research on the subject of oil tanker design assessment. A probabilistic method of assessment, already applied to passenger and cargo ship damage stability, was proposed for the comparison of oil outflow behaviour in collision and grounding accidents. Unfortunately, most of the literature concentrates on the debate over the equivalence of double-hull and mid-deck designs without worrying about improving one concept or the other. The probabilistic assessment is used as a "black-box" tool, fed with an input and yielding an output, without any explicit links between design parameters and oil outflow results. Furthermore, the choice of simplifying assumptions in the application of the probabilistic assessment, obliterates even more these links and limits the usefulness of the results.

The present work starts with a short review and critique of the way the probabilistic method was used in oil outflow studies, highlighting in the process their important features and their weaknesses. An enhanced method is proposed, which has the merit of taking into account the random nature of the damage characteristics in the vertical dimension of the ship. Only side damage cases are addressed but the proposed method allows for bottom damage cases to be treated in exactly the same manner, thus providing a unified framework for the complete assessment of a tanker design.

With the help of the enhanced probabilistic method, a series of systematic variations of the subdivision arrangement in three tanker design concepts is assessed. An attempt is made to chart the relationship between the choice of design parameter values and the environmental performance of the resulting tanker design. The results of the analysis are validated, when possible, with results from other oil outflow studies, while an explanation is proposed for results showing discrepancies. The analysis results are also used to draw basic guidelines for improving the subdivision arrangement of typical single-skin, double-hull and mid-deck tanker designs.

The work shows in conclusion that in each of these concepts the subdivision arrangement can be optimised for a given level of environmental performance and that the probabilistic method of assessment is the way forward in the evolution from purely prescriptive construction regulations to goal-orientated design.

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ACKNOWLEDGEMENT

I would like to extend my warmest thanks to my supervisor Mr. I.E. Winkle for his tireless help and advice.

I would also like to thank Professor D. Faulkner and Dr. R.M. Cameron for their helpful and constructive comments.

Many thanks to my colleagues and friends Mr. C. Tolicas, Dr. A.C. Morandi, Dr. L. Zhu and Mr. A. Glykas for their help and support and for bearing with me in the computer room.

Special thanks to my friends Miss E. Konstantinou and Mr. C. Mazonakis for their support and for helping me locate part of the bibliography.

Last but not least, I thank Mr. D. Percival for his help and advice on computer hardware and software.

AUTHOR'S DECLARATION

Except where reference is made to the work of others, this thesis is believed to be original.

1 INTRODUCTION

1.1 OIL TANKERS AND THE ENVIRONMENT

Oil transportation in bulk by ships is more than a century old. Throughout the history of tanker trade, tankers have evolved to match the world oil demand. This means that the evolution concerned mainly their size. Indeed, while tankers remained close to what could be described as an array of rectangular tanks, the size and number of these tanks has greatly increased over the years. Thus, while ships of 30,000 dwt were regarded as very large in the 1950's, today, tankers of 250,000 dwt are commonplace. Figure 1.1 gives an idea of this size trend.

Unfortunately, as with all other sea trades, losses occur from time to time and the ever increasing size of oil tankers brought an ever increasing threat of accidental oil pollution. Names like *Torrey Canyon*, *Amoco Cadiz*, *Exxon Valdez* and *Braer* are, in the minds of the public, milestones of the realisation of this threat. A far greater number of accidents have not made so big headlines only because their results were not evident or because they were remote from direct human interests.

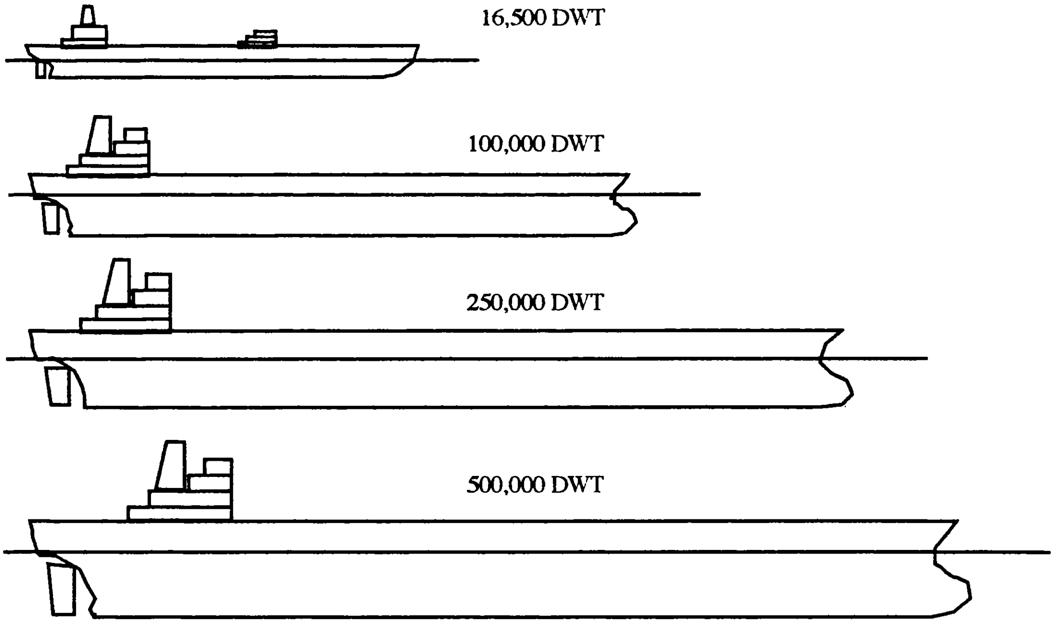


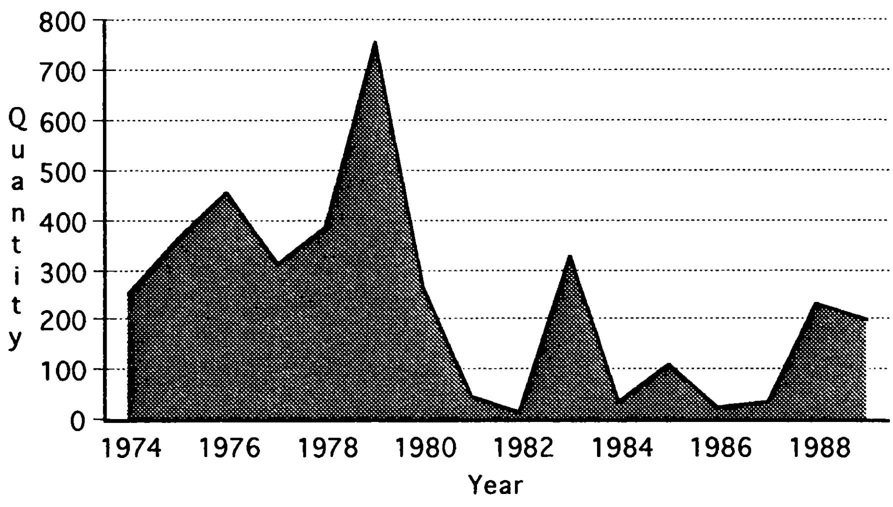
Figure 1.1: Comparison of typical tanker sizes.

Reassuring estimates show that the contribution of tanker accidents to the total annual input of hydrocarbons in the marine environment has dropped from 12.5 % (410,000 tonnes out of 3,200,000 tonnes) in 1981, to 4.7 % (110,000 tonnes out of 2,350,000 tonnes) in 1992 [1]. Table 1.1 and figure 1.2 show the annual quantity of oil spilled due to tanker accidents from 1974 to 1989. From this it is evident that accidental oil pollution from tankers has been at times, very low, eg 15,000 tonnes in 1982. Still, the threat is present: only two collisions of VLCCs in 1979, contributed 550,000 tonnes of spilled oil to the annual statistics. Should we rely on luck to ensure cleaner seas?

A recent INTERTANKO estimate was that: "99.98 % of oil carried by sea arrives at its destination without incident" [2]. Considering that every year over 1,500 million tonnes of oil is transported by sea, even 0.02 % of the oil carried around the world that is lost each year is a very large amount. In its 20 year energy outlook the International Energy Agency predicts that world demand for oil will increase by 1.7 % every year until the year 2010 [3]. How little will that 0.02 % loss seem in a few years?

Year	Quantity	Year	Quantity	Year	Quantity	Year	Quantity
1974	256	1978	388	1982	15	1986	25
1975	368	1979	760	1983	330	1987	35
1976	456	1980	270	1984	35	1988	229
1977	316	1981	50	1985	110	1989	200

Table 1.1: Annual quantity of oil spilled due to tanker accidents in thousand tonnes. (Source ITOPF)



Source: The International Tanker Owners Pollution Federation Ltd (ITOPF)

Figure 1.2: Annual quantity of oil spilled due to tanker accidents in thousand tonnes.

1.2 TOWARDS ENVIRONMENT FRIENDLY TANKERS

The *Torrey Canyon* disaster in 1967 prompted the amendment of the 1954 Convention on the Pollution of the Sea by Oil (OILPOL) in 1971. These amendments introduced the first measures for the construction of tankers aiming to reduce accidental oil outflow and were essentially a reduction in size of the cargo tanks.

In 1973, the expert opinion saw rightly that operational pollution was far more serious of a problem than accidental oil pollution. Therefore the MARPOL convention of 1973 (MARPOL '73) concentrated on adopting regulations for the limitation of operational oil discharges. Nevertheless, at the same time additional measures were introduced, requiring new oil tankers to comply with the new subdivision and damage stability regulations thus improving on the prevention of severe oil pollution following an accident.

More tanker accidents in 1976 and 1977, led to the IMO Conference on Tanker Safety and Pollution Prevention of 1978 (TSPP '78). It was decided to modify Annex I of MARPOL '73 by adding new requirements for the protective location of segregated ballast tanks. This new Protocol has subsequently become known as MARPOL 73/78.

It was again a disaster that prompted further action in the effort against oil pollution from tankers. The grounding in 1989, of the *Exxon Valdez* in Alaska and the subsequent spill of 36,000 tonnes of crude oil, demonstrated the inadequacy of MARPOL 73/78 to produce safer tanker designs. Indeed, the *Exxon Valdez* complied with MARPOL regulations. The United States, having failed to impose their view on the necessity of double bottom construction at the IMO Conference in 1978, decided to take unilateral action this time and voted the U.S. Oil Pollution Act of 1990 (O.P.A.'90). This requires all tankers trading in U.S. waters to feature double hulls. Because of the volume of the tanker trade with the U.S., the O.P.A.'90 has far reaching effects on the tanker industry and its impact is global.

The U.S. view, that double hull designs are the only adequately safe solution, reignited the debate on the effectiveness of different tanker designs to minimise accidental oil pollution. Indeed, several other designs and concepts have been proposed from time to time, claiming better performance against oil spillage after collision or grounding. In particular, designs using the hydrostatic balance principle like the mid-deck, the Coulombi Egg, the loaded double bottom, have divided the tanker community over their potential merits in comparison with double hulls.

Following the U.S. decision the IMO decided to take similar action, leaving however the way open to further research and innovation. At its 32nd session, held on March 1992, the Marine Environment Protection Committee (MEPC) of IMO adopted amendments to Annex I of the MARPOL Convention. According to new regulation 13F introduced, double hulls or double bottoms are required for all new tankers, depending on deadweight, but any other design is accepted if it provides an equivalent level of protection against accidental oil outflow. The mid-deck tanker design was the first to be accepted as such an alternative to double hull construction, after a comparative study showed that the performance of the two designs is equivalent.

1.3 A QUESTION OF EQUIVALENCE

The principle of equivalent protection put forward by the IMO, has been in the centre of much debate and raised many questions about how this equivalence is to be judged. Because of the different concept on which pollution protection is based, for each different design arrangement the behaviour and performance is rather dissimilar for the same accident scenario. Also, if a set of regulations is to be defined regarding the level of pollution protection required from tankers, then an adequate standard must be set by which to compare the proposed designs. Hence, the problem lies in the following:

- Finding a measure of environmental performance for the comparison of different designs on a common basis. This measure should be applicable to any tanker design arrangement irrespective of the concept it is based on.

- Devising a method, preferably simple, for obtaining that measure for a range of accident scenarios that would give a realistic assessment of the protection provided, taking into account the random nature of accidents.

- Defining a level of protection, in terms of a value of the above "measure", which could be accepted as a reasonable standard for tankers to meet.

The IMO Oil Tanker Design (OTD) comparative study [4] addressed the first two aspects, implementing a semi-probabilistic approach for the evaluation of expected oil outflow as the environmental performance measure. The study showed that accidental oil outflow is greatly dependent on the particular tank arrangement. This is perhaps the most important finding, as it points the way to the third aspect of the problem: defining a level of protection.

1.4 IMPROVING OIL TANKER DESIGN

So far, tanker design regulations have been purely prescriptive. What the OTD study and the past have shown is that it is not enough to prescribe double hulls or mid-decks for achieving adequate pollution protection. Several comparative studies show for example that MARPOL compliant designs have wors~~t~~e oil outflow results than pre-MARPOL single-skin designs. Similarly, the same studies show that most of the currently built double-hull designs, with no longitudinal cargo subdivision, are worse performers than traditional single-skin designs.

Instead, a goal-orientated approach to pollution prevention by design, addressing the three aspects mentioned in Section 1.3, is needed. Such an approach supposes a good understanding of the mechanisms and processes involved in accidental oil outflow as well as reliable methods relating design and environmental protection in a cause-effect fashion.

The experimental investigations carried out in recent years have described and partly explained the oil outflow phenomena. Also, in the numerous studies on the subject of accidental oil outflow from tankers, methods for tanker design assessment have been presented. However, the mapping between design and environmental performance was only too rarely dealt with in a systematic way.

1.5 THE PRESENT STUDY

1.5.1 AIMS OF THE STUDY

It is hoped that the present study will contribute useful information for the integration of environmental performance as one of the parameters in the oil tanker design spiral. The specific objectives of this study are listed below:

- Develop a numerical model implementing the probabilistic approach to oil outflow estimation. This model should account for the differences in the arrangement of a wide variety of tanker designs.
- Investigate, with the help of the above model, the relationship between key design parameters and oil outflow following an accident.
- Attempt to explain the mechanism behind the effect of each design parameter on oil outflow.

- Propose some guidelines for improving oil outflow characteristics of a range of tanker concepts.
- Validate, where possible, the findings of other authors.

1.5.2 OUTLINE OF THE STUDY

The material of this work can be divided in three parts corresponding to three basic tasks:

1. Setting the background, presentation and definition of the probabilistic concept and its underlying ideas.
2. Presenting the analysis tool, description and definition of the numerical model implementing the probabilistic concept.
3. Presenting the numerical experiment, description of the input and the output and extraction of the required information from the output.

In the first part, chapter 2 reviews what has been done and how, in the field of accidental oil outflow study, with particular emphasis on the statistical representation of tanker collision data. The lack of statistical data and the consequent absence of a fully probabilistic model are noted. In chapter 3, the probabilistic concept and its application to oil outflow assessment are briefly presented. The notions of probability involved are defined together with the associated random variables. Finally, the quantities used as standard for measuring the pollution potential of oil tankers are defined and explained.

Chapter 4 constitutes the second part, where the numerical model used in this study is defined and described. Two additional random variables, the vertical location and the vertical extent of damage, are introduced in the existing probabilistic model. Two hypothetical probability density functions describe these variables, thus allowing a fully probabilistic description of the hull damage. Although this approach introduces additional uncertainties, it has the advantage of revealing the effect of design features linked to the vertical dimension of the ship. Horizontal subdivision members, like double bottoms and mid-height decks, are such design features. The mechanisms of oil outflow, implemented in the numerical model, are based on a quasi-static description of the phenomena. The governing principle is the hydrostatic equilibrium of oil and seawater and it is based on the assumptions of negligible oil-water mixing and no interaction between oil outflow and water inflow.

// Alt. Density functions.

The numerical experiment is presented in chapters 5 and 6 which present the input data for the numerical model, i.e. the tank arrangement descriptions and the initial conditions respectively. In chapter 6, the post-processing of the numerical output is explained and finally the results are presented in their final format. These results are discussed in chapter 7, where the interaction of design features and oil outflow is explored. The potential for improvement of the design concepts examined is highlighted and suggestions are made for improving tanker designs produced by current practice. The findings are summarised in chapter 8, where suggestions are made also, for further studies on this topic.

2 LITERATURE REVIEW

2.1 THE PROBABILISTIC CONCEPT FOR OIL OUTFLOW ASSESSMENT

The probabilistic concept for the assessment of accidental oil pollution from tankers is not a new one. Since 1977 [5], different probabilistic methods have been proposed for the estimation of the mean oil outflow volume.

Mukherjee [6] introduces such a method as a tool for the investigation of the relationship between subdivision and mean oil outflow volume and finally the optimisation of the former with respect to the latter. The effects of longitudinal and transverse subdivision, along with the influence of non-cargo watertight spaces, on the mean oil outflow volume, are determined for true parametric variations of the tank arrangements. The present study refers to some of these findings in Chapter 7, where discrepancies and similarities in the results, regarding the position of side longitudinal bulkheads, are discussed in the light of the respective assumptions.

The method is based on the determination of the "absolute probability" of each compartment, from relevant probability distribution functions. The term "absolute probability" is defined as the sum of probabilities in the longitudinal and transverse direction, of all the damage locations and extents that affect a given compartment. It therefore consists of the sum of the probability of breaching only that compartment and the probability of breaching all its possible combinations with adjacent compartments or groups of compartments. The main attraction of this concept is that it involves only single compartments, i.e. there is no need to determine any compartment combinations. Therefore, if the tank arrangement changes slightly, only the tanks that have been altered need to be reassessed. On the disadvantages ous side, the assessment of probability alone is not possible, as the absolute probability does not correspond to the real probability value. It follows that all-important quantities, like the probability of zero oil outflow and the extreme 1/10 oil outflow, cannot be evaluated with this method.

Hook [7] and *Michel* and *Tagg* [8] take a different approach to the problem of probabilistic oil outflow evaluation. The total multi-dimensional domain of the joint probability corresponding to the ship, is divided in a large finite number of small elemental parcels. Each such probability parcel corresponds to a certain range of damage locations and extents. The compartment or group of compartments affected by each probability parcel can thus be determined and the corresponding oil outflow can be calculated.

Because this approach works with the 'true' probability values, it does not have the disadvantages of the previous method, enabling the distinction between mean and extreme oil outflow and thus giving a more accurate perception of the performance of a specific configuration. Furthermore, because it is a piecewise integration process, it allows for varying oil outflow values from the same compartment or group of compartments without the need for a 'unified' outflow formula. Since the present work puts the emphasis on realistic oil outflow evaluation, it takes advantage of the above method's flexibility in that respect. It has however a disadvantage in that being an approximative process it introduces a degree of inaccuracy (discussed in Section 4.3.4), although this can be easily kept to a negligible minimum. Also, compared to the method of [6], the approach used here has the drawback of requiring the calculations to be carried out for the whole ship every time an alteration is made to the tank arrangement. This is not though a serious problem as the method is intended only for computer based usage.

The authors of [7] and [8] apply the method solely for the direct comparison of different oil abatement features and do not investigate the relationship between each such feature and oil outflow, although they recognise the method's potential for the latter purpose. Both references have been the basis of the present work which shares most of their assumptions. However, as explained in the following chapters, some important new considerations are introduced in this study that expand the capabilities of the method.

Det norske Veritas Classification A/S [9] presents the results of a comparative study of 18 double-hull and mid-deck tankers, using the Monte-Carlo simulation technique and based on different assumptions of damage location and extents.

Salza and *Cazzulo* [10] and *Hart* and *Hancock* [11] carried out the same comparative study as in [9] using a "simplified" method for the evaluation of the mean oil outflow value. The approach is very similar to the one used in [6] in that it integrates the probability distribution functions over each compartment separately. But instead of using the concept of absolute probability of each compartment, it goes on to determine all the possible combinations of adjacent compartments and treats them as individual compartments of equivalent location and extents. This approach is seen as "simplified" because it categorises all the potential collision and grounding damages into seven accident scenarios, each scenario corresponding to a certain range of damage penetrations, with damage length and height being assumed.

Lastly *Konishi, Shigemi et al.* [12], use an interesting approach for the estimation of oil outflow after grounding. A deterministic link between damage length and damage penetration is introduced in the form of an impact energy equation, with ship speed as a parameter. Thus for any given ship speed, each damage length corresponds to one damage penetration value. The probability of occurrence of each pair of damage characteristics is determined solely from the probability of occurrence of the relevant damage penetration value. The transverse location and extent of the damage are assumed.

This approach is attractive because it eliminates one independent random variable from the whole process of probability calculation. In doing so it introduces an additional factor, ship speed, that should be considered as random as well. However, a tanker's speed is very close to constant on a given route and thus adequate values can be assumed without introducing too great an uncertainty. Furthermore, the introduction of the ship speed parameter allows a rational distinction of low and high energy accidents. Ship speed as a random factor, is not absent from the other methods presented so far. It is inherently included in the damage statistics from which the probability distribution functions are derived.

The adaptation of the above approach to collision damage is far more complicated and would not simplify the current practice. While grounding involves only the damaged vessel's speed and mass, a collision most often will involve two ships thus introducing additional factors like speed and size of the striking vessel, to name but a few.

[9], [10], [11] and [12] are part of a greater study commissioned by IMO [4] for the purpose of resolving the debate over the equivalence of double-hull and mid-deck constructions for accidental oil pollution avoidance. The aim of the study was to compare the individual merits of the two concepts, rather than establish guidelines for oil reduction by better design. Its main conclusion is that although Double-Hulls and Mid-Decks are deemed equivalent, the actual oil outflow performance of each depends on the individual subdivision arrangement within the cargo region. It is this dependence that [6] and indeed the present work attempt to explore and understand.

A noteworthy feature of the IMO study is that it established a standard framework of assumptions for the probabilistic approach to oil outflow evaluation. It also provided an 'official seal of approval' for the probabilistic assessment of oil pollution from tankers, opening the way to future international probability based regulations.

A relevant paper by *Vermeer* [13] does not contribute anything different from what has already been presented.

2.2 PROBABILITY DENSITY FUNCTIONS

The probabilistic concept relies on the derivation of adequate probability density functions for determining the probability of occurrence of a given combination of damage location and extents. For a full description of the collision damage geometry as defined in this study, five random variables are required[1] and correspondingly, five density functions must be derived. The existing statistical data allows probability density functions to be derived for only three random variables:

- longitudinal location of centre of damage,
- longitudinal extent of damage (damage length),
- transverse extent of damage (damage penetration).

2.2.1 LONGITUDINAL LOCATION OF CENTRE OF DAMAGE

In [6] *Mukherjee* supports the argument that there is no evident reason for a ship to be struck at a particular location and therefore assumes an equal probability for damage located at any point along the length of the ship. The relevant statistical data, compiled by IMCO (presently IMO), shows an increased number of incidents in the bow region. But it is argued that the trend results from wrongly including in the statistics the striking vessels. A recent compilation of classification society records for tanker accidents [14] fails to shed any light on this subject as the sample size is small (56 tankers) and the striking ships are still included in the statistics (!).

In its Merchant Shipping Notice No. M.1476 [15] the *Department of Transport* uses the statistics from the IMCO database of 296 cases of ramming, to derive a probability density function for the probabilistic evaluation of damage stability of cargo vessels. These statistics are the same ones used in the 1973 Passenger Rules and contested by many authors including the author of [6].

Both [7] and [8] make use of the same statistics and the same probability density function as in the 1973 Passenger Rules. The density function is similar to the one derived in [15] but avoiding the use of curves at both ends of the distribution. The

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[1] See Section 4.3.1.

present study adopts the same approach and uses the same density function. In [7] the author points out that tanker casualties have been omitted from the IMCO statistics and thus the use of the latter for tankers is not fully adequate. Nevertheless, the author of the present personally feels that these statistics are more reliable than the tanker specific ones in [14], due to the sheer difference in sample size (296 as opposed to 56). Furthermore, it is unlikely that the ship type has any influence on the longitudinal location of damage, although it certainly does influence damage extents.

[10] and [11] on the other hand, use the new statistics presented in [14], while in [9] the same data is approached with caution, merging it with data from a different database of 332 collision cases. The resulting probability density function is symmetrical about midships - hence supporting the views of [6] - and slightly hollow towards the middle. Unfortunately the authors of [9] do not give any details on their additional database.

2.2.2 LONGITUDINAL EXTENT OF DAMAGE (DAMAGE LENGTH)

[6] adopts the relevant IMCO statistical data for the 1973 Passenger Rules but not the corresponding density function. Instead an E-spline is fitted to the data to produce a more accurate representation of the statistical trend. A similar approach is employed in [8] using though a Beta-function. By comparing the oil outflow results from using both the IMCO linear density function and the Beta-function fit, the study concludes that the IMCO pdf produces consistently larger potential oil outflow values because it overestimates the probability of large extents of damage.

The importance of this overestimate is however limited by the remarks in [15] regarding the same distribution. The reference points out that: "The tendency in increasing speed and size of ships during recent years suggests that the average size of damage in cases of collision also is growing." A regression analysis showed that: "...on average, damage length increases with year of collision." Since the IMCO statistics refer to ships built until 1968, an increase of the average damage length can be expected for ships built at present.

[14] does not contribute any new knowledge on this matter apart from showing that for tanker casualties after 1980, there is less than 2% probability for damage length to exceed 0.2 L and about 20% probability to exceed 0.1 L. One should remember though that the sample size of 52 collision incidents is too small to affirm any trend with confidence.

This is the reason why in [9] the older IMCO data rather than the new sample are used. Nevertheless a Beta-function is fitted to give a more accurate pdf. *Hook* [7] however uses the IMCO pdf from the 1973 Passenger Rules. The linear nature of this pdf makes it far easier and quicker to handle as is remarked in [8]. For this reason, in the present work the same IMCO linear pdf was used.

The authors of [10] and [11] do not use a density function for damage length but rather assume the maximum damage length of 0.2 L.

2.2.3 TRANSVERSE EXTENT OF DAMAGE (DAMAGE PENETRATION)

Again, [6] makes use of an E-spline to fit the IMCO statistics for damage penetration. It also assumes a degree of correlation between penetration and damage length. [15] confirms that damage length and penetration are not statistically independent and suggests that penetration increases with damage length. In [9] the same view is held but it is argued that for extreme damage lengths the distribution used by IMCO produces unrealistically high penetrations. A modified distribution is proposed which improves on this and produces extreme penetrations closer to the statistics and the theoretical trend predicted by the energy absorption principle[2].

In [10] and [11] the statistical data presented in [14] are used to derive a probability function for damage penetration. In [8] the authors follow the same approach for damage penetration as they did for damage length, i.e. using the IMCO statistical sample but fitting a Beta-function as the corresponding pdf. The author of [7] chooses again the simplicity of the IMCO linear pdf but corrected for smaller maximum penetration, 67% of the beam as opposed to 80% in the IMCO 1973 Passenger Rules.

2.2.4 VERTICAL LOCATION AND EXTENT OF DAMAGE

All the outflow studies referenced so far, do not use any density function for the vertical location and for the vertical extent of damage. Instead they assume an unlimited vertical extent of damage, thus opening the side of the ship from bottom to deck. At the same time, this assumption removes the need for any definition of vertical location of the damage, further simplifying the damage definition.

The lack of adequate statistical data is to blame, although things are changing as seen from [14] which presents a small sample of data for the non-dimensional vertical extent of damage for tankers of 30,000 tonnes and over. It is interesting to

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[2] Theoretical principle equating the energy absorbed during an impact, with the volume of steel damaged by the impact.

note that only in 9% of the 52 cases the damage extended to the full depth of the ship, while in 76% of cases the vertical extent did not exceed half the depth of the ship. These statistics support the view held in the present study, that there is a flaw in the concept of mean outflow particularly as presented in the "simplified" methods in [10] and [11]. Indeed in oil outflow studies so far, the assumption was made that in collision the vertical extent of damage is from the bottom of the ship up to the deck without limit. Although this assumption is partly justified by the lack of statistical data about the vertical extent of damage, we believe its use for computing expected oil outflow is erroneous. As an extreme damage case it is more suitable for the determination of extreme oil outflow and so, the now established ranking of different tanker design concepts in terms of outflow performance should be reviewed under the light of extreme conditions criteria.

[15] suggests a linear probability function for determining whether a horizontal subdivision member is likely to be damaged or not. However, this probability function does not make any allowance for horizontal subdivision members located below the waterline, considering that such subdivision members are breached in all circumstances. *Tagg* [16] proposes a slightly more refined density function for the vertical extent of damage, as part of a probabilistic method for evaluating the survivability of cargo ships after damage. According to this pdf, the vertical extent of damage varies linearly from zero to the full depth of the ship, with the mean damage extending from bottom to the height of a standard forecastle deck on a similar-size ship. The vertical centre of damage is assumed fixed at the load waterline.

2.3 OIL OUTFLOW ASSUMPTIONS

The assumption that the vertical extent of damage is unlimited from the baseline to the deck of the ship, results in the further assumption that for all collision incidents the total load of the breached tanks is lost to the sea. In [6] to [11] this is the approach followed.

Yamaguchi and *Yamanouchi* [17] present the results of experiments on oil outflow behaviour of double hulls following side or bottom damage. The experiments for side damage included both ruptures below and on the waterline. These results show that the hydrostatic balance hypothesis is also reasonable for oil outflow from side ruptures. The study also concludes that oil retention improves greatly with increasing volume of double hull spaces, as indeed shown in the present work for empty watertight spaces in general.

[18], [19] and [20] are also about experimental studies of oil outflow from double-hull and mid-deck tankers. The main object of these experiments was the determination of the *Initial Exchange Loss* and *Dynamic Effects Loss* for a Mid-deck tanker and the amount of oil retention in double-hull spaces after grounding damage. [19] and [20] report that Initial Exchange Loss of oil is greatly dependent on ship speed, the former ranging from about 1% up to 10% of damaged tank capacity for ship speed of 7 and 15 knots respectively. The size and shape of the bottom breach was also found to affect the oil loss. Dynamic Effects Loss of oil was found to depend on water current speed, presence of waves and size of breach. On oil retention, *Karafiath* and *Bell* [18] found that partial blockage of the bottom rupture greatly reduced oil outflow, i.e. more oil was retained in double-hull spaces. Within the framework of the IMO study on Oil Tanker Design, in [10], [11] and [12] the outflow assumptions are based on those findings. In [10], Initial Exchange Loss and Dynamic Effects Loss factors of 1% are applied to grounding oil outflow calculations for Mid-Decks only. Oil retention is allowed for in Double-Hulls calculations only, ignoring the presence of double sides in Mid-Decks. [11] follows the same procedure but applies the same Initial Exchange Loss factor to Double-Hulls also. The approach in [12] differs slightly as reduced factors are introduced depending on size of breach.

Although the experiments dealt with grounding incidents only, they contribute some useful insight about the phenomena involved in oil outflow. The findings of [17] to [20] constituted a useful factual background for the development of the oil outflow model used in the present study.

3 THE PROBABILISTIC CONCEPT FOR OIL OUTFLOW PREDICTION

3.1 GENERAL BACKGROUND

Wendel in 1960 [21], introduced the probabilistic concept for the evaluation of ship subdivision with respect to survivability after damage. With this new concept, it was now possible to assign a numerical value to the level of safety attained, namely the 'subdivision index'. The concept affected ship design in two ways. First, it provided designers with a framework for the assessment of safety of new designs individually, or for the comparison of alternative designs. Secondly, it enabled the enforcement of realistic minimum standards of safety to be met by all new designs. The probabilistic approach was incorporated into the 1973 IMO Passenger Ship Regulations (A265) and new legislation (SOLAS'90) establishes requirements for the subdivision of dry cargo ships, based on this approach.

The same concept can be applied to tankers, for the purpose of assessing their safety in terms of oil pollution after damage. The end-result of such an assessment should be a quantity representing the 'risk' of pollution from the tanker examined. The concept of risk is mathematically defined as the following product [13]:

$$Risk = [\mathit{Probability\ of\ occurrence\ of\ an\ event}]*[\mathit{Effect\ of\ this\ event}]$$

Practical application of the concept requires statistical information on the occurrence of primary events and a mathematical model in order to quantify the effect of the event considered.

3.2 THE PROBABILITY

Two main probabilities apply to oil pollution following a tanker accident:

- probability that the ship will suffer damage,
- probability associated with any particular damage location and extent.

The approach used in the present study, does not consider the probability of the ship encountering damage, but rather acknowledges that this risk does exist and determines the probability of oil outflow resulting from it. This probability is termed the 'conditional probability', because it pre-supposes the occurrence of an accident, rather than the 'entire probability' that would include the probability of occurrence of the accident itself [7]. The ship is therefore assumed to be involved in a collision.

Although the location and extent of any particular damage occurring are random and therefore cannot be anticipated, when the probability distributions of damage location and extent are known, we can make predictions. The 'conditional probability' is sufficient as the basis for a study where design variables affecting oil outflow are to be compared. A presentation of some principles of probability theory involved in the determination of probabilistic oil outflow follows.

3.2.1 RANDOM VARIABLES AND PROBABILITY

For a random variable, some ranges of its values may be more frequent than others. The frequency of appearance of a value x, is expressed by its probability density function $f(x)$. If the random variable is continuous, then its density function $f(x)$ is represented by a curve (fig. 3.1). The area under this curve, within a given range, represents the probability that the random variable x takes a value within that range. If the continuous random variable x, changes in the range from the smallest possible value x_1, to the largest possible value x_2, then it is certain that x can only take values within that range. This certainty is expressed by assigning a unit value to this related probability being the greatest possible value that probability can take. The previous statements expressed in mathematical terms are as follows:

$$p(x_1 \leq x \leq x_2) = \int_{x_1}^{x_2} f(x)dx = 1.0 \tag{3.1}$$

The probability associated with a smaller range $[x_3, x_4]$ is therefore smaller than the unit value:

$$p(x_3 \leq x \leq x_4) = \int_{x_3}^{x_4} f(x)dx < 1.0 \tag{3.2}$$

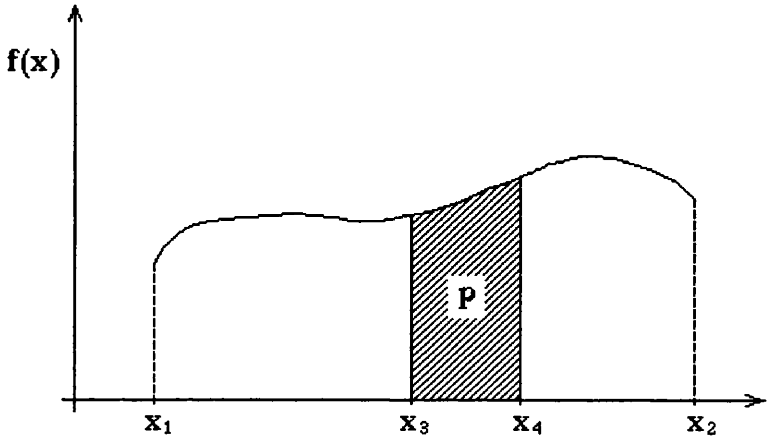

Figure 3.1: Example of probability density function for a one-dimensional, continuous, random variable.

If a random event is described by two continuous random variables x and y, then there is usually a probabilistic link between these variables. Hence there is a two-dimensional joint probability density $f(x,y)$. This probability density $f(x,y)$ is represented by a surface. The concept described above for a single variable also applies in this case except that probability is now represented by volume under the probability density surface rather than area under a curve (fig. 3.2). In mathematical terms we have:

$$p(x_1 \le x \le x_2 : y_1 \le y \le y_2) = \int_{x_1}^{x_2}\int_{y_1}^{y_2} f(x,y)dxdy = 1.0 \qquad (3.3)$$

where x_1, x_2 and y_1, y_2 are the minimum and maximum values that the random variables x and y can achieve respectively. The probability that x and y take values in the intervals $[x_3, x_4]$ and $[y_3, y_4]$ respectively is:

$$p(x_3 \le x \le x_4 : y_3 \le y \le y_4) = \int_{x_3}^{x_4}\int_{y_3}^{y_4} f(x,y)dxdy \le 1.0 \qquad (3.4)$$

In the same way, this concept can be generalised for any number of random variables, $x, y, z, ...$, etc., and we have:

$$p = \iiint ... f(x,y,z,...)dxdydz... = 1.0 \qquad (3.5)$$

where $f(x,y,z,...)$ is the corresponding multi-dimensional joint probability density function.

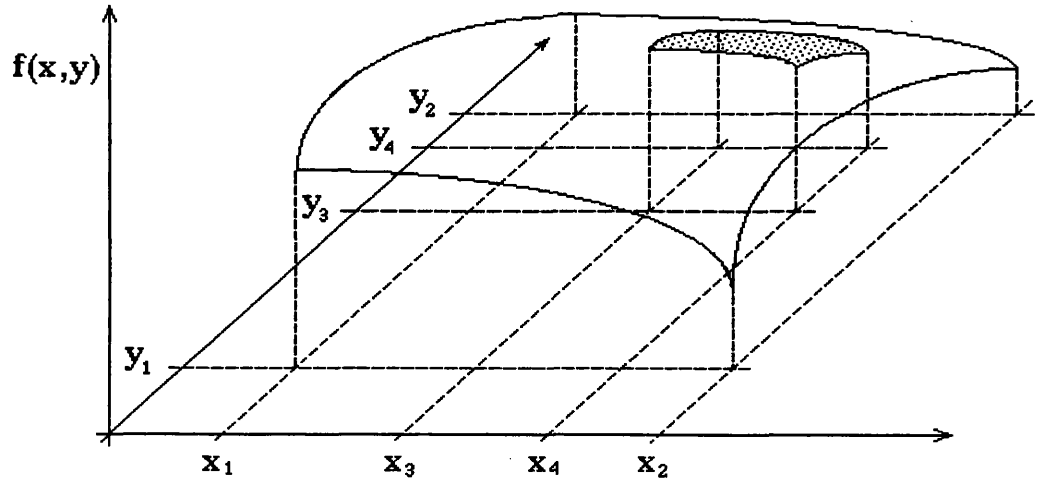

Figure 3.2: Example of probability density function for a two-dimensional, continuous, random variable.

3.2.2 APPLICATION TO SHIP DAMAGE

When a ship is subdivided solely by full depth transverse bulkheads, only the two random variables of longitudinal location of centre of damage and longitudinal extent of damage are needed to determine the probability of a damage breaching a given compartment. Indeed for such a ship, given a longitudinal damage location and extent, for any transverse extent and for any vertical location and extent of the damage, the same group of compartments is always damaged. So the breaching of any compartment grouping in that ship is a two-dimensional event, i.e. fully described by two random variables. The topology of all the possible pairs of longitudinal damage location and extent is shown in figure 3.3.

The abscissa is the longitudinal location of the centre of damage along the length of the ship and the ordinate is the longitudinal extent of damage or damage length. Because the limits of the damage extent are bound by the physical limits of the ship

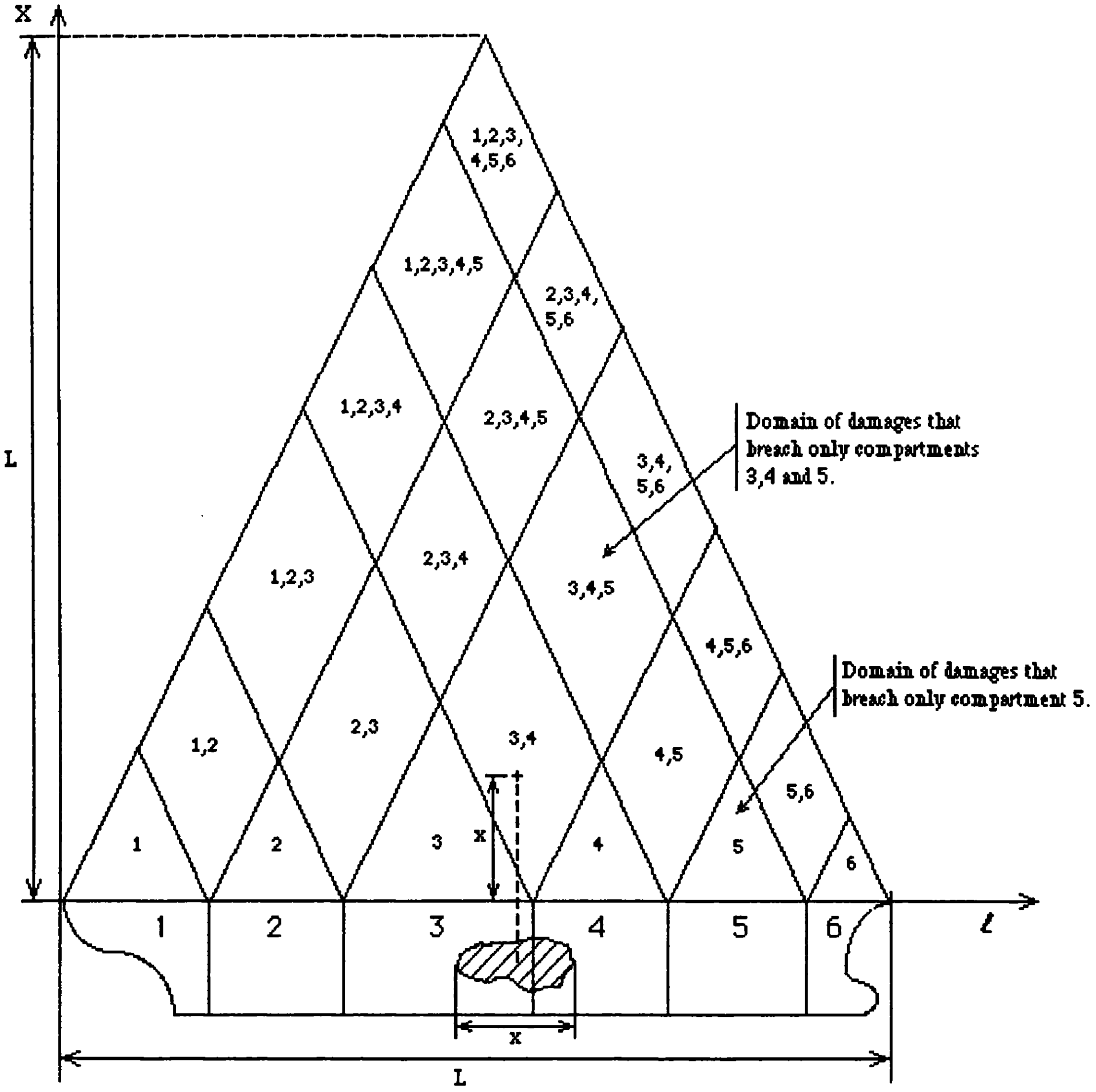

Figure 3.3: Domain of probability for the longitudinal location and extent of damage.

and because the largest possible extent is equal to the length of the ship, the topology is an isosceles triangle with its height equal to the length of the ship. If we consider now a single compartment within that same ship, we can find similarly that the topology of all possible damage location and extent combinations that damage this compartment alone, is an isosceles triangle lying inside the previous one, with its height equal to the length of the single compartment. The same is true for any single compartment or any group of adjacent compartments, such a group being considered as a single compartment of equivalent length. In the latter case, the triangle contains all the damage combinations that breach any compartment of the group. If we subtract from that triangle the area of the smaller triangles, that correspond to each single compartment of that group, the remaining area has the shape of a parallelogram. This parallelogram contains all the damage combinations that breach all the compartments of the group simultaneously. Thus the area of the triangle corresponding to the whole ship is divided into domains, each such domain representing a particular damage case.

From the discussion above, if the joint two-dimensional probability density function $f(l,x)$ is known, the probability associated to any damage case (damage to a particular group of compartments) is:

$$p = \iint_A f(l,x) \cdot dl \cdot dx \tag{3.6}$$

where A is the area of the region corresponding to that damage case. So in fact the probability is the volume of a prism under the probability density surface. Figure 3.4 shows an example for an arbitrary joint probability density function.

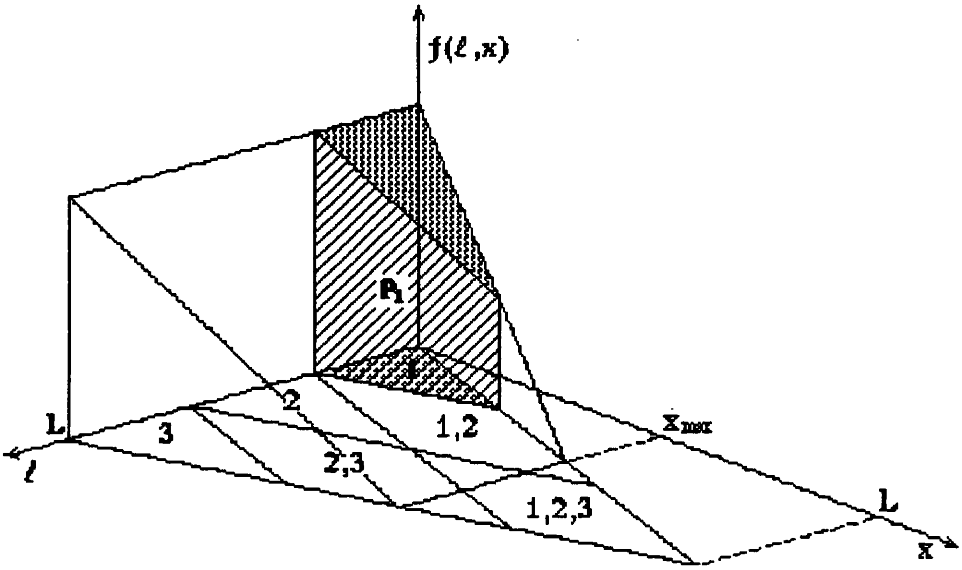

Figure 3.4: Example of an arbitrary joint probability density function for the longitudinal location and extent of damage.

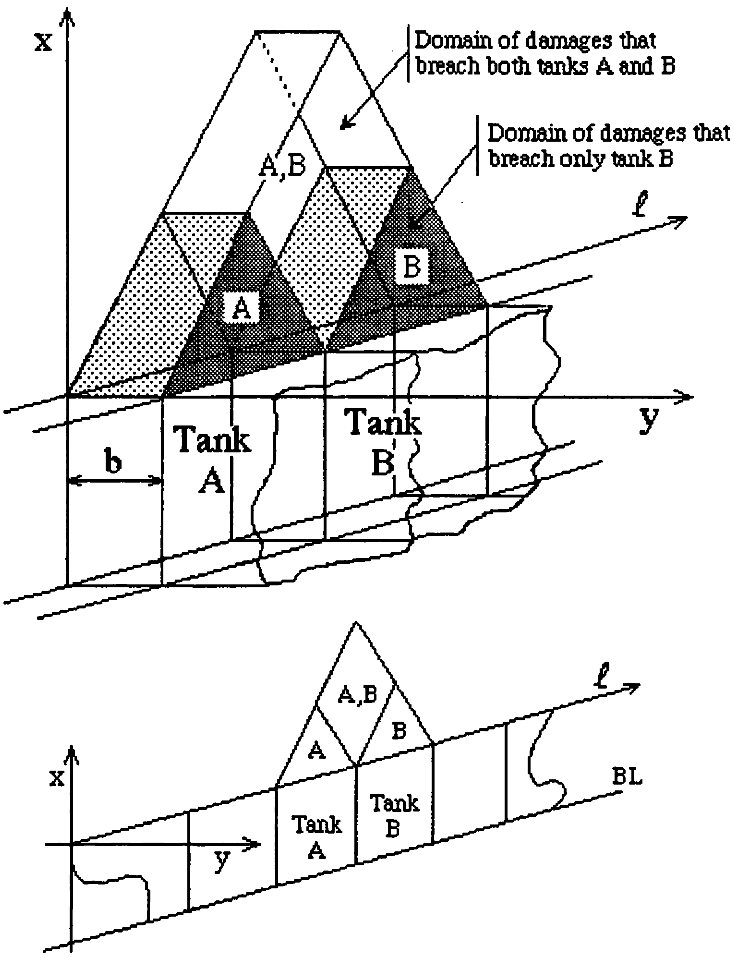

Figure 3.5: Example of the domain of probability for the longitudinal location and extent and the transverse penetration of damage, for two side tanks.

Let us now consider longitudinal bulkheads in addition to the transverse subdivision system described above. In order to fully determine a group of compartments affected by a damage occurrence, a third random variable must be introduced for the description of that damage: damage penetration. Such a damage is a three-dimensional event and thus a three-dimensional joint probability density function $f(l,x,y)$ is needed for the determination of probability. It is not possible to plot such a density function in the same way as the two dimensional case, because this would require four dimensions. However, we can write:

$$p = \iiint_V f(l,x,y) \cdot dl \cdot dx \cdot dy \qquad (3.7)$$

The above equation means that the probability of an event is found by integrating the probability density function over the volume V of the topology containing all the possible combinations of damage location (l) and extents (x,y) that correspond to that event. Figure 3.5 shows an example of such a topology for two rectangular side tanks in the mid-body of a ship.

In addition to the longitudinal and transverse subdivision dealt with so far, most ships, including oil tankers, are subdivided horizontally by double bottoms and watertight decks. These call for two more random variables to be added to any damage description: the vertical location of the centre of damage and the vertical extent of damage. Similarly a five-dimensional joint probability density function is necessary for determining the probability of a damage and we have:

$$p = \iiiint\!\!\int f(l,x,y,h,z)\cdot dl\cdot dx\cdot dy\cdot dh\cdot dz \qquad (3.8)$$

In the case of ship accidents (collisions or groundings) it is however impossible to know the interrelation of all the different random variables and hence it is impossible to determine the multi-dimensional joint probability density function. Instead, it is assumed that these random variables are statistically independent. Then their joint probability density can be expressed as the product of all the individual probability densities for each random variable. For a multi-dimensional random event described by five statistically independent random variables as above, each with probability density $f_1(l)$, $f_2(x)$, $f_3(y)$, $f_4(h)$ and $f_5(z)$ respectively, the joint probability density $f(l,x,y,h,z)$, can be expressed as :

$$f(l,x,y,h,z) = f_1(l)\cdot f_2(x)\cdot f_3(y)\cdot f_4(h)\cdot f_5(z) \qquad (3.9)$$

Therefore in order to calculate the probability of any damage occurring, it is sufficient to know the probability densities of all the random variables describing the damage.

3.3 MEASURES OF PROBABILISTIC OIL OUTFLOW

Probability as calculated above is not of much use on its own, unless it is combined with a measure of the damage consequence to obtain a measure of the 'risk' of that consequence. In the present analysis, the measured consequence is the spillage of oil or 'oil outflow' from the damaged tanks of the ship. By multiplying the theoretical oil outflow, i.e. the volume or mass of oil flowing out of the breached tanks, with the probability of the corresponding damage, we obtain the 'potential oil outflow'. By combining the potential oil outflow values for all the possible combinations of damaged tanks we can obtain a number of 'overall' measures for the ship. These are:

1. Mean or expected oil outflow: the sum of potential outflows for all the possible damage cases. This value is a good indicator of the overall effectiveness of a particular design in limiting oil outflow [8]. As a computed average value however, it is influenced by both low and high extreme values and should be interpreted in connection with these extremes.

2. Extreme (1/10) oil outflow: all the possible damage cases are sorted in ascending order with respect to theoretical oil outflow. A running sum of the corresponding probabilities is computed, beginning at the minimum outflow damage case and proceeding to the maximum outflow damage case. The extreme oil outflow is a weighed average of the potential oil outflow of all the damage cases with a cumulative probability between 0.9 and 1. "This value represents the 'worst case' spill scenario and provides a 'snapshot' evaluation of the behaviour of a vessel subjected to extreme damage" [8].

3. Outflow index: this value is the expected or extreme oil outflow volume expressed as a fraction of the cargo deadmass volume. Because it is non-dimensional it is useful for comparison of tankers of different sizes.

4. Probability of zero oil outflow: this is the sum of the probabilities of all the damage cases that result in zero theoretical oil outflow. As its name implies it represents the probability that a ship will not spill any oil after an accident. For example if a ship is said to have a probability of zero oil outflow of 0.13, this means that in 13% of all casualties there will be no oil spillage. Sometimes the complementary probability value is used, that is the probability of oil outflow [7]. In the previous example the probability of oil outflow is 1-0.13 = 0.87 or 87%.

4 THE NUMERICAL MODEL

4.1 GENERAL DESCRIPTION

The numerical model described in this thesis implements the probabilistic approach to oil outflow prediction, as described in Chapter 3. It determines all the possible unique groupings of adjacent compartments for the given tank arrangement and computes the associated probability and oil outflow for each of them. The method implemented is the one used by *J.P. Hook* [7] and *Michel & Tagg* [8] and is based on the general algorithm devised by *Tagg* [16]. Figure A.1 in Appendix A shows the flowchart of this algorithm as adapted for the purpose of the present study.

The input to the model consists of the geometric description of the tank arrangement, in the form of transverse sections, a table of hydrostatic properties and calibration tables for all watertight compartments. It also includes a set of analysis parameters describing the initial conditions and controlling the behaviour of the model, such as initial draught, wave height, initial and secondary outflow factors, maximum extents of damage, integration step, etc.

Through an iterative process, a unique combination of damage location and extents is selected and applied to the ship at each iteration. By scanning the relevant hull geometry data, the watertight compartments included in or intersected by the damage extents, are determined. A list of damaged compartments together with data pertaining to the position and extents of the breach in each compartment, is produced. Floatation calculations for the current damaged condition are performed in order to determine the new equilibrium waterplane of the ship. The probability of the current damage location and extents is computed and the oil outflow volume from the breached tanks, if any, is calculated assuming the new equilibrium waterplane. At this point, the uniqueness of the damaged compartment grouping is assessed. If the same grouping has already been examined, the two occurrences are merged, adding up the corresponding probability and potential oil outflow values. Theoretical oil outflow values are compared and the two extremes, minimum and maximum, are kept as representative of that grouping. If the current grouping is found to be unique, the current values of probability and oil outflow are saved as representative of the new grouping.

The same process is repeated over and over again, until all possible combinations of damage location and extents have been examined. Once the iterative process is completed, the list of all unique damaged compartment groupings, which is now the list of all possible damage cases, together with the corresponding oil outflow and probability data are stored in files for further analysis.

4.2 MODELLING OF GEOMETRIC INFORMATION

4.2.1 THE SHIP GEOMETRY

The present model uses a full numerical description of the internal subdivision of the hull into watertight spaces. The numerical description consists of three sets of data:

1. Compartment data. This consists of information about the contents of the compartment and the components of which it is made. A compartment of complex shape can be made up from an assembly of simple components.

2. Component data. A component is a defined volume with constant properties. This data set consists of the value of permeability for the volume component and the position of the component with respect to the centreline of the ship.

3. Shape data. Each component is modelled by a number of transverse, plane sections. The data consists of the longitudinal position of each section, followed by a list of co-ordinate pairs. Each co-ordinate pair defines a point of the section on the transverse plane.

Figure 4.1 shows in a schematic way the data hierarchy of the numerical geometry description [22].

This numerical description is created within the Autoship™ computer package from the Autoship Software Corporation. A detailed 3D model of the hull is first created in Autoship. Then, it is exported through a 'Geometry File' to the ModelMaker™ program as a series of transverse sections. In ModelMaker, each tank is modelled by a number of transverse sections fitted within the hull. Several tools are available from the program, for creating with relative ease, the most complex shapes and trim them to fit snugly inside the hull. When the internal arrangement is complete, the modified Geometry File created is input to the AutoHydro™ program of the package, where a calibration table for each compartment is produced, as well as a table of hydrostatic properties for the hull. Samples of the items described above and the formats in which they are used, are given in Appendix A.

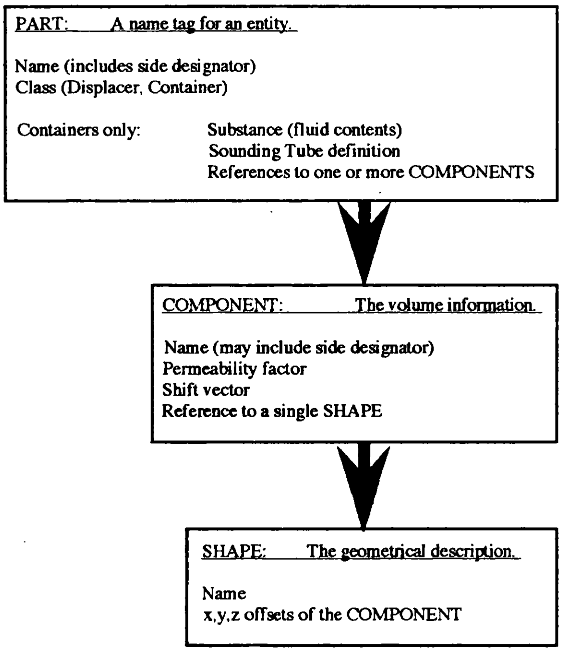

Figure 4.1: Data structure of numerical ship description.

4.2.2 DAMAGE GEOMETRY

Each damage occurrence is modelled as a prism of rectangular cross-section, penetrating the side shell at right angles to the ship's centreline plane. The centroid of the cross-section is the centre of damage. The horizontal and vertical distances of this point from a fixed reference point, are termed the longitudinal and vertical location of damage respectively. Throughout this study, the reference point is taken at the intersection of the centreline of the aftermost defined section of the ship hull with the ship baseline. Thus the longitudinal location of the centre of damage is the horizontal distance of the latter, from the aftermost defined section of the ship hull and the vertical location of the centre of damage is the vertical distance of the same point, from the ship baseline. Three dimensions define the extents of the damage:

1. The longitudinal extent of damage or damage length, is the horizontal dimension of the damage prism, measured on the ship's longitudinal axis.

2. The vertical extent of damage or damage height, is the vertical dimension of the damage prism, measured on the ship's vertical axis.

3. The transverse extent of damage or damage penetration, is measured on the transverse axis of the ship and is the maximum distance of the damage boundary parallel to the centreline plane, from the side shell of the ship.

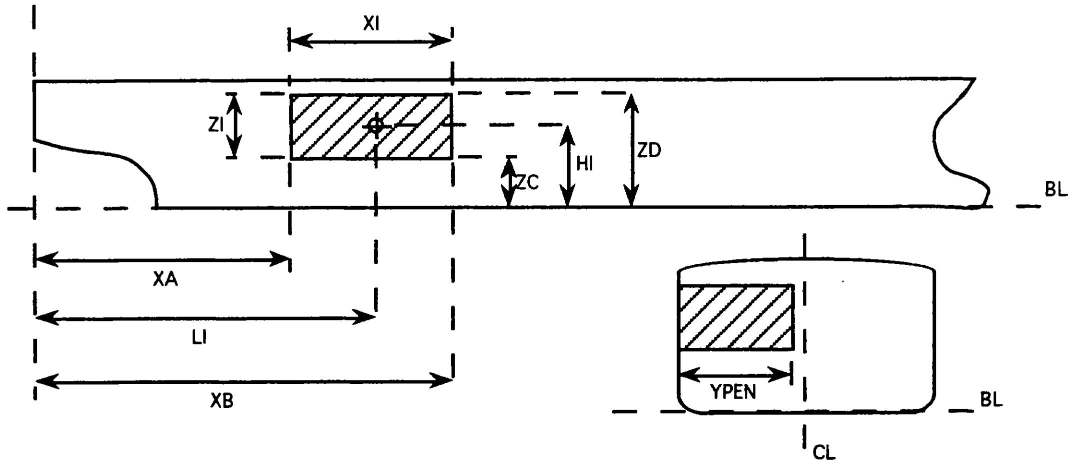

Figure 4.2: Definition of main damage particulars.

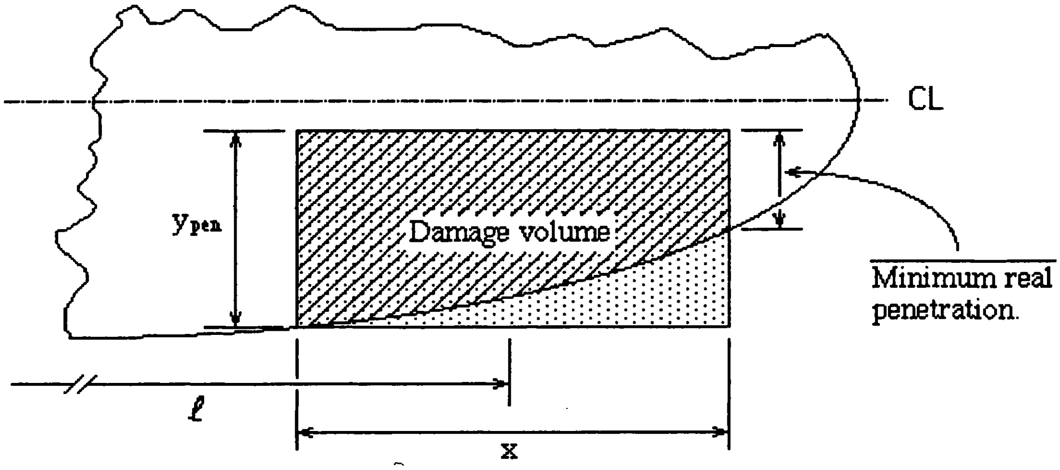

Figure 4.3: Definition of damage penetration.

Figure 4.2 shows the main damage particulars as defined above. Figure 4.3 clarifies the definition of damage penetration.

4.3 PROBABILITY COMPUTATION MODEL

4.3.1 PROBABILITY DENSITY FUNCTIONS

The joint probability of a certain combination of damage location and extents is computed by integrating the corresponding probability density functions. In order to describe a collision damage simply, yet as fully as possible, five variables must be used:

1. Longitudinal location of centre of damage.
2. Vertical location of centre of damage.
3. Longitudinal extent of damage.
4. Vertical extent of damage.
5. Transverse extent of damage or penetration.

These five variables are not independent of each other. However, by assuming they are, we can apply the principle of multiplication, as explained at the end of Section 3.2. Thus we can define the joint probability as:

$$p_{12345} = p_1 \cdot p_2 \cdot p_3 \cdot p_4 \cdot p_5 \qquad (4.1)$$

It is now clear that in order to fully determine the joint probability of a given damage described as above, we need five probability density functions, one for each independent variable. Up to present, only three of the variables have been systematically recorded for collision accidents. These are the longitudinal location and extent of damage and the damage penetration.

4.3.1.1 Longitudinal Location of Centre of Damage

The probability density function used in the present study is the one defined by IMO for the Passenger Ship Stability Rules. This distribution assigns a larger and constant probability to damages occurring in the forward half of the ship, whereas in the after half probability decreases linearly from midships to aft perpendicular. Figure 4.4 shows this probability density function. Many authors have proposed alternative functions[1] that fit the statistical data more accurately. The linear nature of the IMO distribution however, makes it far easier to handle.

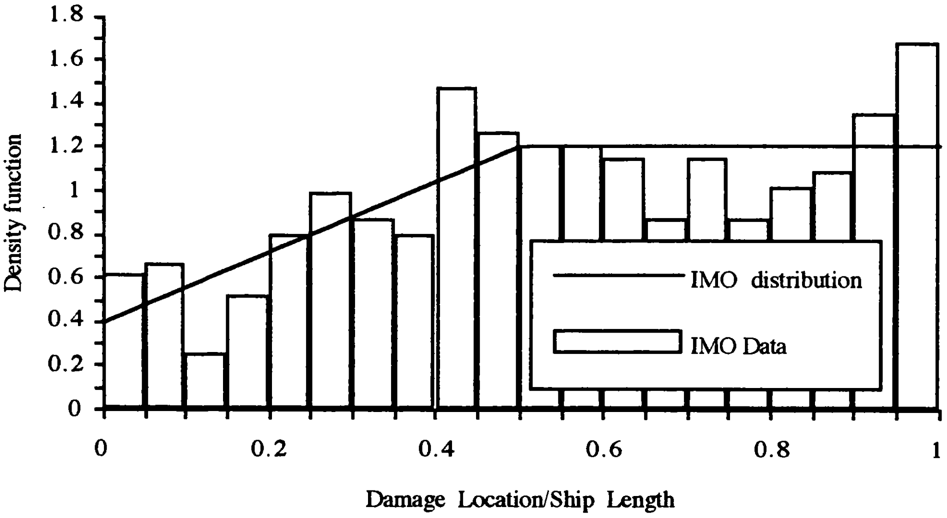

Figure 4.4: Probability density distribution for Longitudinal Location of Centre of Damage.

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[1] Refer to the Literature Review in Chapter 2.

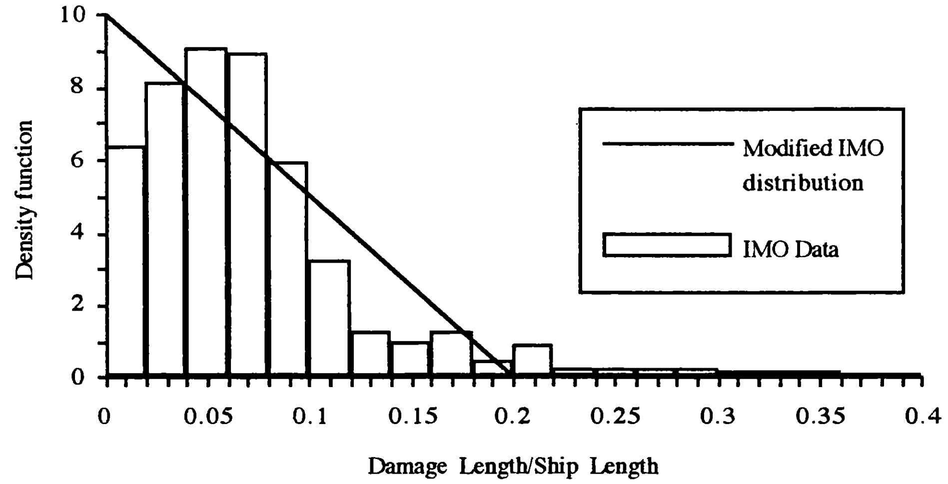


Figure 4.5: Probability density distribution for Longitudinal Extent of Damage.

4.3.1.2 Longitudinal Extent of Damage (Damage Length)

Again the IMO distribution is used, due to its simplicity. Figure 4.5 shows this distribution. The maximum extent of damage is taken as 0.2 L in accordance to the most recent survey regarding tankship accidents. [14]

4.3.1.3 Transverse Extent of Damage (Damage Penetration)

The IMO linear distribution is used once more. But the maximum penetration is taken as 0.6 B instead of 0.8 B. A recent survey [14] shows that for present day tankship designs of over 30,000 dwt, penetration does not exceed 0.5 B. This difference is possibly due to the consideration of smaller ships in the earlier surveys. Indeed, smaller ships are more prone to large penetrations. Still, the result reached by the latest survey cannot be used without question, because the accidents investigated involved mainly one construction type, namely single skin. Also the statistical sample was quite small and predictions cannot be very accurate. By taking the intermediate value of 0.6 B we acknowledge the trend for proportionally smaller damage penetration in larger ships, whilst taking into account the uncertainty and the possibility of larger damage. In any case, this value ensures that the most severe damage case, where the longitudinal centreline bulkhead is breached, is also accounted for. Figure 4.6 shows the probability density function used.

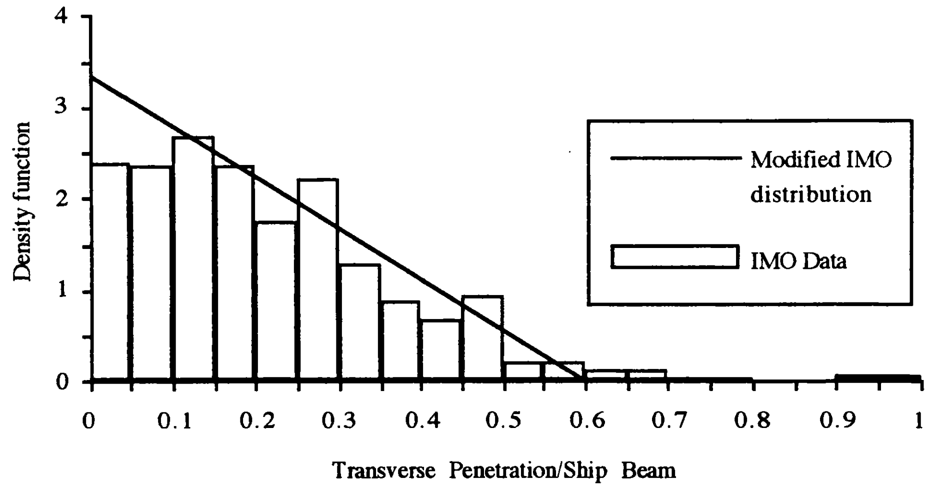


Figure 4.6: Probability density distribution for Transverse Extent of Damage.

4.3.1.4 Vertical Damage Location and Extent

In all the recent studies, these distributions have been omitted by taking the vertical damage to extend from the keel upwards without limit. Because this assumption was seen as a worst case scenario, it was deemed sufficient for assessing the merits of each design. Though it is useful, as it simplifies the computations involved, unfortunately the same studies tried to establish the all-round performance of each design, based on this extreme case assumption. However, in order to fully investigate design concepts like the Mid-Deck tanker and the horizontal subdivision of double side spaces, one has to take into account the effect of such structures, when damaged or intact. Furthermore it is generally recognised that in collision accidents, most of the time, penetration is localised either just below the waterline, when the striking ship has a bulbous bow, or above it due to the bow flare. Only in extreme damage cases does the full stem of the striking ship penetrate the hull, resulting in large vertical extent of damage.

Since no accident data is available for the derivation of realistic probability density functions, the present study uses tentative distributions for the purpose of experimenting and assessing their effect. These distributions incorporate some logical conclusions but are not the result of any detailed or extensive study of the matter. Figures 4.7 and 4.8 show those tentative distributions and Appendix B gives some insight into the considerations that shaped them.

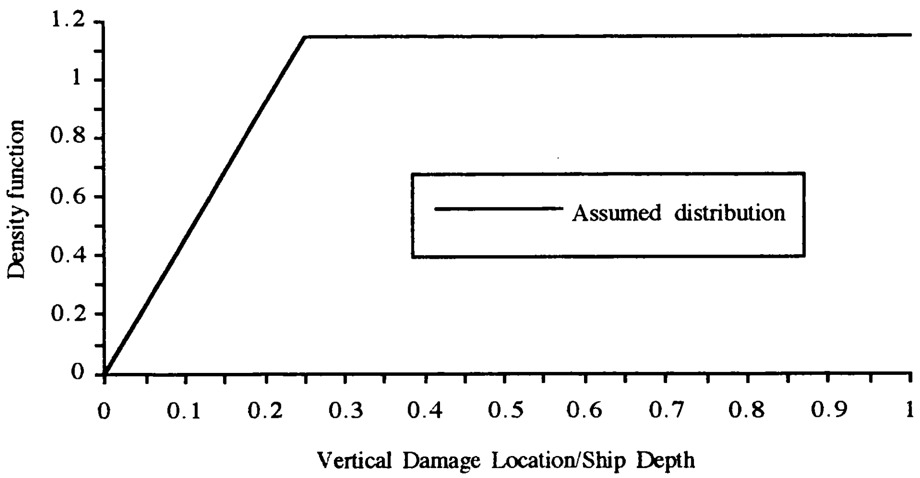


Figure 4.7 Probability density distribution for Vertical Location of Centre of Damage.

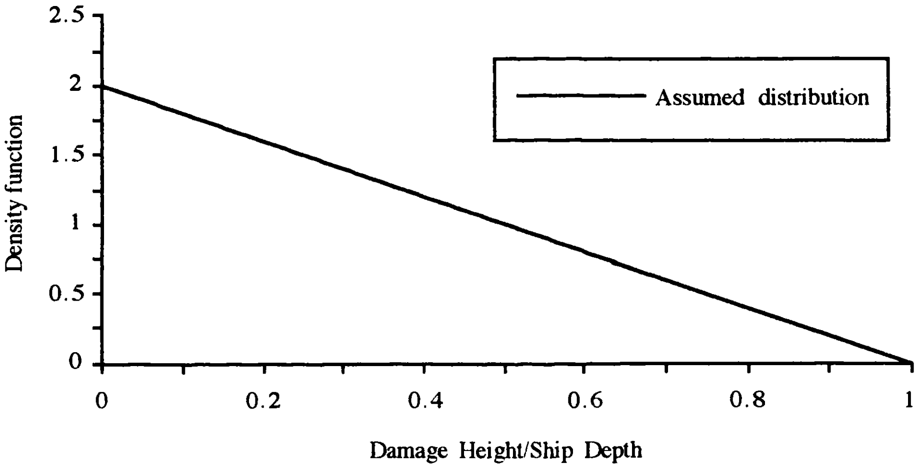


Figure 4.8: Probability density distribution for Vertical Extent of Damage.

4.3.2 METHOD OF COMPUTATION

As mentioned earlier, the numerical model relies on an iterative process. For each iteration within that process, a different combination of values for the five damage variables is examined. In order for the process to be exact, all possible combinations must be examined. Because the random variables describing damage are continuous, this means there is an infinite number of combinations and thus the process should perform an infinite number of iterations. This is unacceptable for a numerical method and therefore a reasonable approximation is sought.

Clearly, what is needed is to replace the continuous random variables with discrete ones. This way the number of possible combinations of the five variables is finite. By dividing the range of each continuous random variable into a defined number of equal intervals and taking the midpoint of each interval as its representative value, we obtain the range of a discrete random variable approximating its continuous counterpart. The larger the number of intervals or the smaller the intervals, the closer the approximation (figure 4.9).

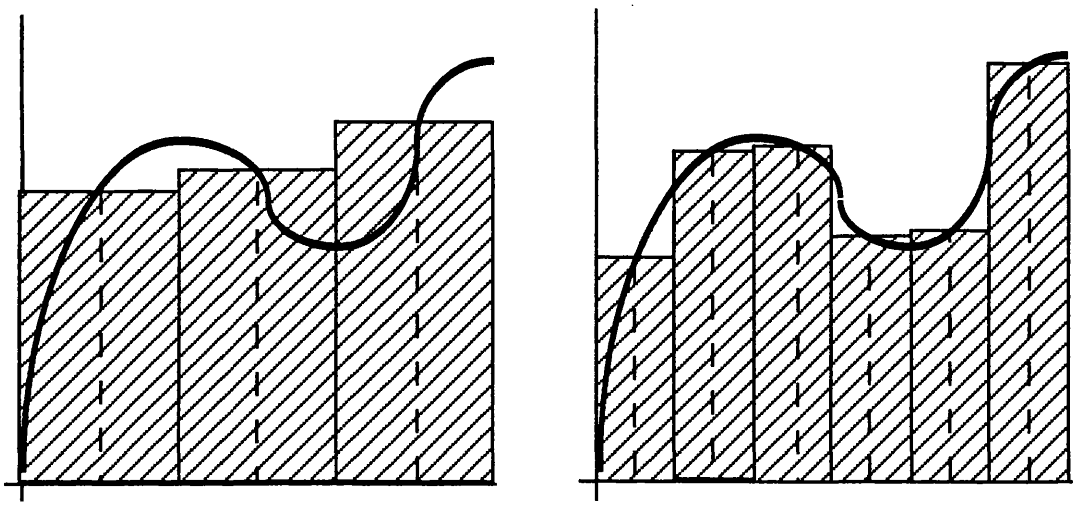


Figure 4.9: Examples of different degree of approximation.

The probability of a continuous random variable taking a value in a given interval is found by integrating the probability density function of that variable over that interval. Thus in our case, to each defined interval [a_i,b_i] of the continuous random variable 'x', corresponds a probability p_i which can be readily computed from the relevant density function:

$$p_i = \int_{a_i}^{b_i} f(x)\,\mathrm{d}x \tag{4.2}$$

The sum of the probabilities for all the defined intervals is by definition:

$$\sum_{i=1}^{n} p_i = 1 \tag{4.3}$$

Now by assigning to each value of the discrete random variable the probability of the corresponding interval of the continuous variable, i.e. by putting $p_i' = p_i$, we ensure that:

$$\sum_{i=1}^{n} p_i' = 1 \tag{4.4}$$

where p_i' is the probability of the i-th value of the range of the discrete random variable.

By applying the same principle to all five independent random variables and provided the five corresponding probability density functions are known, we can compute the probability of any damage with characteristic values lying in the defined ranges.

4.3.3 IMPLEMENTATION

We are ultimately interested in computing the probability of damaging a given compartment or group of adjacent compartments. This probability can be defined as the sum of the probabilities of all the individual damages that affect only that given compartment or group of compartments. Figure 4.10 gives examples, for a single compartment and for a group of two adjacent compartments, of damages with different locations and extents which affect only that particular compartment or group of compartments.

Using the approximation method described previously, all the possible combinations of discrete values of the five damage random variables are applied to the ship. Each such combination affects a certain compartment or group of compartments and according to equation (4.1) has a probability:

$$p_{12345,n} = p_{1,i} \cdot p_{2,j} \cdot p_{3,k} \cdot p_{4,l} \cdot p_{5,m} \tag{4.5}$$

where $p_{u,v}$ denotes the probability associated with the v-th interval of the u-th random variable. By adding up the probabilities of those combinations affecting the same compartment grouping and when all the combinations have been examined, we obtain for each and every compartment grouping possible, the probability of damage.

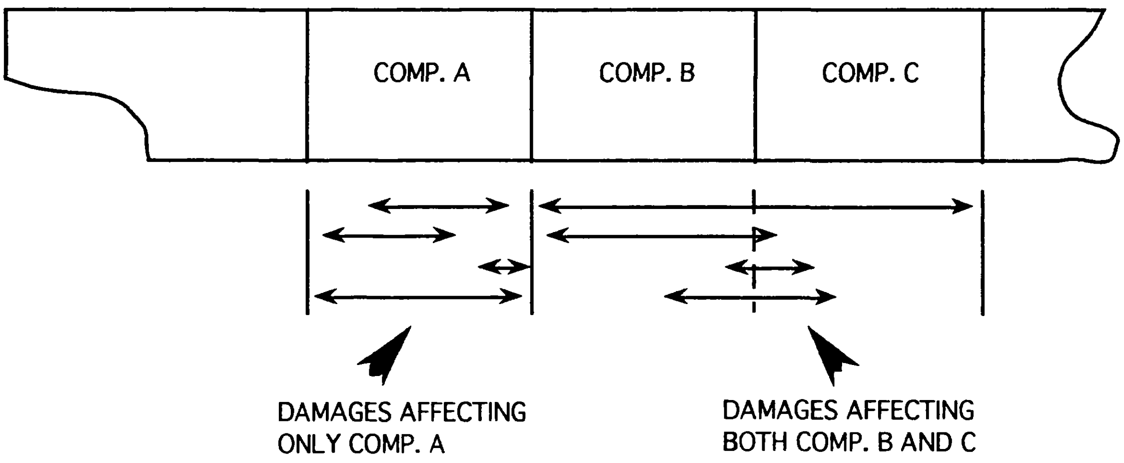


Figure 4.10: Examples of damages affecting a single compartment, or a group of compartments.

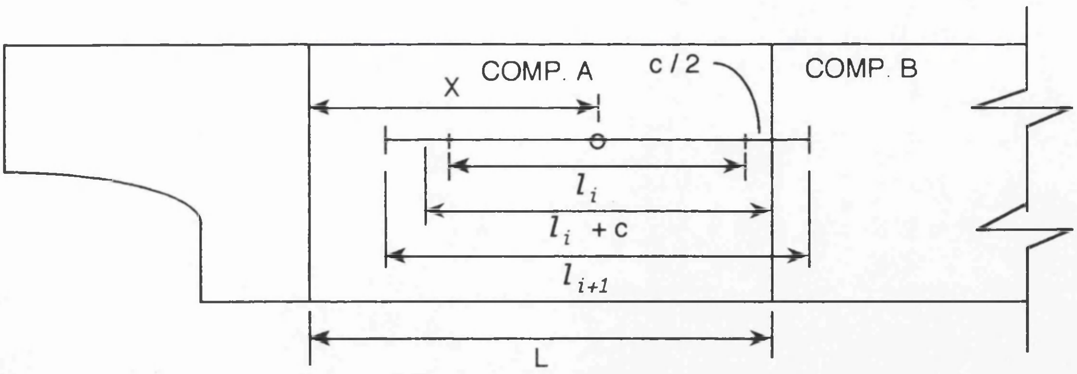


Figure 4.11: Example of possible error in the concept of step coverage of probability domain

4.3.4 LIMITATIONS

From what was said in section 4.2.2, it is obvious that the number of intervals in each random variable range is important. The more, i.e. smaller, intervals in each range, the closest the approximation of the corresponding continuous random variable. Furthermore, it is clear that each of the damage extents is a step function with a constant increment equal to one interval. So it may happen that one damage extent value falls short of the compartment grouping boundaries, but the immediately next value intersects one of the boundaries, thus corresponding to a different compartment grouping. A situation of this kind is shown in figure 4.11.

The watertight compartment A, of length L, is affected by a damage with its centre located at a distance X from the aft transverse bulkhead. The range of the longitudinal damage extent $(0, l_{max}]$ is divided into n equal intervals, corresponding to a damage length increment: $\lambda = l_{max}/n$. The i-th interval therefore corresponds to a damage length: $l_i = i \cdot \lambda$ which is entirely in between the transverse bulkheads of the compartment. The probability $p_{3,i}$ associated with that interval, contributes to the damage probability of compartment A alone. However the (i+1) interval, corresponding to a damage length: $l_{i+1} = (i+1) \cdot \lambda$ intersects the forward bulkhead and this damage affects two compartments, A and B, instead of one. So the probability $p_{3,i+1}$ contributes to the damage probability of compartment grouping AB. This introduces an error in the damage probability results. Indeed, part of the probability $p_{3,i+1}$ is associated with the portion of damage length: $c = 2 \cdot (L - X - l_i/2)$. A damage at the current location, with longitudinal extent: $l' = l_i + c$ will only affect compartment A. Therefore, the corresponding probability should contribute to the damage probability of compartment grouping A and not AB as is the case. The same error can occur in any of the three damage dimensions. From the above example it is clear that in general, the magnitude of the error depends on the following factors:

This can easily be taken into account.

- the size of the centre of damage location intervals (longitudinal and vertical),
- the size of the damage extents intervals (length, height and penetration),
- the watertight subdivision arrangement.

Again, as pointed in the beginning of this section, the smaller the intervals, the lesser the error magnitude. This however, is an overall trend, and does not necessarily apply between any two solutions.

4.4 THE OIL OUTFLOW MECHANISM

4.4.1 IN GENERAL

With a specific gravity ranging between 0.81 and 0.99, crude oil is lighter than water and does not normally mix with it. Thus, the former tends to be displaced and float on top. When actively mixed together, oil in the form of droplets remains in suspension in the water. As soon as the disturbance disappears, the droplets conglomerate and rise again to the interface where they join the main mass of oil. In any case, the amount of oil mixing with water is relatively small and remains in the vicinity of the interface. It is therefore reasonable to assume, for the purpose of oil outflow simulation, that there is always a clearly defined water-oil interface.

Considering the case of a cargo oil tank suddenly becoming open to the sea through damage, the inflow of water and the outflow of oil depend mainly on the relative hydrostatic pressure of each liquid at the location of the breach. When the breach is in the bottom plating of the tank, the mechanism is straightforward: if the hydrostatic pressure of the oil, at the bottom of the tank, is higher than the hydrostatic pressure of the water, then oil flows out of the tank until the oil level drops sufficiently and pressures are equalised. If however, the hydrostatic pressure of the water at the bottom of the tank is higher, then water flows in the tank, displacing the oil away from the bottom plating and the breach and forming a "sealing" layer. The inflow of water stops when again the pressure on either side of the breach is the same.

The same equilibrium condition applies when the breach is located in the side plating of the tank. But now, the phenomenon of oil displacement by water has a major role in the oil outflow mechanism. Water inflow and oil outflow occur simultaneously, with flow-rates proportional to the instantaneous hydrostatic pressure of each liquid. Though initially mixing of oil and water is substantial, eventually all the oil in the tank below the level of the breach is displaced by water and a well-defined interface develops. Equilibrium is achieved when all the oil is displaced and the interface reaches the edge of the breach closest to the free surface of the water. If the breach partly extends above the waterline, then obviously all the oil floating on top of the water in the tank, flows out through the gap above the water surface.

The loss of oil through the mechanism described above is termed *Hydrostatic loss* . Initially however, a quantity of oil is lost due to forces and events that occur during the damage impact. These losses are termed *Initial exchange losses* . After the onset of hydrostatic balance, as described previously, events such as ship motions or sea currents and waves disturb this static equilibrium condition. The resulting secondary oil outflow is known as *Dynamic effect losses* . So far, in oil outflow studies for collision damage, it has always been the case to take the vertical damage to extend from the Baseline upwards without limit. This assumption, apart from disregarding completely any horizontal subdivision in the cargo tank region, gives an oil outflow always equal to the sum of initial cargo load of the breached tanks. Because of this, there was no need to describe the oil outflow mechanism, in the way it was done for bottom damage. However the assumption of unlimited vertical damage extent is only the worst case scenario and has, in reality, a reduced probability of happening. Therefore, these studies always show a significantly high expected oil outflow in collision. In the present study however, localised side damages entirely below or entirely above the waterline are accounted for. Consequently, there are cases where some oil remains in the breached tanks, leading to the need for a rationale on which to base a model for oil outflow prediction. Such a rationale already exists for the case of bottom damage and can be adapted, with few modifications, to the side damage case.

4.4.2 THE OIL OUTFLOW PREDICTION MODEL FOR COLLISION DAMAGE

For each individual breached tank, three different collision damage cases are distinguished:

1. localised damage entirely below the waterline,
2. localised damage entirely above the waterline and
3. damage on the waterline.

4.4.2.1 Localised Damage Entirely Below the Waterline.

A quasi-static approach is implemented in three steps as depicted in figures 4.12(a), (b), (c) and (d). In the initial condition (figure 4.12(a)), the vessel floats at the initial draught T_i with no heel and no trim. The cargo oil tank considered is loaded, with crude oil of specific gravity γ_{oil} up to a height H_i above the tank bottom. The tank bottom itself is located at a height of H_{DB} above the keel. Vapour pressure over the oil surface is p_v. When damage occurs, the tank becomes open to the sea through a breach of vertical extent e_D, with the upper edge of the breach lying at height H_D above the keel.

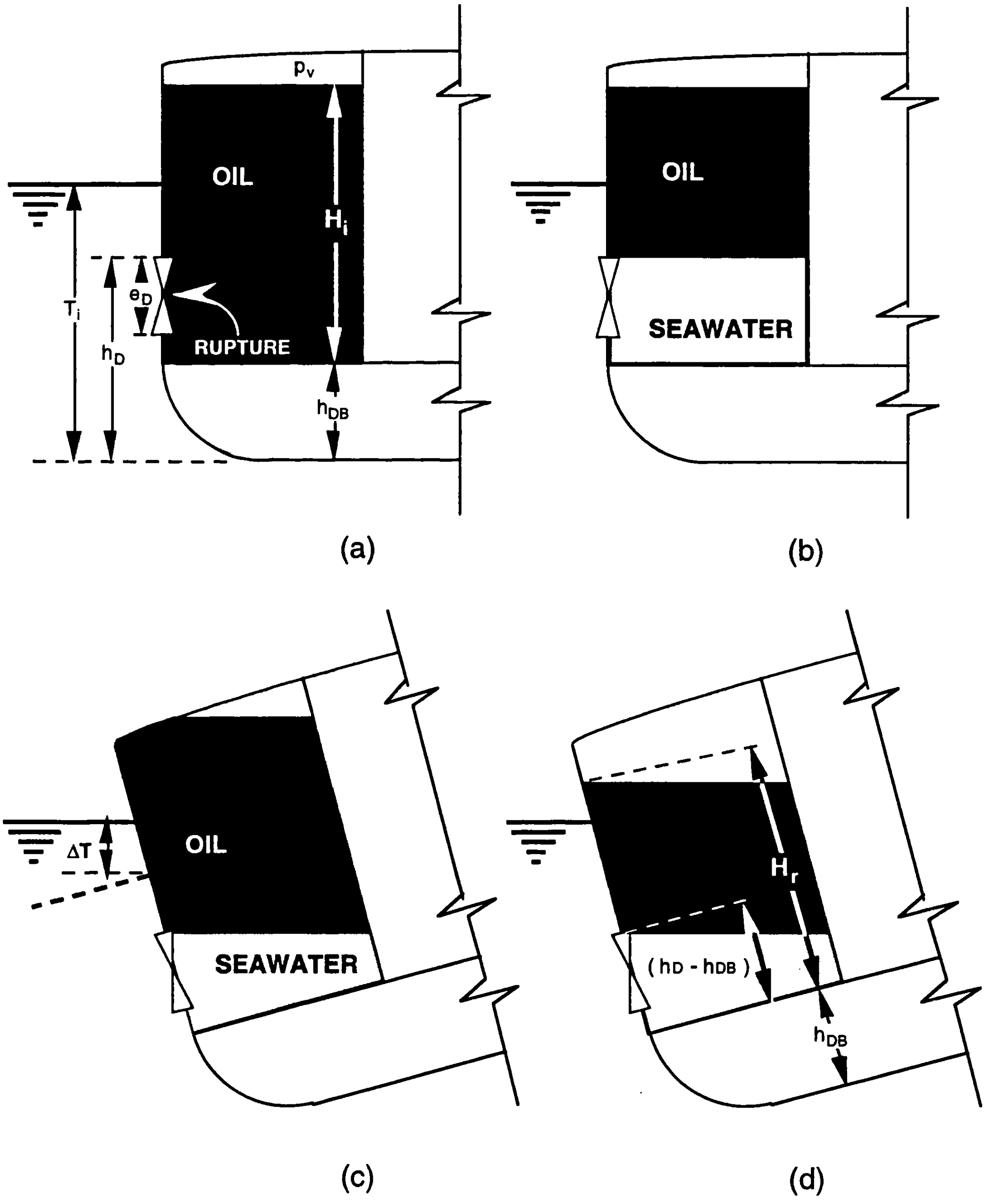


Figure 4.12: Oil outflow modelling when the damage opening is entirely below the waterline.

Step 1: Compartment Flooding (figure 4.12(b)).

The oil in the tank up to the upper edge of the breach is replaced by seawater. The free surface of the oil in the tank remains at the original height H_i above the tank bottom.

Step 2: Onset of vessel equilibrium (figure 4.12(c)).

The vessel is allowed to sink, heel and trim to its final waterline according to damaged stability calculations[2]. The upper edge of the breach lies now at a vertical distance ΔT from the original waterline and the seawater-oil interface is assumed to remain at the level of the upper edge of the breach.

Step 3: Onset of hydrostatic balance (figure 4.12(d)).

The remaining oil in the tank starts flowing out until its hydrostatic pressure at the seawater-oil interface balances the hydrostatic pressure of seawater. Now, the free surface of the oil lies at a height H_f above the tank bottom. Applying the hydrostatic balance principle at the seawater-oil interface gives:

$$\left(H_f + H_{DB} - H_D\right)\cdot \gamma_{oil} + p_v = \left(T_i + \Delta T - H_D\right)\cdot \gamma_{sea} \qquad (4.6)$$

From which we readily calculate H_f. From the tank calibration table, we can now work out the volumes V_i V_f and V_w corresponding to the heights H_i H_f and $\left(H_D - H_{DB}\right)$ Finally, the volume of oil lost from that tank will be:

$$V_{out} = V_i - V_r \qquad (4.7)$$

where:

$$V_r = V_f - V_w \qquad (4.8)$$

is the volume of oil remaining in the tank after hydrostatic balance is achieved.

4.4.2.2 Localised Damage Entirely Above the Waterline.

In this case, depicted in figures 4.13(a), (b) and starting from the same initial condition as above, any oil in the tank above the lower edge of the breach flows out of the tank. Thus, the free surface of the oil remaining in the tank lies now at a height H_f above the tank bottom, where:

$$H_f = H_D - H_{DB} - e_D \qquad (4.9)$$

Then:

$$V_{out} = V_i - V_f \qquad (4.10)$$

---

[2] Refer to Section 4.5.

where V_i and V_f are calculated from the tank calibration table for heights of liquid H_i and H_f respectively.

4.4.2.3 Damage On the Waterline.

The full initial load of cargo flows out of the breached tank and the tank is flooded with seawater up to the waterline. This case is shown in figures 4.14(a), (b). The oil outflow from the considered tank is:

$$V_{out} = V_i \qquad (4.11)$$

where V_i corresponds to a height of liquid in the tank equal to H_i.

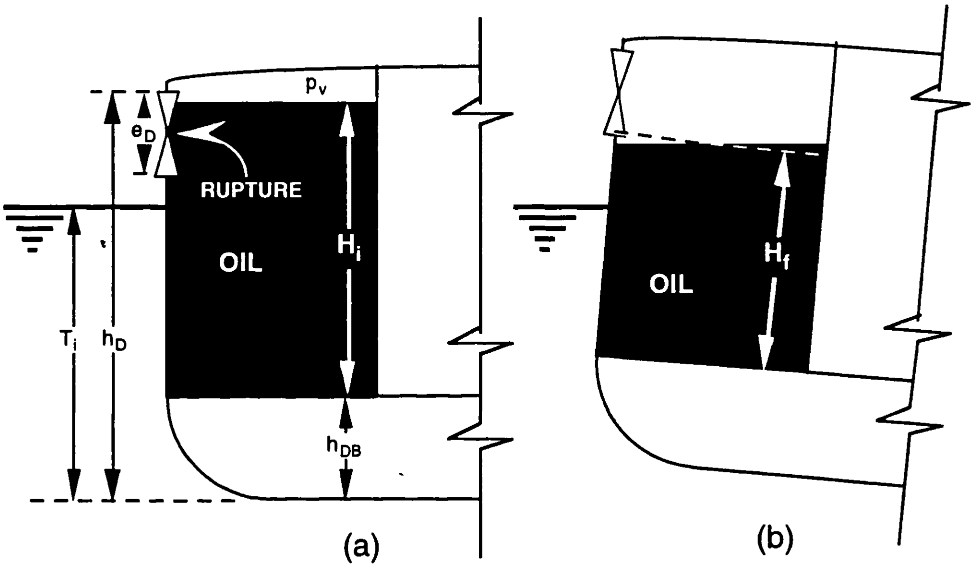


Figure 4.13: Oil outflow modelling when the damage opening is entirely above the waterline.

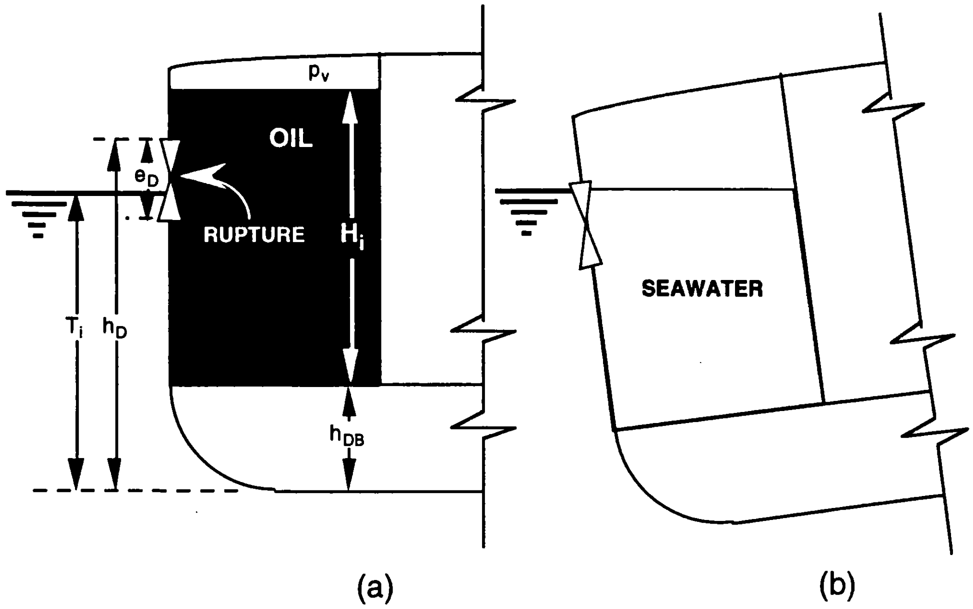


Figure 4.14: Oil outflow modelling when the damage opening is on the waterline.

4.4.3 IMPLEMENTATION

In order to produce a realistic oil outflow model, the existence of empty watertight spaces within the hull and their potential for retaining, under the right conditions, an amount of the outflowing oil has to be taken into account. The same goes when some cargo tanks are only lightly loaded. Indeed such tanks, under certain conditions, have the potential to retain a proportion of the oil flowing out of adjacent damaged tanks. Both these factors have been included in the present numerical model. The damaged compartments are sorted according to the transverse position of the breach in them. Then, starting from the most inward compartment, i.e. farthest from the damaged side plating, the oil outflow is calculated for the individual compartment. This oil outflow is assumed to flow into the next damaged compartment and is added to its initial cargo load and so on. The oil outflow from the last damaged compartment in the list, i.e. one bound by the damaged side shell, is the final value of the oil outflow for this damage case. With this procedure each damaged compartment can retain a volume of oil up to the volume needed for hydrostatic balance in each particular case. Initial exchange and dynamic effect losses are taken into account by increasing the oil outflow from each individual tank by a percentage of the initial cargo load of that tank. Where a tank breach is completely above the waterline only the initial exchange loss factor is applied to that tank, since current can have no effect in that case. If however the tank breach lies athwart the waterline then obviously none of the factors is applied, since all the oil in that tank flows out.

4.5 FLOATATION CALCULATIONS

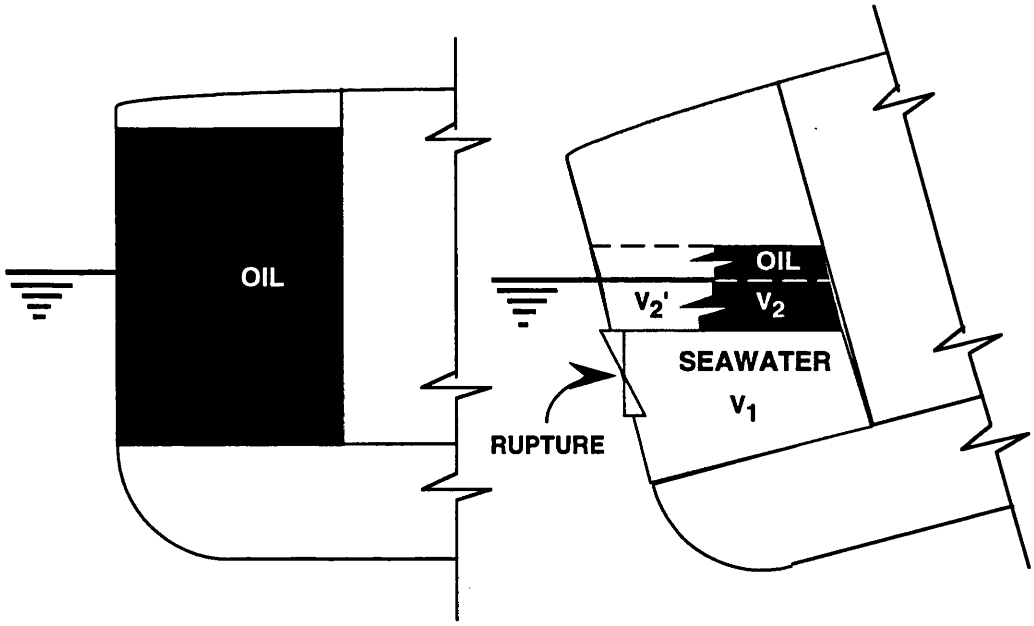
4.5.1 IN GENERAL

Because of the partial unloading and flooding of tanks, heeling and trimming of the vessel may occur, upsetting the hydrostatic balance of the ruptured tanks. The oil outflow model formulated previously, makes different allowances depending on the relative position of the rupture with respect to the free surface of the sea. It is therefore important to determine the new attitude of the damaged ship, in order to know the new position of the rupture in each damaged tank. The two problems of floatation and oil outflow seem interdependent at first, but a closer examination of the oil outflow mechanism reveals two facts:

1. the two problems are just superimposed and
2. oil outflow is dependent on floatation and not the other way round.

Consider a watertight compartment, anywhere along the side of the ship, which after sustaining a side damage, becomes open to the sea. If the compartment was initially empty, then it becomes flooded with seawater up to the new equilibrium waterline or up to its top horizontal boundary, whichever is lower. In any case, the amount of buoyancy the ship has lost is known and we can readily calculate the values of heel, trim and sinkage, that determine the new equilibrium waterline. If however, the compartment was initially loaded with oil, as in figure 4.15(a), then from the mechanism described in the previous section, we know that seawater will flow into the compartment thus adding weight and oil will flow out removing weight from the ship. We also know that in the final equilibrium condition the contents of the damaged compartment are likely to be as depicted in figure 4.15(b). Seawater will occupy the volume V_1 of the compartment up to the upper breach limit. And floating on top of that, there will be the hydrostatically balanced volume of oil, V_2. By definition, that volume of oil V_2 is equivalent to the virtual volume of water V_2', bounded by the actual seawater-oil interface and the current equilibrium waterplane. We can therefore consider that the compartment in the final condition, contains only seawater, up to the equilibrium waterline.

It is clear now, that the final equilibrium condition is equivalent to the one attained by superimposing the effects of removing all the oil from the tank and of flooding the empty tank with seawater. Knowing the initial volume of oil in the compartment and the amount of buoyancy the ship has lost, it is therefore possible to determine the final equilibrium waterplane, without having to calculate the actual oil outflow.



(a) (b)

Figure 4.15: Initial and final volumes of water and oil in breached tank at equilibrium.

Once the final attitude of the ship is determined, we can apply the hydrostatic balance hypothesis, as described in Section 4.4, to compute the oil outflow from the damaged compartment.

4.5.2 IMPLEMENTATION

From the procedure described above, it is obvious that the method used for the floatation calculations is the lost buoyancy method. When a damaged compartment grouping is determined by the applied damage particulars, the weights and moments of weight of the oil in each non empty compartment in the grouping are summed. Then the floatation calculations are performed assuming that all the compartments intersected by the initial waterplane, are flooded with seawater. Allowance is made for those compartments of the grouping lying entirely below the initial waterplane, in the way described in the previous section. When the heel, trim and sinkage are computed, the corresponding total weight and moments of weight of oil are duly incorporated in the calculations. The formula used for heel is the 'wall-sided' formula.

4.5.3 LIMITATIONS

The method and formulas used for the floatation calculations are satisfactory so long as the final waterplane does not intersect the keel or the deck. For large angles of trim or heel, where the above requirement is not fulfilled, a trial and error method of calculation is needed. Such a task would considerably slow down the calculation procedure, so it has been omitted for the sake of simplicity and speed.

Also, for large damages, when considerable part of the waterplane is destroyed, the principal axes rotate in addition to their parallel displacement with respect to their original position. The calculations described so far, ignore this rotation and thus introduce an error in the results. However for ships with low L/B ratio and a relatively full symmetrical waterplane, this error is very small [23].

Finally, the eventuality that the rupture in a compartment, lifts clear of the water through ship heel or trim, before flooding is complete, is ignored. In fact, the computational model assumes a unique flooding scenario for a given grouping of damaged compartments, irrespective of the damage extents that apply. The event described above, is more likely in the case of damage with small extents and close to the waterline.

5 THE SAMPLE SHIPS

5.1 OIL TANKER DESIGN AND OIL OUTFLOW

As explained in 3.3, the notion of risk in terms of probabilistic (or potential) oil outflow has two components:

- the probability of the cause, i.e. the probability of an oil containing compartment or group of compartments being damaged and
- the gravity of the effect, in this case the amount of oil spilled, termed theoretical oil outflow.

Therefore, in order to reduce probabilistic oil outflow, one or both of the above components must be reduced.

Because the total probability is distributed over a domain covering the whole ship, every single compartment of the ship is associated with a component of that probability. The actual probability associated with any compartment depends on the dimensions and location of that compartment. Clearly, any compartment not containing oil does not contribute to the total potential oil outflow. So, if we maximize the probability associated with those compartments, we effectively minimize the probability corresponding to the oil containing compartments and hence their contribution to potential oil outflow. This is the principle behind the statutory requirement for the protective location of segregated ballast tanks. The same principle is used in such concepts as the double hull and double sides.

Oil outflow can also be reduced by appropriate design. Theoretical oil outflow from a group of damaged compartments is the aggregate of the contribution of each individual compartment in the group. Consequently, the smaller the compartments are, the smaller is the amount of oil potentially lost for the same number of damaged compartments. By increasing the number of subdivision members, we divide the ship into many smaller compartments. The probability domain for the entire ship also gets fragmented into smaller parcels, to match the greater number of compartments. Since the total probability remains unchanged, this fragmentation would have no effect on the total potential oil outflow. However, because the oil volume elements are smaller, potential oil outflow from each compartment is reduced and consequently total potential outflow is reduced.

?

Theoretical oil outflow can be reduced by other means as well. The provision of empty spaces surrounding damaged tanks offers the potential benefit of retaining a variable amount of the oil spilled within the ship hull. This is a secondary benefit of the double hull and double sides concept, but is also used, in a slightly different way, in the rescue tank concept [24, 25]. The mid-height deck (or mid-deck) concept achieves a similar oil retention effect, but within the damaged cargo space, by cancelling the cause of oil outflow, i.e. the positive pressure head difference between the inside and the outside of the cargo spaces. Because this last concept relies on the introduction of additional horizontal subdivision, it also benefits from the aforementioned advantages of denser subdivision.

5.2 THE CONCEPTS AND ARRANGEMENTS INVESTIGATED

Three basic concepts have been investigated: the single skin segregated ballast tank concept, the double hull and the mid-deck concept. These three concepts have been chosen because they cover the primary range of existing and proposed solutions to the problem of accidental oil pollution from tankers. Indeed, any other concepts, with few exceptions, share the working principles of one of these three. Appendix C.2 groups the drawings of the tank arrangements by concept.

5.2.1 SINGLE SKIN ARRANGEMENTS WITH SEGREGATED BALLAST IN WING TANKS

These arrangements correspond to the conventional single skin tanker concept having two longitudinal bulkheads dividing the cargo space into centre and wing tanks. Sixteen such arrangements were examined. The arrangements were created by altering two design variables: the number of transverse bulkheads within the cargo carrying region of the ship and the relative position of the two longitudinal bulkheads. Four groups were distinguished corresponding to arrangements with 3, 4, 6 and 8 transverse bulkheads, thus creating four groups of similar tank arrays: [4x3], [5x3], [7x3] and [9x3][1]. Within each group, there are four different positions of the longitudinal bulkheads. Each arrangement is defined by the value of the B_W/B_C ratio, where B_W and B_C are the breadths of the wing and centre tanks respectively. The four selected values of the ratio are: 0.25, 0.5, 0.75 and 1.0 . All the arrangements feature wing ballast tanks alternating with wing cargo tanks in order to allow for the requirement of protective location of ballast spaces. The number of ballast tanks is

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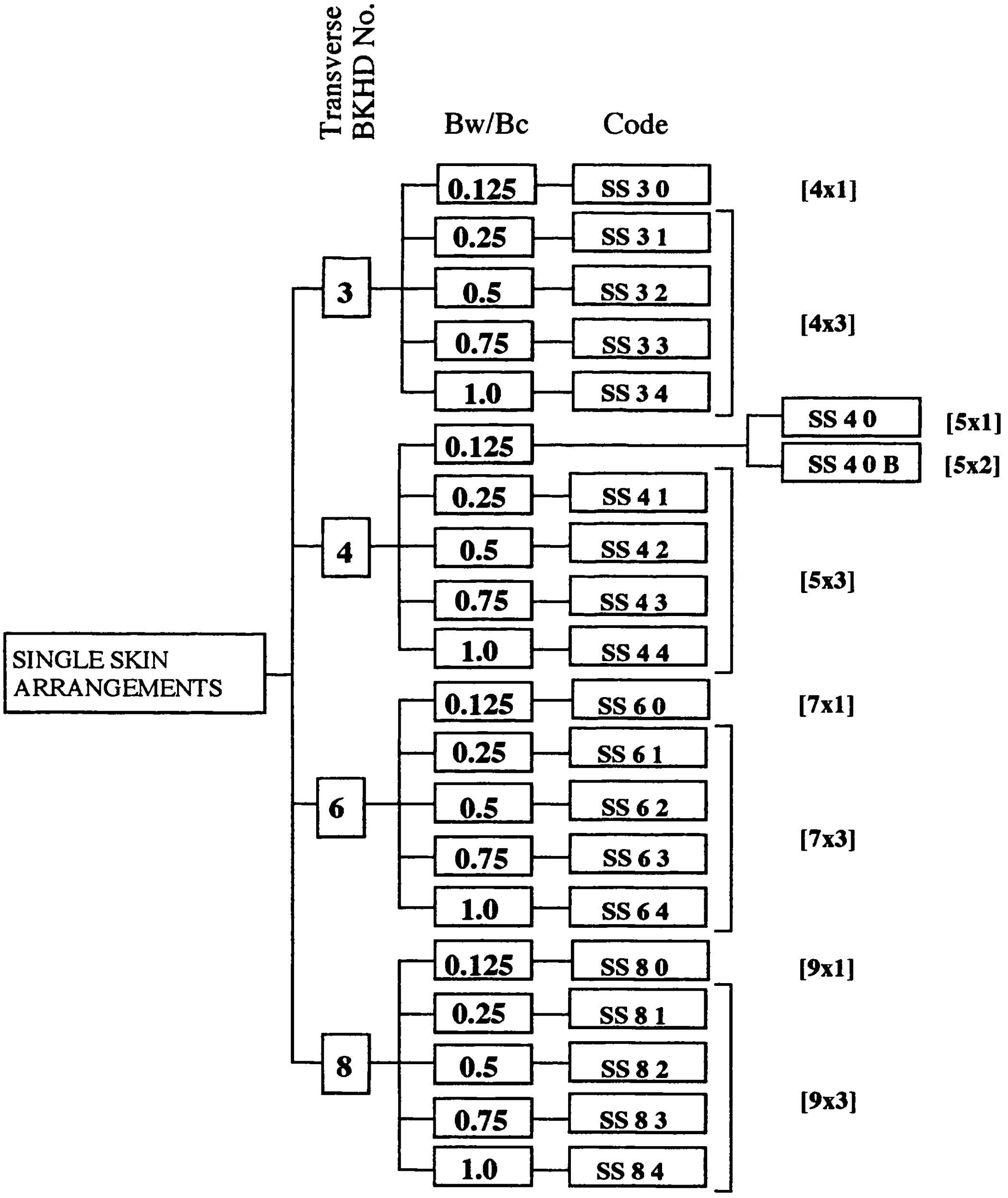
[1] A matrix dimensions notation was adopted, and will be used throughout this study, to refer to a specific group of arrangements. This notation has the format:

[number of COT.s longitudinally x number of COT.s transversely].

such as to meet a ballast requirement of about 70,000 m^3, giving a ballast to cargo capacity ratio ranging from 30% to 35%. This range of values has been taken from a sample of existing tanker designs [26, 27, 28].

The smaller the value of B_W/B_C ratio, the greater is the number of wing tanks that are needed to accommodate the required ballast and the greater is the proportion of the ship side covered by the ballast tanks. The limiting condition is when the ballast tanks cover the whole length of the cargo carrying portion of the ship. In order to investigate this condition, a fifth value of $B_W/B_C = 0.125$ was included in the study, creating four additional arrangements, one for each tank array group.



Note: Code "0" indicates a double-sided arrangement

Figure 5.1: Single-Skin arrangements groupings.

These correspond to double-side arrangements with a side tank breadth of B/10 and the cargo carried only in a single set of centre tanks. Taking as a basis the [5x1] double-side arrangement, a further arrangement was introduced by adding a third longitudinal bulkhead, on the centreline of the ship, making it effectively a [5x2] arrangement. Figure 5.1 distinguishes schematically the 21 arrangements discussed above.

Within this range of arrangements it is possible to investigate the effect on oil outflow, of the following parameters:

- number of transverse bulkheads,
- position of longitudinal bulkheads,
- tank volume,
- relative size of wing and centre tanks,
- extent of protection from SBTs.

5.2.2 DOUBLE-HULL ARRANGEMENTS

Twenty seven different arrangements were produced by varying three design features in a parametric fashion. Three cases of longitudinal subdivision within the cargo carrying portion of the hull were examined:

- no longitudinal bulkhead,
- one longitudinal bulkhead on the ship's centreline
- and finally, two longitudinal bulkheads dividing the cargo region into two wing and one centre tank of equal breadths.

In each case, three different groups were distinguished according to the particular double-hull space configuration. The three different configurations examined are:

- L-shaped double-hull spaces - two ballast tanks in section,
- U-shaped double hull spaces - one ballast tank in section,
- segregated double sides and double bottom - three ballast tanks in section.

In each group three ratios of double bottom to double side capacities[2] were selected, close to the values: 1:2, 1:1, 2:1. These ratios result in arrangements with the characteristic double hull space dimensions, as shown in table 5.1 below.

Volume ratio V_{DB}/V_{DS}	Bottom height **h (m)**	Side breadth **b (m)**
0.497	1.850	3.700
1.034	2.830	2.830
2.155	3.800	1.900

Table 5.1: Double hull space volume ratios and corresponding dimensions.

In all the arrangements the transverse subdivision consists of 4 transverse bulkheads producing [5x1], [5x2] and [5x3] cargo tank arrays. Figure 5.2 shows the breakdown of the 27 arrangements into the different categories, as explained above.

The investigation of the double-hull arrangements concentrates on the effect of the following parameters:

- number of longitudinal bulkheads,
- tank volume,
- volume distribution within double hull,
- configuration of SBTs (double-hull spaces).

5.2.3 MID-HEIGHT DECK ARRANGEMENTS

These arrangements feature full depth double sides, where all the required ballast must be accommodated. Therefore the same condition applies as for the double-side arrangements presented previously. The present arrangements are in fact derived from the latter, with the addition of the horizontal subdivision. The breadth of the double sides is therefore B/10. The basis arrangement is the [5x1] double side. From that, 18 mid-deck arrangements are derived by varying three design variables, namely mid-deck location height, longitudinal subdivision of cargo space and double side configuration. Figure 5.3 shows the categorization of the 18 arrangements.

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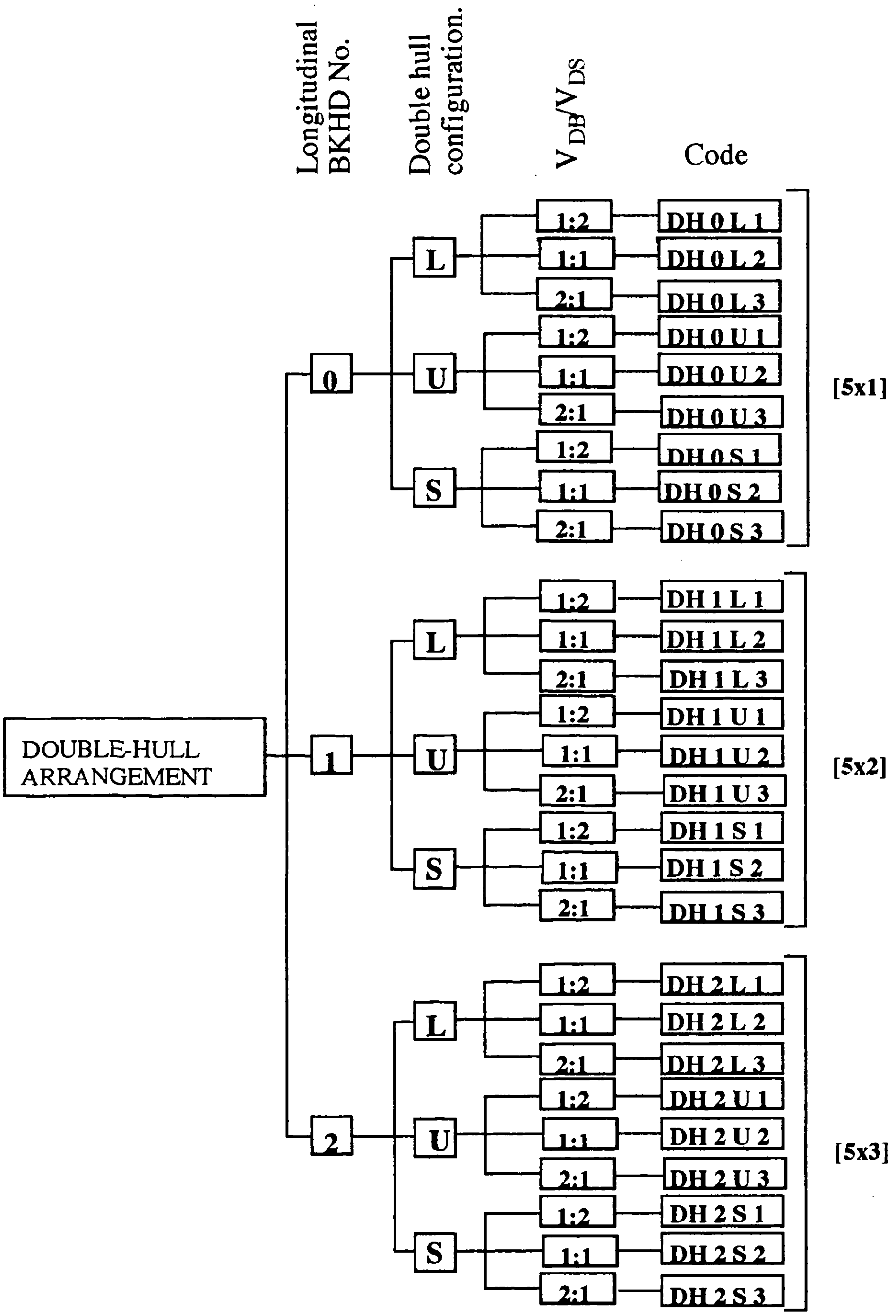
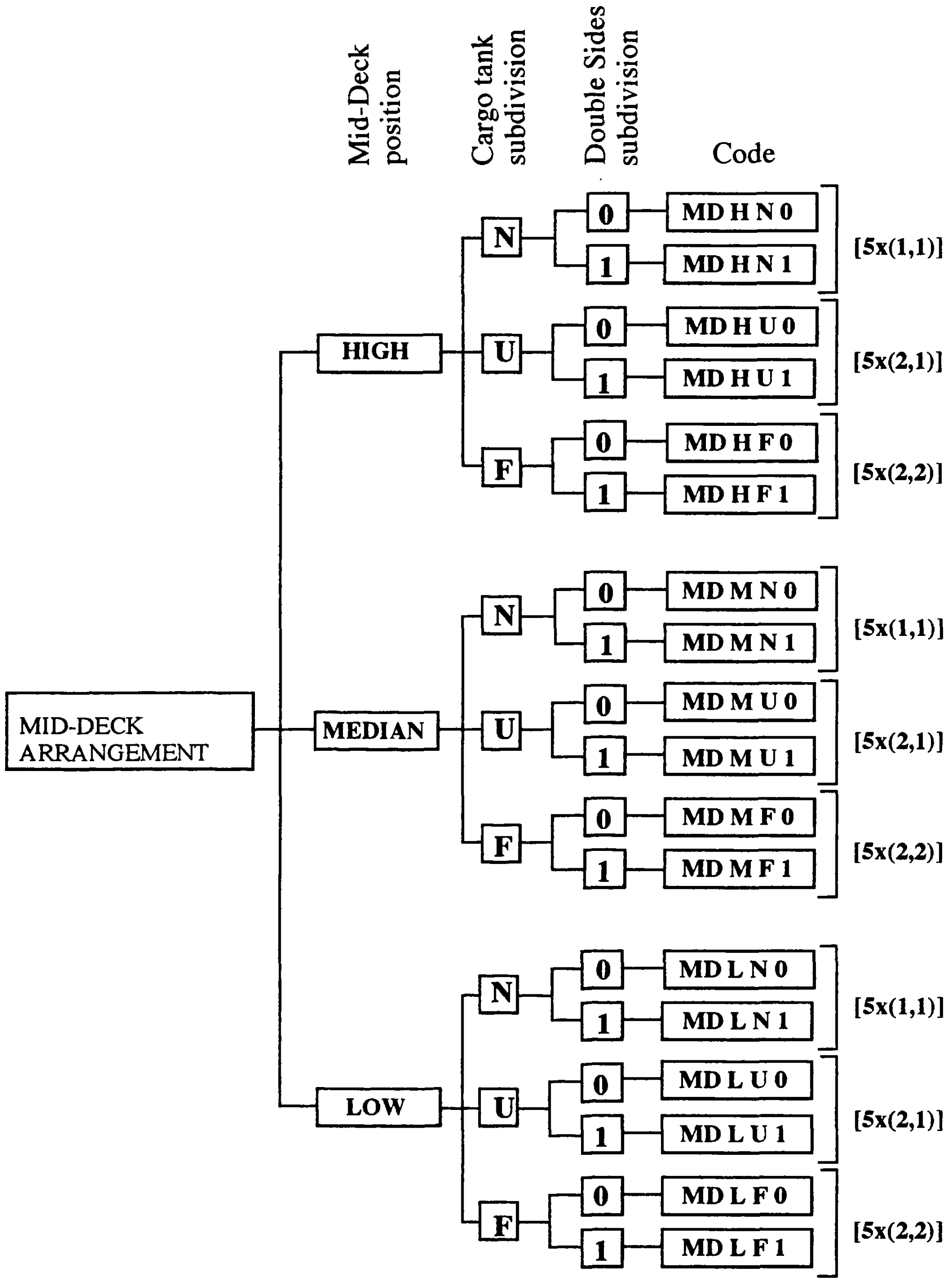
[2] The total capacity of the double hull remains constant for all the arrangements. Only the distribution of the capacity between the double bottom and the double sides varies according to the V_{DB}/V_{DS} ratio. V_{DB} is the volume of the double bottom over the full beam of the vessel. and V_{DS} is the volume of the double-side space, from deck level down to the tank top, on both sides of the hull.



Note: L, U, S identify the double hull space configuration.
S= Double Bottom + Double Sides.

Figure 5.2: Double-Hull arrangements groupings.

Three positions of the horizontal subdivision deck are considered and are referred to as *High*, *Median* and *Low*. They correspond to heights of 20.0, 13.5 and 7.0 m above keel respectively. For each mid-deck position, three possible cargo tank configurations, with respect to longitudinal subdivision, are examined:



Note: N= No Long'l BKHD,
U= Long'l BKHD in upper cargo tanks only,
F= Full depth Long'l BKHD.

0= Full height Double Sides,
1= Horizontally subdivided Double Sides.

Figure 5.3: Mid-Deck arrangements groupings.

- no longitudinal subdivision,
- a partial longitudinal subdivision, with one centreline bulkhead in the upper cargo space only,
- full longitudinal subdivision, with a centreline bulkhead in both the upper and lower cargo spaces[3].

Finally two different double-side configurations are considered:

- undivided, full depth double sides
- and full depth double sides, horizontally subdivided at the height of the mid-deck.

The above range of arrangements allows the investigation of the effect of the following factors:

- vertical position (height) of horizontal subdivision,
- configuration of double-side spaces,
- tank volume,
- relative size of upper and lower cargo tanks,
- longitudinal subdivision of cargo spaces.

5.3 EXTERNAL HULL FORM

All the tank arrangements are accommodated within identical hull forms with the same principal dimensions. Apart from the advantage of having to numerically define only one hull geometry, this allows a more accurate comparison of the performance of each design. Each combination of damage particulars, corresponds to exactly the same locations and extents of damage, in all of the arrangements. Furthermore, the length of the cargo carrying portion of the ship is kept the same as is the layout and dimensions of the compartments outside this portion. Thus, any differences in the performance of the different designs can only be attributed to differences in the configuration and the corresponding design variables of the cargo region.

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[3] From this point onwards in this study, these three cargo tank configurations are referred to as [5x(1,1)], [5x(2,1)] and [5x(2,2)] respectively. The notation used, is consistent with the one described so far. The numbers in the parentheses show the number of tanks in the transverse direction, in the upper and lower cargo spaces, in that order.

The principal dimensions were chosen to agree with the current design practice as embodied in a sample of recently built ships [26, 27, 28]. Table 5.2 below gives the main dimensions and figures C.1 to C.4, in Appendix C.1, depict the actual hull form.

L_{OA} (m)	290.00
L_{BP} (m)	285.00
B_{max} (m)	50.00
D (m)	27.01
$T_{(load)}$ (m)	19.00
Δ (tonne)	230,806
C_b	0.832

Table 5.2: Main dimensions of external hull.

The numerical description of the hull was used with the AutoHydro program of the Autoship package in order to obtain a table of Hydrostatic properties. These are presented as table C.1 in Appendix C.3.

6 ANALYSES PERFORMED AND RESULTS

6.1 INITIAL ASSUMPTIONS AND ANALYSIS PARAMETERS

Section 5.2 highlights the effort to limit, as much as possible, the number of variables in the analysis of all the different tank configurations, so that more accurate conclusions can be drawn from their comparison. In order to preserve this reciprocity, the framework of the analyses must be kept constant as well. Thus the same initial conditions are taken irrespective of the arrangement examined.

Although each tank configuration results in a somewhat different dead-weight, the displacement is taken as constant at 230,806 tonnes in sea-water, corresponding to an even keel draught of 19.0 m. All tanks with the exception of water ballast tanks are taken 98% full, leaving a 2% margin for expansion. All the ballast tanks are taken to be dry. The assumed specific gravity of cargo oil is 0.924 and a value of 0.870 is assumed for fuel oil in the bunkers. A positive pressure equivalent to a two metre water column is applied at the free surface of all the oil carrying tanks. The permeability values were taken as follows:

- Tanks 0.985
- Other watertight spaces 1.0

Typically, the Engine room and other watertight spaces containing machinery have permeability values below 1.0. Nevertheless the above value was assumed in order to simplify the modelling procedure. The effect of this assumption on the oil outflow results is minimal because:

- there are very few damages cases that involve at the same time cargo tanks and the aforementioned spaces.

- The watertight spaces concerned are located in the extreme ends of the ship, on the centreline. Consequently any damage to those spaces will cause trim but no heel. The cargo spaces are located in the mid-body of the ship where local draught is proportionally less affected by trim.

- The watertight spaces concerned, with the exception of a large Engine room, have relatively small capacities. Furthermore, some of these spaces (e.g. Steering gear room) are located above the load waterline and thus do not flood when damaged.

For stability calculations the value of KG is assumed to be 18 m. The free surface of the sea is considered to be calm, i.e. without any waves. However, the effect of the flow of water around the hull is taken into account. This effect can be compared to the effect of sea current. Experiments [18, 19] have shown that the presence of sea current significantly affects the oil outflow from bottom ruptures after grounding accidents, causing additional loss of oil under hydrostatic equilibrium conditions. In the light of these findings a "Dynamic loss" factor of 1% of the damaged tank cargo capacity was introduced into grounding oil outflow calculations reported in [4]. The similarity of the oil outflow mechanism after grounding and after collision, as described in Section 4.4.1, suggests a similar approach to oil outflow computation. In the absence of specific data the present study uses the same dynamic loss factor as above, depending on the position of the rupture relative to the waterline[1]. Similarly, an "Initial exchange loss" factor of 1% of the cargo capacity of the damaged tanks is used, again in agreement with [4].

The importance of the choice of intervals in the ranges of the five damage parameters, was explained in 4.3.4. After trial and error, the following increment steps were found adequate for the iteration process:

- Longitudinal location of centre of damage 5.0 m.
- Longitudinal extent of damage 1.0 m.
- Vertical location of centre of damage 3.0 m.
- Vertical extent of damage 3.0 m.
- Transverse extent of damage 1.0 m.

6.2 NUMERICAL MODEL OUTPUT

A computer program written by the author implements the numerical model for probability and oil outflow as described in chapter 4. For each tank arrangement the program produces two main output files. The first file contains a list of all the possible combinations of damaged compartments. The second file gives for each of these combinations the associated probability, the minimum and maximum theoretical oil outflow volumes that occurred and the potential oil outflow value. It was pointed out in section 2.3 that all oil outflow studies compute a single

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[1] Refer to section 4.4.3.

theoretical outflow volume value for each damaged compartment grouping. Unlike these, the present study computes a separate probability and theoretical outflow volume value for each one of the damage occurrences that affect a given compartment grouping. Thus the probability value associated with a compartment grouping is the sum of probabilities of all damage occurrences affecting that grouping. Similarly the potential oil outflow value is the sum of all the partial probability and theoretical outflow volume products. Of all the values of theoretical outflow volume from a given compartment grouping, the minimum and maximum are recorded and included in the output list as mentioned above.

Appendix A.3 gives a sample of the output files described.

6.3 POST-PROCESSING OF NUMERICAL MODEL OUTPUT

In order to extract the required information for each tank arrangement, the raw data must be further processed. For this purpose the output files were "exported" to a Microsoft EXCEL™ spreadsheet. Then the data was manipulated in accordance to the method presented in [8]. The list of compartment groupings and their associated data was first sorted in ascending order with respect to the maximum theoretical oil outflow value. Starting from the grouping with the lowest maximum theoretical outflow and working through to the grouping with the highest value, a running sum of the corresponding probability values was calculated. This 'cumulative' probability was then plotted against the corresponding maximum theoretical oil outflow values. The oil outflow chart thus produced for each arrangement, "...provides a picture of the vessel's ability to resist oil spillage when damaged."[8] Additionally, the last value of cumulative probability provides a check for errors in the probability computation, as the total probability should, ideally, add up to a value of 1.0 . For all the arrangements investigated the total probability results obtained were consistently over 0.998 .

Next the sum of the potential oil outflow values for all the tank groupings was calculated yielding the expected oil outflow value. The extreme 1/10 oil outflow value was calculated by summing the potential outflow values with an associated cumulative probability of 0.9 and over and dividing that sum by 0.1 . Lastly the sum of all the probability values corresponding to a maximum theoretical outflow value of zero, yielded the value of the zero oil outflow probability. Subsequently, for ease of comparison, the oil outflow volume results were made non-dimensional by dividing them with the cargo dead-weight volume. Similarly the zero oil outflow probability values were scaled with respect to the water ballast volume for each arrangement, taking as a reference the water ballast volume for the double sides only arrangements.

6.4 THE FINAL RESULTS

Tables D.2, D.4 and D.6 in Appendix D, summarize the processed results for the probability of zero oil outflow, expected and extreme 1/10 oil outflow, from the analysis of all the Single-Skin, Double-Hull and Mid-Deck arrangements respectively. Within each concept, the results are grouped according to the design parameters that produced the different arrangements in that concept group[2]. Thus for Single-Skin arrangements, the results are grouped according to:

- Number of transverse bulkheads.
- Tank Breadth Ratio.

Similarly, the results for Double-Hulls are grouped according to:

- Number of longitudinal bulkheads.
- Double-Hull space configuration.
- Ratio of double bottom to double sides capacity.

Lastly, for Mid-Deck arrangements the results are grouped according to:

- Mid-deck position.
- Extent of cargo tank longitudinal subdivision.
- Double sides configuration.

The results are then plotted against selected variables. The graphs are assembled in Appendix D.1.

When the number of data points allowed, trend-lines were fitted. The type of fit was selected to give the highest possible correlation factor ‘r’, with the simplest possible equation. Where a linear fit is chosen, the gradient of the trend-line provides a useful measure of the rate of change of the outflow measure in relation to the variable investigated. Non-linear trend-lines on the other hand, highlight the presence of local maximum or minimum values.

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[2] See figures 5.1, 5.2 and 5.3 in chapter 5.

6.4.1 SINGLE SKIN ARRANGEMENTS WITH WING BALLAST TANKS

Figures D.1, D.2 and D.3 show the oil outflow results for this concept, against the average non-dimensional cargo tank volume. For the purpose of this study, the average cargo tank volume is defined as the arithmetic mean:

$$\overline{V}_t = \frac{\sum V_t}{n} \tag{6.1}$$

where V_t is the volume of any cargo tank within the maximum penetration depth of 0.6 B and n is the number of such cargo tanks. The tank volume is made non-dimensional by dividing with the total cargo capacity of each arrangement.

Figures D.4 to D.6 and D.7 to D.8 present those same results against the non-dimensional volume of single wing and centre tanks respectively. Because the probability of zero oil outflow depends on the ballast capacity, in this case the wing tank volume, there is no need to plot the former against centre tank volume and the graph is omitted.

The correlation between the expected and extreme oil outflow results and the Tank Breadth Ratio (B_W/B_C) is shown in the graphs of figures D.9 and D.10 respectively. The data points are grouped by non-dimensional tank length, in other words according to the number of transverse bulkheads in the corresponding tank arrangements. The graph in figure D.9.b is extracted from reference [6][3] and presents a similar attempt to correlate expected oil outflow ($\overline{V}$) and non-dimensional wing tank breadth (Y_W) for single skin arrangements with 2 longitudinal bulkheads and varying number of transverse bulkheads. The outflow results in figure D.9.b assume that every second wing tank, either side, is a segregated ballast tank. This graph is discussed in Section 7.2.1 in comparison with the graph of figure D.9.

Figures D.11 and D.12 present the alternative way of plotting the same outflow results. The outflow values are plotted against the non-dimensional tank length L_t/L - where L_t is the tank length and L=LBP is the ship length between perpendiculars - and the data points are grouped according to the B_W/B_C ratio. Figure D.13 shows the zero oil outflow probability results in that same format.

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[3] Figure 4.20 from page 112 of [6].

Figure D.14 shows the corrected probability of zero oil outflow[4] against the non-dimensional wing tank breadth (B_t/B). The wing tank breadth is made non-dimensional by dividing with the maximum beam (B) of the ship. The probability values 'before correction', are given in table D.2 .

6.4.2 DOUBLE-HULL ARRANGEMENTS

Figures D.15 and D.16 show the plots of expected outflow and extreme outflow, in that order, versus the non-dimensional average cargo tank volume. The data points are grouped by type of double-hull configuration and by double bottom to double sides capacity ratio (V_{DB}/V_{DS}) value. Figure D.17 presents the probability of zero oil outflow against the double bottom to double sides capacity ratio (V_{DB}/V_{DS}). In this case, for any V_{DB}/V_{DS} ratio value, the results for all types of double sides configuration coincide.

6.4.3 MID-DECK ARRANGEMENTS

Figures D.18 and D.19 give the correlation of expected and extreme oil outflow with the non-dimensional average volume of one upper and one lower cargo tank. Similarly, figures D.20 and D.21 present the same outflow results against the non-dimensional volume of the upper cargo tank while figures D.22 and D.23 show the respective results against the non-dimensional volume of the lower cargo tank. In figures D.24 to D.26, the graphs show the relationship between the oil outflow results and the ratio of lower to upper tank volume (V_l/V_u).

In figures D.27 and D.28 the oil outflow results are plotted against the relative height at which the mid-deck is positioned (H_t/D), where (D) is the depth of the ship. The probability of zero oil outflow is shown plotted against the same variable in figure D.29. These probability results do not need any correction because all the mid-deck arrangements have the same double sides volume and consequently the same ballast capacity as the Double-Sides only configurations used as the reference.

In all the graphs mentioned above, the data points are grouped according to the extent of longitudinal subdivision and according to the configuration of the double sides in the corresponding tank arrangements.

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[4] As defined at the end of the last paragraph of section 6.2.

6.4.4 ADDITIONAL GRAPHS

In order to highlight the differences and similarities in the performance of the three concepts investigated, the expected and extreme oil outflow results and the results of probability of zero oil outflow of all three concepts are merged into the respective graphs in figures D.30 to D.32 of Appendix D.2.

6.5 OIL OUTFLOW CHARTS

Appendix D.3 contains the oil outflow charts, defined earlier in 6.3, for all the tank arrangements investigated. In contrast with the single-valued outflow measures, which present outflow performance in a narrow set of conditions, the outflow charts give a fuller picture of the outflow performance of a tank arrangement for all possible accident occurrences. By grouping several charts into one, it is possible to compare at a glance different tank configurations and even different tanker concepts. The comparisons however, are more of qualitative than quantitative nature. To obtain a quantitative comparison from an outflow chart, it is necessary to isolate a single event or a set of events from that chart. Then of course, this comparison will convey information only about the particular event or set of events and about the conditions pertaining to them. The outflow measures defined so far, are examples of that sort of process.

For ease of comparison, all the charts feature the same scale for theoretical oil outflow volume. Although the values of theoretical oil outflow are not non-dimensional, the comparison is not affected to any significant extent because all the arrangements examined have about the same cargo capacity. With few exceptions, the individual outflow charts for each arrangement are grouped in such a way as to highlight the effect of only one design variable at a time.

Figures D.34 to D.37 show the oil outflow charts of all the single-skin arrangements (including Double-Sides only configurations) in groups of constant tank length, i.e. with the same number of transverse bulkheads. Thus, the effect of varying tank breadth ratio (B_W/B_C) is exposed.

Figures D.38 to D.42 show the opposite relationship. The outflow charts are grouped for constant tank breadth ratio and thus make evident the effect of tank length or of the number of transverse bulkheads. The double-sided tank arrangement **SS40B** was included in both figures D.38 and D.39, for comparison with the other Double-Side arrangements and with the configurations of the same B_W/B_C ratio value (=0.250) respectively.

The effect of the number of longitudinal bulkheads is highlighted from the outflow charts in figures D.44 to D.52. Each figure corresponds to a group of arrangements with identical double hull configuration and V_{DB}/V_{DS} ratio value.

In figures D.53 to D.55 the same data is presented but now the type of double hull configuration is the variable while the number of longitudinal bulkheads and the value of the V_{DB}/V_{DS} ratio are kept constant. Similarly, figures D.56 to D.64 show the effect of varying V_{DB}/V_{DS} ratio within groups of double-hull arrangements with the same double hull layout and the same number of longitudinal bulkheads.

Figures D.66 to D.71 present the oil outflow charts for the Mid-Deck arrangements. More specifically, the outflow charts in figures D.66, D.67 and D.68 expose the effect of the extent of longitudinal subdivision for three respective positions of the mid-deck. Figures D.69 to D.71 present the inverse case, with the vertical position of the mid-deck being treated as the variable for three different extents of longitudinal subdivision.

Finally, figures D.72, D.73 and D.74 show the effect of the addition of horizontal subdivision in comparison to the addition of a centreline longitudinal bulkhead, for three vertical positions of the former.

6.6 COMPARISON WITH PUBLISHED RESULTS

Although several oil outflow studies were carried out by different authors presented in Chapter 2, their results are not always directly comparable with the results herein.

The reasons for this are:

- Different initial assumptions in the analysis, e.g. different probability density functions and different damage assumptions.
- Different computation methods, e.g. “simplified” vs. “iterative” methods.
- Different tank arrangements examined.
- Different purpose of analysis (see Section 2.1, second and fifth paragraphs in particular).

Where feasible the oil outflow results were compared in two ways:

1. With respect to the absolute magnitude of the results.

The results given in [6] show slightly higher expected oil outflow values for both single skin and double hull arrangements. This is expected since in [6] the theoretical oil outflow is taken equal to the full load of the damaged tanks, without any mitigating factors.

There is no agreement however, neither with the expected oil outflow results obtained with the "simplified" methods of [10, 11], nor with the results of the similar study in [9]. The values given in the above references are consistently lower than the values obtained in the present study. The important differences in the methodologies and the assumptions of each work, as highlighted in Chapters 2 and 4, explain the discrepancy.

Should summarise the results at least.

The "iterative" methods in [7, 8] give higher values of expected oil outflow for the same reason as explained earlier in the case of [6].

As far as the probability of zero oil outflow is concerned, the only comparable data are the results calculated in [7, 8]. The values given in [7] agree quite well, taking into account the differences in the tank arrangements examined, with the results presented herein. On the other hand the probability values given in [8] are much lower, almost by a factor of three, suggesting that they represent only damages in the cargo region of the ship, thus omitting a significant portion of the total probability domain.

2. With respect to the relative magnitude of the results, or effectively their trends.

The oil outflow results in [7, 8, 9, 10, 11] do not lend themselves to this kind of comparison as they are obtained from distinct arrangements with too many differences. The results in [6] are the only available data for comparison and show similar trends to the ones discovered in the present study. Further discussion on the similarities follows in Section 7.2.1.

7 EFFECT OF DESIGN PARAMETERS ON OIL OUTFLOW

7.1 EFFECT OF TANK VOLUME

From the definition of potential oil outflow and as anticipated in Section 5.1, we can expect an increase of oil outflow with increasing cargo tank volume. The results confirm this trend.

7.1.1 SINGLE SKIN ARRANGEMENTS WITH WING BALLAST TANKS

When the average volume of cargo tanks increases there is a clear trend for potential oil outflow to increase too. As shown in figures D.1 and D.2, this trend is linear for both expected and extreme oil outflow values. The corresponding trend line slopes are 36% and 208%. The data points on each graph are grouped according to the non-dimensional length of the cargo tanks (L_t/L), and according to their Tank Breadth Ratio (B_W/B_C). In the case of expected oil outflow (figure D.1), this grouping reveals two additional underlying trends:

1. As the average tank volume decreases under constant tank length, i.e. through increase of the Tank Breadth Ratio (TBR)[1], the value of expected oil outflow first decreases, following more or less closely the overall trend, up to a TBR of 0.25. Beyond this ratio, the value of expected oil outflow for each tank length dips to a minimum, in the region corresponding to TBR values between 0.5 and 0.75, before rising back to the overall trend level at the TBR value of 1.0. This departure from the primary trend is possibly due to the differing water ballast arrangement from one tank configuration to the other.

2. Decreasing the average tank volume under constant TBR, i.e. through decrease of tank length, brings a straightforward decrease in expected oil outflow. The trend is roughly the same for all TBR values.

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[1] Because the maximum damage penetration is taken to be 0.6B, for Tank Breadth Ratios (B_W/B_C) of up to 2.0, any damage sustained involves wing tanks only on the damaged side of the ship. Since this study examines Tank Breadth Ratio values up to 1.0, the average cargo tank volume includes wing cargo tanks on one side of the ship only. Therefore, under constant ship beam and tank length, the average cargo tank volume decreases when centre tank breadth decreases and wing cargo tank breadth correspondingly increases, or effectively when the Tank Breadth Ratio (B_W/B_C) increases.

In the case of the extreme 1/10 oil outflow values (figure D.2), the data points seem to fit closer to the overall linear trend than in the case of expected oil outflow. Because extreme oil outflow generally reflects the outcome of high penetration incidents, it is less dependent on the position of the longitudinal bulkhead or the Tank Breadth Ratio. In the same way the water ballast arrangement, which depends solely on the wing tank dimensions, has a lesser effect on this trend.

By plotting the outflow results separately against the centre cargo tank volume and the wing cargo tank volume, we can extract further information. Figures D.7 and D.8 show expected and extreme oil outflow values against the non-dimensional centre cargo tank volume. As expected, the trend is more definite in the case of extreme oil outflow. This happens because extreme oil outflow is associated with the worst spilling incidents which occur when centre tanks are ruptured, in addition to the wing tanks. The fact that expected oil outflow is associated with incidents with smaller penetration (which primarily affect wing tanks), is reflected in the somewhat larger scatter of values around the trend for expected oil outflow.

Similar observations can be made from the graphs of outflow values against wing tank volume. A marked trend exists in the case of expected oil outflow (figure D.4), showing a linear increase with increasing tank volume. However, this trend appears to depend quite strongly on one additional factor: Tank Breadth Ratio. This could be explained by the fact that with narrower wing tanks the number of wing ballast tanks increases and therefore the value of the expected oil outflow becomes increasingly dependent on the centre tank volume. The limiting case of this is the full double side arrangements, where all the wing tanks are used for water ballast and therefore their volume has less impact than the centre tank volume on expected oil outflow.

The plotting of extreme oil outflow values against wing tank volume (figure D.5) also supports the above hypothesis. As explained above, extreme oil outflow depends mainly on the volume of centre cargo tanks which explains the wide scatter of values in the graph. However, with increasing wing tank volume under constant tank length, i.e. increasing only breadth, a negative trend of decreasing extreme outflow values emerges. Increasing the breadth of wing tanks under constant tank length, means that the breadth of centre tanks decreases since the beam of the vessel is kept the same. Consequently the volume of centre cargo tanks decreases, leading to lesser extreme outflow values.

7.1.2 DOUBLE HULL ARRANGEMENTS

Again, oil outflow increases in a linear fashion (figures D.15 and D.16), with increasing size of cargo tanks. With this set of results the trend is more clearly defined than with Single-Skin configurations. This is expected, since within each Double-Hull configuration the cargo tanks are all the same size. Furthermore, the ballast is evenly distributed along the side of the ship, in the double hull. This even distribution of cargo and ballast volume gives more uniform results across the range of Double-Hull configurations.

The slope of the expected outflow trend line (figure D.15) is somewhat steeper than before at 40%, while the extreme outflow slope (figure D.16) is flatter at only 136%, as compared to 208% for Single-Skin arrangements. For each cargo tank volume, the expected outflow and extreme outflow values lie within bandwidths of about 2% and 7% of the deadweight volume respectively. That variation in oil outflow is due to the different distribution of ballast between sides and bottom and the different configuration of the ballast tanks.

7.1.3 MID-DECK ARRANGEMENTS

For this category of arrangements potential outflow also shows a tendency to increase with increasing cargo tank volume (figures D.18 and D.19). However, there is a wide scatter in the outflow values for each tank volume, due to the effect of the horizontal tank subdivision. The bandwidth delimiting the scatter is maximum for the case of configurations with partial longitudinal subdivision, i.e. with a longitudinal centreline bulkhead in the upper cargo spaces only, about 4% and 20% of the deadweight volume for expected and extreme outflow values respectively. This represents variations of 50% and 100% correspondingly.

7.2 EFFECT OF RELATIVE SIZE OF ADJACENT TANKS

Referring back to Section 5.2, the tank configurations examined allow the investigation of the effect on oil outflow of relative size of tanks for the following cases:

- wing and centre cargo tanks in conventional single skin arrangements,
- upper and lower cargo tanks in mid-deck arrangement.

In practical terms, under this heading the effect of the position of the longitudinal bulkheads in Single Skin designs and the horizontal subdivision in Mid-Deck designs can be investigated.

7.2.1 RELATIVE SIZE OF WING AND CENTRE CARGO TANKS

Since all the cargo tanks within a given tank arrangement have the same length and height, it follows that the relative size of wing and centre cargo tanks is determined by the ratio of their breadths (B_W/B_C), referred to, in this study, as the Tank Breadth Ratio (TBR).

Figures D.9 and D.10 show the expected oil outflow and extreme oil outflow respectively, plotted against Tank Breadth Ratio. As far as expected oil outflow is concerned, the data shows a consistent trend for every tank length, presenting a minimum expected outflow value for TBR values somewhere between 0.5 and 0.75. Comparing the graph in figure D.9 with the graph of figure D.9.b in Appendix D.1.1, the similarities are strong. However, two important differences distinguish them:

1. The data points in the latter graph follow a smooth second order curve, whereas the results of this study produce an irregular path.
2. The curves in figure D.9.b indicate a minimum outflow value for a TBR value of approximately 1.167 [2] as opposed to the TBR value in the range 0.5 to 0.75 suggested by the data in figure D.9.

Both differences originate in the assumptions made in [6].

Bearing in mind the definition of potential outflow and the principles presented in Section 5.1, it is clear that for any increase in wing tank breadth, under constant tank length and depth, a directly proportional increase of the contribution to oil outflow from these tanks can be expected. Similarly, the contribution of centre tanks decreases since their volume decreases. The relative magnitude of the changes in the two components determines the resultant change in the expected oil outflow value.

Referring back to the third paragraph of Section 6.3.1, it is evident that for the parametric variations examined in [6], it is the number of segregated wing ballast tanks that is kept constant rather than the ballast volume. Consequently, when increasing wing tank breadth, the balance between wing cargo and wing ballast tank volume is not affected and the volumes of both increase in the same continuous fashion. Since the corresponding change in centre cargo tank volume is also smooth, it follows that the change in expected oil outflow will be a continuous function of wing tank breadth. Hence the smooth curves exhibited in figure D.9.b.

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[2] The corresponding "optimum" wing tank breadth of 0.35 is translated into a TBR value through the simple relation:

$$B_w/B_c = \frac{Y_w}{(1-2\cdot Y_w)} \qquad (7.1)$$

On the other hand, the present study assumes a constant ballast volume constraint. This means that when wing tank breadth increases and hence wing tank volume increases, the number of wing ballast tanks has to decrease in order to keep the total ballast capacity in the prescribed range. Accordingly the number of wing cargo tanks increases, introducing a step change in total wing cargo tank volume. Also, the shift of ballast volume in the longitudinal direction induces a change in the probability component associated with the longitudinal location of damage. These step changes in wing cargo tank volume and the associated probability explain the irregular nature of the graph in figure D.9.

Concentrating on the "optimum" wing tank breadth now, as explained this value depends directly on the balance of the oil outflow contributions from wing and centre cargo tanks and hence on the distribution of cargo capacity between wing and centre tanks. In comparison with the assumption of [6], the ballast volume constraint introduced in this study, results in a more rapid increase of wing cargo tank volume with increasing tank breadth. The corresponding decrease in centre cargo tank volume is not affected. Therefore it is clear that the "optimum" volume distribution will now occur at a reduced wing tank breadth, i.e. at a lower TBR value.

In order to highlight the similarity of the two sets of results discussed above, a second order curve was fitted to the data. As expected it agrees quite well with the data for each tank length, giving a family of similar curves with tank length as parameter. A particularly strong similarity divides the curves and their associated data in two pairs corresponding to the pairs of tank arrays [7x3], [4x3] and [9x3], [5x3][3]. The link that possibly explains the similarity is that within each pair the transverse bulkhead spacing of the second tank array is exactly twice that of the first tank array. Thus the transverse bulkhead positions coincide resulting in oil outflows of different magnitude but following the same pattern. Additional data is required to confirm this hypothesis.

The observation of extreme oil outflow data yields the same conclusions, with the exception of the minimum value appearing now closer to the tank breadth ratio value of 1.0 . Again the same 'pairing' is noticed in the second order curve fits.

7.2.2 RELATIVE SIZE OF UPPER AND LOWER CARGO TANKS

In this case the relative size of tanks is determined by the volume ratio V_l/V_u where V_l is the lower cargo space volume and V_u the upper one. Figures D.24 and D.25 show

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[3] The double-sided arrangements [7x1], [4 x1], [9x1] and [5x1] are grouped with the tank arrays featuring the same number of transverse bulkheads.

the expected and extreme outflow values respectively, plotted against this volume ratio.

In the case of expected oil outflow it is clear that larger lower cargo spaces, i.e. values of the ratio greater than 1.0, are detrimental to oil outflow. Furthermore, the data shows a minimum for ratio values around 1.0, for configurations with the same subdivision in the lower and upper cargo spaces. This suggests that oil outflow is minimum when the horizontal subdivision is placed at approximately mid-height of the ship depth. More data points are needed to validate this, especially for the configurations with different subdivision in lower and upper spaces. If this latter type of arrangement also showed minimum outflow for $V_l/V_u = 1.0$ then this would imply that really, the condition for minimum outflow is equal volume of upper and lower cargo spaces and not the position of the oiltight deck at mid-height.

With respect to bottom damage only, the position of the mid-deck achieving a favorable hydrostatic balance of the cargo is given by the formula [29]:

$$H \leq \frac{\rho_w \cdot d_{min} + p_{aw} - p_{ao_{max}}}{\rho_{o_{max}}} \qquad (7.2)$$

where H is the allowable height of the horizontal oil tight deck from the base line, d_{min} is the minimum draught, p_{aw} and $p_{ao_{max}}$ are the pressure above the free surface of the sea and the maximum pressure above the free surface of the cargo oil respectively. Similarly, ρ_w and $\rho_{o_{max}}$ are respectively, the density of seawater and the maximum density of the cargo oil.

Putting the corresponding values for this study, in equation (7.2) we obtain the result: $H = 18.91$ m. This result means that for any of the above configurations of the longitudinal subdivision, the optimum position of the mid-deck, with respect to side damages, ensures adequate hydrostatic balance for oil containment in the case of bottom damages.

Nevertheless, figure D.27 shows that when a full depth longitudinal bulkhead is fitted, the position of the mid-deck becomes less critical with respect to side damages.

When examining extreme outflow values, the same observation as above can be made. There is no obvious minimum value though, with the exception of the configurations with a full height centreline bulkhead, which agree with the finding for expected outflow.

7.3 EFFECT OF DISTRIBUTION OF SEGREGATED BALLAST VOLUME

As explained in section 5.1, the location and volume of non oil containing watertight spaces, influence the oil outflow characteristics of any particular tanker design. Within current practice limits, the only such spaces that the designer can experiment with are the segregated ballast tanks.

7.3.1 SINGLE SKIN ARRANGEMENTS WITH WING BALLAST TANKS.

It is usual design practice to use a sufficient number of wing tanks as segregated ballast tanks. Typically, these ballast tanks are staggered with wing cargo tanks along the ship mid-body. The MARPOL regulations brought the concept of the protective location of water ballast tanks and consequently the trend was to narrow the wing tanks in order to spread the ballast over the ship side. However, the trend did not lead to the obvious solution of accommodating water ballast in full double sides and cargo in centre tanks only. Indeed, that would call for 'unwanted' additional tank subdivision to keep individual cargo tank volume within the limits set by MARPOL.

The results of the present study show that in terms of 'total' pollution prevention, the concept of protective location of water ballast is sound. However, the practice of alternating ballast and cargo wing tanks, although having certain advantages, does not serve the pollution avoidance cause. Examining figure D.14, it emerges that for the same wing tank breadth, configurations with fewer large ballast tanks, i.e. longer, are more effective than those with short tanks having more numerous staggered ballast tanks. The gain in probability of zero oil outflow, up to 10%, is more evident in tank arrangements with wide wing tanks. Figure 7.1 gives a graphical explanation of the above and shows that it is preferable to group ballast tanks together, thus emulating the arrangements with longer ballast tanks.

Another advantage of having larger, if fewer, ballast tanks is that oil outflow is potentially reduced because ballast tanks can retain a larger quantity of oil from adjacent damaged cargo tanks.

Taking the concept of protective location of water ballast to the extreme we arrive at the Double-Sides configuration where all the wing tanks are used as ballast tanks. The probability of zero oil outflow is thus maximised but the price to pay is higher expected and extreme oil outflow values when the inner longitudinal bulkhead is breached and no additional longitudinal subdivision is provided in the cargo space.

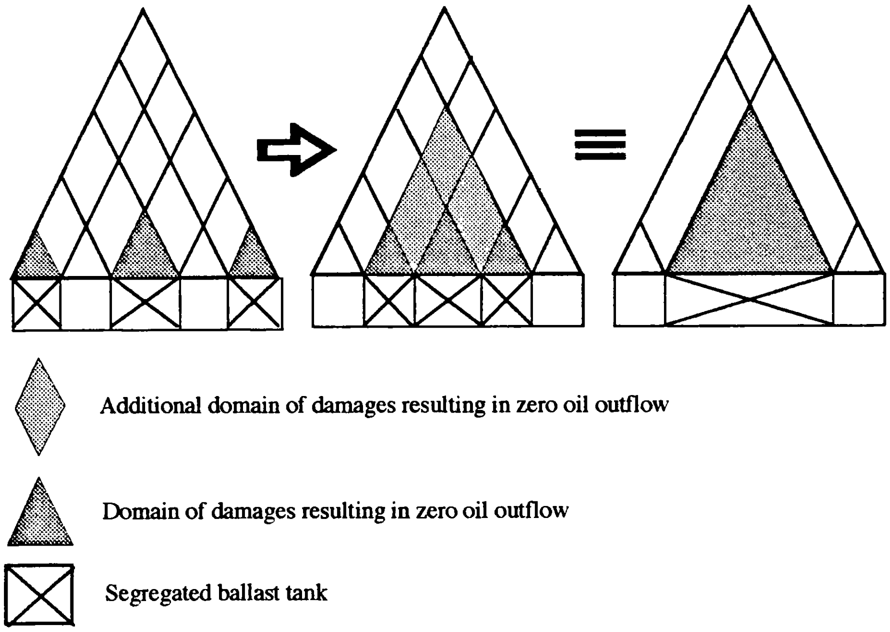

Figure 7.1: Effect of grouping or joining ballast tanks together.

7.3.2 DOUBLE HULL ARRANGEMENTS

In Double Hulls the water ballast capacity is distributed between the double sides and the double bottom. Hence the breadth of the double hull spaces is smaller than in arrangements with double sides only. As a consequence the probability of zero oil outflow is reduced in Double-Hull arrangements. The difference of course depends on the breadth of double sides but as an indication it is about 5% lower for the Double Hull arrangements with a double hull breadth of 3.7 metres as compared with the full double side breadth of 5.0 metres. The results show a decrease of about 8% in that probability when the V_{DB}/V_{DS} ratio[4] increases from 0.497 to 2.155, corresponding to a double side breadth decrease from 3.7 to 1.9 metres.

For damages where oil outflow does occur, the arrangements with wider sides perform better. The results show a slight decrease, less than 2% of total cargo capacity, in expected outflow values when the V_{DB}/V_{DS} ratio decreases from 2.155 to 0.497 . The explanation lies in the fact that with wider double-hull sides the probability of penetrating a cargo tank is lower. Also, wider double hull sides can retain a larger percentage of the oil spilled from adjacent cargo tanks.

7.3.3 MID-DECK ARRANGEMENTS

These arrangements feature double sides that accommodate the segregated water ballast capacity. Therefore the results for the probability of zero oil outflow coincide,

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[4] For a definition of the ratio refer to Footnote 2, Section 5.2.2.

within a 0.2% margin, with the results for the double-sided configurations derived from Single-Skin arrangements. The horizontal subdivision of the ballast spaces does not appear to have any noticeable effect on these results.

7.4 SYNTHESIS

So far, the analysis has highlighted some characteristics of the individual cargo or ballast tank that influence oil outflow. In the following sections, these findings are combined to determine how subdivision characteristics affect oil outflow.

Examining the oil outflow charts in Appendix D.3, three different regions can be distinguished, each corresponding to an accident scenario:

- accidents resulting in no oil outflow. The probability of zero oil outflow is the significant quantity of this lower region of each chart.
- Highly probable accidents that result in low to moderate oil outflow. They correspond to the middle region of the outflow charts and the expected oil outflow value is a reasonably good indicator of performance for these cases.
- Less probable accidents resulting in severe oil outflow. They correspond to the top part of the outflow charts and are best described by the extreme 1/10 outflow value.

7.4.1 TRANSVERSE SUBDIVISION

Traditionally, transverse bulkheads in the cargo region of the ship are more or less equally spaced. Therefore, the prevalent subdivision characteristic, in this case, is the number of bulkheads. By varying the number of transverse bulkheads, the designer can control the average volume of cargo and ballast tanks and thus greatly influence the oil outflow response of the ship. Comparison of figures D.34 to D.37 (Appendix D.3.1) reveals that the number of transverse bulkheads affects oil outflow in all three regions described previously.

Increasing the number of transverse bulkheads creates more smaller segregated water ballast tanks. This fragments the probability domain and even reduces it, if the ballast tanks are staggered with cargo tanks as shown in Section 7.3.1. Also, smaller ballast tanks can retain less oil from a damaged cargo tank. The negative effect of staggering ballast and cargo tanks is revealed in the outflow charts (figures D.34 to D.37) as an increasing divergence of the value of the zero oil outflow probability below the maximum value of 33%, with increasing number of bulkheads. As an indication, this variation rises from about 3% for 3 bulkhead arrangements (figure D.34), to 8% and 13% for 4 and 6 bulkhead arrangements respectively (figures D.35, D.36), reaching 15% in the case of tank arrangements with 8 transverse bulkheads (figure D.37).

In the middle region of the outflow charts, i.e. for highly probable accidents resulting in moderate oil outflow, an increasing number of transverse bulkheads translates positively into decreasing oil outflow. The improvement is substantial although the expected outflow values do not reflect it so well. Taking an average value of expected outflow for each category of tank arrangements, the variation amounts to less than 3% of the total cargo capacity, or 6,712 m^3 of oil, in the best instance. However, by sampling the outflow charts in figures D.34 to D.37 and comparing the 'worst performer' from each group of arrangements, one can see for example that while there is a 70% probability that outflow from a 3 bulkhead configuration will not exceed 64,000 m^3 (figure D.34), if one bulkhead is added the same level of probability corresponds to a 49,000 m^3 limit (figure D.35). This corresponds to a reduction of more than 23% or in terms of total cargo capacity 6.7%. If two further bulkheads are added, the 70% probability level will now correspond to an outflow limit of about 35,000 m^3 (figure D.36), an additional improvement of 28.5%. Similar results apply across almost the whole range of probability levels, from 40% to 90%.

Lastly, for low probability incidents linked to extreme oil outflows, an accurate indicator of variation is the extreme 1/10 outflow value. Using an average value of extreme oil outflow for comparing each group of arrangements and increasing the number of transverse bulkheads from 3 to 4, 4 to 6 and from 6 to 8, the improvement is noticeable, with a reduction in extreme oil outflow of 11.7%, 8.1% and 4.6% respectively in terms of total cargo capacity.

7.4.2 LONGITUDINAL SUBDIVISION

Two parameters define longitudinal subdivision:

- the number of longitudinal bulkheads and
- their position relative to each other and to the ship's side.

In the following discussion (Sections 7.4.2.1 and 7.4.2.2), only the effects of longitudinal bulkheads subdividing the cargo spaces are considered, thus excluding discussion of the effects of the longitudinal bulkheads forming the double sides in relevant configurations.

7.4.2.1 Effect of Number of Longitudinal Bulkheads

As with transverse subdivision, the designer can vary the number and volume of cargo tanks by varying the number of longitudinal bulkheads. The change of tank volume that results mainly affects oil outflow volume. The probability of zero oil outflow is more dependent on volume changes due to the position rather than number of bulkheads, as explained in section 7.4.2.2.

Referring to the oil outflow charts in figures D.44 to D.52 of Appendix D.3.2, one can clearly see the improvement with increasing number of bulkheads in Double-Hull configurations. The provision of a centreline bulkhead proves to be a highly efficient measure, cutting oil outflow back by about 50%, across the range of possible damages. This finding is confirmed by similar results for Double-Sides only and Mid-Deck arrangements (figure D.72 of Appendix D.3.4 and figures D.66 to D.68 of Appendix D.3.3). Replacing the centreline bulkhead with two side bulkheads achieves only a further 17% reduction in oil outflow.

In terms of expected oil outflow, the provision of a centreline bulkhead on Double-Hull arrangements, yields a reduction of 36% to 42%. The corresponding results for Double-Sides only and Mid-Deck arrangements are 31% and 42% to 51% respectively. The corresponding values for extreme oil outflow are: 32% to 44%, 30% and 26% to 53% respectively.

7.4.2.2 Effect of Position of Longitudinal Bulkheads

Under this heading we examine configurations with at least two longitudinal bulkheads within the cargo space. In Single-Skin configurations, apart from adjusting average tank volume, the tanker designer can control the number of segregated wing ballast tanks and the balance of ballast and cargo volumes in the wing portions of the ship, by shifting the position of longitudinal bulkheads inboard or outboard. This influences both the probability of zero oil outflow and the potential oil outflow values. In partly or wholly double-skinned arrangements however, the shifting of the longitudinal bulkheads affects only cargo tanks and therefore influences only oil outflow volume.

Starting with Single-Skin arrangements and the probability of zero oil outflow, figure D.14 shows that the wider the wing ballast tanks in general, the lower the zero outflow probability. However, it was explained in section 7.3.1 that this is not an absolute trend and other factors, such as tank volume and grouping, can improve or worsen the performance for a given ballast tank breadth. This is probably the reason for the absence of a single trend in the graph of figure D.14.

Figures D.11 and D.12 show expected and extreme oil outflow values respectively, against the non-dimensional length of tank. The data in the graphs is grouped according to the Tank Breadth Ratio value. From the graphs emerges the fact that for a given tank length potential oil outflow decreases as the Tank Breadth Ratio increases, i.e. when the wing tanks become wider. Tracing the trend lines for each tank breadth group of data points reveals that when tank breadth is kept constant, expected oil outflow varies almost linearly with tank length.

Moving towards higher tank breadth ratio values, the linear trend of the expected oil outflow values remains. But beyond the ratio value of 0.5 the trend lines tend to lie within a narrow band, suggesting a decreasing influence of wing tank breadth. More data points are needed, covering the tank breadth ratio values between 0.25 and 0.5 and beyond 1.0, to remove any uncertainty. Nevertheless, the evidence discussed here in conjunction with the findings in Section 7.2.1 point to the existence of a lower limit, a line of minimum expected oil outflow, corresponding to an optimum value of the tank breadth ratio. This optimum value of the ratio appears to lie somewhere between 0.5 and 0.75. In practical terms this means that, in a two longitudinal bulkhead arrangement and for any tank length, the optimum position of the side longitudinal bulkhead is somewhere between 0.25 and 0.3 of the ship's beam. Figures D.12 and D.10 relating to extreme oil outflow lead to the same sort of conclusions as above, however the optimum tank breadth ratio value is nearer 1.0 . In other words the optimum position of the side bulkhead for minimum extreme outflow is close to 0.33 of the ship's beam. This is logical based on the findings in section 7.1.1 that for any given tank length, this position of the longitudinal bulkhead results in the lowest average tank volume. Therefore it is not surprising that it yields the lowest extreme outflow value as well.

From the discussion so far, it is clear that the conditions for maximum probability of zero oil outflow and minimum expected and extreme oil outflow are contradictory. This fact is further evidenced by the outflow charts in figures D.38 to D.42 in Appendix D.3.1, showing that the configurations with higher probability of zero oil outflow have a poorer oil outflow pattern.

7.4.3 HORIZONTAL SUBDIVISION

The oil outflow studies referred to in Section 2.2.4, are based on the assumption that the vertical extent of damage in a collision is from the bottom of the ship up to the deck without limit. This assumption, though partly justified, completely obscured the potential benefits of horizontal subdivision in collision incidents. Figures D.72 to D.74 in Appendix D.3.4 demonstrate that the provision of an oil tight horizontal subdivision deck, or as it is commonly known a mid-height deck, has a very similar effect to that of fitting a centreline longitudinal bulkhead on a Double-Sides only arrangement.

The resultant reduction in oil outflow ranges from 23% to 52% but remains fairly constant close to 50%, in the case of the arrangement with the mid-deck positioned at the middle of the ship's depth (figure D.73). These results make the Mid-Deck configurations an attractive alternative, especially when their superior performance in grounding accidents [7, 8, 9, 10, 11, 12] is taken into account.

7.4.4 DOUBLE-SIDES AND DOUBLE-HULL

Both Double-Sides and Double-Hull arrangements have been introduced as measures to ensure total cargo containment in case of rupture of a ship's hull. The all important parameter in these arrangements is the distance between the outer and inner shell. The wider the gap between the two, the larger the damage extents that can be sustained without involving the cargo spaces. However, the dimensions of the watertight spaces thus created are defined by their use. The most common use, as dedicated ballast tanks, means that the dimensions are determined by the maximum amount of ballast the ship has to carry in order to meet both the operational and the regulatory minimum draught requirements[5]. That in its turn, is determined by the geometry of the hull: a slender, low Cb geometry needs less added weight to sink to a required draught, than a fuller, high Cb form.

In the present study all the alternative arrangements where accommodated within geometrically identical hulls. Consequently the required water ballast volume is the same for all the configurations. This means that all the Double-Sides only arrangements feature the same double-sides width and therefore yield the same zero oil outflow probability result. The corresponding zero oil outflow probabilities for Double-Hulls are lower because the side ballast spaces are narrower as pointed out in Section 7.3.2. Nevertheless, one should not compare the two only on the basis of side collision damages. Clearly, the Double Hull configurations would show a higher

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[5] IMO specifies that ballast capacity should be sufficient to allow the following conditions with lightship and water ballast only:

1. Minimum draught amidships = 0.02 L+2.0 (m) where L the length of the ship.
2. Maximum trim aft = 0.015 L.
3. Full immersion of propeller.

value of zero outflow probability for bottom damage, whereas Double-Sides only arrangements would spill oil in virtually all such cases.

The internal segregation of double-hull spaces appears to have no significant effect on any aspect of oil outflow as shown in figures D.53 to D.55 of Appendix D.3.2. The small discrepancies in the outflow patterns are probably due to the different floatation characteristics of each arrangement. Indeed some damages result in different extents of asymmetric flooding in L-type and separate double-sides and double bottom arrangements. In Mid-Deck arrangements the extension of the horizontal subdivision into the double sides produced small to negligible differences in oil outflow as indicated by the oil outflow results in Table D.6 and in figures D.18 to D.29 of Appendix D.1.3. The fact that these differences appear more significant in the case of extreme oil outflow results would suggest a link with the reduced volume of subdivided double side ballast tanks and their reduced capacity for retaining oil from adjacent damaged cargo tanks. However, the sign of the difference is not the same for all the mid-deck configurations thus hinting a more complex situation. Additional variations of the Mid-Deck arrangements should provide more insight into this aspect.

7.4.5 IMPROVING OIL OUTFLOW PERFORMANCE IN COLLISION

Referring back to the beginning of Section 7.4, there are clearly two aspects of oil outflow performance that can be improved upon by adequate design:

- the ability to withstand damage without any spillage of oil, i.e. maximizing the probability of zero oil outflow and
- the limitation of oil outflow to a minimum for any damage occurrence, i.e. minimizing expected and extreme oil outflow.

The requirements for improving those two aspects are, most of the time, clashing. Which aspect is more desirable and should thus be given the priority in optimizing a design is highly debatable.

7.4.5.1 Maximizing the Probability of Zero Oil Outflow

The probability of zero oil outflow depends on:

- volume of non-oil carrying spaces,
- location and distribution of this volume within the hull of the ship.

Main non-oil carrying spaces in any oil tanker are all the spaces forward of the collision bulkhead, the spaces aft from the pump room bulkhead (excluding oil bunkers and cofferdams) and the segregated water ballast tanks. The volume of these spaces is bound at the low end, by the minimum requirements of regulations and by the design specifications. At the high end, it is bound by the economic considerations which demand the maximization of the cargo carrying capacity for any given size of ship. As the factor of accidental oil pollution avoidance does not enter in the above equation, beyond the regulatory requirements, there is no obvious gain from altering the balance of volumes to the detriment of oil carrying capacity and designs will continue to aim at the regulatory lower bound.

It follows that any improvement must stem from the optimization of the location and distribution of the non-oil carrying spaces. The purpose of the collision bulkhead and the size of modern tankers respectively preclude any change in the location of the spaces forward and aft of the cargo carrying portion of the ship. Thus the only option left is rearranging the segregated ballast tank configuration.

The discussion in Sections 7.3 and 7.4.4 clearly shows that for maximum probability of zero oil outflow, segregated water ballast should be accommodated in double sides. The analysis results and logic dictate that the wider the double sides, the higher the protection against oil outflow following an accident. At this point it should be reminded that the present study deals with cases of side damage only. Therefore the apparent superiority of Double-Sides only arrangements as opposed to Double-Hull arrangements is valid strictly in that narrow context.

As a second option, water ballast can be accommodated in wing tanks. Figure D.14 in Appendix D.1.1 shows that for this type of configuration, although the breadth of wing tanks has a strong effect, the length of wing tanks is the important parameter. The graph shows that irrespective of wing tank breadth, the arrangements with longer wing tanks have the best 'no-outflow' performance. This suggests that ideally the best ballast configuration with any given wing tank breadth is to have a single wing ballast tank. Of course this suggestion ignores any damage stability consideration and is impractical from an operational point of view as well. There is increasing pressure in the international maritime community for new damage stability regulations enforcing long raking damage criteria [30] which will effectively put an upper limit to the length of ballast tanks. Even so, the above finding can still be applied by grouping several shorter ballast tanks together as proposed in Section 7.3.1. Conventional configurations with several staggered ballast tanks should be avoided, when operational and structural considerations allow.

7.4.5.2 Minimizing Expected and Extreme Oil Outflow

The oil outflow results obtained by the present study revealed two important parameters affecting the amount of oil spilled from a side shell rupture:

1. the size (volume) of individual oil tanks and
2. the relative size of adjacent oil tanks.

The size of individual oil tanks is adjusted by the provision of adequate subdivision in the cargo carrying region of the ship. The results indicate that the smaller the cargo tank volume, the lower the expected and extreme oil outflow values. In practical terms there is a lower limit to the size of cargo tanks because for any given size of ship, the smaller the tanks are, the larger their number and too many tanks carry the penalty of extra building and maintenance costs as well as lower deadweight due to increased structural weight. Furthermore, with increasing number of tanks the required loading and unloading patterns become increasingly complicated because of the need to ensure that hull bending during those operations remains within the limits of the structural strength of the hull girder. A few tankers are known to have "jack-knifed" through improper loading or unloading procedure.

The initial stability of certain double-hull designs also needs to be monitored during loading and unloading operations, as it was pointed out that for some load conditions stability becomes marginal. [30, 31] This means additional constraints and complications in the loading-unloading procedures which become worse with increasing number of cargo tanks.

From an operational and maintenance point of view, the provision of subdivision in the form of a horizontal oil tight deck is seen with scepticism [4] as it is a novel solution for which there is no operational experience yet. Ignoring such considerations, it can be said that a horizontal oil tight deck is approximately as efficient as a centreline longitudinal bulkhead, provided the former is optimally positioned. This optimum position appears to be at about mid-height between the keel and the weather deck. However, as discussed in Section 7.2.2 more data is needed to validate that finding.

The question of relative efficiency of transverse and longitudinal subdivision involves the investigation of the effect of tank L/B ratio on oil outflow and could not be addressed with the selected set of sample arrangements.

In the case of arrangements featuring double sides, the provision of at least one longitudinal bulkhead is highly desirable as it reduces oil outflow almost by half. The importance of the provision of a centreline bulkhead in those arrangements is equally highlighted in other oil outflow studies. [4]

When two longitudinal bulkheads are introduced, the factor of relative size of adjacent tanks becomes important. Concentrating on longitudinal subdivision, the results show that irrespective of transverse subdivision there is an optimum balance of capacity between the centre and the wing cargo tanks. This balance is achieved at the optimum position of the side longitudinal bulkhead. In determining the optimum bulkhead position special care must be exercised in controlling the other design variables, as the latter influence the outcome. The discussion in Section 7.2.1 highlights the very common fact that the answers you get depend on how you ask the questions. In this case the approach to the problem of optimum wing tank breadth in [6], although perfectly valid in theory, is not conclusive for practical oil tanker design purposes. Indeed any oil tanker design is a tentative solution to a sum of requirements and constraints. One of the requirements is the carrying capacity of the ship, while the main dimensions are a set of constraints and both should therefore be treated as constants in any attempt to optimize the design with respect to oil outflow. The present work takes these considerations into account and points to a more useful result.

For minimum expected oil outflow the optimum position of the side longitudinal bulkhead, when the segregated water ballast is accommodated in wing tanks, lies in the region from 0.25 to 0.3 of the ship breadth. As the author of [6] rightly points out, this result depends on the amount of ballast and the mean damage penetration, higher values of the latter shifting the optimum bulkhead position inwards. The extreme oil outflow being associated with the larger penetration values, it is thus expected that the optimum bulkhead position for minimum extreme outflow will be inward from the previously suggested values. The results support this hypothesis, locating the optimum position at around 1/3 of the ship breadth. In practice the longitudinal bulkhead should be positioned for minimum expected outflow as this is associated with the most probable damages.

Lastly, regardless of the cargo tank configuration, the ballast tanks should be as large as possible in order to maximize the potential for retaining oil spilled from adjacent cargo tanks.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The present work describes a numerical model for the probabilistic estimation of oil spillage from a tanker involved in a collision. Only damages to the side of the ship are considered. The model is then used as a tool for the investigation of the impact tank arrangement has on oil outflow. Parametric variations of one novel and two conventional arrangements are examined and the relationship between cargo subdivision parameters and oil outflow characteristics is tentatively quantified. At the same time similar results published by other authors are compared and validated where possible.

Although this study is not original, in the sense that the subject of probabilistic estimation of oil outflow from tankers has been researched previously by a good many authors, it introduces two particularities that it is hoped will make some useful contributions to this highly topical subject.

1. It introduces a simple yet realistic model for the correlation of theoretical oil outflow and the random damage location and extents. The currently available literature shows concern and effort at modelling as realistically and accurately as possible oil outflow from bottom damages due to grounding or stranding accidents, yet completely neglects this aspect for collision accidents. The surge in collision accidents involving tankers in 1994 [2] is a reminder that tanker collisions are as likely as grounding or stranding accidents and therefore merit a fair share of attention.

   The model presented herein adopts a quasi-static approach based on the assumptions that:

   - mixing of oil and water is negligible and
   - outflow of oil and inflow of water do not interact.

   Dynamic components to the phenomenon of oil outflow, such as transient effects of impact forces and effects of ship motion, sea currents and waves, are taken into account indirectly in the form of outflow correction factors as explained in Section 4.4.3.

2. In the present study, the possibility of localised damage in the vertical dimension of the ship is recognised and addressed. Three different cases are distinguished:
    a. Localised damage entirely below the waterline.
    b. Localised damage entirely above the waterline.
    c. Damages extending across the waterline.

    Because of the lack of relevant statistical data, studies using the probabilistic concept for collision accidents assessment in general, address only case (c) of the above, while probabilistic oil outflow studies in particular, narrow even further the range of possible damages by assuming only full depth damage extent, from ship bottom to deck. In doing so, they obliterate any link of oil outflow with subdivision variations along the vertical axis of the ship. The present study fills this gap by using two hypothetical probability density functions for the vertical damage location and extent of damage. Probability being the weighing factor in the 'risk' of oil outflow, it only affects the magnitude of the effect of any parameter on oil outflow. Therefore, although the above approach introduces an element of uncertainty in the magnitude of the oil outflow results, its merit lies in revealing previously undetected effects of subdivision on oil outflow.

In implementing the probabilistic concept this study has adopted the proven method of "piecewise" summation of probability over the total probability domain, as used in [7] and [8]. This method, as opposed to the 'simplified' methods presented in [10] and [11], can cope with any shape of compartment thus allowing the investigation of tank arrangements with inclined bulkheads and tanks with unusual shapes[1].

The numerical model works in a satisfactory way producing coherent sets of results.

Comparison with results published by other authors shows significant differences in terms of absolute magnitude of outflow quantities but these are consistent with the differences in the initial assumptions and the modelling of probability and oil outflow.

When comparing sets of 'equivalent' results, the trends exhibited in the results of this study are consistent with the trends derived in similar studies, leading to similar conclusions.

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[1] Such concepts include the "POLMIS" tanker [32], the "Coulombi Egg" tanker [24] and the "Tube" tanker [33].

There are two different aspects in reducing accidental oil pollution from a given tanker design:

1. Improving the effectiveness of oil containment features, i.e. increasing the probability of zero oil outflow.

2. Limiting the amount of oil spilled after an accident, i.e. reducing potential oil outflow.

In the context of the present study, in which only collision accidents are addressed, the probability of oil outflow is found dependent on:

- the segregated water ballast capacity and
- the distribution of the segregated ballast capacity within the cargo space.

Double sides are the most effective for any given ballast capacity and their effectiveness increases linearly with increasing double-sides breadth.

If the segregated water ballast capacity is provided by wing tanks, the probability of zero oil outflow increases with increasing length of the wing ballast tanks.

This effectively means that the requirement for "protective location of segregated ballast tanks" stipulated in the MARPOL regulations is sound. However, in order to achieve their full protection potential the wing ballast tanks should be grouped together, ideally forming continuous double sides. Even grouping wing ballast tanks in pairs is significantly better than single wing ballast tanks alternating with wing cargo tanks.

The analysis of the results reveals two key variables affecting potential oil outflow from any tank arrangement:

1. The average size of elemental oil volumes, i.e. the average volume of individual cargo tanks.

2. The balance of cargo capacity either side of the longitudinal and/or horizontal subdivision members in relevant configurations, i.e. the relative size of wing and centre tanks and/or the relative size of upper and lower cargo tanks respectively.

The effect of any subdivision parameters on potential oil outflow can be explained in terms of the relationship of subdivision parameters to the two variables above.

Both expected and extreme oil outflow increase with increasing average cargo tank volume, extreme outflow increasing by about twice the increase in average tank volume.

For any value of average tank volume, expected and extreme oil outflow become minimum for a specific ratio of cargo capacity either side of a side longitudinal bulkhead in relevant configurations. This ratio depends on the average damage penetration and the segregated water ballast capacity.

Similarly for arrangements featuring horizontal subdivision in the cargo space, expected oil outflow becomes minimum for a certain ratio of cargo capacity above and below the mid-deck.

In terms of the subdivision parameters the previous statements mean that:

- Increasing subdivision in the cargo space reduces potential oil outflow and, more significantly, extreme oil outflow.
- For any extent of transverse subdivision, there is a unique optimum position of the side longitudinal bulkhead which results in minimum expected or extreme oil outflow. This optimum position is dependent on the distribution of probability in the transverse axis of the ship and on the amount of water ballast.
- There is an optimum position of the mid-deck that results in minimum expected oil outflow.

The optimum position of a longitudinal bulkhead in a twin bulkhead arrangement with wing ballast tanks is between 0.25 B and 0.3 B from the side shell. This result applies for a mean damage penetration of 0.2 B and a ballast ratio of 33%.

From the results obtained it appears that the optimum position of the mid-deck depends on the relative extent of subdivision in the upper and lower cargo spaces. When the upper and lower cargo spaces are equally subdivided, the optimum mid-deck position is midway between the weather deck and the baseline of the ship.

The oil outflow results corresponding to the double-sided configurations (including Double-Hulls), highlight the need to provide additional longitudinal subdivision in these configurations. This point, also recognised in other oil outflow studies, raises doubts about the adequacy of the MARPOL 73/78 requirements on tank size and bulkhead spacing.

The present study also highlights a point previously ignored, that horizontal subdivision in the cargo space is also effective in reducing oil outflow in collision accidents. When optimally positioned, its effectiveness is comparable to that of a centreline longitudinal bulkhead. If considered in conjunction with the benefits of horizontal subdivision in grounding accidents, this finding makes the Mid-Deck concept an attractive alternative and certainly worthy of further attention.

When designing tankers with oil pollution avoidance in perspective, there seems to be two distinct schools of thought:

1. tanker design aiming at 'total oil containment' in most probable situations, or
2. tanker design aiming at minimum loss of oil in any situation.

This division puts the emphasis on different oil outflow performance indicators for each case, the probability of zero oil outflow for the first category and potential oil outflow volume for the second category. In connection to the use of these indicators the following suggestions should be given attention:

- The probability of zero oil outflow should not be taken on its own as an indicator of the extent to which 'total oil containment' is achieved but should be taken in conjunction with a measure of the hull area protected, e.g. the attained value of (J) in the Protective Location requirement of the MARPOL regulations.
- Although expected oil outflow is a good measure of overall performance in oil outflow, it should be coupled with the corresponding extreme oil outflow or the probability of zero oil outflow to ensure that the extreme high or low values of outflow do not distort the true image.

8.2 RECOMMENDATIONS

The research presented in this thesis originally started with an aim to assess oil outflow characteristics in all possible damage situations thus including grounding and stranding. Unfortunately, initially unseen difficulties in developing the numerical model and, at a later stage, the enormous amount of data to be processed and analysed, meant that only collisions could be investigated in the limited time available. For the same reasons, the range of tanker concepts and tank arrangements examined is limited. This limited range of arrangements was selected in view of extracting information for as many variables as possible. The combination of limited sample of arrangement variations with the large number of variables means that the results yield useful trends but lack enough detail to allow the deduction of precise relationships.

As often apparent from the discussion in Chapter 7, many questions are left unanswered or have not even been asked. Nevertheless, the present study has set up and demonstrated a solid and consistent framework for further investigations on the subject. Such work could concentrate on one or more of the following aspects:

a. Refining and improving the model. Areas of the model that can be improved include both theoretical oil outflow and probability calculations. The inclusion of variable outflow correction factors for Initial Exchange and Dynamic Effects losses would bring the oil outflow model in line with the findings of experiments [18, 19, 20] that these losses depend on the damage extents. The probability calculation could be refined by using more representative density functions. The linear density functions used in this study have the advantage of simplicity but if the model is to be used for quantitative assessments, a more accurate probability result is needed. The use of E-spline curves as in [6] seems a good alternative, as they combine the advantages of flexibility in the modelling of statistical data with that of producing smooth continuous curves which can be integrated analytically. Still in the area of probability calculation, the accuracy of potential oil outflow results could be improved by removing the error caused when the iteration steps and the spacing of the subdivision members are incompatible, as discussed in Section 4.3.4. Using in the iteration process a variable interval length, becoming smaller in the vicinity of subdivision members, should solve this problem without increasing prohibitively the number of iterations. However, the existing iteration algorithm and all the procedures nested in it, would need extensive modifications in order to implement this solution.

b. Adapting the model for grounding and stranding analyses. In order to fully assess the effectiveness of subdivision in abating oil outflow, the full spectrum of probable damages must be considered thus including bottom damages due to grounding or stranding. Because of the similarities in the oil outflow mechanism, the existing model for side damage can be adapted with very few modifications.

c. Parametric studies. A lot of work remains to be done in this area. The following are some of the parameters that could be studied or examined in more detail with respect to oil outflow:

- Tank L/B ratio under constant tank volume. The result of the study should give an indication of the relative efficiency of transverse and longitudinal subdivision.

- Tank Breadth Ratio. This parameter needs to be studied in more detail as it is linked to the optimum position of side longitudinal bulkheads. Tank arrangements with more than two longitudinal bulkheads also need to be examined in this context.

- Vertical position of horizontal subdivision. Intermediate positions to those examined herein need to be investigated in order to reach a clear conclusion about the optimum mid-deck position. This particular parameter should also be examined in relation to the two hypothetical probability distributions for the vertical location and extent of damage.

- Relative density of transverse subdivision in side and center tanks, i.e. having different number of transverse bulkheads each side of a side longitudinal bulkhead.

Different tanker concepts could also be investigated with the existing numerical model, bringing into play additional design parameters, e.g. tankers with inclined longitudinal bulkheads, or perhaps hybrid tanker concepts combining a double hull and horizontal subdivision in the cargo space like the COBO concept [34].

d. Tanker design optimization. The results of the detailed parametric studies could be used to develop a mathematical model linking directly an oil outflow performance indicator to the main design parameters of a tanker concept. This mathematical model could then be incorporated in a general optimization model.

APPENDIX A FLOWCHART AND SAMPLE INPUT AND OUTPUT FILES

A.1 FLOWCHART FOR NUMERICAL MODEL

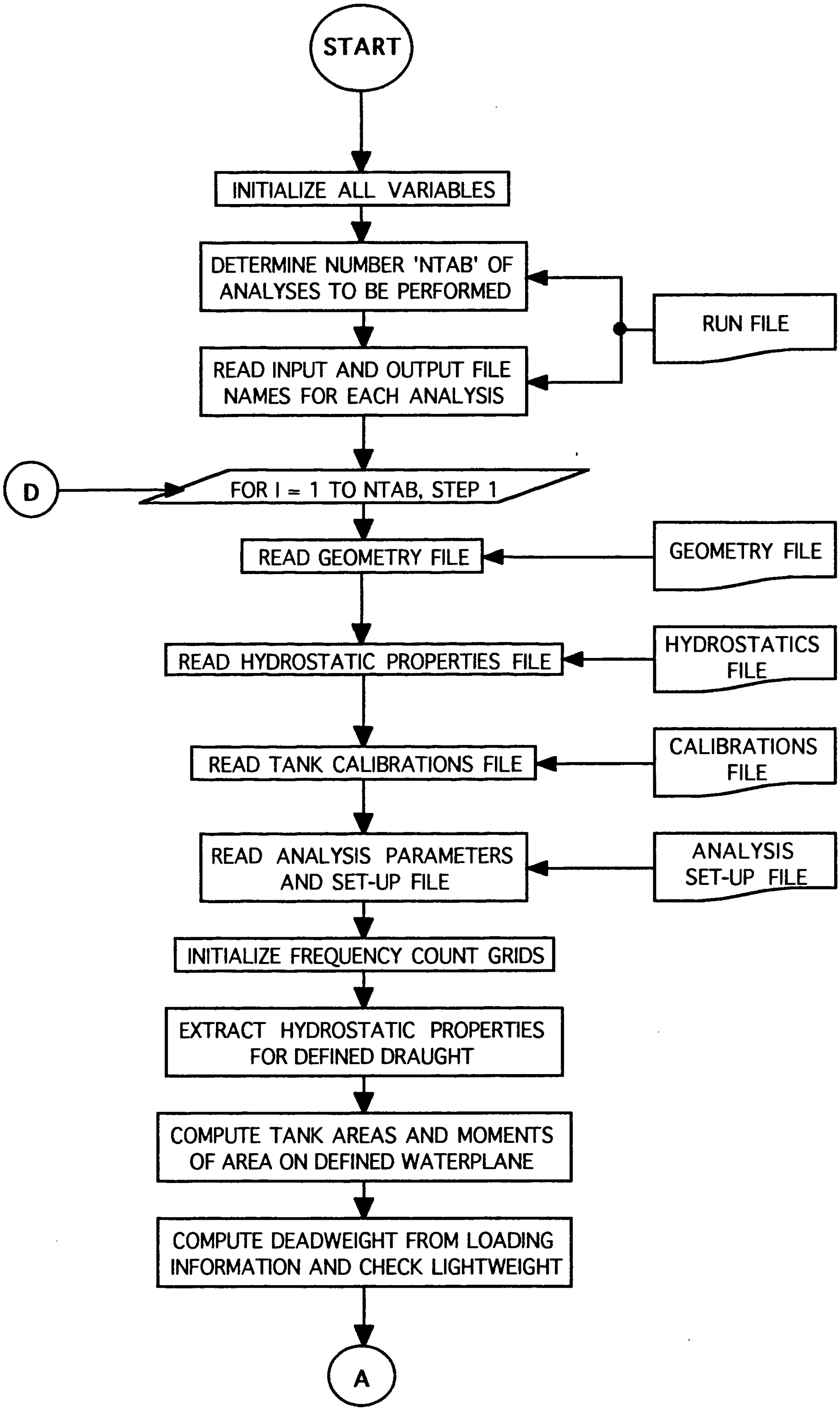

Figure A.1(a): Flowchart of numerical model for the estimation of probabilistic oil outflow from an oil tanker with side damage.

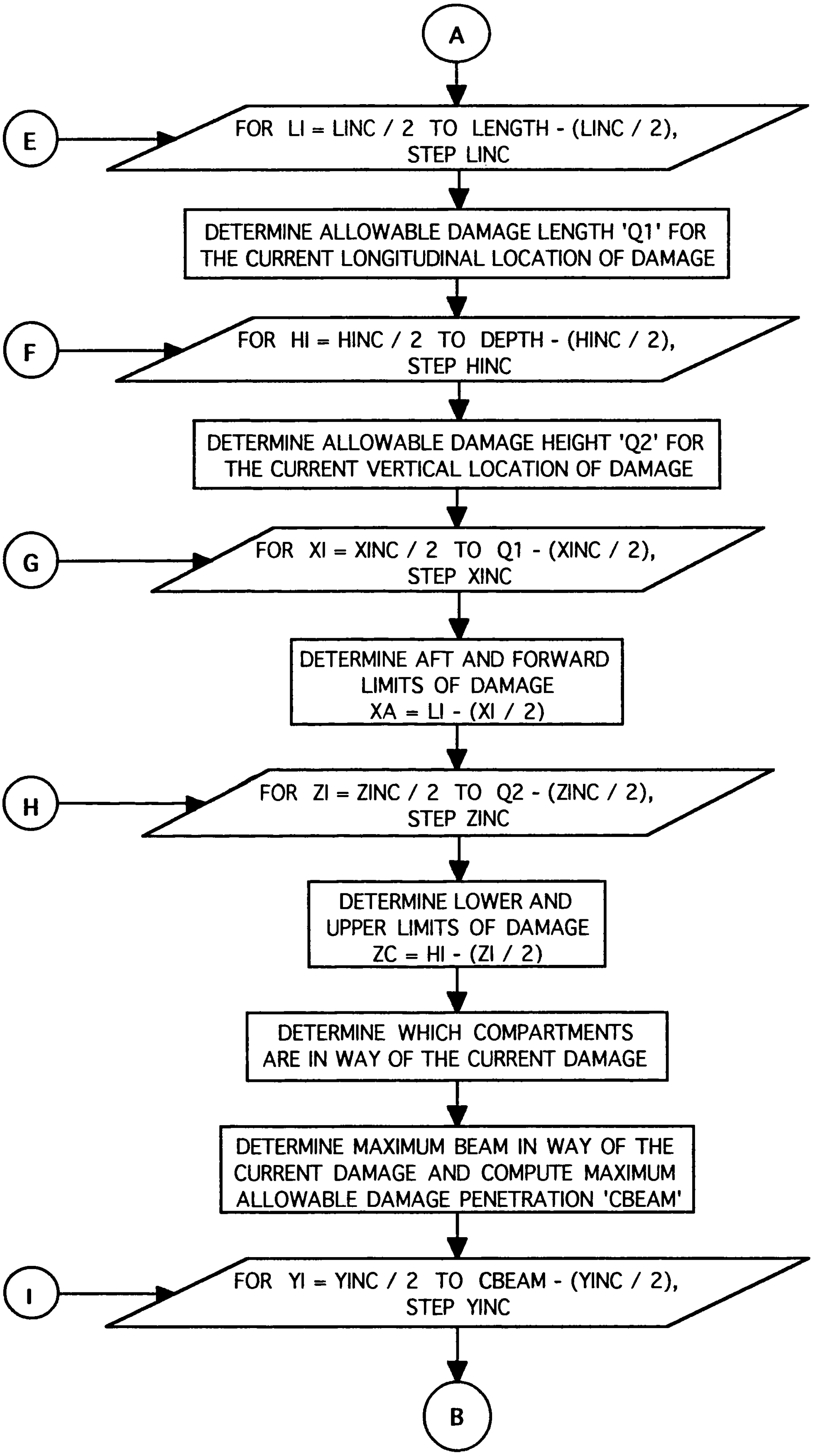

Figure A.1(b): Flowchart continued (1).

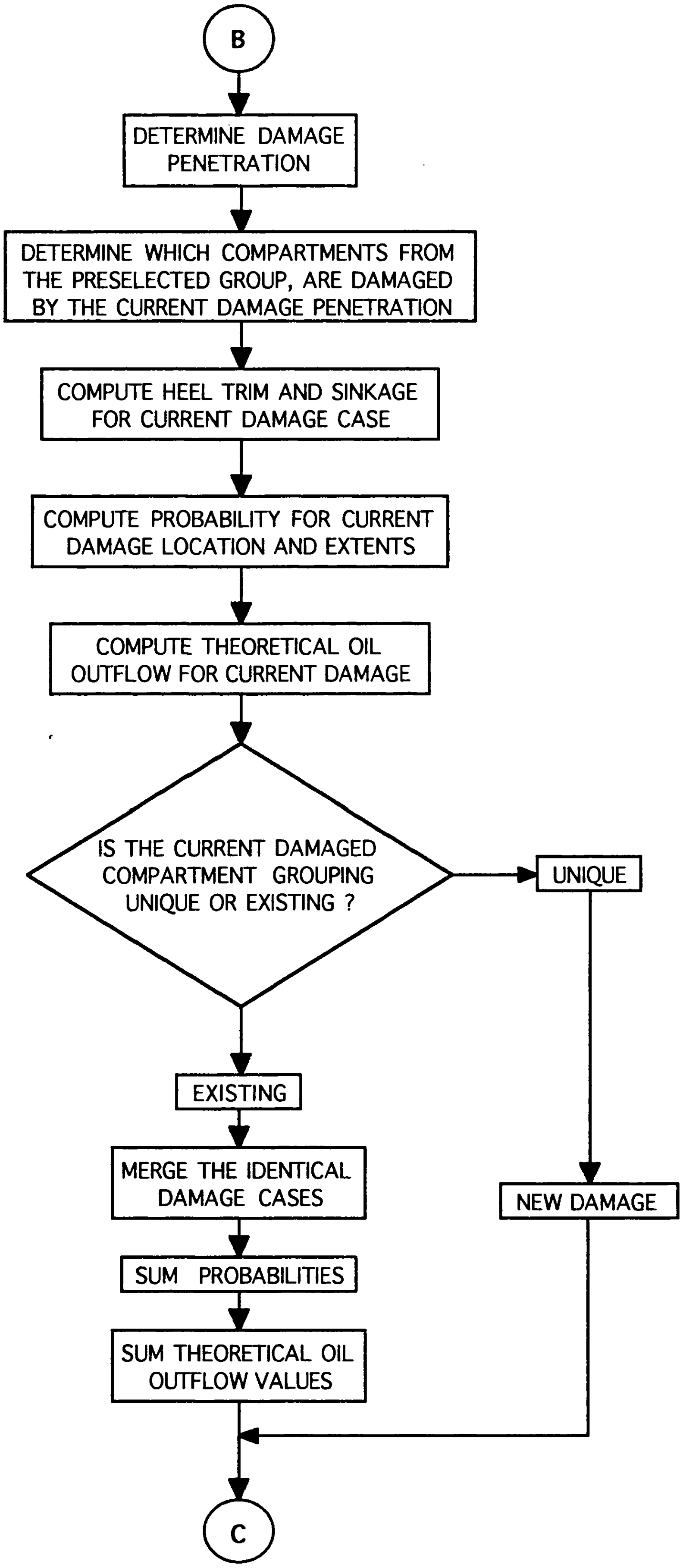

Figure A.1(c): Flowchart continued (2).

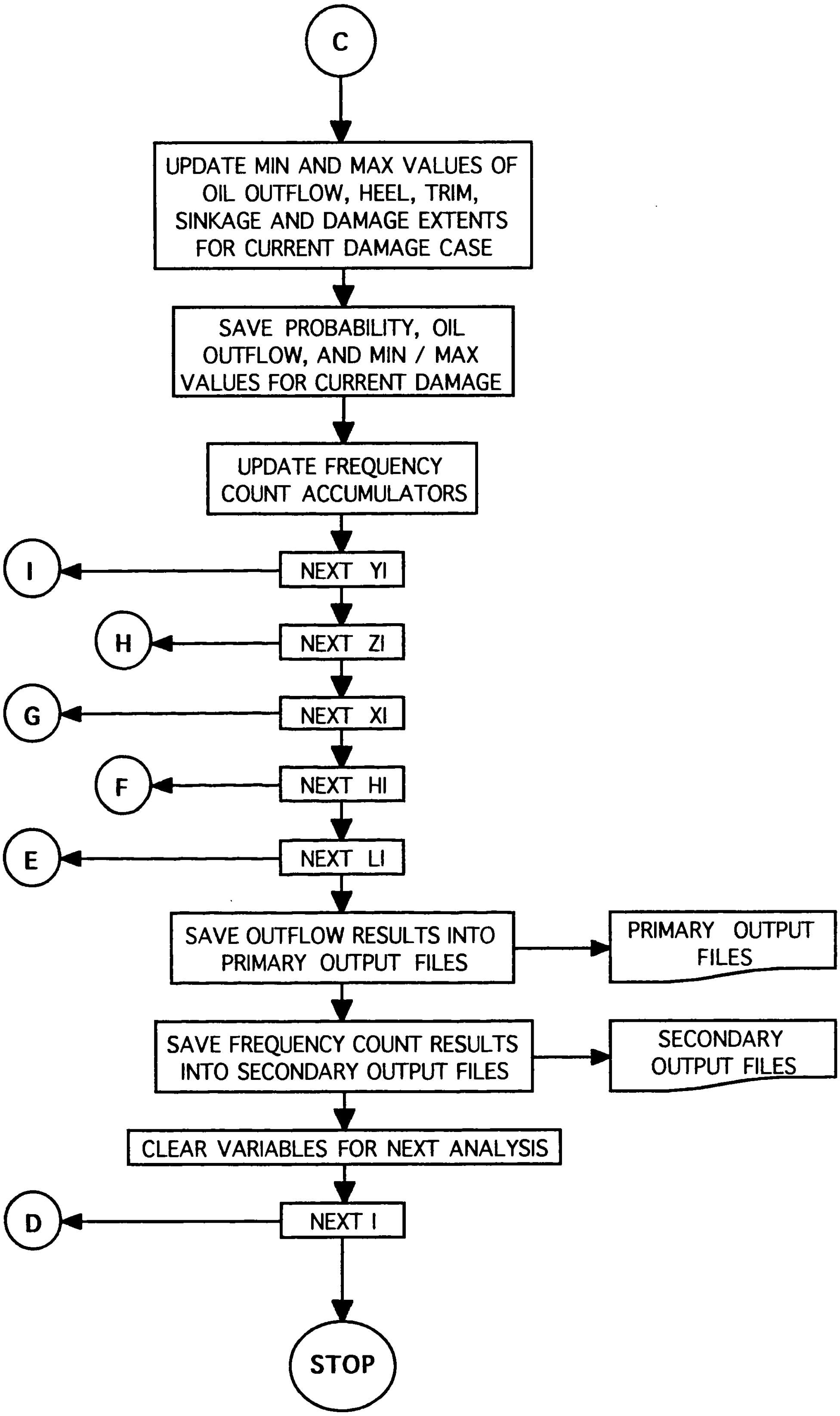

Figure A.1(d): Flowchart continued (3).

A.2 SAMPLE INPUT FILES

A.2.1 RUN FILE

```
SS01.GF0     GEOMETRY            SS05.GF0     BLOCK No 4          SS16.GF0     BLOCK No 7
SS_H.DAT     HYDROSTATICS
SS01_C.DAT   CALIBRATIONS        SS05_C.DAT                       SS16_C.DAT
SS_A.DAT     ANALYSIS SET-UP
SS01.OUT     GENERIC OUTPUT      SS05.OUT                         SS16.OUT
*            BLOCK SEPARATOR     *                                *
SS02.GF0     BLOCK No 2          SS12.GF0     BLOCK No 5          SS17.GF0     BLOCK No 8

SS02_C.DAT                       SS12_C.DAT                       SS17_C.DAT

SS02.OUT                         SS12.OUT                         SS17.OUT
*                                *                                *
SS03.GF0     BLOCK No 3          SS15.GF0     BLOCK No 6          SS18.GF0     BLOCK No 9

SS03_C.DAT                       SS15_C.DAT                       SS18_C.DAT

SS03.OUT                         SS15.OUT                         SS18.OUT
*                                *                                **
```

A.2.2 GEOMETRY FILE

FILE CREATED BY MODELMAKER™

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72.325,29.905
72.441,33.661
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74.034,65.999
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77.467,43.053
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672.5722,4
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492.126,4
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606.9554,4
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S3
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344.4882,4
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360.8924,4
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377.2966,4
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393.7008,4
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426.5092,4
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459.3176,4
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S4
10
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246.063,4
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262.4672,4
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278.8714,4
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311.6798,4
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69.882,88.583
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S5
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42.542,88.583
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82.021,4
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51.29,88.583
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98.4352,4
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60.039,88.583
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114.8294,4
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64.961,88.583
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131.2336,4
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147.6378,4
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164.042,4
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69.882,88.583
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*
S6X
2
738.189,5
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69.882,6.07
69.882,88.583
0.0,88.583
0.0,6.07
754.5931,5
0.0,6.07
69.882,6.07
69.882,88.583
0.0,88.583
0.0,6.07
0.0,0.0,0.0
*
S7X
2
738.189,5
0.0,6.07
69.882,6.07
69.882,88.583
0.0,88.583
0.0,6.07
754.5931,5
0.0,6.07
69.882,6.07
69.882,88.583
0.0,88.583
0.0,6.07
0.0,0.0,0.0
**
C1
0
1
0,0,0
S2X
***
FP_TANK\Fore Peak tank
SEA WATER
4
1.025
0,0,0
1
C1
2
49.213,0.0,0.0
49.213,0.0,64.961
**
C2
0
1
0,0,0
S30
***
FP_BOSSUN\Fore Peak Bossun
NIL
4
0
0,0,0
1
C2
2
49.213,0.0,64.961
49.213,0.0,88.629
**
C3
0
1
0,0,0
S40
***
AP_TANK\After Peak Tank
SEA WATER
4
1.025
0,0,0
1
C3
2
885.827,0.0,42.93
885.827,0.0,64.961
**
C4
0
1
0,0,0
S50
***
SG_ROOM\Steering Gear Room
NIL
4
0
0,0,0
1
C4
2
885.827,0.0,64.961
885.827,0.0,88.629
**
C5
0
1
0,0,0
S6
***
ENG_ROOM\Engine Room
NIL
4
0
0,0,0
1
C5
2
803.806,0.0,14.764
803.806,0.0,88.629
**
C6
0
1
0,0,0
S7X0
***
ENG_DB\Engine Room Double B
NIL
4
0
0,0,0
1
C6
2
803.806,0.0,0.0
803.806,0.0,14.764
**
C7
0
1
0,0,0
S8X
***
PMP_ROOM\Pump Room
NIL
4
0
0,0,0
1
C7
2
754.593,0.0,0.0
754.593,0.0,29.528
**
C8
-1
.985
0,0,0
S9
***
FO_TANK.P\Fuel Oil Tank (PORT)
FO
4
.87
0,0,0
1
C8
2
770.997,-29.528,29.528
770.997,-29.528,88.629
**
C9
1
1
0,0,0
S10
***
FO_TANK.S\Fuel Oil Tank (STAR)
FO
4
.87
0,0,0
1
C9
2
770.997,29.528,29.528
```

```
770.997,29.528,88.629
**
C10
-1
1
0,0,0
S11
***
AWB_TANK.P\After Water Ballast
SEA WATER
4
1.025
0,0,0
1
C10
2
787.402,-59.055,14.764
787.402,-59.055,88.629
**
C11
1
.985
0,0,0
S12
***
AWB_TANK.S\After Water Ballast
SEA WATER
4
1.025
0,0,0
1
C11
2
787.402,59.055,14.764
787.402,59.055,88.629
**
C12
1
.985
0,0,0
S13
***
DS1.S
SEA WATER
4
1.025
0,0,0
1
C12
2
656.168,69.882,0.0
656.168,69.882,88.583
**
C13
1
.985
0,0,0
S14
***
DS2.S
SEA WATER
4
1.025
0,0,0
1
C13
2
524.934,69.882,0.0
524.934,69.882,88.583
**
C14
1
.985
0,0,0
S15
***
DS3.S
SEA WATER
4
1.025
0,0,0
1
C14
2
393.701,69.882,0.0
393.701,69.882,88.583
**
C15
1
.985
0,0,0
S16
***
DS4.S
SEA WATER
4
1.025
0,0,0
1
C15
2
229.659,69.882,0.0
```

```
229.659,69.882,88.583
**
C16
1
.985
0,0,0
S17X
***
DS5.S
SEA WATER
4
1.025
0,0,0
1
C16
2
164.042,69.882,0.0
164.042,69.882,88.583
**
C12.P
-1
.985
0,0,0
S18
***
DS1.P
SEA WATER
4
1.025
0,0,0
1
C12.P
2
656.168,-69.882,0.0
656.168,-69.882,88.583
**
C13.P
-1
.985
0,0,0
S19
***
DS2.P
SEA WATER
4
1.025
0,0,0
1
C13.P
2
524.934,-69.882,0.0
524.934,-69.882,88.583
**
C14.P
-1
.985
0,0,0
S20
***
DS3.P
SEA WATER
4
1.025
0,0,0
1
C14.P
2
393.701,-69.882,0.0
393.701,-69.882,88.583
**
C15.P
-1
.985
0,0,0
S21
***
DS4.P
SEA WATER
4
1.025
0,0,0
1
C15.P
2
229.659,-69.882,0.0
229.659,-69.882,88.583
**
C16.P
-1
.985
0,0,0
S22X
***
DS5.P
SEA WATER
4
1.025
0,0,0
1
C16.P
2
164.042,-69.882,0.0
```

```
164.042,-69.882,88.583
**
CC1
0
.985
0,0,0
S1
***
COT1
HO
4
.924
0,0,0
1
CC1
2
656.168,0.0,6.07
656.168,0.0,88.583
**
CC2
0
.985
0,0,0
S2
***
COT2
HO
4
.924
0,0,0
1
CC2
2
524.934,0.0,6.07
524.934,0.0,88.583
**
CC3
0
.985
0,0,0
S3
***
COT3
HO
4
.924
0,0,0
1
CC3
2
393.701,0.0,6.07
393.701,0.0,88.583
**
CC4
0
.985
0,0,0
S4
***
COT4
HO
4
.924
0,0,0
1
CC4
2
229.659,0.0,6.07
229.659,0.0,88.583
**
CC5
0
.985
0,0,0
S5
***
COT5
HO
4
.924
0,0,0
1
CC5
2
98.425,0.0,6.07
98.425,0.0,88.583
**
CC6
1
.985
0,0,0
S6X
***
SLP_TANK.S
SEW
4
1.025
0,0,0
1
CC6
2
738.189,32.808,6.07
```

```
738.189,32.808,88.583
**
CC6.P
-1
.985
0,0,0
S7X
***
SLP_TANK.P
SEW
4
1.025
0,0,0
1
CC6.P
2
738.189,-32.808,6.07
738.189,-32.808,88.583
****
```

A.2.3 TANK CALIBRATION TABLE

FILE CREATED BY AUTOHYDRO™ (Extract for one tank only)

```
{NEWPAGE}##
26


{BOLD}TANK SOUNDING TABLE{NORMAL}No Trim, No Heel

{BOX}
2
{BOLD}@2Fore Peak tank{NORMAL}@52Contents: SEA WATER at SpGr = 1.025

{LINE}
2
{VLINE}
2
{BOLD}Sounding @13Volume @24Weight @36LCG @46TCG @56VCG @68FSM @80Ullage

{VLINE}
2
 m@15Cu.m@28MT@37m@47m@57m@67MT-m@80 m{NORMAL}

{LINE}
2
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000 @44##0.000
@54##0.000 @64######0.00 @80###0.00
0 0 0 0 0 0 4065.259 19.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
1 171.7136 176.0077 8.999667 1.73523E-08 .5539542 4514.581 18.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
2 404.014 414.1172 8.816189 6.903325E-08 1.106934 7017.031 17.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
3 664.1956 680.8052 8.746791 2.304174E-08 1.657165 8739.952 16.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
4 935.6189 959.0162 8.715959 1.605072E-08 2.194117 9569.717 15.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
5 1210.731 1241.009 8.701769 4.521791E-08 2.718422 9417.868 14.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
6 1480.554 1517.578 8.700541 7.53621E-08 3.225028 8376.212 13.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
7 1731.823 1775.132 8.716378 9.969844E-08 3.698761 7038.842 12.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
8 1962.128 2011.195 8.754998 8.795909E-08 4.141058 6058.749 11.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
9 2175.363 2229.762 8.814061 7.933317E-08 4.561409 5542.543 10.80011
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
10 2377.039 2436.482 8.884203 7.266643E-08 4.970126 5362.9 9.800113
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
11 2571.633 2635.942 8.956603 4.115948E-08 5.374494 5444.727 8.800113
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
12 2768.618 2837.854 9.027534 3.797214E-08 5.79235 5674.51 7.800113
{BOX}
```

```
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
13 2965.293 3039.447 9.091806 1.138885E-08 6.216413 6003.041 6.800113
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
14 3168.012 3247.235 9.149956 3.257818E-08 6.658427 6408.143 5.800113
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
15 3375.277 3459.684 9.199949 3.024562E-08 7.114115 6883.264 4.800113
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
16 3589.074 3678.827 9.241834 2.812198E-08 7.586799 7435.499 3.800112
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
17 3813.688 3909.058 9.276045 2.616206E-08 8.085161 8082.566 2.800112
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
18 4046.097 4147.279 9.301915 2.439078E-08 8.601814 8823.348 1.800113
{BOX}
1
###0.00@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
19 4288.971 4396.227 9.31982 2.278323E-08 9.141931 9673.96 .8001126
{BOX}
1
FULL@11#####0.00 @19#######0.00 @34##0.000a @44##0.000
@54##0.000 @64######0.00 @80###0.00
4491.89 4604.22 9.328534 5.207822E-08 9.592656 0 -.1998874
{LINE}
2
```

A.2.4 HYDROSTATIC PROPERTIES TABLE

FILE CREATED BY AUTOHYDRO™

```
{NEWPAGE}##
34
{BOLD}{CENTER}HYDROSTATIC PROPERTIES{NORMAL}{BOLD}{NORMAL}

{BOLD}{CENTER}No Trim, No Heel, VCG = 0.000{NORMAL}

{LINE}
2
{VLINE}
2
{BOLD} LCF @10Displacement Buoyancy Ctr. @48Weight/
@66Moment/{NORMAL}

{VLINE}
2
{BOLD} Draft @11Weight(MT) @28LCB @38VCB @49 cm @58LCF
@66deg Trim @79KML @87 KMT {NORMAL}

{LINE}
2
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
1 10567.95 131.7618 .5124654 111.5743 131.5415 884444.3 4794.666 180.7177
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
2 22004.83 131.5497 1.027881 116.5176 131.1925 941243 2450.542 97.62635
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
3 33795.57 131.4175 1.542426 118.8782 131.0333 971780.1 1647.353 67.55737
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
4 45742.45 131.3115 2.05419 119.8662 131.0005 986343.6 1235.342 51.76899
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
5 57746.64 131.2547 2.562909 120.1331 131.0885 991804.4 983.9608 42.13366
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
6 69761.7 131.247 3.068973 120.1253 131.3503 991328.9 814.1027 35.89802
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
```

```
@56##0.000a @66#######0 @76####0.00 @86###0.000
7 81771.95 131.2919 3.573058 120.0385 131.7536 988800.3 692.7599 31.63984
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
8 93773.7 131.3855 4.075754 119.9809 132.2547 987125.1 603.0727 28.60708
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
9 105777.1 131.5172 4.577859 120.0647 132.7721 989524.4 535.9366 26.38514
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
10 117800.6 131.6757 5.080257 120.373 133.2913 998327 485.5163 24.72972
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
11 129866.3 131.8559 5.583806 120.8984 133.8637 1013278 447.0033 23.48514
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
12 141995.4 132.0583 6.089251 121.6223 134.504 1034063 417.2067 22.54539
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
13 154215.3 132.2934 6.597687 122.7667 135.524 1067447 396.5495 21.84414
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
14 166573.1 132.5887 7.110237 124.5029 137.1304 1119736 385.114 21.33517
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
15 179104.2 132.9567 7.627494 126.1183 138.5517 1168954 373.9126 20.97663
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
16 191813.9 133.386 8.149207 127.9338 140.1518 1226070 366.196 20.73964
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
17 204686.5 133.8528 8.674346 129.4389 141.3705 1273464 356.4315 20.59749
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
18 217691.5 134.3284 9.20151 130.6241 142.2073 1310874 344.9834 20.52754
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
19 230806.1 134.7947 9.729783 131.6321 142.8243 1343210 333.4072 20.51719
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
20 244013.1 135.2415 10.25856 132.4949 143.256 1371646 322.0383 20.55417
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
21 257301.2 135.6637 10.78755 133.2503 143.5472 1397430 311.1478 20.63106
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
22 270660.7 136.0576 11.31649 133.9329 143.7305 1421528 300.8906 20.7443
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
23 284085.8 136.4223 11.8453 134.5527 143.8084 1444398 291.2834 20.88708
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
24 297570.9 136.757 12.37388 135.1433 143.8049 1466928 282.4209 21.05898
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
25 311113.7 137.0625 12.90227 135.7057 143.7248 1489191 274.2267 21.25575
{BOX}
1
@2##0.000 @10######,##0.00 @26##0.000a @36##0.000 @46#####0.00
@56##0.000a @66#######0 @76####0.00 @86###0.000
26 324711.6 137.3386 13.43044 136.2522 143.5784 1511508 266.6804 21.47567
{LINE}
2
{CENTER}Distances in Meters. Water Specific Gravity = 1.025. Moment in m-MT.{NORMAL}

Draft is from Baseline.
```

A.2.5 ANALYSIS SET-UP FILE

```
GLOBAL                               geometry file header (title)
0000                                 geometry file reference No
285.0 50.0 27.014 19.0               length beam depth draught (metres)
18.0                                 KG estimated
0.0 0.0 0.0 0.0                      tide values (4)
0.0 0.0 0.0 0.0                      wave values (4)
1.0 1.0 1.0 1.0                      initial exchange values (4) (%)
1.0 1.0 1.0 1.0                      dynamic effects values (4) (%)
STATS                                include frequency counts
7                                    number of frequency count grids
1. 0. 5. 0. 57. 0.                   1st parameter's scale particulars
13. 1. 10. 0. 6. 10.                 2nd    "      "      "
2. 0. 5. 0. 6. 0.                    2nd grid
13. 1. 10. 0. 6. 10.
3. 0. 5. 0. 12. 0.                   3rd grid
13. 1. 10. 0. 6. 10.
4. 0. 5. 0. 6. 0.                    4th grid
13. 1. 10. 0. 6. 10.
5. 0. 1. 0. 40. 0.                   5th grid
13. 1. 10. 0. 6. 10.
6. 1. 10. 0. 4. 10.                  6th grid
13. 1. 10. 0. 6. 10.
7. 1. 10. 0. 5. 10.                  7th grid
13. 1. 10. 0. 6. 10.
DAM_Y                                include damaged stability
0.0 0.0 0.0                          stability criteria (not used)
ITERM                                user defined iteration steps
5.0 1.0 20.0 5.0 5.0 100.0 1.0 70.0  iteration step values
ULL_G                                global ullage pressure value applied
2.0                                  global ullage pressure value (H2O m)
LOADG                                global load fraction value applied
98.0                                 global load fraction value (%)
END
```

A.3 SAMPLE OUTPUT FILES

A.3.1 DAMAGE CASE LIST

FILE BEFORE POST-PROCESSING

```
1  1. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
2  1. 2. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
3  2. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
4  16. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
5  16. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
6  1. 16. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
7  1. 16. 21. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
8  1. 16. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
9  1. 2. 16. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
10  1. 2. 16. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
11  1. 2. 16. 21. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
12  2. 16. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
13  2. 16. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
14  16. 21. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
15  15. 16. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
16  15. 16. 25. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
17  1. 15. 16. 25. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
18  1. 15. 16. 20. 21. 25. 26. 0. 0. 0. 0. 0. 0. 0. 0.
19  1. 2. 15. 16. 25. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0.
20  1. 2. 15. 16. 20. 21. 25. 26. 0. 0. 0. 0. 0. 0. 0.
21  2. 15. 16. 25. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
22  15. 16. 20. 21. 25. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0.
23  15. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
24  15. 25. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
25  15. 20. 25. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
26  14. 15. 16. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
27  14. 15. 16. 24. 25. 26. 0. 0. 0. 0. 0. 0. 0. 0. 0.
28  14. 15. 16. 19. 20. 21. 24. 25. 26. 0. 0. 0. 0. 0. 0.
29  14. 15. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
30  14. 15. 24. 25. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
31  14. 15. 19. 20. 24. 25. 0. 0. 0. 0. 0. 0. 0. 0. 0.
32  14. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
33  14. 24. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
34  14. 19. 24. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
35  13. 14. 15. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
36  13. 14. 15. 23. 24. 25. 0. 0. 0. 0. 0. 0. 0. 0. 0.
37  13. 14. 15. 18. 19. 20. 23. 24. 25. 0. 0. 0. 0. 0. 0.
38  13. 14. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
39  13. 14. 23. 24. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
40  13. 14. 18. 19. 23. 24. 0. 0. 0. 0. 0. 0. 0. 0. 0.
41  13. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
42  13. 23. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
43  13. 18. 23. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
44  12. 13. 14. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
45  12. 13. 14. 22. 23. 24. 0. 0. 0. 0. 0. 0. 0. 0. 0.
46  12. 13. 14. 17. 18. 19. 22. 23. 24. 0. 0. 0. 0. 0. 0.
47  12. 13. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
48  12. 13. 22. 23. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
49  12. 13. 17. 18. 22. 23. 0. 0. 0. 0. 0. 0. 0. 0. 0.
50  12. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
51  12. 22. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
52  12. 17. 22. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
53  12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
54  12. 13. 17. 18. 22. 23. 27. 28. 0. 0. 0. 0. 0. 0. 0.
55  12. 13. 22. 23. 27. 28. 0. 0. 0. 0. 0. 0. 0. 0. 0.
56  7. 12. 13. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
57  7. 12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0. 0. 0. 0.
58  7. 12. 13. 17. 18. 22. 23. 27. 28. 0. 0. 0. 0. 0. 0.
59  7. 12. 13. 22. 23. 27. 28. 0. 0. 0. 0. 0. 0. 0. 0.
60  7. 9. 12. 13. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
61  7. 9. 12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0. 0. 0.
```

FILE AFTER POST-PROCESSING

```
1 1.
2 1. 2.
3 2.
4 16.
5 16. 26.
6 1. 16. 26.
7 1. 16. 21. 26.
8 1. 16.
9 1. 2. 16.
10 1. 2. 16. 26.
11 1. 2. 16. 21. 26.
12 2. 16.
13 2. 16. 26.
14 16. 21. 26.
15 15. 16.
16 15. 16. 25. 26.
17 1. 15. 16. 25. 26.
18 1. 15. 16. 20. 21. 25. 26.
19 1. 2. 15. 16. 25. 26.
20 1. 2. 15. 16. 20. 21. 25. 26.
21 2. 15. 16. 25. 26.
22 15. 16. 20. 21. 25. 26.
23 15.
24 15. 25.
25 15. 20. 25.
26 14. 15. 16.
27 14. 15. 16. 24. 25. 26.
28 14. 15. 16. 19. 20. 21. 24. 25. 26.
29 14. 15.
30 14. 15. 24. 25.
31 14. 15. 19. 20. 24. 25.
32 14.
33 14. 24.
34 14. 19. 24.
35 13. 14. 15.
36 13. 14. 15. 23. 24. 25.
37 13. 14. 15. 18. 19. 20. 23. 24. 25.
38 13. 14.
39 13. 14. 23. 24.
40 13. 14. 18. 19. 23. 24.
41 13.
42 13. 23.
43 13. 18. 23.
44 12. 13. 14.
45 12. 13. 14. 22. 23. 24.
46 12. 13. 14. 17. 18. 19. 22. 23. 24.
47 12. 13.
48 12. 13. 22. 23.
49 12. 13. 17. 18. 22. 23.
50 12.
51 12. 22.
52 12. 17. 22.
53 12. 13. 22. 23. 27.
54 12. 13. 17. 18. 22. 23. 27. 28.
55 12. 13. 22. 23. 27. 28.
56 7. 12. 13.
57 7. 12. 13. 22. 23. 27.
58 7. 12. 13. 17. 18. 22. 23. 27. 28.
59 7. 12. 13. 22. 23. 27. 28.
60 7. 9. 12. 13.
61 7. 9. 12. 13. 22. 23. 27.
```

```
62  5. 7. 9. 12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0. 0.
63  5. 7. 9. 12. 13. 22. 23. 27. 28. 0. 0. 0. 0. 0. 0.
64  5. 7. 9. 12. 13. 17. 18. 22. 23. 27. 28. 0. 0. 0. 0.
65  9. 12. 13. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
66  9. 12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0. 0. 0. 0.
67  5. 9. 12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0. 0. 0.
68  5. 9. 12. 13. 22. 23. 27. 28. 0. 0. 0. 0. 0. 0. 0.
69  12. 22. 27. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
70  12. 17. 22. 27. 28. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
71  12. 22. 27. 28. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
72  7. 12. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
73  7. 12. 22. 27. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
74  7. 12. 17. 22. 27. 28. 0. 0. 0. 0. 0. 0. 0. 0. 0.
75  6. 7. 12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0. 0. 0.
76  6. 7. 12. 13. 17. 18. 22. 23. 27. 28. 0. 0. 0. 0. 0.
77  7. 12. 22. 27. 28. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
78  6. 7. 11. 12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0. 0.
79  5. 6. 7. 11. 12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0.
80  5. 6. 7. 11. 12. 13. 22. 23. 27. 28. 0. 0. 0. 0. 0.
81  7. 11. 12. 13. 22. 23. 27. 0. 0. 0. 0. 0. 0. 0. 0.
82  5. 6. 7. 11. 12. 13. 17. 18. 22. 23. 27. 28. 0. 0. 0.
83  7. 9. 12. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
84  7. 9. 12. 22. 27. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
85  5. 7. 9. 12. 22. 27. 0. 0. 0. 0. 0. 0. 0. 0. 0.
86  5. 7. 9. 12. 22. 27. 28. 0. 0. 0. 0. 0. 0. 0. 0.
87  5. 7. 9. 12. 17. 22. 27. 28. 0. 0. 0. 0. 0. 0. 0.
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222 3. 5. 9. 11. 12. 27.
223 3. 5. 9. 11. 12. 27. 28.
224 3. 4. 7. 9. 11. 12. 27.
225 3. 4. 5. 7. 9. 11. 12. 27.
226 3. 4. 5. 7. 9. 11. 12. 27. 28.
227 4. 7. 9. 11. 12. 27.
228 4. 6. 7. 9. 11. 12. 27.
229 3. 4. 5. 6. 7. 9. 11. 12. 27. 28.
230 3. 4. 9. 11.
231 3. 4. 5. 9. 11.
232 4. 9. 11.
233 3. 4. 9. 11. 12. 27.
234 3. 4. 5. 9. 11. 12. 27.
235 3. 4. 5. 9. 11. 12. 27. 28.
236 4. 9. 11. 12. 27.
237 4. 5. 9. 11.
238 4. 5. 9. 11. 12. 27.
239 4. 5. 9. 11. 12. 27. 28.
240 3. 5. 6. 11.
241 3. 5. 11.
242 3. 4. 5. 6. 11.
243 3. 4. 5. 11.
244 4. 11.
245 4. 6. 11.
246 4. 5. 11.
247 3. 5.
248 3. 5. 6.
249 3.
250 3. 4.
251 4.
FILE REFERENCE:
SHIP:DH01.GF0 REF.No:0001
```

A.3.2 OIL OUTFLOW RESULTS

FILE BEFORE POST-PROCESSING

```
 1 0.2539E-01    0.0     0.0     0.0     0.0     0.0     0.0
 2 0.1078E-01    0.0     0.0     0.0     0.0     0.0     0.0
 3 0.1338E-01    0.0     0.0     0.0     0.0     0.0     0.0
 4 0.2803E-01    0.0     0.0     0.0     0.0     0.0     0.0
 5 0.6706E-01    0.0 30370.7   915.9   915.9   915.9   915.9
 6 0.1188E-01    0.0 18532.3   122.0   122.0   122.0   122.0
 7 0.6559E-04    0.0 12987.3     0.2     0.2     0.2     0.2
 8 0.2889E-03    0.0     0.0     0.0     0.0     0.0     0.0
 9 0.3564E-03    0.0     0.0     0.0     0.0     0.0     0.0
10 0.6006E-02 30370.7 30370.7   182.4   182.4   182.4   182.4
11 0.6756E-05 30370.7 30370.7     0.2     0.2     0.2     0.2
12 0.1018E-02    0.0     0.0     0.0     0.0     0.0     0.0
13 0.6462E-02  2456.5 30370.7    35.6    35.6    35.6    35.6
14 0.1243E-03    0.0 30370.7     0.6     0.6     0.6     0.6
15 0.1484E-01    0.0     0.0     0.0     0.0     0.0     0.0
16 0.6086E-01    0.0 76910.2  2135.5  2135.5  2135.5  2135.5
17 0.9805E-03    0.0 46930.9    26.2    26.2    26.2    26.2
18 0.6888E-05    0.0 32888.8     0.0     0.0     0.0     0.0
19 0.5811E-03 76910.2 76910.2    44.7    44.7    44.7    44.7
20 0.5533E-06 76910.2 76910.2     0.0     0.0     0.0     0.0
21 0.6756E-03  6220.9 76910.2     9.4     9.4     9.4     9.4
22 0.1139E-03    0.0 76910.2     1.3     1.3     1.3     1.3
23 0.2110E-01    0.0     0.0     0.0     0.0     0.0     0.0
24 0.8975E-01    0.0 46539.5  1907.5  1907.5  1907.5  1907.5
25 0.1725E-03    0.0 46539.5     1.2     1.2     1.2     1.2
26 0.1871E-03    0.0     0.0     0.0     0.0     0.0     0.0
27 0.7957E-03    0.0 123449.7   44.8    44.8    44.8    44.8
28 0.1530E-05    0.0 123449.7    0.0     0.0     0.0     0.0
29 0.1470E-01    0.0     0.0     0.0     0.0     0.0     0.0
30 0.6252E-01    0.0 93079.0  2656.9  2656.9  2656.9  2656.9
31 0.1202E-03    0.0 93079.0     1.6     1.6     1.6     1.6
32 0.2110E-01    0.0     0.0     0.0     0.0     0.0     0.0
33 0.8975E-01    0.0 46539.5  2283.7  2283.7  2283.7  2283.7
34 0.1725E-03    0.0 46539.5     1.2     1.2     1.2     1.2
35 0.1871E-03    0.0     0.0     0.0     0.0     0.0     0.0
36 0.7957E-03    0.0 139618.5   50.7    50.7    50.7    50.7
37 0.1530E-05    0.0 139618.5    0.0     0.0     0.0     0.0
38 0.1454E-01    0.0     0.0     0.0     0.0     0.0     0.0
39 0.6184E-01   14.3 93778.6  3307.1  3307.1  3307.1  3307.1
40 0.1189E-03    0.0 93079.0     1.6     1.6     1.6     1.6
41 0.1912E-01    0.0     0.0     0.0     0.0     0.0     0.0
42 0.8135E-01  3764.3 47470.3  2465.6  2465.6  2465.6  2465.6
43 0.1564E-03  1492.0 46539.5     1.9     1.9     1.9     1.9
44 0.1696E-03    0.0     0.0     0.0     0.0     0.0     0.0
45 0.7213E-03 10874.8 137136.4   67.6    67.6    67.6    67.6
46 0.1387E-05    0.0 134447.5    0.0     0.0     0.0     0.0
47 0.1178E-01    0.0     0.0     0.0     0.0     0.0     0.0
48 0.4955E-01  7110.4 89666.1  3324.4  3324.4  3324.4  3324.4
49 0.9526E-04 20781.8 89666.1     4.2     4.2     4.2     4.2
50 0.1468E-01    0.0     0.0     0.0     0.0     0.0     0.0
51 0.5201E-01  3346.1 42195.8  1545.5  1545.5  1545.5  1545.5
52 0.9999E-04  7823.4 41368.5     1.6     1.6     1.6     1.6
53 0.5249E-03  7319.5 92303.3    37.8    37.8    37.8    37.8
54 0.1043E-05 50339.1 94940.5     0.1     0.1     0.1     0.1
55 0.1778E-04  7528.7 94940.5     1.3     1.3     1.3     1.3
56 0.2058E-04    0.0     0.0     0.0     0.0     0.0     0.0
57 0.8254E-04 68854.7 92303.3     7.1     7.1     7.1     7.1
58 0.8675E-06 50846.0 79080.5     0.1     0.1     0.1     0.1
59 0.2231E-05 86722.9 94940.5     0.2     0.2     0.2     0.2
60 0.3103E-04    0.0  2816.0     0.0     0.0     0.0     0.0
61 0.9505E-04 93309.5 95175.7     9.0     9.0     9.0     9.0
62 0.3048E-04 93309.5 95175.7     2.9     2.9     2.9     2.9
63 0.4286E-05 95895.0 97812.9     0.4     0.4     0.4     0.4
64 0.1700E-06 95895.0 97812.9     0.0     0.0     0.0     0.0
65 0.7697E-04    0.0  2872.3     0.1     0.1     0.1     0.1
66 0.2379E-03  7319.5 95175.7    14.8    14.8    14.8    14.8
```

```
67 0.7633E-04  7319.5 95175.7    4.7    4.7    4.7    4.7
68 0.1116E-04  7528.7 97812.9    0.7    0.7    0.7    0.7
69 0.8447E-02  3555.2 44833.0  279.6  279.6  279.6  279.6
70 0.1679E-04 18233.3 46539.5    0.4    0.4    0.4    0.4
71 0.2861E-03  3764.3 47470.3   10.2   10.2   10.2   10.2
72 0.1386E-02    0.0     0.0    0.0    0.0    0.0    0.0
73 0.2478E-02 23123.1 41528.9   79.7   79.7   79.7   79.7
74 0.2278E-04 18579.6 33678.3    0.5    0.5    0.5    0.5
75 0.2948E-06 73795.6 73795.6    0.0    0.0    0.0    0.0
76 0.1809E-07 55914.4 55914.4    0.0    0.0    0.0    0.0
77 0.5857E-04 33157.8 42214.1    2.2    2.2    2.2    2.2
78 0.2309E-06 87249.7 92303.3    0.0    0.0    0.0    0.0
79 0.7518E-06 88528.5 92303.3    0.1    0.1    0.1    0.1
80 0.3640E-07 94940.5 94940.5    0.0    0.0    0.0    0.0
81 0.1768E-06 92303.3 92303.3    0.0    0.0    0.0    0.0
82 0.4550E-08 79329.9 79329.9    0.0    0.0    0.0    0.0
83 0.1747E-02  2816.0  2872.3    5.0    5.0    5.0    5.0
84 0.2534E-02 43310.0 47705.4  119.4  119.4  119.4  119.4
85 0.8004E-03 41660.9 47705.4   37.4   37.4   37.4   37.4
86 0.1126E-03 47086.1 50342.6    5.6    5.6    5.6    5.6
87 0.4464E-05 47057.5 49579.4    0.2    0.2    0.2    0.2
88 0.4005E-06 92303.3 92303.3    0.0    0.0    0.0    0.0
89 0.2181E-07 94940.5 94940.5    0.0    0.0    0.0    0.0
90 0.8785E-06 93309.5 95175.7    0.1    0.1    0.1    0.1
91 0.1402E-05 93309.5 95175.7    0.1    0.1    0.1    0.1
92 0.7636E-07 95895.0 97812.9    0.0    0.0    0.0    0.0
93 0.2252E-06 93309.5 95175.7    0.0    0.0    0.0    0.0
94 0.7331E-06 93309.5 95175.7    0.1    0.1    0.1    0.1
95 0.3549E-07 95895.0 97812.9    0.0    0.0    0.0    0.0
96 0.2498E-06  2816.0  2872.3    0.0    0.0    0.0    0.0
97 0.4436E-08 95895.0 97812.9    0.0    0.0    0.0    0.0
98 0.3332E-02    0.0  2872.3    6.4    6.4    6.4    6.4
99 0.6247E-02  3555.2 47705.4  193.6  193.6  193.6  193.6
100 0.2004E-02  3555.2 47705.4   62.1   62.1   62.1   62.1
101 0.2930E-03  3764.3 50342.6    9.6    9.6    9.6    9.6
102 0.2854E-05  7319.5 95175.7    0.2    0.2    0.2    0.2
103 0.5346E-05  7319.5 95175.7    0.3    0.3    0.3    0.3
104 0.2912E-06  7528.7 97812.9    0.0    0.0    0.0    0.0
105 0.1350E-05    0.0  2872.3    0.0    0.0    0.0    0.0
106 0.3218E-03 23417.2 28951.2    8.3    8.3    8.3    8.3
107 0.1974E-04 19044.6 24999.4    0.4    0.4    0.4    0.4
108 0.2521E-03 29243.7 40680.0    8.4    8.4    8.4    8.4
109 0.8205E-03 26420.8 36640.5   24.5   24.5   24.5   24.5
110 0.3973E-04 30727.9 39094.2    1.4    1.4    1.4    1.4
111 0.1930E-03 35660.3 41448.6    7.3    7.3    7.3    7.3
112 0.4966E-05 27929.9 32379.9    0.1    0.1    0.1    0.1
113 0.4371E-03 33603.1 38328.6   15.6   15.6   15.6   15.6
114 0.2381E-04 38427.6 44132.8    1.0    1.0    1.0    1.0
115 0.9571E-03 44308.3 47705.4   45.3   45.3   45.3   45.3
116 0.1512E-02 42656.4 47705.4   71.0   71.0   71.0   71.0
117 0.8203E-04 48561.7 50342.6    4.1    4.1    4.1    4.1
118 0.2448E-03 46770.0 47705.4   11.6   11.6   11.6   11.6
119 0.7908E-03 44369.7 47705.4   37.3   37.3   37.3   37.3
120 0.3827E-04 49355.5 50342.6    1.9    1.9    1.9    1.9
121 0.3599E-03  2816.0  2872.3    1.0    1.0    1.0    1.0
122 0.4715E-05 46420.1 49873.6    0.2    0.2    0.2    0.2
123 0.3089E-02  3555.2 47705.4   96.0   96.0   96.0   96.0
124 0.5700E-02  3555.2 47705.4  177.0  177.0  177.0  177.0
125 0.3099E-03  3764.3 50342.6   10.2   10.2   10.2   10.2
126 0.1944E-02    0.0  2872.3    2.6    2.6    2.6    2.6
127 0.1662E-02   209.1  2585.5    2.4    2.4    2.4    2.4
128 0.3304E-05  1051.4  5171.0    0.0    0.0    0.0    0.0
129 0.5629E-04   418.3  5171.0    0.2    0.2    0.2    0.2
130 0.1288E-02    0.0     0.0    0.0    0.0    0.0    0.0
131 0.5359E-03    0.0   476.2    0.1    0.1    0.1    0.1
132 0.4580E-05   965.3  2070.9    0.0    0.0    0.0    0.0
133 0.1178E-04  1548.8  2178.3    0.0    0.0    0.0    0.0
134 0.1165E-02  2816.0  2872.3    3.3    3.3    3.3    3.3
135 0.2079E-03   967.9  2872.3    0.4    0.4    0.4    0.4
136 0.5141E-03  5401.5  5509.6    2.8    2.8    2.8    2.8
137 0.1609E-03   831.6  5401.5    0.4    0.4    0.4    0.4
138 0.2263E-04  2541.4  7987.0    0.1    0.1    0.1    0.1
```

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139 0.8975E-06  2913.2  7987.0   0.0   0.0   0.0   0.0
140 0.2377E-02  242.7  2816.0   3.5   3.5   3.5   3.5
141 0.5167E-03  349.8  2872.3   1.0   1.0   1.0   1.0
142 0.1256E-02  209.1  5509.6   4.3   4.3   4.3   4.3
143 0.4029E-03  209.1  5401.5   0.9   0.9   0.9   0.9
144 0.5891E-04  418.3  7987.0   0.2   0.2   0.2   0.2
145 0.3479E-03   0.0   0.0   0.0   0.0   0.0   0.0
146 0.1029E-03   0.0   0.0   0.0   0.0   0.0   0.0
147 0.6317E-05  909.4  917.6   0.0   0.0   0.0   0.0
148 0.2094E-03   0.0   0.0   0.0   0.0   0.0   0.0
149 0.8830E-03   0.0   0.0   0.0   0.0   0.0   0.0
150 0.1849E-03   0.0   0.0   0.0   0.0   0.0   0.0
151 0.8065E-04  161.5  476.2   0.0   0.0   0.0   0.0
152 0.2625E-03  161.5  476.2   0.1   0.1   0.1   0.1
153 0.1271E-04  985.3  1404.2   0.0   0.0   0.0   0.0
154 0.6174E-04  2637.2  2637.2   0.2   0.2   0.2   0.2
155 0.1589E-05  1398.5  1464.3   0.0   0.0   0.0   0.0
156 0.4720E-03   0.0   0.0   0.0   0.0   0.0   0.0
157 0.1110E-02   0.0  2816.0   0.8   0.8   0.8   0.8
158 0.1478E-02   0.0  2816.0   2.1   2.1   2.1   2.1
159 0.1977E-03  2816.0  2872.3   0.6   0.6   0.6   0.6
160 0.7689E-03   0.0  2816.0   0.9   0.9   0.9   0.9
161 0.1399E-03  476.2  476.2   0.1   0.1   0.1   0.1
162 0.7617E-05  1668.1  1758.6   0.0   0.0   0.0   0.0
163 0.3053E-03  5401.5  5509.6   1.7   1.7   1.7   1.7
164 0.4738E-03  636.9  5401.5   0.9   0.9   0.9   0.9
165 0.2551E-04  2323.6  7987.0   0.1   0.1   0.1   0.1
166 0.7780E-04  5401.5  5509.6   0.4   0.4   0.4   0.4
167 0.2478E-03  844.8  5401.5   0.5   0.5   0.5   0.5
168 0.1199E-04  2560.1  7987.0   0.0   0.0   0.0   0.0
169 0.1437E-05  2750.5  7987.0   0.0   0.0   0.0   0.0
170 0.4082E-02   0.0  2816.0   6.2   6.2   6.2   6.2
171 0.5197E-02   0.0  2872.3   8.4   8.4   8.4   8.4
172 0.9737E-03  209.1  5509.6   3.4   3.4   3.4   3.4
173 0.1748E-02  209.1  5401.5   3.9   3.9   3.9   3.9
174 0.9475E-04  418.3  7987.0   0.4   0.4   0.4   0.4
175 0.1094E-02   0.0   0.0   0.0   0.0   0.0   0.0
176 0.2449E-03   0.0   0.0   0.0   0.0   0.0   0.0
177 0.1781E-02   0.0   0.0   0.0   0.0   0.0   0.0
178 0.9062E-02   0.0   0.0   0.0   0.0   0.0   0.0
179 0.1500E-01   0.0   0.0   0.0   0.0   0.0   0.0
180 0.5091E-05 47705.4 47705.4   0.2   0.2   0.2   0.2
181 0.6968E-07 49993.5 50148.2   0.0   0.0   0.0   0.0
182 0.8939E-05 47705.4 47705.4   0.4   0.4   0.4   0.4
183 0.8168E-06 50342.6 50342.6   0.0   0.0   0.0   0.0
184 0.2884E-06 50342.6 50342.6   0.0   0.0   0.0   0.0
185 0.4182E-06 46770.0 46770.0   0.0   0.0   0.0   0.0
186 0.4266E-05 46770.0 46770.0   0.2   0.2   0.2   0.2
187 0.5786E-07 49355.5 49355.5   0.0   0.0   0.0   0.0
188 0.2414E-04 47705.4 47705.4   1.2   1.2   1.2   1.2
189 0.1846E-05 50342.6 50342.6   0.1   0.1   0.1   0.1
190 0.8894E-06 46770.0 46770.0   0.0   0.0   0.0   0.0
191 0.9072E-05 46770.0 46770.0   0.4   0.4   0.4   0.4
192 0.4941E-06 49355.5 49355.5   0.0   0.0   0.0   0.0
193 0.8445E-06 46770.0 46770.0   0.0   0.0   0.0   0.0
194 0.5400E-06 46770.0 46770.0   0.0   0.0   0.0   0.0
195 0.1745E-06 49355.5 49355.5   0.0   0.0   0.0   0.0
196 0.4900E-05 46770.0 46770.0   0.2   0.2   0.2   0.2
197 0.4998E-04 46770.0 46770.0   2.3   2.3   2.3   2.3
198 0.2722E-05 49355.5 49355.5   0.1   0.1   0.1   0.1
199 0.2115E-04  3555.2 46770.0   0.3   0.3   0.3   0.3
200 0.6122E-04  3555.2 11580.2   0.4   0.4   0.4   0.4
201 0.3334E-05  3764.3 12261.4   0.0   0.0   0.0   0.0
202 0.2711E-02   0.0   0.0   0.0   0.0   0.0   0.0
203 0.5827E-02   0.0   0.0   0.0   0.0   0.0   0.0
204 0.6288E-02   0.0   0.0   0.0   0.0   0.0   0.0
205 0.2590E-04   0.0  1425.7   0.0   0.0   0.0   0.0
206 0.4474E-05  1105.6  1577.7   0.0   0.0   0.0   0.0
207 0.6122E-07  2471.3  2471.3   0.0   0.0   0.0   0.0
208 0.4605E-04  312.8  1833.7   0.1   0.1   0.1   0.1
209 0.1161E-05  2816.0  2816.0   0.0   0.0   0.0   0.0
210 0.2187E-04  2816.0  2816.0   0.1   0.1   0.1   0.1
```

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211 0.7855E-05  1105.6  1577.7   0.0    0.0    0.0    0.0
212 0.7177E-06  2922.3  3866.5   0.0    0.0    0.0    0.0
213 0.2534E-06  3429.1  3743.8   0.0    0.0    0.0    0.0
214 0.3675E-06  5401.5  5401.5   0.0    0.0    0.0    0.0
215 0.3748E-05  5401.5  5401.5   0.0    0.0    0.0    0.0
216 0.5085E-07  7987.0  7987.0   0.0    0.0    0.0    0.0
217 0.1238E-03  1133.8  2702.6   0.3    0.3    0.3    0.3
218 0.2469E-05  2816.0  2816.0   0.0    0.0    0.0    0.0
219 0.4645E-04  2816.0  2816.0   0.1    0.1    0.1    0.1
220 0.3982E-05  2816.0  2816.0   0.0    0.0    0.0    0.0
221 0.2960E-05  2816.0  2816.0   0.0    0.0    0.0    0.0
222 0.2121E-04  1105.6  1577.7   0.0    0.0    0.0    0.0
223 0.1622E-05  3079.5  4023.6   0.0    0.0    0.0    0.0
224 0.7816E-06  5401.5  5401.5   0.0    0.0    0.0    0.0
225 0.7972E-05  5401.5  5401.5   0.0    0.0    0.0    0.0
226 0.4342E-06  7987.0  7987.0   0.0    0.0    0.0    0.0
227 0.7421E-06  5401.5  5401.5   0.0    0.0    0.0    0.0
228 0.4745E-06  5401.5  5401.5   0.0    0.0    0.0    0.0
229 0.1533E-06  7987.0  7987.0   0.0    0.0    0.0    0.0
230 0.1360E-04  2816.0  2816.0   0.0    0.0    0.0    0.0
231 0.2559E-03  2816.0  2816.0   0.7    0.7    0.7    0.7
232 0.9379E-04     0.0 2816.0  0.1    0.1    0.1    0.1
233 0.4306E-05  5401.5  5401.5   0.0    0.0    0.0    0.0
234 0.4392E-04  5401.5  5401.5   0.2    0.2    0.2    0.2
235 0.2392E-05  7987.0  7987.0   0.0    0.0    0.0    0.0
236 0.1858E-04   209.1  5401.5  0.0    0.0    0.0    0.0
237 0.3142E-03     0.0  510.4  0.0    0.0    0.0    0.0
238 0.5379E-04   209.1  681.2   0.0    0.0    0.0    0.0
239 0.2930E-05   418.3  1362.4   0.0    0.0    0.0    0.0
240 0.8857E-04    0.0    0.0   0.0    0.0    0.0    0.0
241 0.1333E-02    0.0    0.0   0.0    0.0    0.0    0.0
242 0.6588E-04    0.0    0.0   0.0    0.0    0.0    0.0
243 0.2977E-02    0.0    0.0   0.0    0.0    0.0    0.0
244 0.1046E-02    0.0    0.0   0.0    0.0    0.0    0.0
245 0.3161E-05    0.0    0.0   0.0    0.0    0.0    0.0
246 0.2739E-02    0.0    0.0   0.0    0.0    0.0    0.0
247 0.6915E-03    0.0    0.0   0.0    0.0    0.0    0.0
248 0.6651E-05    0.0    0.0   0.0    0.0    0.0    0.0
249 0.3464E-02    0.0    0.0   0.0    0.0    0.0    0.0
250 0.3865E-02    0.0    0.0   0.0    0.0    0.0    0.0
251 0.4898E-02    0.0    0.0   0.0    0.0    0.0    0.0
FILE REFERENCE:
SHIP:DH01.GF0   REF.No:0001
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FILE AFTER EXPORTING IN MICROSOFT EXCEL™ SPREADSHEET

FILE	REFERENCE:
SHIP:DH01.GF0	REF.No:0001

CASE	PROBABILITY	MINOUT	MAXOUT	OUT 1	OUT 2	OUT 3	OUT 4
1	2.54E-02	0.0	0.0	0.0	0.0	0.0	0.0
2	1.08E-02	0.0	0.0	0.0	0.0	0.0	0.0
3	1.34E-02	0.0	0.0	0.0	0.0	0.0	0.0
4	2.80E-02	0.0	0.0	0.0	0.0	0.0	0.0
5	6.71E-02	0.0	30370.7	915.9	915.9	915.9	915.9
6	1.19E-02	0.0	18532.3	122.0	122.0	122.0	122.0
7	6.56E-05	0.0	12987.3	0.2	0.2	0.2	0.2
8	2.89E-04	0.0	0.0	0.0	0.0	0.0	0.0
9	3.56E-04	0.0	0.0	0.0	0.0	0.0	0.0
10	6.01E-03	30370.7	30370.7	182.4	182.4	182.4	182.4
11	6.76E-06	30370.7	30370.7	0.2	0.2	0.2	0.2
12	1.02E-03	0.0	0.0	0.0	0.0	0.0	0.0
13	6.46E-03	2456.5	30370.7	35.6	35.6	35.6	35.6
14	1.24E-04	0.0	30370.7	0.6	0.6	0.6	0.6
15	1.48E-02	0.0	0.0	0.0	0.0	0.0	0.0
16	6.09E-02	0.0	76910.2	2135.5	2135.5	2135.5	2135.5
17	9.81E-04	0.0	46930.9	26.2	26.2	26.2	26.2
18	6.89E-06	0.0	32888.8	0.0	0.0	0.0	0.0
19	5.81E-04	76910.2	76910.2	44.7	44.7	44.7	44.7
20	5.53E-07	76910.2	76910.2	0.0	0.0	0.0	0.0
21	6.76E-04	6220.9	76910.2	9.4	9.4	9.4	9.4
22	1.14E-04	0.0	76910.2	1.3	1.3	1.3	1.3
23	2.11E-02	0.0	0.0	0.0	0.0	0.0	0.0
24	8.98E-02	0.0	46539.5	1907.5	1907.5	1907.5	1907.5
25	1.73E-04	0.0	46539.5	1.2	1.2	1.2	1.2
26	1.87E-04	0.0	0.0	0.0	0.0	0.0	0.0
27	7.96E-04	0.0	123449.7	44.8	44.8	44.8	44.8
28	1.53E-06	0.0	123449.7	0.0	0.0	0.0	0.0
29	1.47E-02	0.0	0.0	0.0	0.0	0.0	0.0
30	6.25E-02	0.0	93079.0	2656.9	2656.9	2656.9	2656.9

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 31    1.20E-04       0.0    93079.0     1.6     1.6     1.6     1.6
 32    2.11E-02       0.0        0.0     0.0     0.0     0.0     0.0
 33    8.98E-02       0.0    46539.5  2283.7  2283.7  2283.7  2283.7
 34    1.73E-04       0.0    46539.5     1.2     1.2     1.2     1.2
 35    1.87E-04       0.0        0.0     0.0     0.0     0.0     0.0
 36    7.96E-04       0.0   139618.5    50.7    50.7    50.7    50.7
 37    1.53E-06       0.0   139618.5     0.0     0.0     0.0     0.0
 38    1.45E-02       0.0        0.0     0.0     0.0     0.0     0.0
 39    6.18E-02      14.3    93778.6  3307.1  3307.1  3307.1  3307.1
 40    1.19E-04       0.0    93079.0     1.6     1.6     1.6     1.6
 41    1.91E-02       0.0        0.0     0.0     0.0     0.0     0.0
 42    8.14E-02    3764.3    47470.3  2465.6  2465.6  2465.6  2465.6
 43    1.56E-04    1492.0    46539.5     1.9     1.9     1.9     1.9
 44    1.70E-04       0.0        0.0     0.0     0.0     0.0     0.0
 45    7.21E-04   10874.8   137136.4    67.6    67.6    67.6    67.6
 46    1.39E-06       0.0   134447.5     0.0     0.0     0.0     0.0
 47    1.18E-02       0.0        0.0     0.0     0.0     0.0     0.0
 48    4.96E-02    7110.4    89666.1  3324.4  3324.4  3324.4  3324.4
 49    9.53E-05   20781.8    89666.1     4.2     4.2     4.2     4.2
 50    1.47E-02       0.0        0.0     0.0     0.0     0.0     0.0
 51    5.20E-02    3346.1    42195.8  1545.5  1545.5  1545.5  1545.5
 52   10.00E-05    7823.4    41368.5     1.6     1.6     1.6     1.6
 53    5.25E-04    7319.5    92303.3    37.8    37.8    37.8    37.8
 54    1.04E-06   50339.1    94940.5     0.1     0.1     0.1     0.1
 55    1.78E-05    7528.7    94940.5     1.3     1.3     1.3     1.3
 56    2.06E-05       0.0        0.0     0.0     0.0     0.0     0.0
 57    8.25E-05   68854.7    92303.3     7.1     7.1     7.1     7.1
 58    8.68E-07   50846.0    79080.5     0.1     0.1     0.1     0.1
 59    2.23E-06   86722.9    94940.5     0.2     0.2     0.2     0.2
 60    3.10E-05       0.0     2816.0     0.0     0.0     0.0     0.0
 61    9.51E-05   93309.5    95175.7     9.0     9.0     9.0     9.0
 62    3.05E-05   93309.5    95175.7     2.9     2.9     2.9     2.9
 63    4.29E-06   95895.0    97812.9     0.4     0.4     0.4     0.4
 64    1.70E-07   95895.0    97812.9     0.0     0.0     0.0     0.0
 65    7.70E-05       0.0     2872.3     0.1     0.1     0.1     0.1
 66    2.38E-04    7319.5    95175.7    14.8    14.8    14.8    14.8
 67    7.63E-05    7319.5    95175.7     4.7     4.7     4.7     4.7
 68    1.12E-05    7528.7    97812.9     0.7     0.7     0.7     0.7
 69    8.45E-03    3555.2    44833.0   279.6   279.6   279.6   279.6
 70    1.68E-05   18233.3    46539.5     0.4     0.4     0.4     0.4
 71    2.86E-04    3764.3    47470.3    10.2    10.2    10.2    10.2
 72    1.39E-03       0.0        0.0     0.0     0.0     0.0     0.0
 73    2.48E-03   23123.1    41528.9    79.7    79.7    79.7    79.7
 74    2.28E-05   18579.6    33678.3     0.5     0.5     0.5     0.5
 75    2.95E-07   73795.6    73795.6     0.0     0.0     0.0     0.0
 76    1.81E-08   55914.4    55914.4     0.0     0.0     0.0     0.0
 77    5.86E-05   33157.8    42214.1     2.2     2.2     2.2     2.2
 78    2.31E-07   87249.7    92303.3     0.0     0.0     0.0     0.0
 79    7.52E-07   88528.5    92303.3     0.1     0.1     0.1     0.1
 80    3.64E-08   94940.5    94940.5     0.0     0.0     0.0     0.0
 81    1.77E-07   92303.3    92303.3     0.0     0.0     0.0     0.0
 82    4.55E-09   79329.9    79329.9     0.0     0.0     0.0     0.0
 83    1.75E-03    2816.0     2872.3     5.0     5.0     5.0     5.0
 84    2.53E-03   43310.0    47705.4   119.4   119.4   119.4   119.4
 85    8.00E-04   41660.9    47705.4    37.4    37.4    37.4    37.4
 86    1.13E-04   47086.1    50342.6     5.6     5.6     5.6     5.6
 87    4.46E-06   47057.5    49579.4     0.2     0.2     0.2     0.2
 88    4.01E-07   92303.3    92303.3     0.0     0.0     0.0     0.0
 89    2.18E-08   94940.5    94940.5     0.0     0.0     0.0     0.0
 90    8.79E-07   93309.5    95175.7     0.1     0.1     0.1     0.1
 91    1.40E-06   93309.5    95175.7     0.1     0.1     0.1     0.1
 92    7.64E-08   95895.0    97812.9     0.0     0.0     0.0     0.0
 93    2.25E-07   93309.5    95175.7     0.0     0.0     0.0     0.0
 94    7.33E-07   93309.5    95175.7     0.1     0.1     0.1     0.1
 95    3.55E-08   95895.0    97812.9     0.0     0.0     0.0     0.0
 96    2.50E-07    2816.0     2872.3     0.0     0.0     0.0     0.0
 97    4.44E-09   95895.0    97812.9     0.0     0.0     0.0     0.0
 98    3.33E-03       0.0     2872.3     6.4     6.4     6.4     6.4
 99    6.25E-03    3555.2    47705.4   193.6   193.6   193.6   193.6
100    2.00E-03    3555.2    47705.4    62.1    62.1    62.1    62.1
101    2.93E-04    3764.3    50342.6     9.6     9.6     9.6     9.6
102    2.85E-06    7319.5    95175.7     0.2     0.2     0.2     0.2
103    5.35E-06    7319.5    95175.7     0.3     0.3     0.3     0.3
104    2.91E-07    7528.7    97812.9     0.0     0.0     0.0     0.0
105    1.35E-06       0.0     2872.3     0.0     0.0     0.0     0.0
106    3.22E-04   23417.2    28951.2     8.3     8.3     8.3     8.3
107    1.97E-05   19044.6    24999.4     0.4     0.4     0.4     0.4
108    2.52E-04   29243.7    40680.0     8.4     8.4     8.4     8.4
109    8.21E-04   26420.8    36640.5    24.5    24.5    24.5    24.5
110    3.97E-05   30727.9    39094.2     1.4     1.4     1.4     1.4
111    1.93E-04   35660.3    41448.6     7.3     7.3     7.3     7.3
112    4.97E-06   27929.9    32379.9     0.1     0.1     0.1     0.1
113    4.37E-04   33603.1    38328.6    15.6    15.6    15.6    15.6
114    2.38E-05   38427.6    44132.8     1.0     1.0     1.0     1.0
115    9.57E-04   44308.3    47705.4    45.3    45.3    45.3    45.3
116    1.51E-03   42656.4    47705.4    71.0    71.0    71.0    71.0
117    8.20E-05   48561.7    50342.6     4.1     4.1     4.1     4.1
118    2.45E-04   46770.0    47705.4    11.6    11.6    11.6    11.6
119    7.91E-04   44369.7    47705.4    37.3    37.3    37.3    37.3
120    3.83E-05   49355.5    50342.6     1.9     1.9     1.9     1.9
121    3.60E-04    2816.0     2872.3     1.0     1.0     1.0     1.0
122    4.72E-06   46420.1    49873.6     0.2     0.2     0.2     0.2
123    3.09E-03    3555.2    47705.4    96.0    96.0    96.0    96.0
124    5.70E-03    3555.2    47705.4   177.0   177.0   177.0   177.0
125    3.10E-04    3764.3    50342.6    10.2    10.2    10.2    10.2
126    1.94E-03       0.0     2872.3     2.6     2.6     2.6     2.6
127    1.66E-03     209.1     2585.5     2.4     2.4     2.4     2.4
128    3.30E-06    1051.4     5171.0     0.0     0.0     0.0     0.0
129    5.63E-05     418.3     5171.0     0.2     0.2     0.2     0.2
130    1.29E-03       0.0        0.0     0.0     0.0     0.0     0.0
131    5.36E-04       0.0      476.2     0.1     0.1     0.1     0.1
132    4.58E-06     965.3     2070.9     0.0     0.0     0.0     0.0
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133      1.18E-05     1548.8     2178.3    0.0    0.0    0.0    0.0
134      1.17E-03     2816.0     2872.3    3.3    3.3    3.3    3.3
135      2.08E-04      967.9     2872.3    0.4    0.4    0.4    0.4
136      5.14E-04     5401.5     5509.6    2.8    2.8    2.8    2.8
137      1.61E-04      831.6     5401.5    0.4    0.4    0.4    0.4
138      2.26E-05     2541.4     7987.0    0.1    0.1    0.1    0.1
139      8.98E-07     2913.2     7987.0    0.0    0.0    0.0    0.0
140      2.38E-03      242.7     2816.0    3.5    3.5    3.5    3.5
141      5.17E-04      349.8     2872.3    1.0    1.0    1.0    1.0
142      1.26E-03      209.1     5509.6    4.3    4.3    4.3    4.3
143      4.03E-04      209.1     5401.5    0.9    0.9    0.9    0.9
144      5.89E-05      418.3     7987.0    0.2    0.2    0.2    0.2
145      3.48E-04        0.0        0.0    0.0    0.0    0.0    0.0
146      1.03E-04        0.0        0.0    0.0    0.0    0.0    0.0
147      6.32E-06      909.4      917.6    0.0    0.0    0.0    0.0
148      2.09E-04        0.0        0.0    0.0    0.0    0.0    0.0
149      8.83E-04        0.0        0.0    0.0    0.0    0.0    0.0
150      1.85E-04        0.0        0.0    0.0    0.0    0.0    0.0
151      8.07E-05      161.5      476.2    0.0    0.0    0.0    0.0
152      2.63E-04      161.5      476.2    0.1    0.1    0.1    0.1
153      1.27E-05      985.3     1404.2    0.0    0.0    0.0    0.0
154      6.17E-05     2637.2     2637.2    0.2    0.2    0.2    0.2
155      1.59E-06     1398.5     1464.3    0.0    0.0    0.0    0.0
156      4.72E-04        0.0        0.0    0.0    0.0    0.0    0.0
157      1.11E-03        0.0     2816.0    0.8    0.8    0.8    0.8
158      1.48E-03        0.0     2816.0    2.1    2.1    2.1    2.1
159      1.98E-04     2816.0     2872.3    0.6    0.6    0.6    0.6
160      7.69E-04        0.0     2816.0    0.9    0.9    0.9    0.9
161      1.40E-04      476.2      476.2    0.1    0.1    0.1    0.1
162      7.62E-06     1668.1     1758.6    0.0    0.0    0.0    0.0
163      3.05E-04     5401.5     5509.6    1.7    1.7    1.7    1.7
164      4.74E-04      636.9     5401.5    0.9    0.9    0.9    0.9
165      2.55E-05     2323.6     7987.0    0.1    0.1    0.1    0.1
166      7.78E-05     5401.5     5509.6    0.4    0.4    0.4    0.4
167      2.48E-04      844.8     5401.5    0.5    0.5    0.5    0.5
168      1.20E-05     2560.1     7987.0    0.0    0.0    0.0    0.0
169      1.44E-06     2750.5     7987.0    0.0    0.0    0.0    0.0
170      4.08E-03        0.0     2816.0    6.2    6.2    6.2    6.2
171      5.20E-03        0.0     2872.3    8.4    8.4    8.4    8.4
172      9.74E-04      209.1     5509.6    3.4    3.4    3.4    3.4
173      1.75E-03      209.1     5401.5    3.9    3.9    3.9    3.9
174      9.48E-05      418.3     7987.0    0.4    0.4    0.4    0.4
175      1.09E-03        0.0        0.0    0.0    0.0    0.0    0.0
176      2.45E-04        0.0        0.0    0.0    0.0    0.0    0.0
177      1.78E-03        0.0        0.0    0.0    0.0    0.0    0.0
178      9.06E-03        0.0        0.0    0.0    0.0    0.0    0.0
179      1.50E-02        0.0        0.0    0.0    0.0    0.0    0.0
180      5.09E-06    47705.4    47705.4    0.2    0.2    0.2    0.2
181      6.97E-08    49993.5    50148.2    0.0    0.0    0.0    0.0
182      8.94E-06    47705.4    47705.4    0.4    0.4    0.4    0.4
183      8.17E-07    50342.6    50342.6    0.0    0.0    0.0    0.0
184      2.88E-07    50342.6    50342.6    0.0    0.0    0.0    0.0
185      4.18E-07    46770.0    46770.0    0.0    0.0    0.0    0.0
186      4.27E-06    46770.0    46770.0    0.2    0.2    0.2    0.2
187      5.79E-08    49355.5    49355.5    0.0    0.0    0.0    0.0
188      2.41E-05    47705.4    47705.4    1.2    1.2    1.2    1.2
189      1.85E-06    50342.6    50342.6    0.1    0.1    0.1    0.1
190      8.89E-07    46770.0    46770.0    0.0    0.0    0.0    0.0
191      9.07E-06    46770.0    46770.0    0.4    0.4    0.4    0.4
192      4.94E-07    49355.5    49355.5    0.0    0.0    0.0    0.0
193      8.45E-07    46770.0    46770.0    0.0    0.0    0.0    0.0
194      5.40E-07    46770.0    46770.0    0.0    0.0    0.0    0.0
195      1.75E-07    49355.5    49355.5    0.0    0.0    0.0    0.0
196      4.90E-06    46770.0    46770.0    0.2    0.2    0.2    0.2
197      5.00E-05    46770.0    46770.0    2.3    2.3    2.3    2.3
198      2.72E-06    49355.5    49355.5    0.1    0.1    0.1    0.1
199      2.12E-05     3555.2    46770.0    0.3    0.3    0.3    0.3
200      6.12E-05     3555.2    11580.2    0.4    0.4    0.4    0.4
201      3.33E-06     3764.3    12261.4    0.0    0.0    0.0    0.0
202      2.71E-03        0.0        0.0    0.0    0.0    0.0    0.0
203      5.83E-03        0.0        0.0    0.0    0.0    0.0    0.0
204      6.29E-03        0.0        0.0    0.0    0.0    0.0    0.0
205      2.59E-05        0.0     1425.7    0.0    0.0    0.0    0.0
206      4.47E-06     1105.6     1577.7    0.0    0.0    0.0    0.0
207      6.12E-08     2471.3     2471.3    0.0    0.0    0.0    0.0
208      4.61E-05      312.8     1833.7    0.1    0.1    0.1    0.1
209      1.16E-06     2816.0     2816.0    0.0    0.0    0.0    0.0
210      2.19E-05     2816.0     2816.0    0.1    0.1    0.1    0.1
211      7.86E-06     1105.6     1577.7    0.0    0.0    0.0    0.0
212      7.18E-07     2922.3     3866.5    0.0    0.0    0.0    0.0
213      2.53E-07     3429.1     3743.8    0.0    0.0    0.0    0.0
214      3.68E-07     5401.5     5401.5    0.0    0.0    0.0    0.0
215      3.75E-06     5401.5     5401.5    0.0    0.0    0.0    0.0
216      5.09E-08     7987.0     7987.0    0.0    0.0    0.0    0.0
217      1.24E-04     1133.8     2702.6    0.3    0.3    0.3    0.3
218      2.47E-06     2816.0     2816.0    0.0    0.0    0.0    0.0
219      4.65E-05     2816.0     2816.0    0.1    0.1    0.1    0.1
220      3.98E-06     2816.0     2816.0    0.0    0.0    0.0    0.0
221      2.96E-06     2816.0     2816.0    0.0    0.0    0.0    0.0
222      2.12E-05     1105.6     1577.7    0.0    0.0    0.0    0.0
223      1.62E-06     3079.5     4023.6    0.0    0.0    0.0    0.0
224      7.82E-07     5401.5     5401.5    0.0    0.0    0.0    0.0
225      7.97E-06     5401.5     5401.5    0.0    0.0    0.0    0.0
226      4.34E-07     7987.0     7987.0    0.0    0.0    0.0    0.0
227      7.42E-07     5401.5     5401.5    0.0    0.0    0.0    0.0
228      4.75E-07     5401.5     5401.5    0.0    0.0    0.0    0.0
229      1.53E-07     7987.0     7987.0    0.0    0.0    0.0    0.0
230      1.36E-05     2816.0     2816.0    0.0    0.0    0.0    0.0
231      2.56E-04     2816.0     2816.0    0.7    0.7    0.7    0.7
232      9.38E-05        0.0     2816.0    0.1    0.1    0.1    0.1
233      4.31E-06     5401.5     5401.5    0.0    0.0    0.0    0.0
234      4.39E-05     5401.5     5401.5    0.2    0.2    0.2    0.2
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235	2.39E-06	7987.0	7987.0	0.0	0.0	0.0	0.0
236	1.86E-05	209.1	5401.5	0.0	0.0	0.0	0.0
237	3.14E-04	0.0	510.4	0.0	0.0	0.0	0.0
238	5.38E-05	209.1	681.2	0.0	0.0	0.0	0.0
239	2.93E-06	418.3	1362.4	0.0	0.0	0.0	0.0
240	8.86E-05	0.0	0.0	0.0	0.0	0.0	0.0
241	1.33E-03	0.0	0.0	0.0	0.0	0.0	0.0
242	6.59E-05	0.0	0.0	0.0	0.0	0.0	0.0
243	2.98E-03	0.0	0.0	0.0	0.0	0.0	0.0
244	1.05E-03	0.0	0.0	0.0	0.0	0.0	0.0
245	3.16E-06	0.0	0.0	0.0	0.0	0.0	0.0
246	2.74E-03	0.0	0.0	0.0	0.0	0.0	0.0
247	6.92E-04	0.0	0.0	0.0	0.0	0.0	0.0
248	6.65E-06	0.0	0.0	0.0	0.0	0.0	0.0
249	3.46E-03	0.0	0.0	0.0	0.0	0.0	0.0
250	3.87E-03	0.0	0.0	0.0	0.0	0.0	0.0
251	4.90E-03	0.0	0.0	0.0	0.0	0.0	0.0

POST-PROCESSED MICROSOFT EXCEL™ SPREADSHEET

FILE	REFERENCE:
SHIP:DH01.GF0	REF.No:0001

CASE	PROBABILITY	MINOUT	MAXOUT	OUT 1	OUT 2	OUT 3	OUT 4	cum.prob.
1	2.54E-02	0.0	0.0	0.0	0.0	0.0	0.0	2.54E-02
2	1.08E-02	0.0	0.0	0.0	0.0	0.0	0.0	3.62E-02
3	1.34E-02	0.0	0.0	0.0	0.0	0.0	0.0	4.96E-02
4	2.80E-02	0.0	0.0	0.0	0.0	0.0	0.0	7.76E-02
8	2.89E-04	0.0	0.0	0.0	0.0	0.0	0.0	7.79E-02
9	3.56E-04	0.0	0.0	0.0	0.0	0.0	0.0	7.82E-02
12	1.02E-03	0.0	0.0	0.0	0.0	0.0	0.0	7.92E-02
15	1.48E-02	0.0	0.0	0.0	0.0	0.0	0.0	9.41E-02
23	2.11E-02	0.0	0.0	0.0	0.0	0.0	0.0	1.15E-01
26	1.87E-04	0.0	0.0	0.0	0.0	0.0	0.0	1.15E-01
29	1.47E-02	0.0	0.0	0.0	0.0	0.0	0.0	1.30E-01
32	2.11E-02	0.0	0.0	0.0	0.0	0.0	0.0	1.51E-01
35	1.87E-04	0.0	0.0	0.0	0.0	0.0	0.0	1.51E-01
38	1.45E-02	0.0	0.0	0.0	0.0	0.0	0.0	1.66E-01
41	1.91E-02	0.0	0.0	0.0	0.0	0.0	0.0	1.85E-01
44	1.70E-04	0.0	0.0	0.0	0.0	0.0	0.0	1.85E-01
47	1.18E-02	0.0	0.0	0.0	0.0	0.0	0.0	1.97E-01
50	1.47E-02	0.0	0.0	0.0	0.0	0.0	0.0	2.12E-01
56	2.06E-05	0.0	0.0	0.0	0.0	0.0	0.0	2.12E-01
72	1.39E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.13E-01
130	1.29E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.14E-01
145	3.48E-04	0.0	0.0	0.0	0.0	0.0	0.0	2.15E-01
146	1.03E-04	0.0	0.0	0.0	0.0	0.0	0.0	2.15E-01
148	2.09E-04	0.0	0.0	0.0	0.0	0.0	0.0	2.15E-01
149	8.83E-04	0.0	0.0	0.0	0.0	0.0	0.0	2.16E-01
150	1.85E-04	0.0	0.0	0.0	0.0	0.0	0.0	2.16E-01
156	4.72E-04	0.0	0.0	0.0	0.0	0.0	0.0	2.17E-01
175	1.09E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.18E-01
176	2.45E-04	0.0	0.0	0.0	0.0	0.0	0.0	2.18E-01
177	1.78E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.20E-01
178	9.06E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.29E-01
179	1.50E-02	0.0	0.0	0.0	0.0	0.0	0.0	2.44E-01
202	2.71E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.46E-01
203	5.83E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.52E-01
204	6.29E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.59E-01
240	8.86E-05	0.0	0.0	0.0	0.0	0.0	0.0	2.59E-01
241	1.33E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.60E-01
242	6.59E-05	0.0	0.0	0.0	0.0	0.0	0.0	2.60E-01
243	2.98E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.63E-01
244	1.05E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.64E-01
245	3.16E-06	0.0	0.0	0.0	0.0	0.0	0.0	2.64E-01
246	2.74E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.67E-01
247	6.92E-04	0.0	0.0	0.0	0.0	0.0	0.0	2.67E-01
248	6.65E-06	0.0	0.0	0.0	0.0	0.0	0.0	2.68E-01
249	3.46E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.71E-01
250	3.87E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.75E-01
251	4.90E-03	0.0	0.0	0.0	0.0	0.0	0.0	2.80E-01
131	5.36E-04	0.0	476.2	0.1	0.1	0.1	0.1	2.80E-01
151	8.07E-05	161.5	476.2	0.0	0.0	0.0	0.0	2.80E-01
152	2.63E-04	161.5	476.2	0.1	0.1	0.1	0.1	2.81E-01
161	1.40E-04	476.2	476.2	0.1	0.1	0.1	0.1	2.81E-01
237	3.14E-04	0.0	510.4	0.0	0.0	0.0	0.0	2.81E-01
238	5.38E-05	209.1	681.2	0.0	0.0	0.0	0.0	2.81E-01
147	6.32E-06	909.4	917.6	0.0	0.0	0.0	0.0	2.81E-01
239	2.93E-06	418.3	1362.4	0.0	0.0	0.0	0.0	2.81E-01
153	1.27E-05	985.3	1404.2	0.0	0.0	0.0	0.0	2.81E-01
205	2.59E-05	0.0	1425.7	0.0	0.0	0.0	0.0	2.81E-01
155	1.59E-06	1398.5	1464.3	0.0	0.0	0.0	0.0	2.81E-01
206	4.47E-06	1105.6	1577.7	0.0	0.0	0.0	0.0	2.81E-01
211	7.86E-06	1105.6	1577.7	0.0	0.0	0.0	0.0	2.81E-01
222	2.12E-05	1105.6	1577.7	0.0	0.0	0.0	0.0	2.81E-01
162	7.62E-06	1668.1	1758.6	0.0	0.0	0.0	0.0	2.81E-01
208	4.61E-05	312.8	1833.7	0.1	0.1	0.1	0.1	2.81E-01
132	4.58E-06	965.3	2070.9	0.0	0.0	0.0	0.0	2.81E-01
133	1.18E-05	1548.8	2178.3	0.0	0.0	0.0	0.0	2.81E-01
207	6.12E-08	2471.3	2471.3	0.0	0.0	0.0	0.0	2.81E-01
127	1.66E-03	209.1	2585.5	2.4	2.4	2.4	2.4	2.83E-01
154	6.17E-05	2637.2	2637.2	0.2	0.2	0.2	0.2	2.83E-01
217	1.24E-04	1133.8	2702.6	0.3	0.3	0.3	0.3	2.83E-01
60	3.10E-05	0.0	2816.0	0.0	0.0	0.0	0.0	2.83E-01
140	2.38E-03	242.7	2816.0	3.5	3.5	3.5	3.5	2.86E-01
157	1.11E-03	0.0	2816.0	0.8	0.8	0.8	0.8	2.87E-01
158	1.48E-03	0.0	2816.0	2.1	2.1	2.1	2.1	2.88E-01
160	7.69E-04	0.0	2816.0	0.9	0.9	0.9	0.9	2.89E-01

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 170     4.08E-03       0.0    2816.0      6.2      6.2      6.2      6.2   2.93E-01
 209     1.16E-06    2816.0    2816.0      0.0      0.0      0.0      0.0   2.93E-01
 210     2.19E-05    2816.0    2816.0      0.1      0.1      0.1      0.1   2.93E-01
 218     2.47E-06    2816.0    2816.0      0.0      0.0      0.0      0.0   2.93E-01
 219     4.65E-05    2816.0    2816.0      0.1      0.1      0.1      0.1   2.93E-01
 220     3.98E-06    2816.0    2816.0      0.0      0.0      0.0      0.0   2.93E-01
 221     2.96E-06    2816.0    2816.0      0.0      0.0      0.0      0.0   2.93E-01
 230     1.36E-05    2816.0    2816.0      0.0      0.0      0.0      0.0   2.93E-01
 231     2.56E-04    2816.0    2816.0      0.7      0.7      0.7      0.7   2.93E-01
 232     9.38E-05       0.0    2816.0      0.1      0.1      0.1      0.1   2.93E-01
  65     7.70E-05       0.0    2872.3      0.1      0.1      0.1      0.1   2.93E-01
  83     1.75E-03    2816.0    2872.3      5.0      5.0      5.0      5.0   2.95E-01
  96     2.50E-07    2816.0    2872.3      0.0      0.0      0.0      0.0   2.95E-01
  98     3.33E-03       0.0    2872.3      6.4      6.4      6.4      6.4   2.99E-01
 105     1.35E-06       0.0    2872.3      0.0      0.0      0.0      0.0   2.99E-01
 121     3.60E-04    2816.0    2872.3      1.0      1.0      1.0      1.0   2.99E-01
 126     1.94E-03       0.0    2872.3      2.6      2.6      2.6      2.6   3.01E-01
 134     1.17E-03    2816.0    2872.3      3.3      3.3      3.3      3.3   3.02E-01
 135     2.08E-04     967.9    2872.3      0.4      0.4      0.4      0.4   3.02E-01
 141     5.17E-04     349.8    2872.3      1.0      1.0      1.0      1.0   3.03E-01
 159     1.98E-04    2816.0    2872.3      0.6      0.6      0.6      0.6   3.03E-01
 171     5.20E-03       0.0    2872.3      8.4      8.4      8.4      8.4   3.08E-01
 213     2.53E-07    3429.1    3743.8      0.0      0.0      0.0      0.0   3.08E-01
 212     7.18E-07    2922.3    3866.5      0.0      0.0      0.0      0.0   3.08E-01
 223     1.62E-06    3079.5    4023.6      0.0      0.0      0.0      0.0   3.08E-01
 128     3.30E-06    1051.4    5171.0      0.0      0.0      0.0      0.0   3.08E-01
 129     5.63E-05     418.3    5171.0      0.2      0.2      0.2      0.2   3.08E-01
 137     1.61E-04     831.6    5401.5      0.4      0.4      0.4      0.4   3.08E-01
 143     4.03E-04     209.1    5401.5      0.9      0.9      0.9      0.9   3.09E-01
 164     4.74E-04     636.9    5401.5      0.9      0.9      0.9      0.9   3.09E-01
 167     2.48E-04     844.8    5401.5      0.5      0.5      0.5      0.5   3.09E-01
 173     1.75E-03     209.1    5401.5      3.9      3.9      3.9      3.9   3.11E-01
 214     3.68E-07    5401.5    5401.5      0.0      0.0      0.0      0.0   3.11E-01
 215     3.75E-06    5401.5    5401.5      0.0      0.0      0.0      0.0   3.11E-01
 224     7.82E-07    5401.5    5401.5      0.0      0.0      0.0      0.0   3.11E-01
 225     7.97E-06    5401.5    5401.5      0.0      0.0      0.0      0.0   3.11E-01
 227     7.42E-07    5401.5    5401.5      0.0      0.0      0.0      0.0   3.11E-01
 228     4.75E-07    5401.5    5401.5      0.0      0.0      0.0      0.0   3.11E-01
 233     4.31E-06    5401.5    5401.5      0.0      0.0      0.0      0.0   3.11E-01
 234     4.39E-05    5401.5    5401.5      0.2      0.2      0.2      0.2   3.11E-01
 236     1.86E-05     209.1    5401.5      0.0      0.0      0.0      0.0   3.11E-01
 136     5.14E-04    5401.5    5509.6      2.8      2.8      2.8      2.8   3.12E-01
 142     1.26E-03     209.1    5509.6      4.3      4.3      4.3      4.3   3.13E-01
 163     3.05E-04    5401.5    5509.6      1.7      1.7      1.7      1.7   3.13E-01
 166     7.78E-05    5401.5    5509.6      0.4      0.4      0.4      0.4   3.13E-01
 172     9.74E-04     209.1    5509.6      3.4      3.4      3.4      3.4   3.14E-01
 138     2.26E-05    2541.4    7987.0      0.1      0.1      0.1      0.1   3.14E-01
 139     8.98E-07    2913.2    7987.0      0.0      0.0      0.0      0.0   3.14E-01
 144     5.89E-05     418.3    7987.0      0.2      0.2      0.2      0.2   3.15E-01
 165     2.55E-05    2323.6    7987.0      0.1      0.1      0.1      0.1   3.15E-01
 168     1.20E-05    2560.1    7987.0      0.0      0.0      0.0      0.0   3.15E-01
 169     1.44E-06    2750.5    7987.0      0.0      0.0      0.0      0.0   3.15E-01
 174     9.48E-05     418.3    7987.0      0.4      0.4      0.4      0.4   3.15E-01
 216     5.09E-08    7987.0    7987.0      0.0      0.0      0.0      0.0   3.15E-01
 226     4.34E-07    7987.0    7987.0      0.0      0.0      0.0      0.0   3.15E-01
 229     1.53E-07    7987.0    7987.0      0.0      0.0      0.0      0.0   3.15E-01
 235     2.39E-06    7987.0    7987.0      0.0      0.0      0.0      0.0   3.15E-01
 200     6.12E-05    3555.2   11580.2      0.4      0.4      0.4      0.4   3.15E-01
 201     3.33E-06    3764.3   12261.4      0.0      0.0      0.0      0.0   3.15E-01
   7     6.56E-05       0.0   12987.3      0.2      0.2      0.2      0.2   3.15E-01
   6     1.19E-02       0.0   18532.3    122.0    122.0    122.0    122.0   3.27E-01
 107     1.97E-05   19044.6   24999.4      0.4      0.4      0.4      0.4   3.27E-01
 106     3.22E-04   23417.2   28951.2      8.3      8.3      8.3      8.3   3.27E-01
   5     6.71E-02       0.0   30370.7    915.9    915.9    915.9    915.9   3.94E-01
  10     6.01E-03   30370.7   30370.7    182.4    182.4    182.4    182.4   4.00E-01
  11     6.76E-06   30370.7   30370.7      0.2      0.2      0.2      0.2   4.00E-01
  13     6.46E-03    2456.5   30370.7     35.6     35.6     35.6     35.6   4.07E-01
  14     1.24E-04       0.0   30370.7      0.6      0.6      0.6      0.6   4.07E-01
 112     4.97E-06   27929.9   32379.9      0.1      0.1      0.1      0.1   4.07E-01
  18     6.89E-06       0.0   32888.8      0.0      0.0      0.0      0.0   4.07E-01
  74     2.28E-05   18579.6   33678.3      0.5      0.5      0.5      0.5   4.07E-01
 109     8.21E-04   26420.8   36640.5     24.5     24.5     24.5     24.5   4.08E-01
 113     4.37E-04   33603.1   38328.6     15.6     15.6     15.6     15.6   4.08E-01
 110     3.97E-05   30727.9   39094.2      1.4      1.4      1.4      1.4   4.08E-01
 108     2.52E-04   29243.7   40680.0      8.4      8.4      8.4      8.4   4.08E-01
  52     1.00E-04    7823.4   41368.5      1.6      1.6      1.6      1.6   4.08E-01
 111     1.93E-04   35660.3   41448.6      7.3      7.3      7.3      7.3   4.09E-01
  73     2.48E-03   23123.1   41528.9     79.7     79.7     79.7     79.7   4.11E-01
  51     5.20E-02    3346.1   42195.8   1545.5   1545.5   1545.5   1545.5   4.63E-01
  77     5.86E-05   33157.8   42214.1      2.2      2.2      2.2      2.2   4.63E-01
 114     2.38E-05   38427.6   44132.8      1.0      1.0      1.0      1.0   4.63E-01
  69     8.45E-03    3555.2   44833.0    279.6    279.6    279.6    279.6   4.72E-01
  24     8.98E-02       0.0   46539.5   1907.5   1907.5   1907.5   1907.5   5.61E-01
  25     1.73E-04       0.0   46539.5      1.2      1.2      1.2      1.2   5.62E-01
  33     8.98E-02       0.0   46539.5   2283.7   2283.7   2283.7   2283.7   6.51E-01
  34     1.73E-04       0.0   46539.5      1.2      1.2      1.2      1.2   6.51E-01
  43     1.56E-04    1492.0   46539.5      1.9      1.9      1.9      1.9   6.52E-01
  70     1.68E-05   18233.3   46539.5      0.4      0.4      0.4      0.4   6.52E-01
 185     4.18E-07   46770.0   46770.0      0.0      0.0      0.0      0.0   6.52E-01
 186     4.27E-06   46770.0   46770.0      0.2      0.2      0.2      0.2   6.52E-01
 190     8.89E-07   46770.0   46770.0      0.0      0.0      0.0      0.0   6.52E-01
 191     9.07E-06   46770.0   46770.0      0.4      0.4      0.4      0.4   6.52E-01
 193     8.45E-07   46770.0   46770.0      0.0      0.0      0.0      0.0   6.52E-01
 194     5.40E-07   46770.0   46770.0      0.0      0.0      0.0      0.0   6.52E-01
 196     4.90E-06   46770.0   46770.0      0.2      0.2      0.2      0.2   6.52E-01
 197     5.00E-05   46770.0   46770.0      2.3      2.3      2.3      2.3   6.52E-01
 199     2.12E-05    3555.2   46770.0      0.3      0.3      0.3      0.3   6.52E-01
  17     9.81E-04       0.0   46930.9     26.2     26.2     26.2     26.2   6.53E-01
  42     8.14E-02    3764.3   47470.3   2465.6   2465.6   2465.6   2465.6   7.34E-01
  71     2.86E-04    3764.3   47470.3     10.2     10.2     10.2     10.2   7.34E-01
  84     2.53E-03   43310.0   47705.4    119.4    119.4    119.4    119.4   7.37E-01
  85     8.00E-04   41660.9   47705.4     37.4     37.4     37.4     37.4   7.38E-01
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 99    6.25E-03    3555.2    47705.4    193.6    193.6    193.6    193.6  7.44E-01
100    2.00E-03    3555.2    47705.4     62.1     62.1     62.1     62.1  7.46E-01
115    9.57E-04   44308.3    47705.4     45.3     45.3     45.3     45.3  7.47E-01
116    1.51E-03   42656.4    47705.4     71.0     71.0     71.0     71.0  7.48E-01
118    2.45E-04   46770.0    47705.4     11.6     11.6     11.6     11.6  7.49E-01
119    7.91E-04   44369.7    47705.4     37.3     37.3     37.3     37.3  7.49E-01
123    3.09E-03    3555.2    47705.4     96.0     96.0     96.0     96.0  7.52E-01
124    5.70E-03    3555.2    47705.4    177.0    177.0    177.0    177.0  7.58E-01
180    5.09E-06   47705.4    47705.4      0.2      0.2      0.2      0.2  7.58E-01
182    8.94E-06   47705.4    47705.4      0.4      0.4      0.4      0.4  7.58E-01
188    2.41E-05   47705.4    47705.4      1.2      1.2      1.2      1.2  7.58E-01
187    5.79E-08   49355.5    49355.5      0.0      0.0      0.0      0.0  7.58E-01
192    4.94E-07   49355.5    49355.5      0.0      0.0      0.0      0.0  7.58E-01
195    1.75E-07   49355.5    49355.5      0.0      0.0      0.0      0.0  7.58E-01
198    2.72E-06   49355.5    49355.5      0.1      0.1      0.1      0.1  7.58E-01
 87    4.46E-06   47057.5    49579.4      0.2      0.2      0.2      0.2  7.58E-01
122    4.72E-06   46420.1    49873.6      0.2      0.2      0.2      0.2  7.58E-01
181    6.97E-08   49993.5    50148.2      0.0      0.0      0.0      0.0  7.58E-01
 86    1.13E-04   47086.1    50342.6      5.6      5.6      5.6      5.6  7.58E-01
101    2.93E-04    3764.3    50342.6      9.6      9.6      9.6      9.6  7.59E-01
117    8.20E-05   48561.7    50342.6      4.1      4.1      4.1      4.1  7.59E-01
120    3.83E-05   49355.5    50342.6      1.9      1.9      1.9      1.9  7.59E-01
125    3.10E-04    3764.3    50342.6     10.2     10.2     10.2     10.2  7.59E-01
183    8.17E-07   50342.6    50342.6      0.0      0.0      0.0      0.0  7.59E-01
184    2.88E-07   50342.6    50342.6      0.0      0.0      0.0      0.0  7.59E-01
189    1.85E-06   50342.6    50342.6      0.1      0.1      0.1      0.1  7.59E-01
 76    1.81E-08   55914.4    55914.4      0.0      0.0      0.0      0.0  7.59E-01
 75    2.95E-07   73795.6    73795.6      0.0      0.0      0.0      0.0  7.59E-01
 16    6.09E-02       0.0    76910.2   2135.5   2135.5   2135.5   2135.5  8.20E-01
 19    5.81E-04   76910.2    76910.2     44.7     44.7     44.7     44.7  8.21E-01
 20    5.53E-07   76910.2    76910.2      0.0      0.0      0.0      0.0  8.21E-01
 21    6.76E-04    6220.9    76910.2      9.4      9.4      9.4      9.4  8.21E-01
 22    1.14E-04       0.0    76910.2      1.3      1.3      1.3      1.3  8.21E-01
 58    8.68E-07   50846.0    79080.5      0.1      0.1      0.1      0.1  8.21E-01
 82    4.55E-09   79329.9    79329.9      0.0      0.0      0.0      0.0  8.21E-01
 48    4.96E-02    7110.4    89666.1   3324.4   3324.4   3324.4   3324.4  8.71E-01
 49    9.53E-05   20781.8    89666.1      4.2      4.2      4.2      4.2  8.71E-01
 53    5.25E-04    7319.5    92303.3     37.8     37.8     37.8     37.8  8.71E-01
 57    8.25E-05   68854.7    92303.3      7.1      7.1      7.1      7.1  8.72E-01
 78    2.31E-07   87249.7    92303.3      0.0      0.0      0.0      0.0  8.72E-01
 79    7.52E-07   88528.5    92303.3      0.1      0.1      0.1      0.1  8.72E-01
 81    1.77E-07   92303.3    92303.3      0.0      0.0      0.0      0.0  8.72E-01
 88    4.01E-07   92303.3    92303.3      0.0      0.0      0.0      0.0  8.72E-01
 30    6.25E-02       0.0    93079.0   2656.9   2656.9   2656.9   2656.9  9.34E-01
 31    1.20E-04       0.0    93079.0      1.6      1.6      1.6      1.6  9.34E-01
 40    1.19E-04       0.0    93079.0      1.6      1.6      1.6      1.6  9.34E-01
 39    6.18E-02      14.3    93778.6   3307.1   3307.1   3307.1   3307.1  9.96E-01
 54    1.04E-06   50339.1    94940.5      0.1      0.1      0.1      0.1  9.96E-01
 55    1.78E-05    7528.7    94940.5      1.3      1.3      1.3      1.3  9.96E-01
 59    2.23E-06   86722.9    94940.5      0.2      0.2      0.2      0.2  9.96E-01
 80    3.64E-08   94940.5    94940.5      0.0      0.0      0.0      0.0  9.96E-01
 89    2.18E-08   94940.5    94940.5      0.0      0.0      0.0      0.0  9.96E-01
 61    9.51E-05   93309.5    95175.7      9.0      9.0      9.0      9.0  9.96E-01
 62    3.05E-05   93309.5    95175.7      2.9      2.9      2.9      2.9  9.96E-01
 66    2.38E-04    7319.5    95175.7     14.8     14.8     14.8     14.8  9.97E-01
 67    7.63E-05    7319.5    95175.7      4.7      4.7      4.7      4.7  9.97E-01
 90    8.79E-07   93309.5    95175.7      0.1      0.1      0.1      0.1  9.97E-01
 91    1.40E-06   93309.5    95175.7      0.1      0.1      0.1      0.1  9.97E-01
 93    2.25E-07   93309.5    95175.7      0.0      0.0      0.0      0.0  9.97E-01
 94    7.33E-07   93309.5    95175.7      0.1      0.1      0.1      0.1  9.97E-01
102    2.85E-06    7319.5    95175.7      0.2      0.2      0.2      0.2  9.97E-01
103    5.35E-06    7319.5    95175.7      0.3      0.3      0.3      0.3  9.97E-01
 63    4.29E-06   95895.0    97812.9      0.4      0.4      0.4      0.4  9.97E-01
 64    1.70E-07   95895.0    97812.9      0.0      0.0      0.0      0.0  9.97E-01
 68    1.12E-05    7528.7    97812.9      0.7      0.7      0.7      0.7  9.97E-01
 92    7.64E-08   95895.0    97812.9      0.0      0.0      0.0      0.0  9.97E-01
 95    3.55E-08   95895.0    97812.9      0.0      0.0      0.0      0.0  9.97E-01
 97    4.44E-09   95895.0    97812.9      0.0      0.0      0.0      0.0  9.97E-01
104    2.91E-07    7528.7    97812.9      0.0      0.0      0.0      0.0  9.97E-01
 27    7.96E-04       0.0   123449.7     44.8     44.8     44.8     44.8  9.97E-01
 28    1.53E-06       0.0   123449.7      0.0      0.0      0.0      0.0  9.97E-01
 46    1.39E-06       0.0   134447.5      0.0      0.0      0.0      0.0  9.97E-01
 45    7.21E-04   10874.8   137136.4     67.6     67.6     67.6     67.6  9.98E-01
 36    7.96E-04       0.0   139618.5     50.7     50.7     50.7     50.7  9.99E-01
 37    1.53E-06       0.0   139618.5      0.0      0.0      0.0      0.0  9.99E-01

SUM    9.99E-01              expected  22616.0  22616.0  22616.0  22616.0

                            xtrm 1/10  93525.1  93525.1  93525.1  93525.1
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APPENDIX B SOME THOUGHTS ON THE VERTICAL LOCATION AND EXTENT OF SIDE DAMAGES

Considering only ship-ship collisions (rammings), the vertical location of the centre of damage and the vertical extent of damage are expected to depend on:

- The bow profile of the ramming vessel.
- The relative size of the two ships involved.
- The respective draughts of the two ships.
- The structural arrangement of the ships.
- The energy of the impact.

The shape of the bow of the ramming vessel influences to a large extent the location of the damage on the side of the rammed vessel. A highly raked stem post will tend to penetrate the hull opposite above the waterline (figure B.1), whereas a protruding bulbous bow will most often penetrate the hull of the stricken vessel below the waterline (figure B.2). A vertical stem post on the other hand will produce a damage extending across the waterline of the rammed vessel (figure B.3).

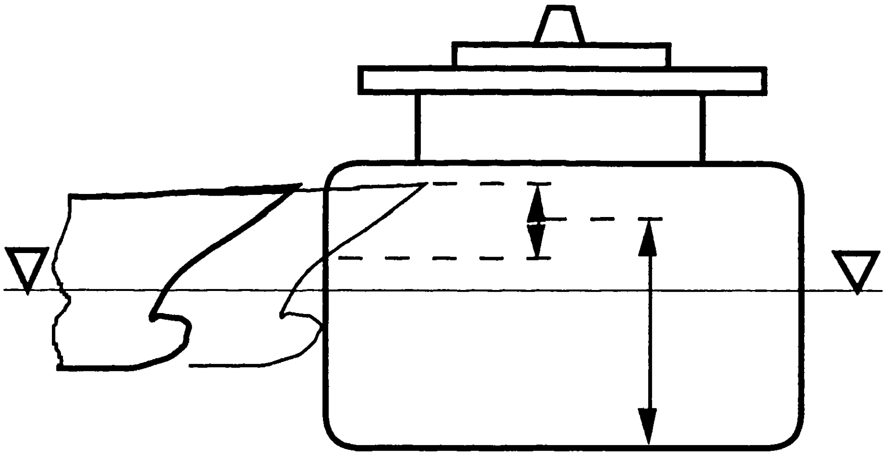


Figure B.1: Example of Vertical Location and Extent of Damage when a tanker is rammed by a highly raked stem post.

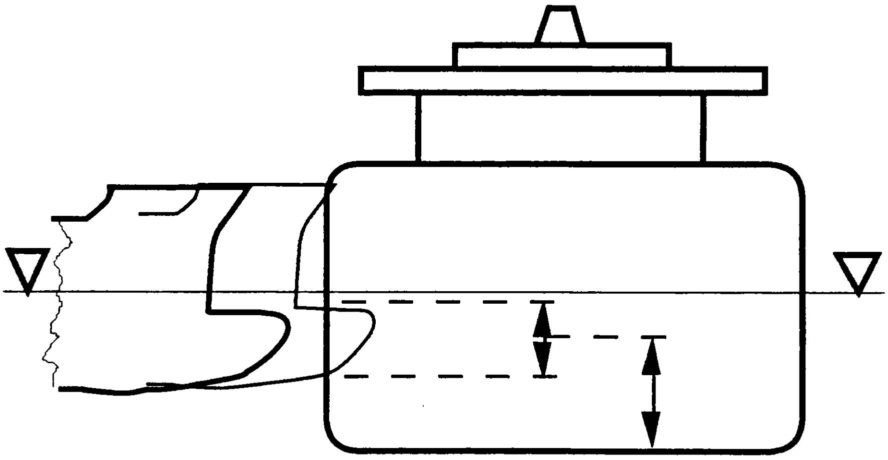


Figure B.2: Example of Vertical Location and Extent of Damage when a tanker is rammed by a protruding bulbous bow.

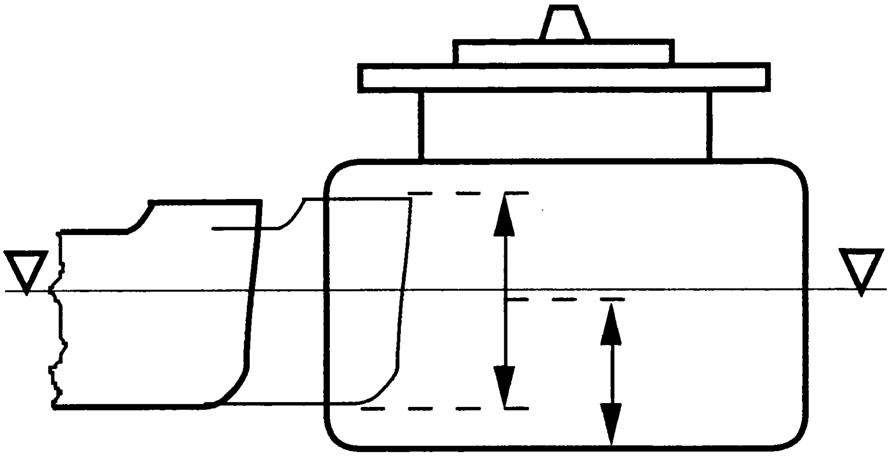


Figure B.3: Example of Vertical Location and Extent of Damage when a tanker is rammed by a vertical stem post.

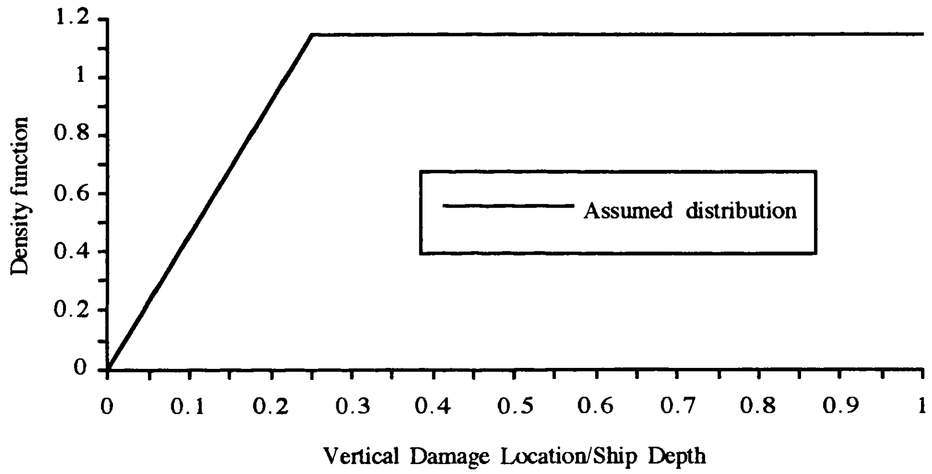


Figure B.4 Probability density distribution for Vertical Location of Centre of Damage.

The respective loaded draughts of the two vessels influence the location of the centre of damage. The tankers examined in the present work are large in dimensions, close to VLCC size. Thus there are few ships that match their size and loaded draught. So if such a tanker is rammed by another ship, the centre of damage is not very likely to be near the tanker's baseline. Furthermore, the recess in the damaged hull corresponding to the round of bilge, diminishes even more the likelihood of the centre of damage being located in that low area.

Therefore, the hypothetical probability density function (pdf) for the vertical location of the centre of damage (figure B.4) shows a reduced frequency of occurrence of damages in the lowest quarter of the ship's depth. This frequency increases from nil at the baseline, to a constant value at 0.25 D and above. For the size of tankers examined herein, the above point of discontinuity corresponds to 7.0 m above the baseline (as compared to the corresponding round of bilge radius of 5.0 m). The value of 0.25 D was chosen arbitrarily for convenience, the only requirement being that the low probability region should contain the region of the round of bilge.

The relative size of the two vessels will determine the vertical extent of damage. The maximum possible extent in each case is the depth of the smallest of the two ships involved in the ramming.

Lastly, the structural arrangement of the bow and the side together with the energy of the impact, determine the depth of penetration of the bow of the ramming vessel into the side of the rammed vessel. Consequently, for impacts involving non-vertical stem posts, they also determine the vertical extent of damage.

Again, for the type of ships examined herein, the probability of occurrence of damages extending over the full depth of the ship is rather remote. Therefore, for the vertical extent of damage, a pdf similar to the pdf for damage penetration was chosen (figure B.5). This pdf gives a steadily decreasing frequency of occurrence of damages with increasing vertical extent.

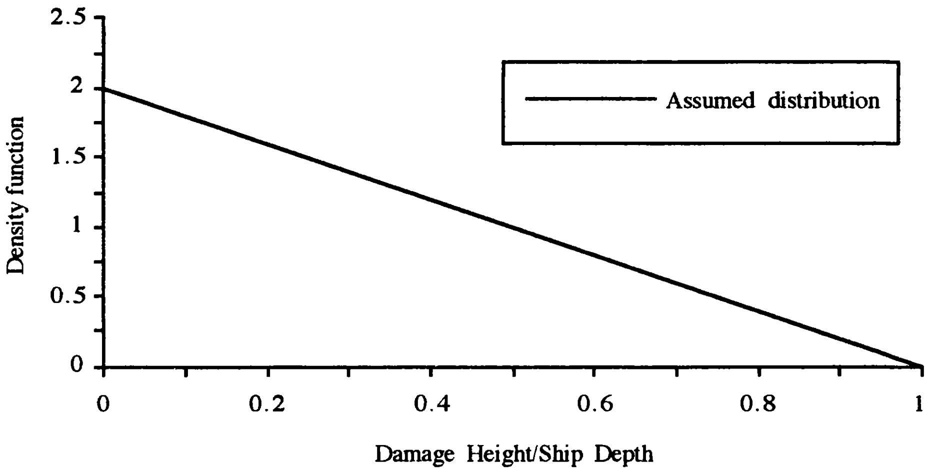


Figure B.5: Probability density distribution for Vertical Extent of Damage.

APPENDIX C STANDARD HULL AND TANK ARRANGEMENTS

C.1 THE STANDARD HULL

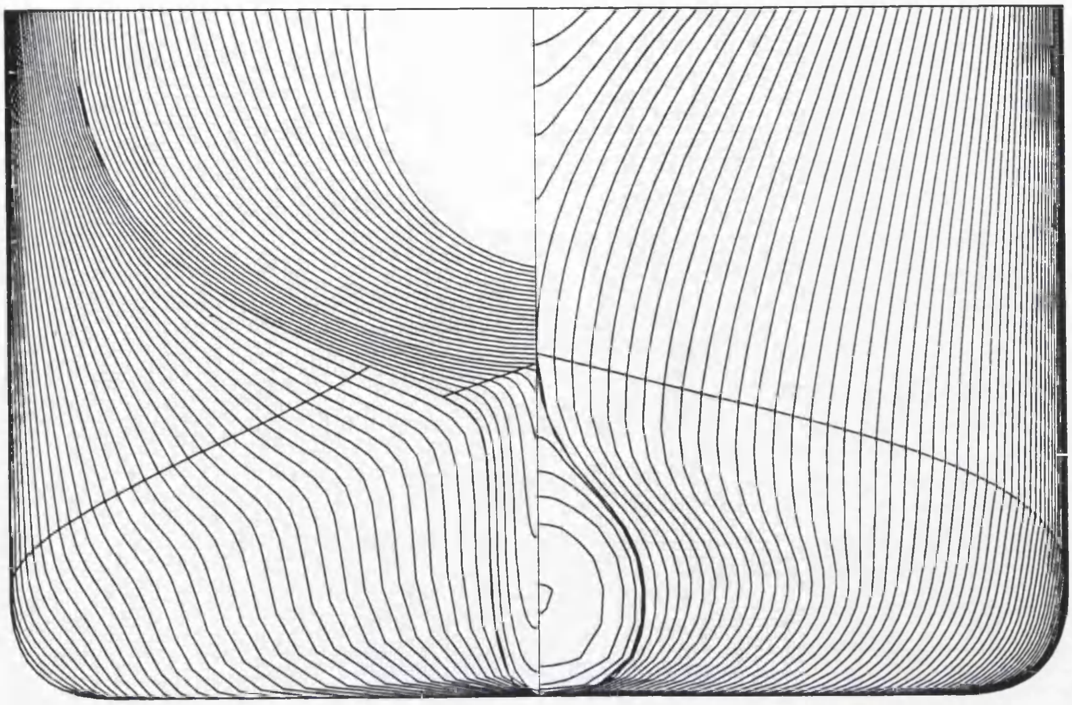


Figure C.1: Body plan of the standard tanker hull used for all the models in the study.

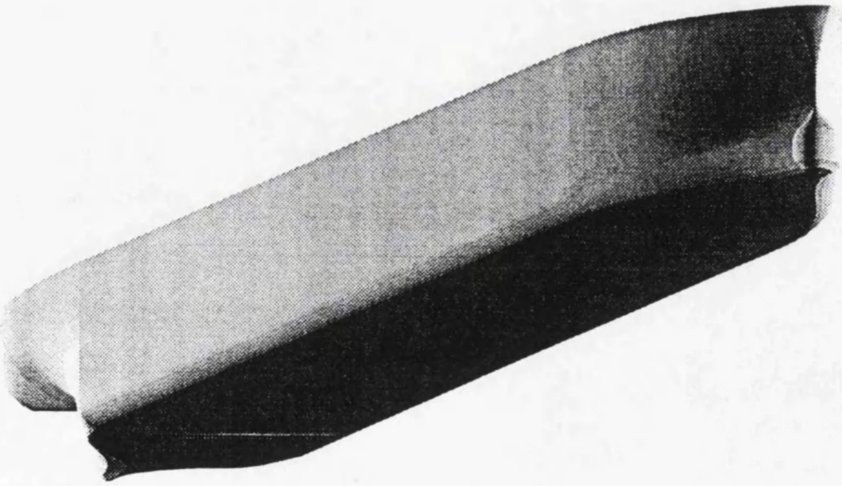


Figure C.2: Three-dimensional rendering of the standard tanker hull.

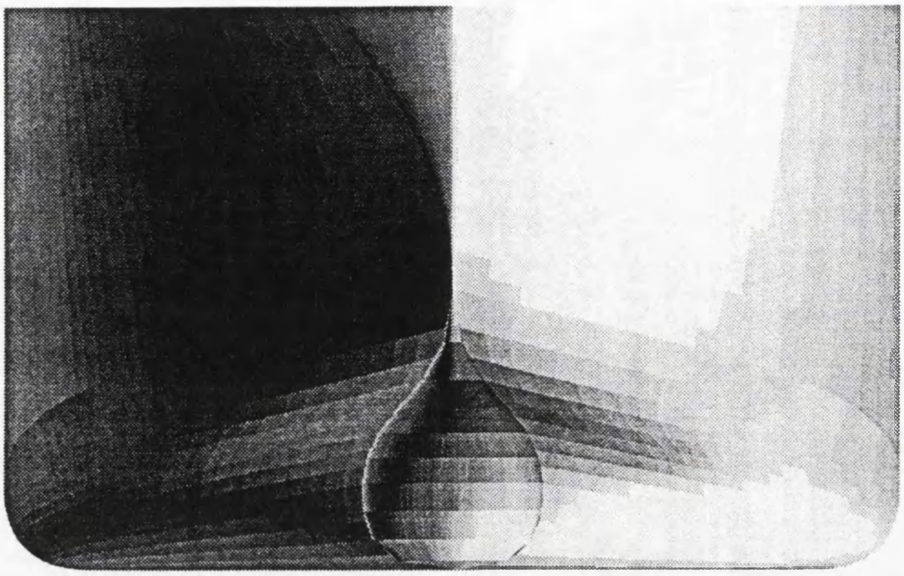


Figure C.3: Rendered fore-body of the standard tanker hull.

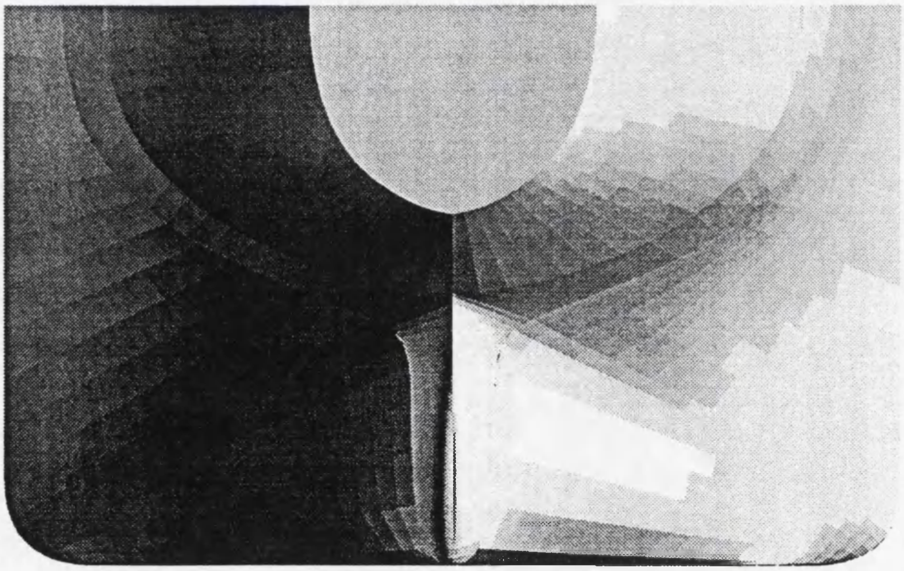
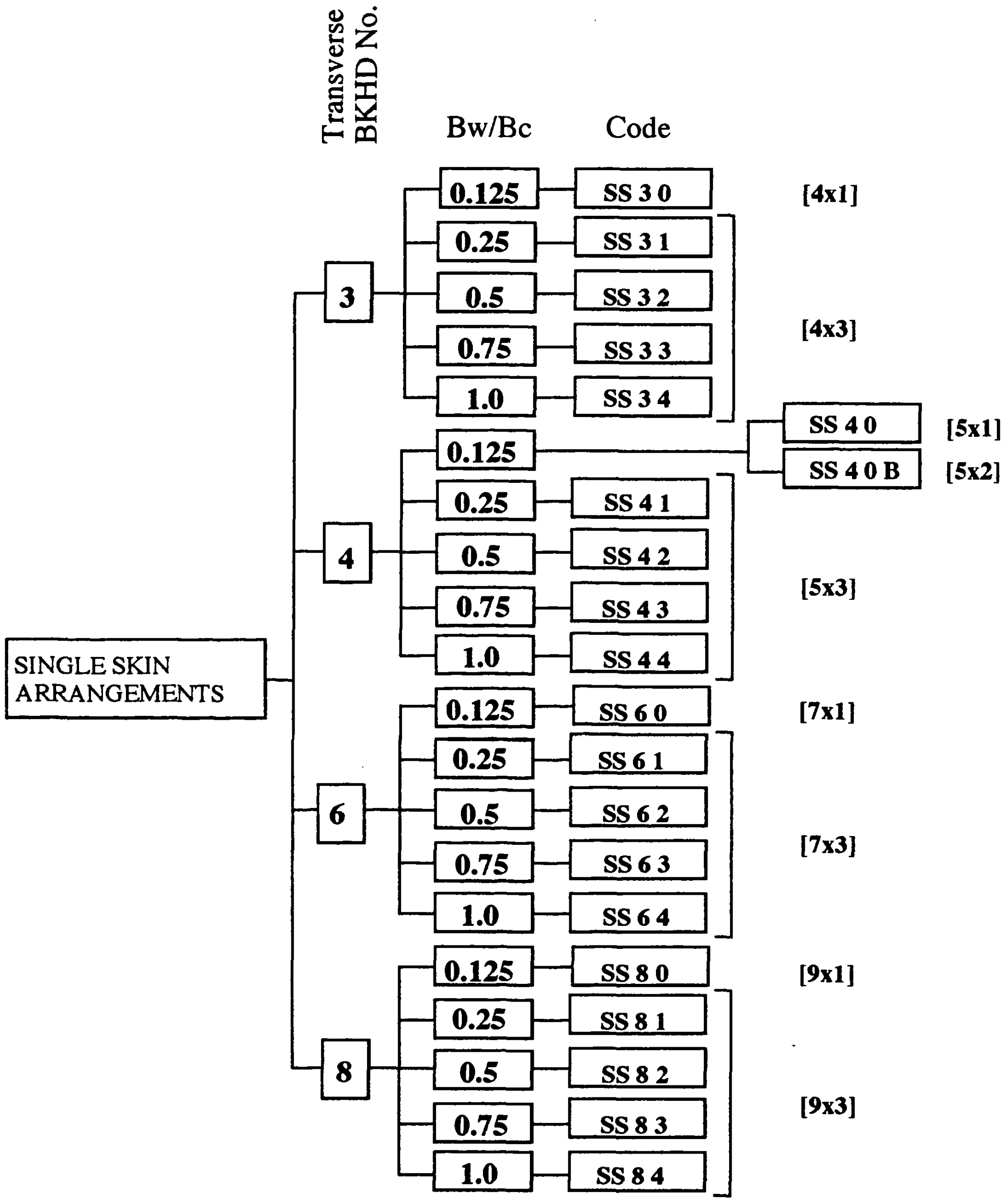


Figure C.4: Rendered after-body of the standard tanker hull.

C.2 THE TANK ARRANGEMENTS

C.2.1 SINGLE-SKIN ARRANGEMENTS WITH WING BALLAST TANKS



Note: Code "0" indicates a double-sided arrangement

Figure C.5: Variations of Single-Skin arrangements and corresponding codes.

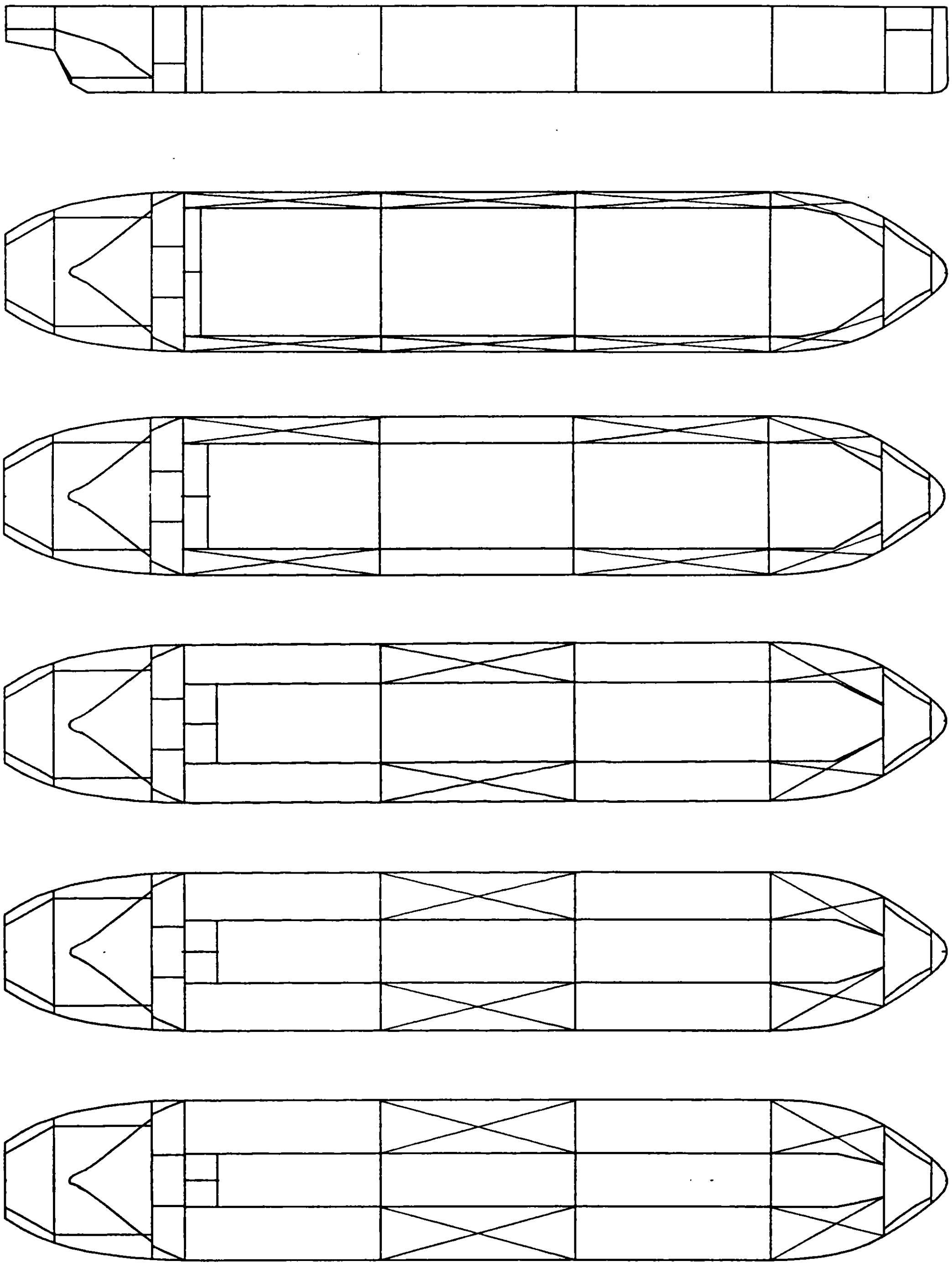


Figure C.6: Tank arrangements of the SS 3... series of variations.

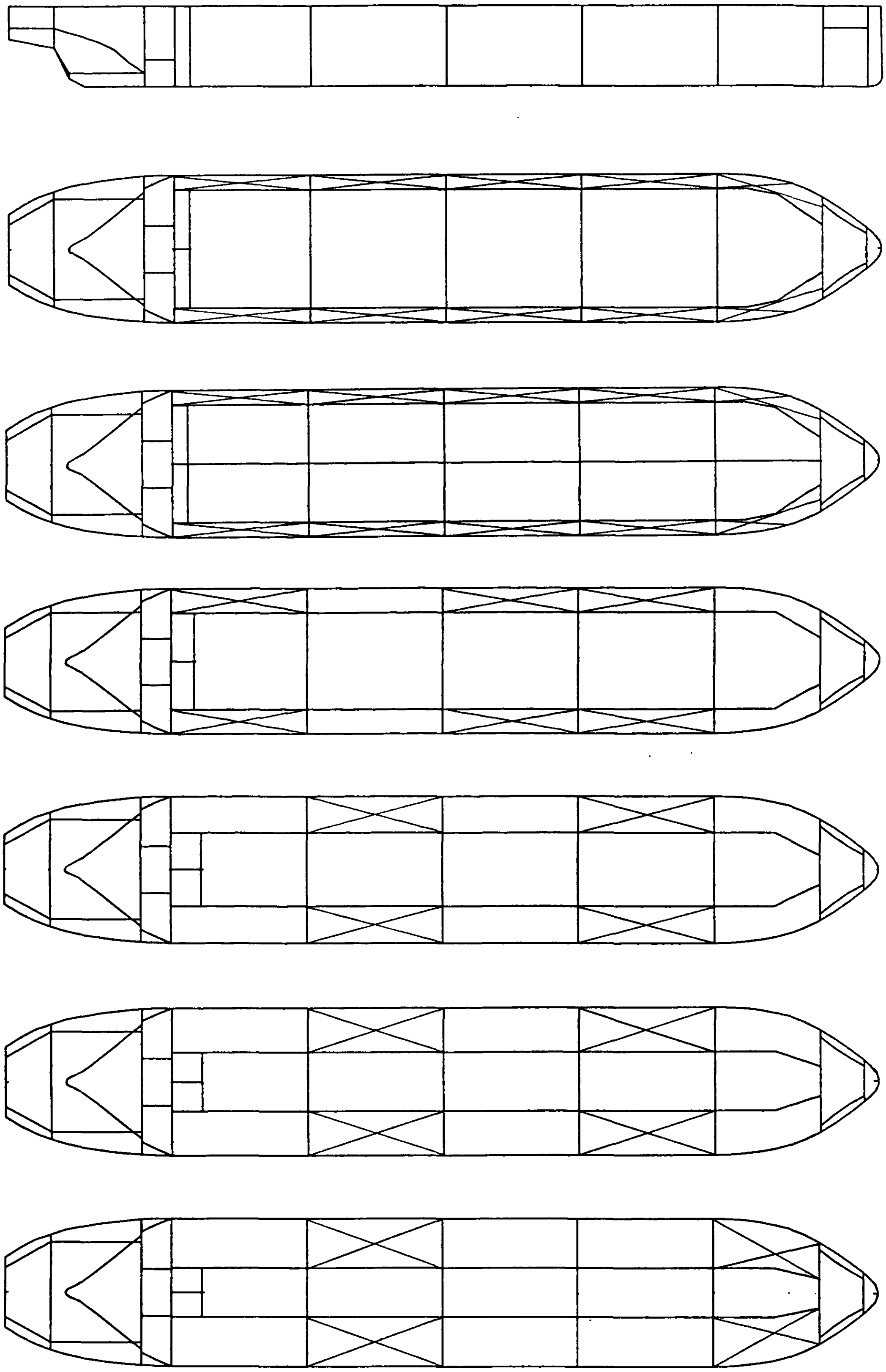


Figure C.7: Tank arrangements of the SS 4... series of variations.

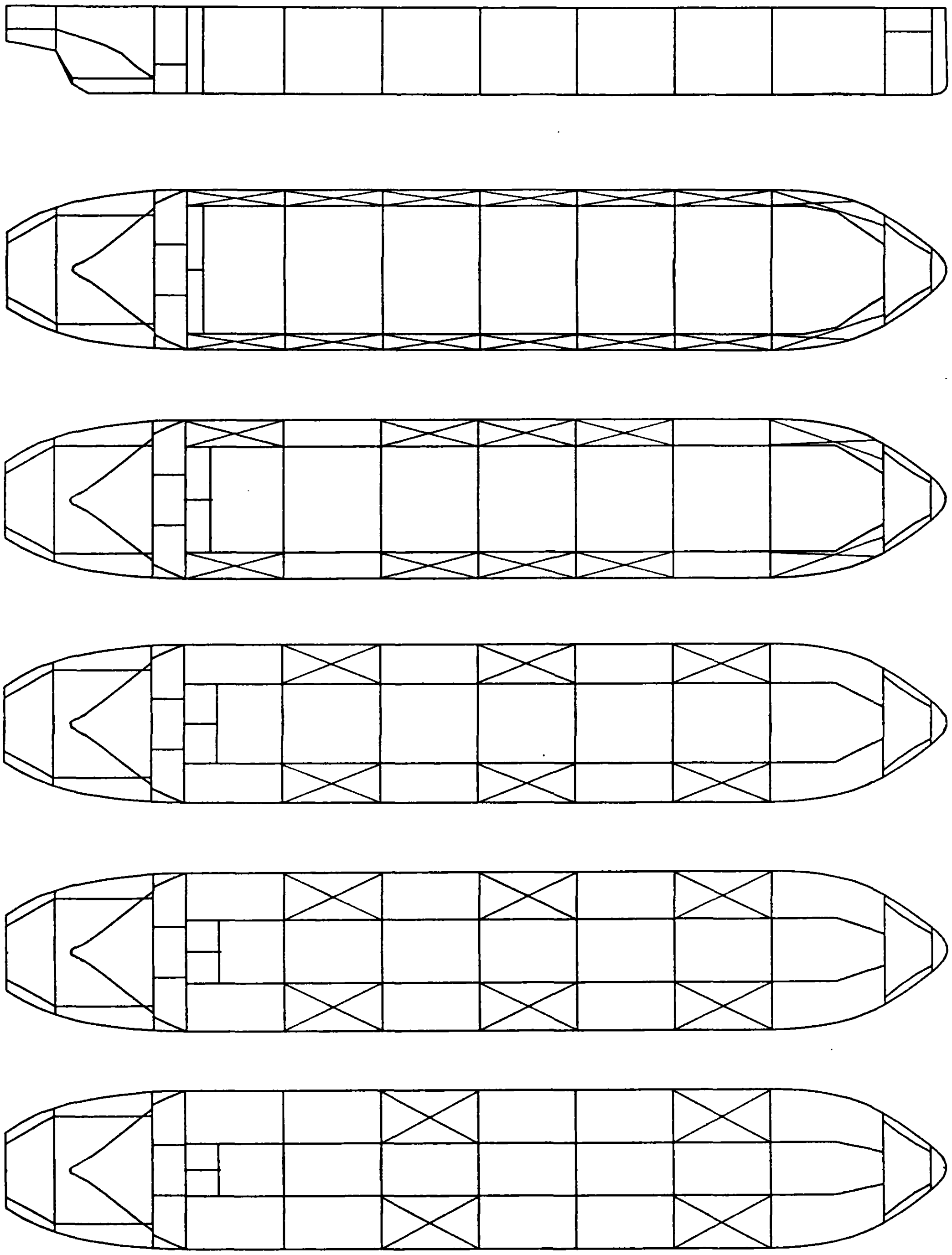


Figure C.8: Tank arrangements of the SS 6... series of variations.

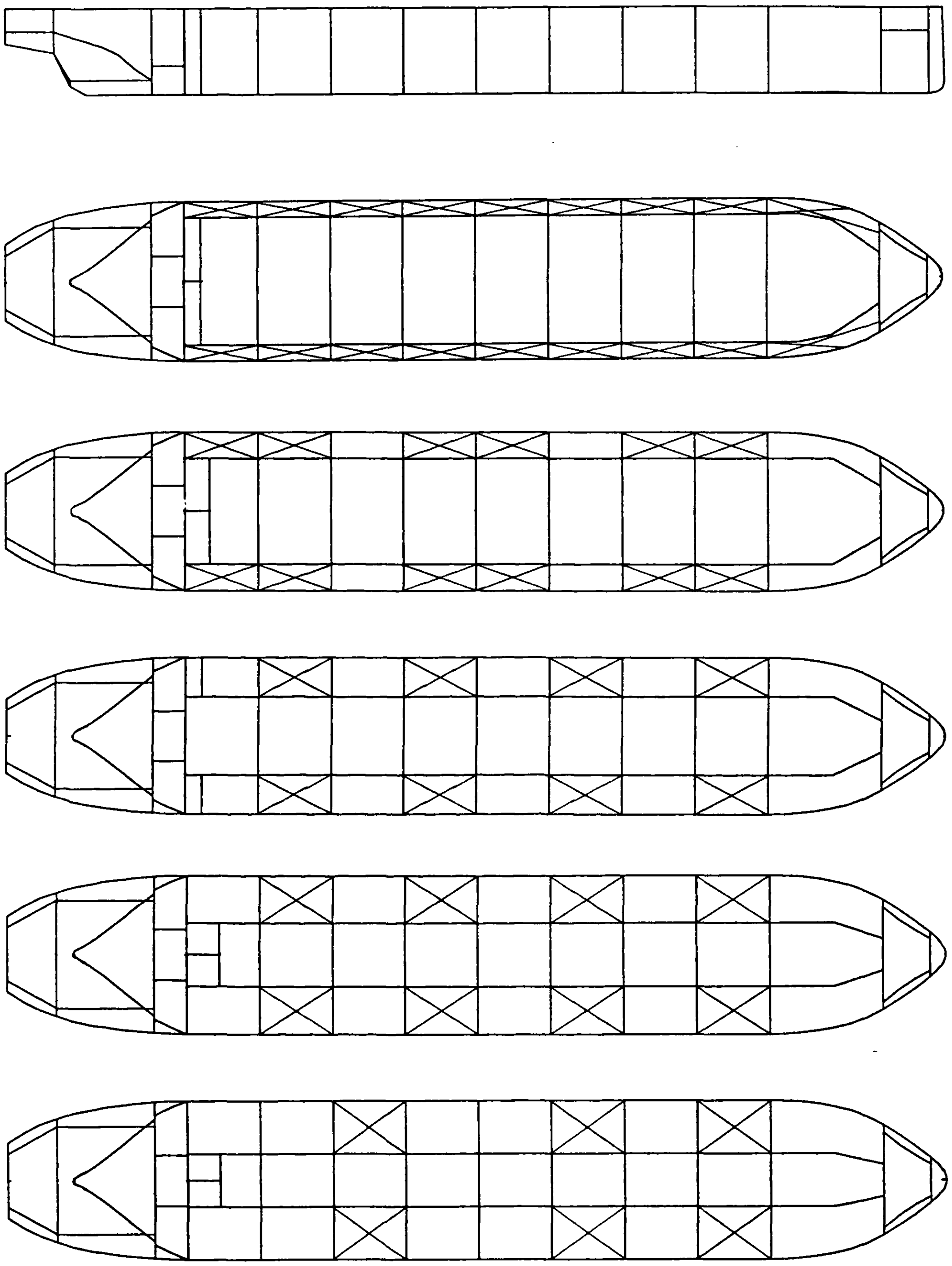
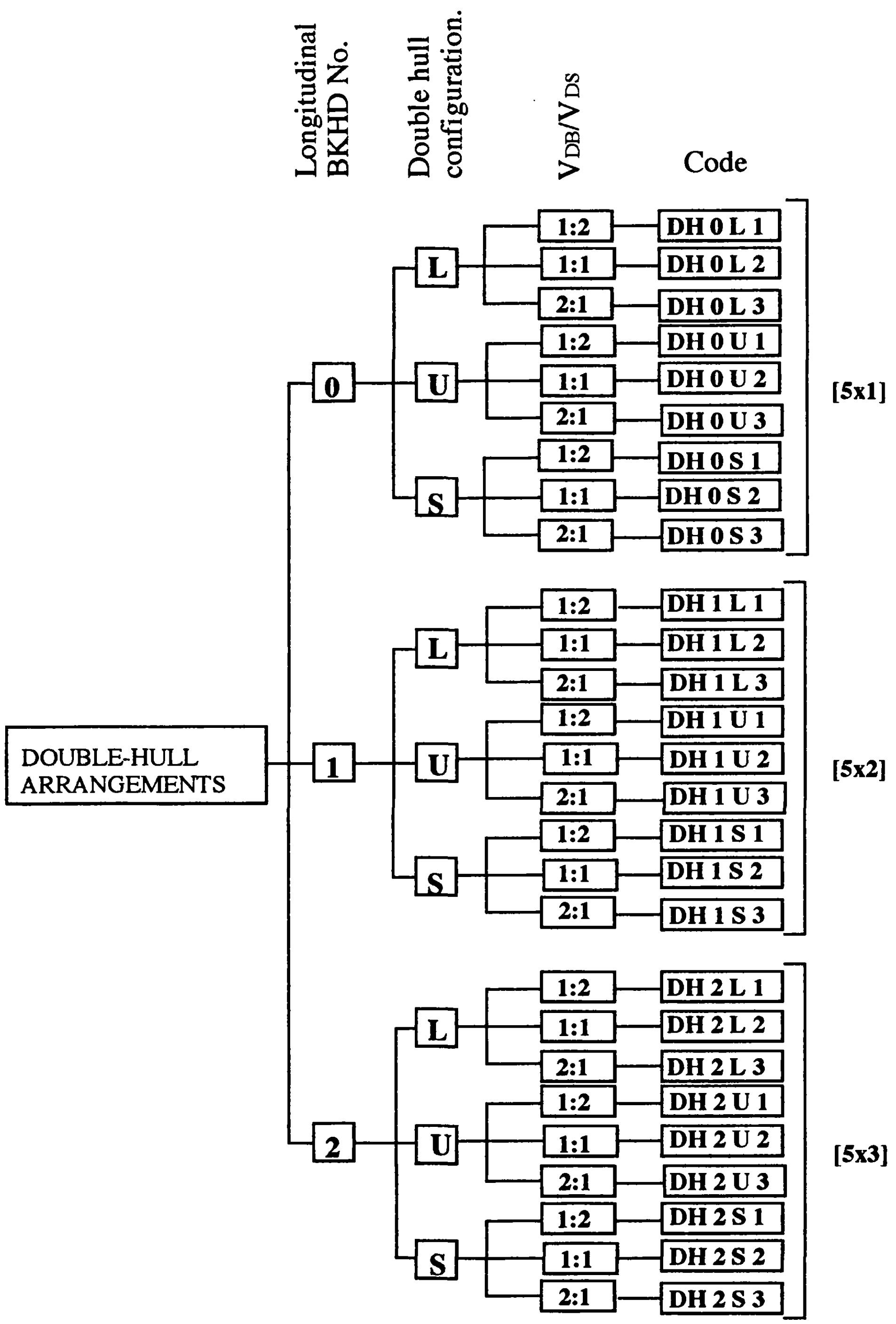


Figure C.9: Tank arrangements of the SS 8... series of variations.

C.2.2 DOUBLE-HULL ARRANGEMENTS



Note: L, U, S identify the double hull space configuration.
S= Double Bottom + Double Sides.

Figure C.10: Variations of Double-Hull arrangements and corresponding codes.

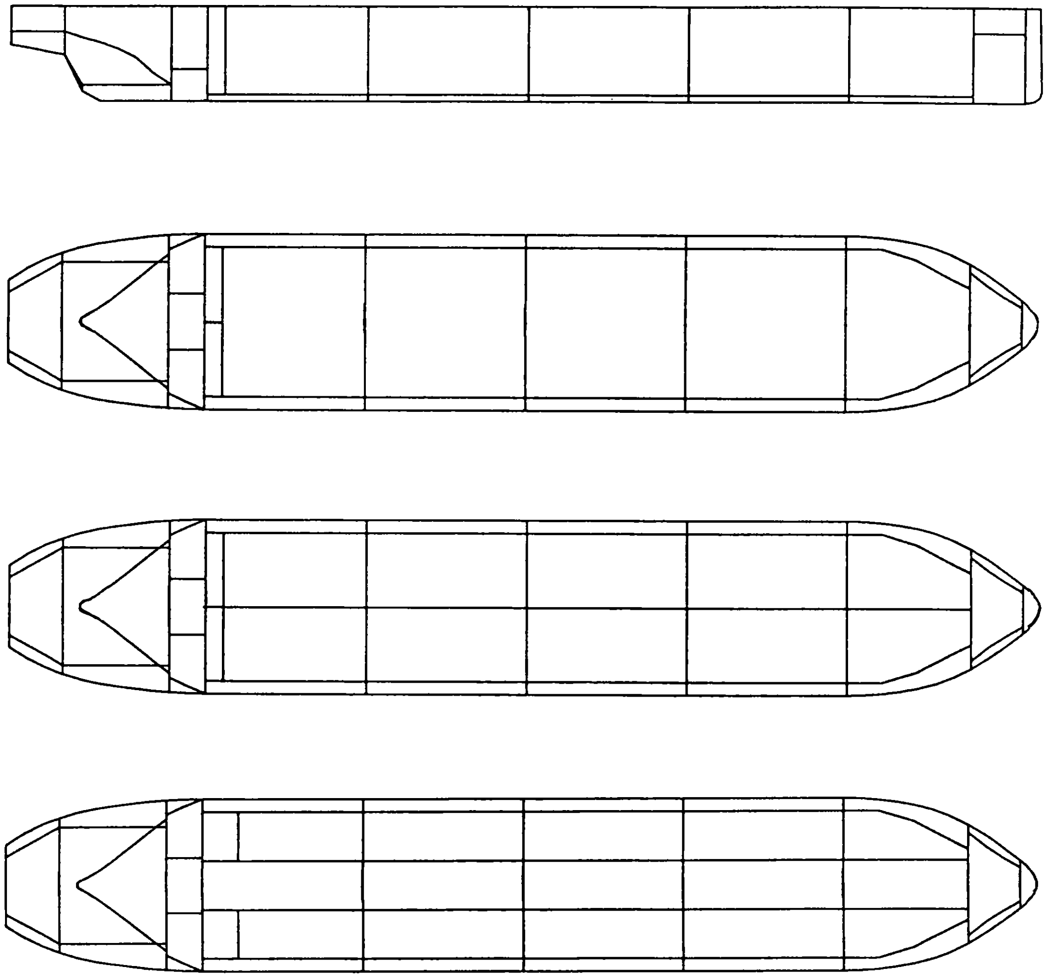


Figure C.11: Tank arrangements of the DH... series of variations, with a V_{DB}/V_{DS} value of 0.5.

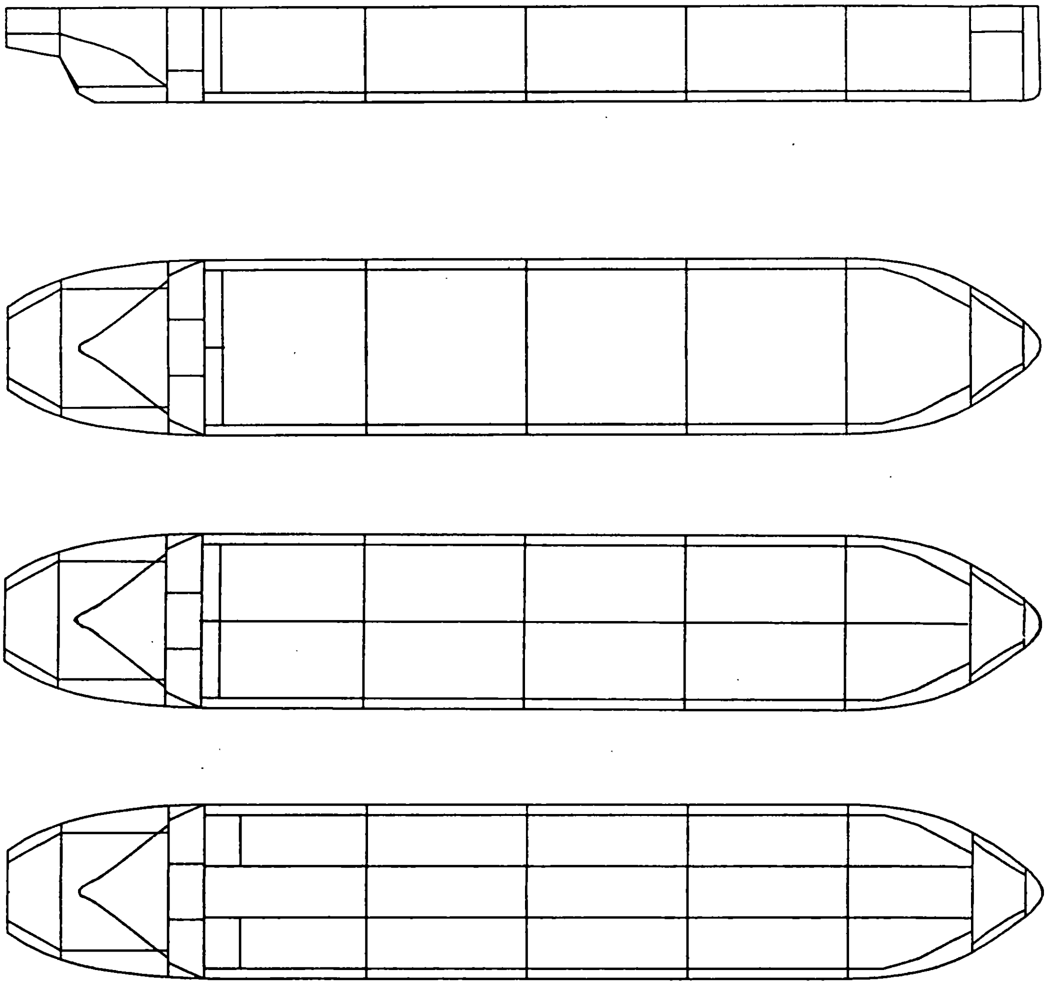


Figure C.12: Tank arrangements of the DH... series of variations, with a V_{DB}/V_{DS} value of 1.0.

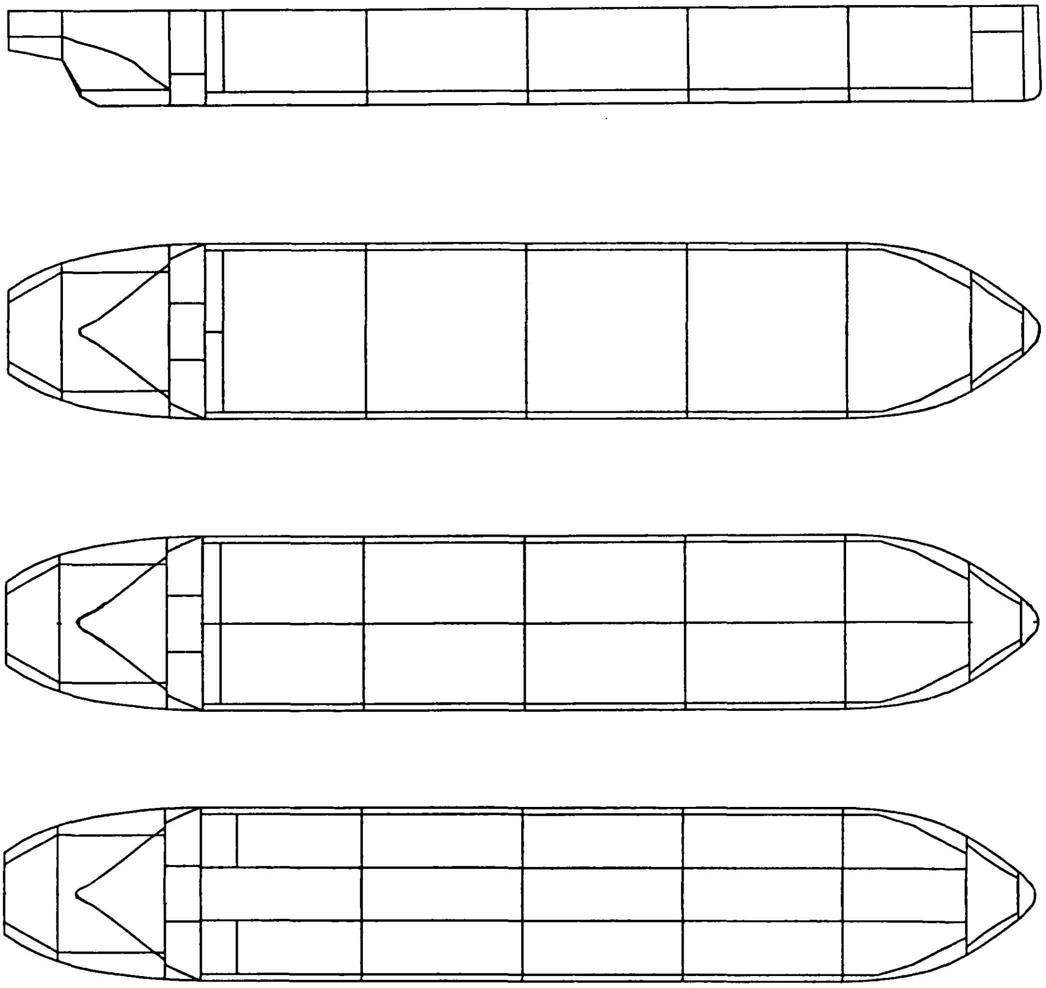
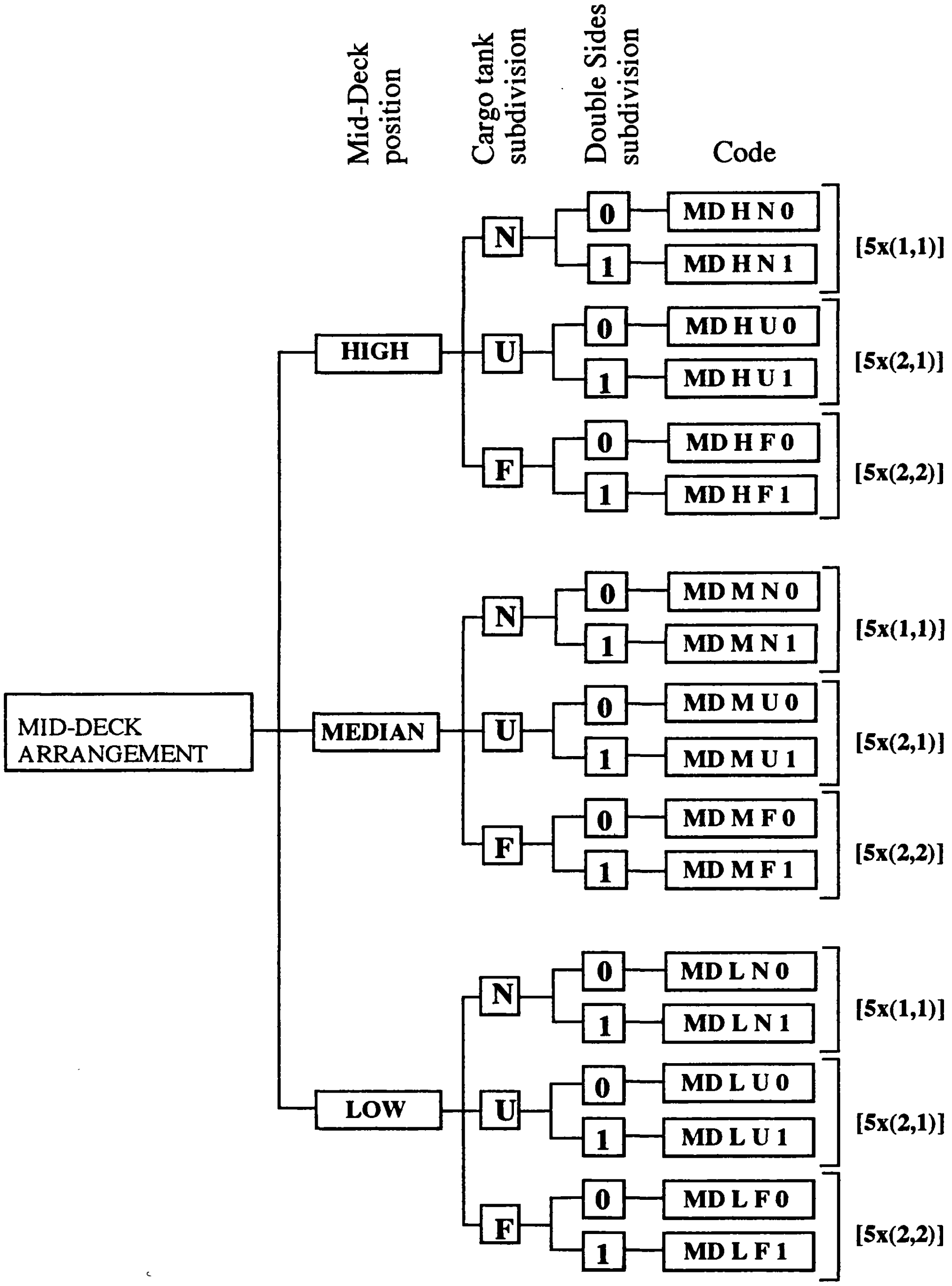


Figure C.13: Tank arrangements of the DH... series of variations, with a V_{DB}/V_{DS} value of 2.0.

C.2.3 MID-DECK ARRANGEMENTS



Note: N= No Long'l BKHD,
U= Long'l BKHD in upper cargo tanks only,
F= Full depth Long'l BKHD.

0= Full height Double Sides,
1= Horizontally subdivided Double Sides.

Figure C.14: Variations of Mid-Deck arrangements and corresponding codes.

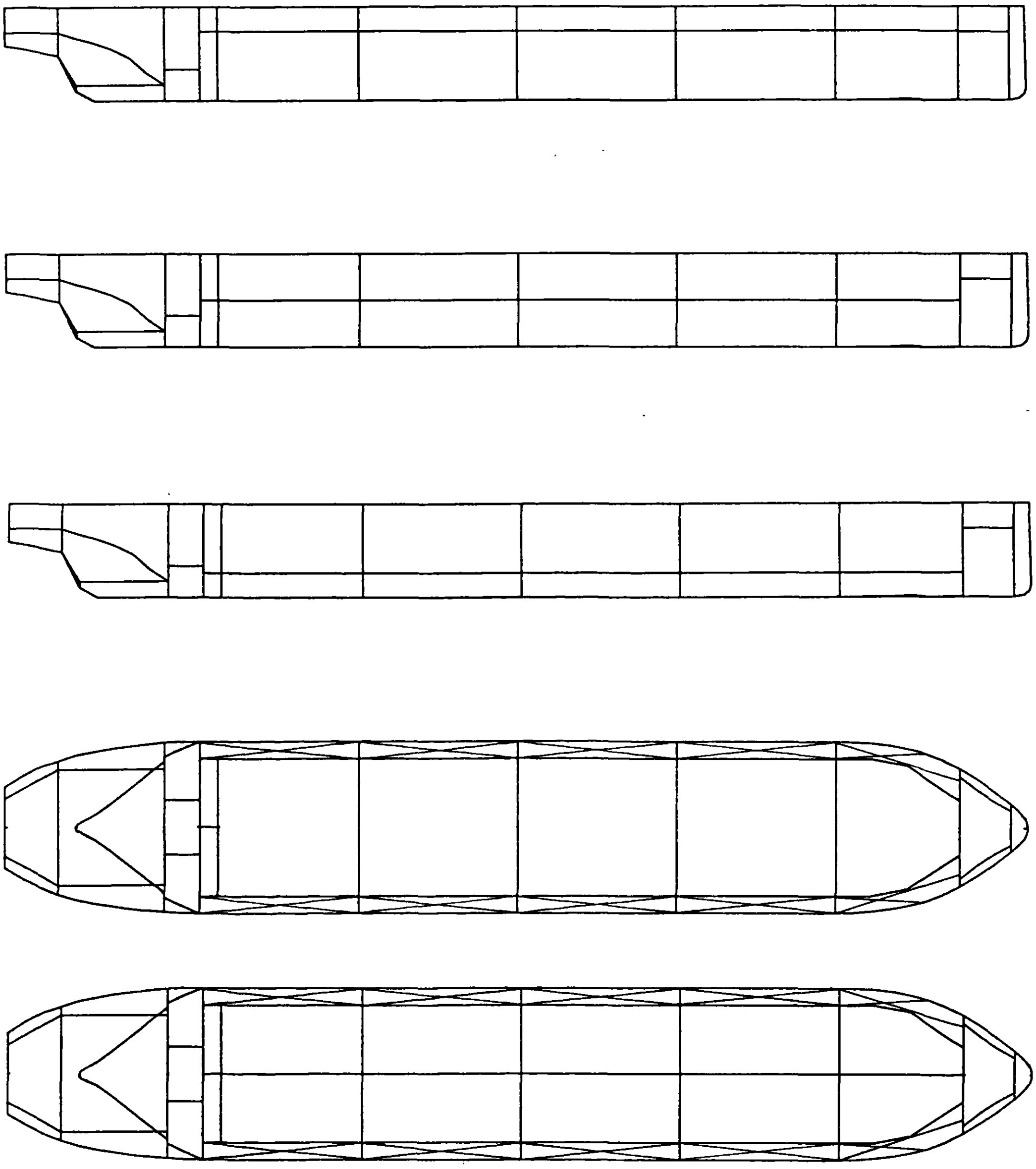


Figure C.15: Tank arrangements of the MD... series of variations.

C.3 HYDROSTATIC PROPERTIES

T (m)	Δ (tonne)	LCB FP (m)	VCB (m)	TPC	LCF FP (m)	MCT deg	KML (m)	KMT (m)
0.500	5,096.00	131.862a	0.255	106.82	131.785a	833560	9370.99	333.992
1.500	16,224.89	131.643a	0.770	114.55	131.300a	918154	3242.00	126.274
2.500	27,870.86	131.481a	1.285	117.89	131.088a	958328	1969.89	79.779
3.500	39,757.07	131.358a	1.799	119.53	131.014a	980564	1412.99	58.664
4.500	51,741.66	131.277a	2.309	120.06	131.025a	990072	1096.24	46.408
5.500	63,754.15	131.244a	2.816	120.16	131.189a	992324	891.71	38.700
6.500	75,767.74	131.263a	3.321	120.10	131.529a	990478	748.93	33.579
7.500	87,773.48	131.333a	3.825	119.99	131.998a	987404	644.48	30.000
8.500	99,774.20	131.447a	4.327	120.00	132.518a	987568	567.06	27.412
9.500	111,784.70	131.594a	4.829	120.19	133.038a	993172	509.00	25.498
10.500	123,826.80	131.763a	5.332	120.61	133.568a	1005061	465.00	24.064
11.500	135,921.70	131.954a	5.836	121.24	134.170a	1022995	431.18	22.982
12.500	148,091.20	132.170a	6.343	122.14	134.963a	1049082	405.84	22.169
13.500	160,371.40	132.430a	6.853	123.56	136.257a	1091121	389.78	21.568
14.500	172,814.50	132.763a	7.368	125.29	137.824a	1143529	379.09	21.139
15.500	185,435.00	133.163a	7.888	127.08	139.421a	1199308	370.52	20.845
16.500	198,231.60	133.617a	8.411	128.74	140.826a	1251561	361.71	20.658
17.500	211,174.10	134.091a	8.938	130.06	141.826a	1293036	350.79	20.555
18.500	224,236.20	134.563a	9.466	131.15	142.545a	1327742	339.22	20.517
19.500	237,398.80	135.021a	9.994	132.07	143.057a	1357636	327.63	20.529
20.500	250,647.80	135.456a	10.523	132.89	143.421a	1384850	316.53	20.589
21.500	263,972.40	135.864a	11.052	133.60	143.646a	1409576	305.92	20.683
22.500	277,365.60	136.244a	11.581	134.25	143.778a	1433215	296.03	20.812
23.500	290,821.00	136.593a	12.110	134.85	143.812a	1455751	286.77	20.969
24.500	304,335.40	136.913a	12.638	135.43	143.778a	1478151	278.26	21.155
25.500	317,905.70	137.204a	13.166	135.98	143.662a	1500150	270.34	21.363
26.500	331,530.90	137.466a	13.694	136.52	143.483a	1522756	263.14	21.594

Water specific gravity = 1.025 tonne/m^3

No Trim, No Heel, VCG = 0.000

Moment in [tonne X m].

Table C.1: Hydrostatic properties of standard tanker hull.

APPENDIX D TABLES OF RESULTS AND GRAPHS

D.1 RESULTS OF OIL OUTFLOW ANALYSES

D.1.1 SINGLE-SKIN ARRANGEMENTS WITH WING BALLAST TANKS

	Cargo	Tank Volume				Tank Volume index						
Code	Capacity	Centre	Wing	Mean	Average*	Centre	Wing	Mean	Average*	Bw/Bc	Bw/B	Lt/L
SS30	223736	64800	8100	36450	64800	28.96%	3.62%	16.29%	28.96%	0.125	0.100	0.210
SS31	214638	54001	13500	33751	45901	25.16%	6.29%	15.72%	21.39%	0.250	0.167	0.210
SS32	220106	40500	20250	30375	33750	18.40%	9.20%	13.80%	15.33%	0.500	0.250	0.210
SS33	208702	32400	24300	28350	29700	15.52%	11.64%	13.58%	14.23%	0.750	0.300	0.210
SS34	201201	27000	27000	27000	27000	13.42%	13.42%	13.42%	13.42%	1.000	0.333	0.210
SS40	223739	48600	6075	27338	48600	21.72%	2.72%	12.22%	21.72%	0.125	0.100	0.158
SS41	220509	40500	10125	25313	31821	18.37%	4.59%	11.48%	14.43%	0.250	0.167	0.158
SS42	220233	30375	15188	22782	24680	13.79%	6.90%	10.34%	11.21%	0.500	0.250	0.158
SS43	208459	24300	18225	21263	22022	11.66%	8.74%	10.20%	10.56%	0.750	0.300	0.158
SS44	214136	20250	20250	20250	20250	9.46%	9.46%	9.46%	9.46%	1.000	0.333	0.158
SS40B	223722	24300	6075	15188	24300	10.86%	2.72%	6.79%	10.86%	0.250	0.100	0.158
SS60	223736	32400	4050	18225	32400	14.48%	1.81%	8.15%	14.48%	0.125	0.100	0.105
SS61	214638	27000	6750	16875	22500	12.58%	3.14%	7.86%	10.48%	0.250	0.167	0.105
SS62	220190	20250	10125	15188	16568	9.20%	4.60%	6.90%	7.52%	0.500	0.250	0.105
SS63	208459	16200	12150	14175	14727	7.77%	5.83%	6.80%	7.06%	0.750	0.300	0.105
SS64	226610	13500	13500	13500	13500	5.96%	5.96%	5.96%	5.96%	1.000	0.333	0.105
SS80	223739	24300	3038	13669	24300	10.86%	1.36%	6.11%	10.86%	0.125	0.100	0.079
SS81	220509	20250	5062	12656	16453	9.18%	2.30%	5.74%	7.46%	0.250	0.167	0.079
SS82	220233	15188	7594	11391	12476	6.90%	3.45%	5.17%	5.66%	0.500	0.250	0.079
SS83	208459	12150	9112	10631	11065	5.83%	4.37%	5.10%	5.31%	0.750	0.300	0.079
SS84	220142	10125	10125	10125	10125	4.60%	4.60%	4.60%	4.60%	1.000	0.333	0.079

Note: (Average*) refers to the definition in Section 6.4.1.

Table D.1: Tank arrangement particulars.

	Potential Oil Outflow					Corrected			
	Expected value		Extreme value		Probability of	Probability of	Maximum Oil Outflow		
Code	(m^3)	index	(m^3)	index	Zero Outflow	Zero Outflow	(m^3)	index	Probability
SS30	28487	12.73%	144672	64.66%	32.91%	32.91%	127604	57.03%	5.39E-07
SS31	19648	9.15%	90127	41.99%	34.80%	33.39%	119420	55.64%	5.39E-07
SS32	14400	6.54%	73187	33.25%	30.20%	29.72%	99480	45.20%	1.10E-06
SS33	14895	7.14%	66955	32.08%	33.11%	30.88%	87516	41.93%	1.10E-06
SS34	14528	7.22%	45631	22.68%	34.30%	30.85%	79582	39.55%	1.10E-06
SS40	21522	9.62%	95172	42.54%	32.84%	32.84%	140741	62.90%	7.39E-04
SS41	16256	7.37%	86435	39.20%	29.36%	28.94%	126904	57.55%	5.29E-04
SS42	12440	5.65%	57078	25.92%	25.16%	24.77%	112682	51.17%	3.21E-04
SS43	11533	5.53%	44850	21.51%	27.47%	25.59%	102032	48.95%	2.24E-04
SS44	13578	6.34%	54583	25.49%	28.91%	27.68%	97475	45.52%	2.14E-04
SS40B	14796	6.61%	66342	29.65%	32.84%	32.84%	140742	62.91%	2.76E-05
SS60	19848	8.87%	75321	33.67%	32.90%	32.90%	95703	42.78%	5.79E-03
SS61	13052	6.08%	50933	23.73%	32.60%	31.28%	86295	40.20%	4.14E-03
SS62	9545	4.33%	39741	18.05%	21.55%	21.21%	79542	36.12%	1.10E-06
SS63	9387	4.50%	29918	14.35%	23.18%	21.59%	71566	34.33%	1.10E-06
SS64	11167	4.93%	31852	14.06%	19.98%	20.24%	66283	29.25%	1.68E-03
SS80	17105	7.65%	59961	26.80%	32.84%	32.85%	100865	45.08%	7.39E-04
SS81	11622	5.27%	42442	19.25%	25.61%	25.25%	96613	43.81%	5.29E-04
SS82	8838	4.01%	35860	16.28%	19.23%	18.93%	80829	36.70%	3.54E-04
SS83	6894	3.31%	24532	11.77%	20.65%	19.24%	71696	34.39%	2.47E-04
SS84	9567	4.35%	26734	12.14%	18.77%	18.47%	69582	31.61%	1.94E-04

Table D.2: Oil Outflow results.

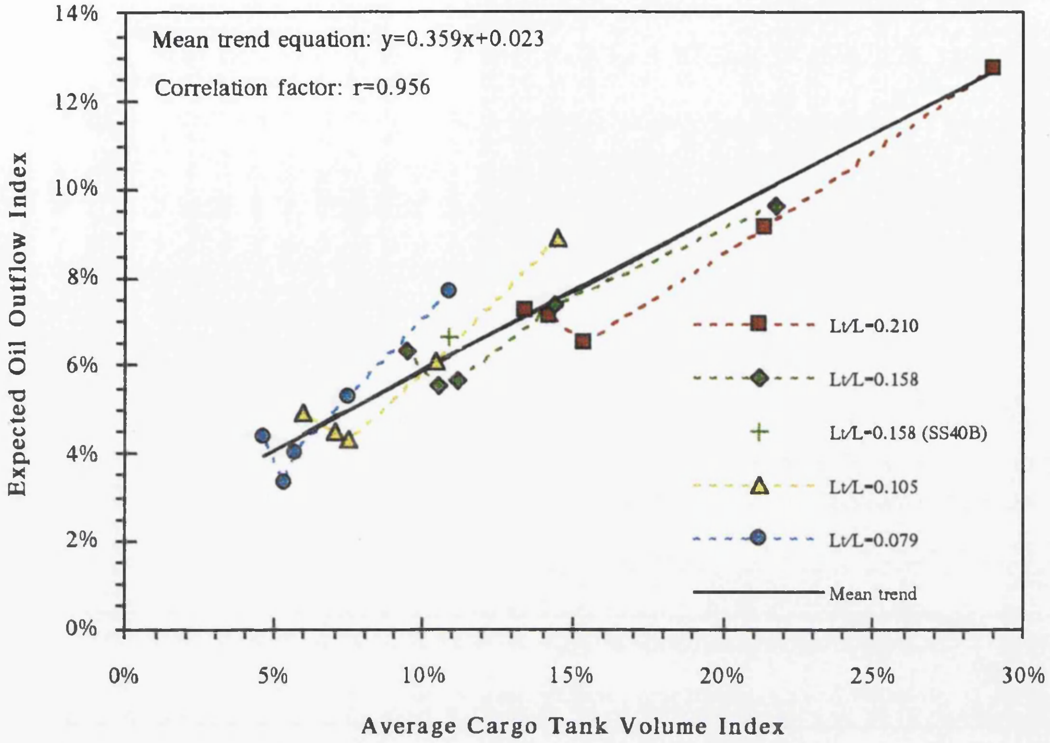


Figure D.1: Effect of Average Cargo Tank Volume on Expected Oil Outflow.

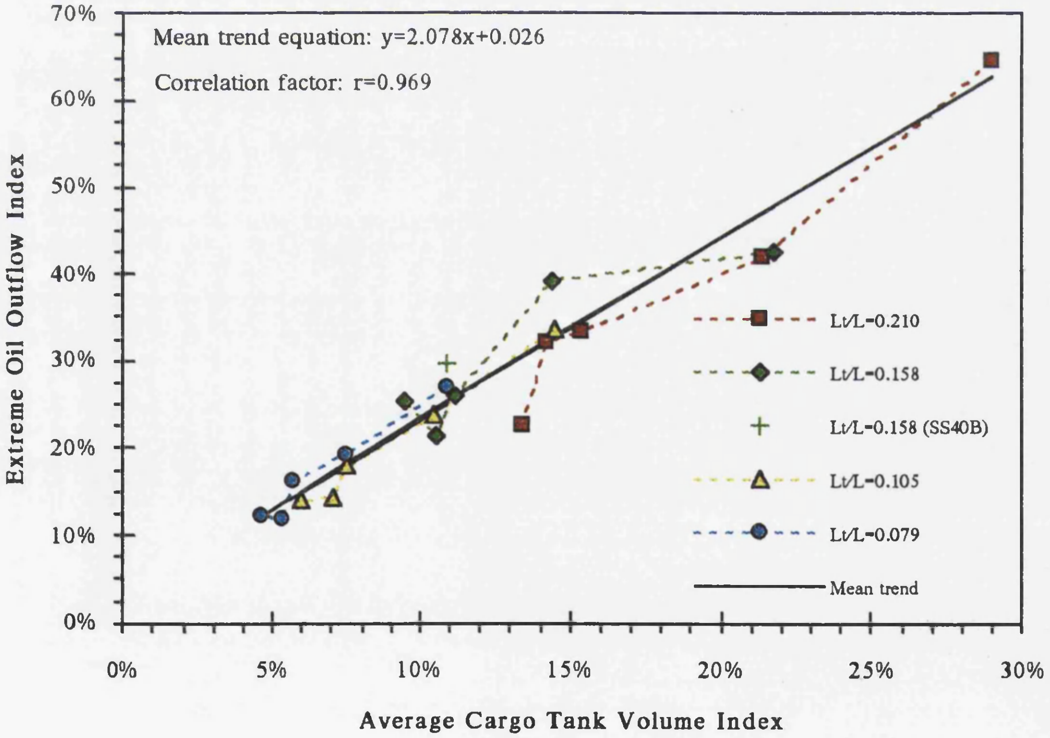


Figure D.2: Effect of Average Cargo Tank Volume on Extreme Oil Outflow.

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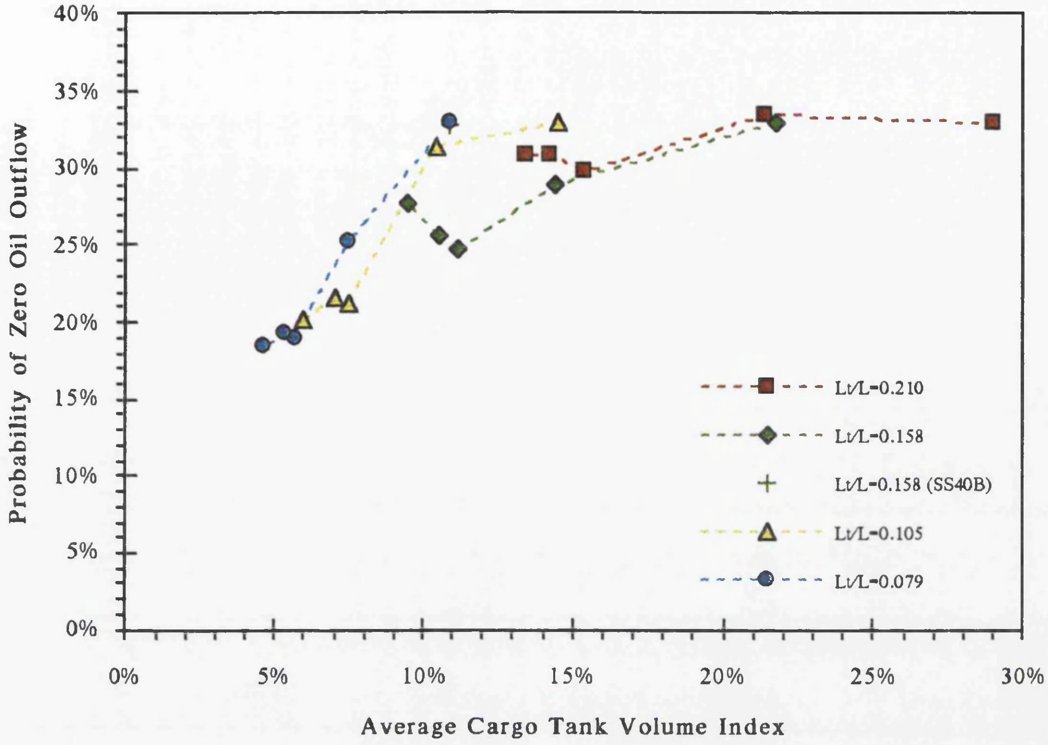

Figure D.3: Effect of Average Cargo Tank Volume on the Probability of Zero Oil Outflow.

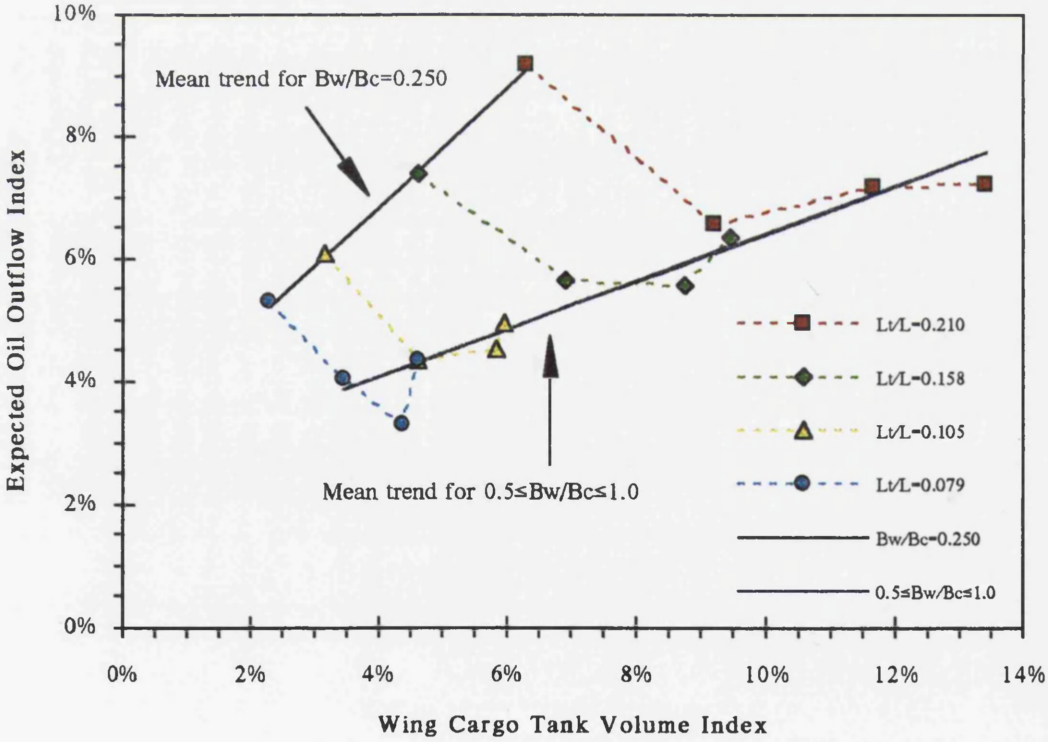

Figure D.4: Influence of Tank Breadth Ratio on the relationship of Expected Oil Outflow to Wing Cargo Tank Volume.

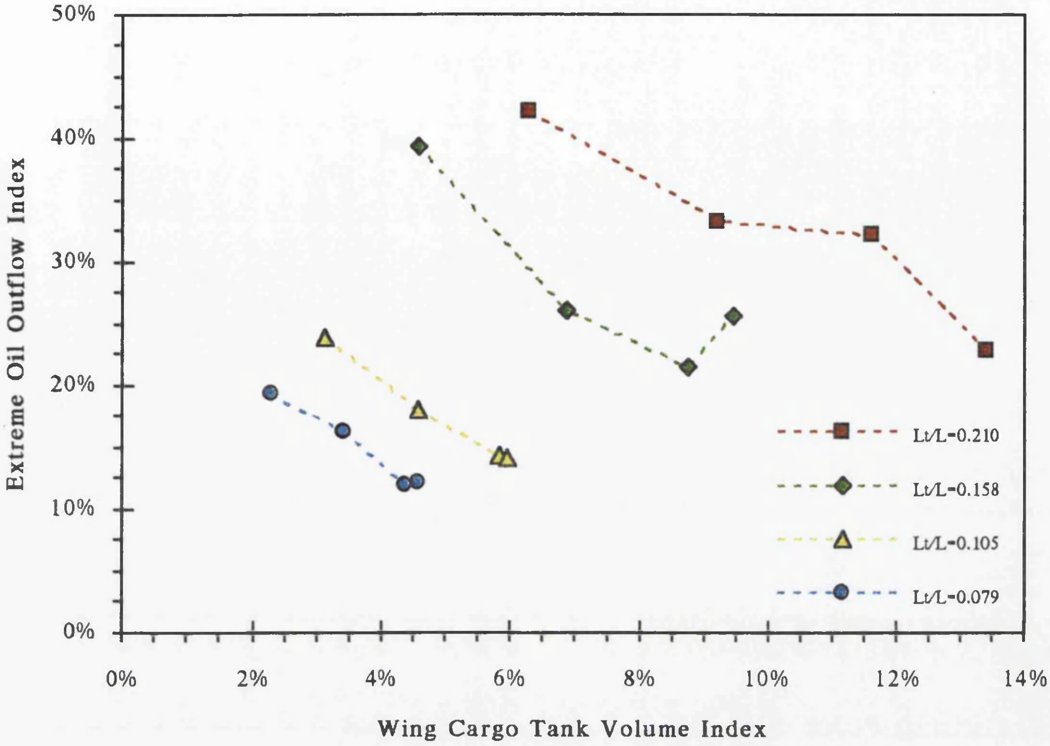

Figure D.5: Effect of Wing Cargo Tank Volume on Extreme Oil Outflow.

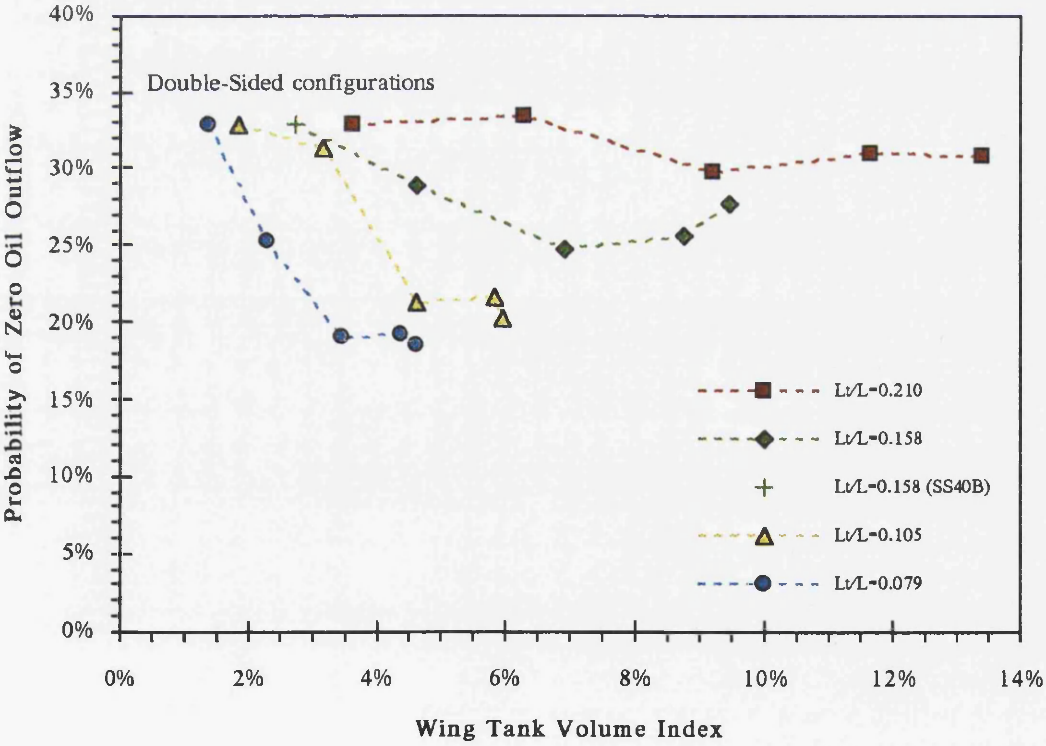

Figure D.6: Effect of Wing Tank Volume on the Probability of Zero Oil Outflow.

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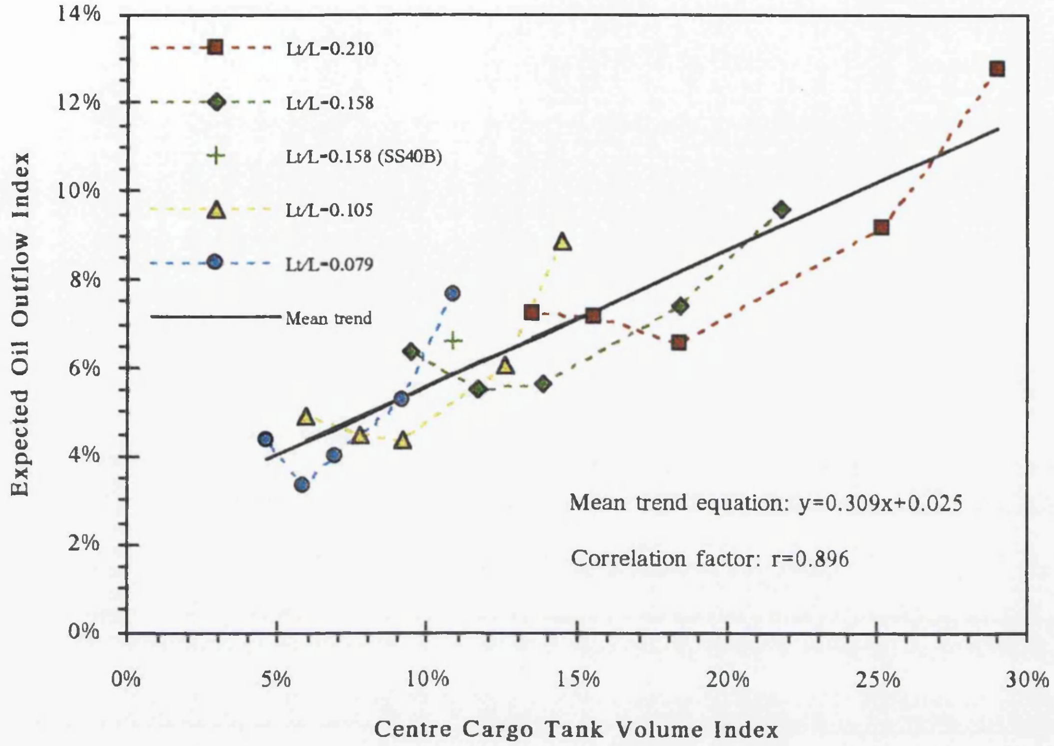

Figure D.7: Correlation of Expected Oil Outflow and Centre Cargo Tank Volume.

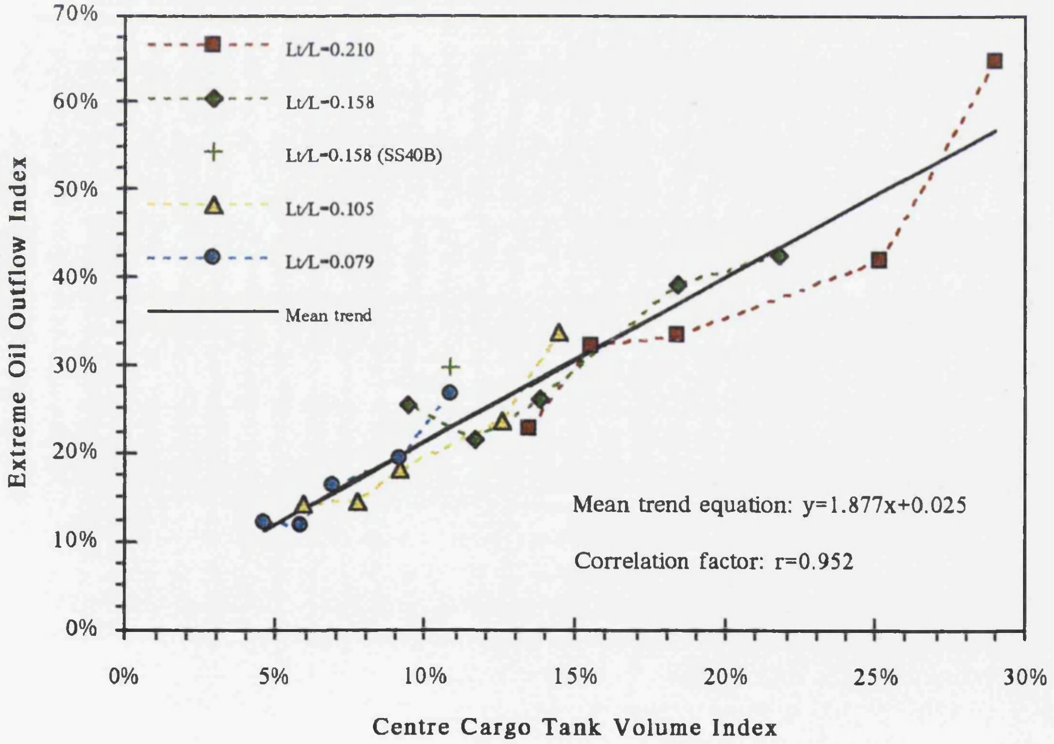

Figure D.8: Correlation of Extreme Oil Outflow and Centre Cargo Tank Volume.

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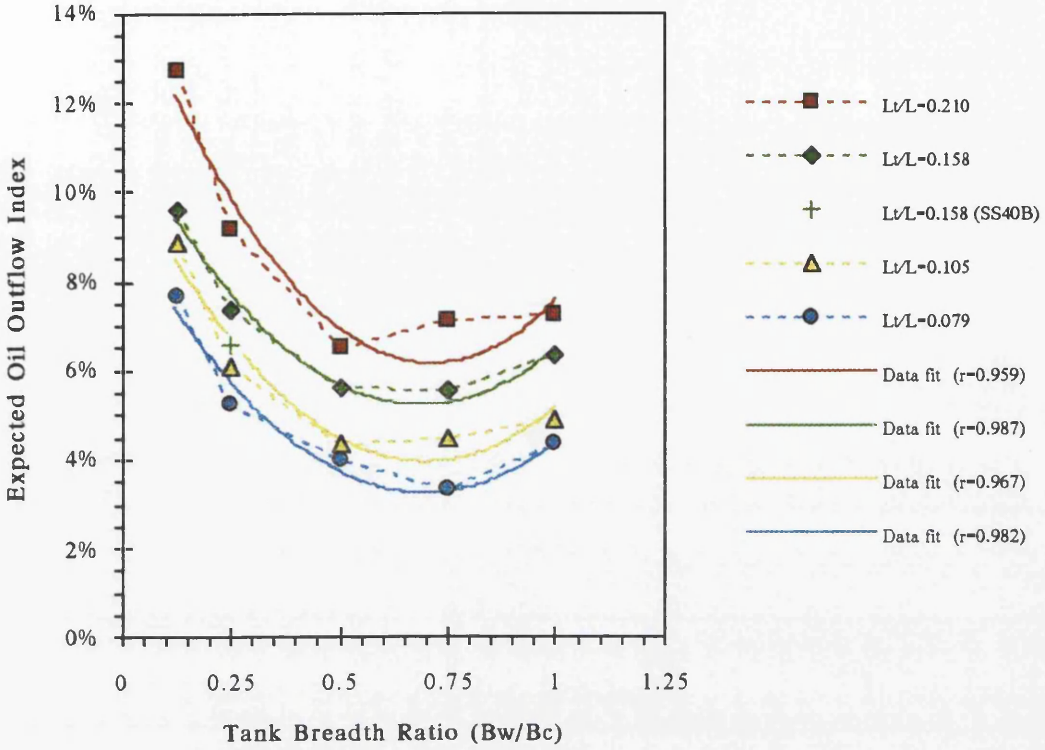

Figure D.9: Effect of Tank Breadth Ratio on Expected Oil Outflow.

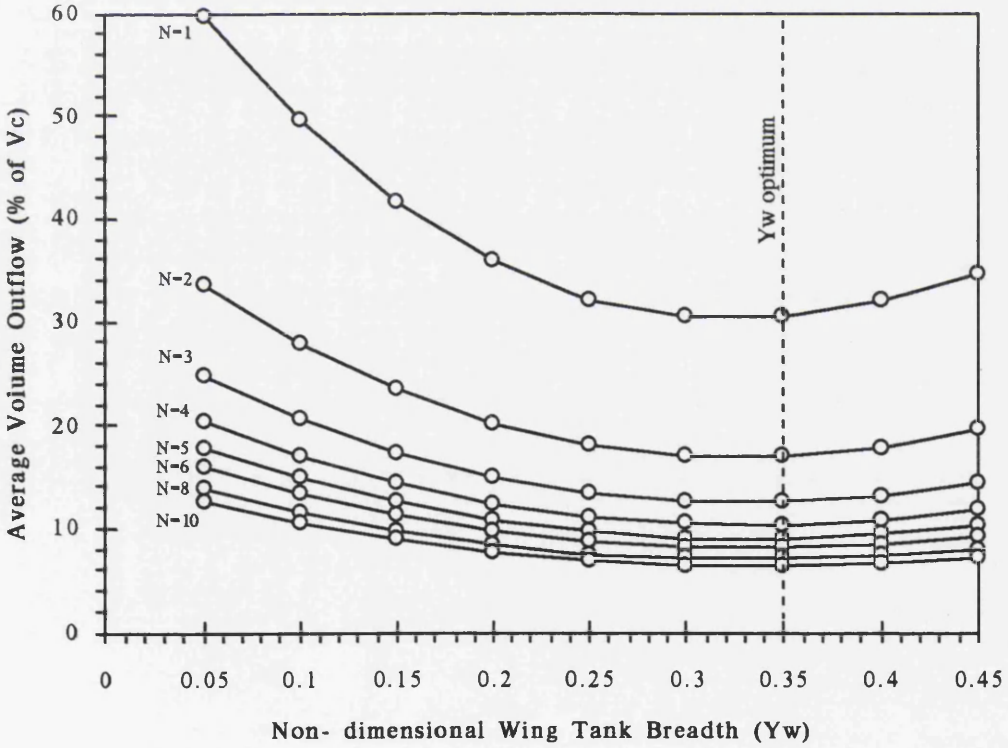

Figure D.9.b: Optimum Breadth of Wing Tank when Ballast is accommodated in alternate Wing Tanks for varying number of transverse bulkheads ‘N’. (Source: Reference [6]).

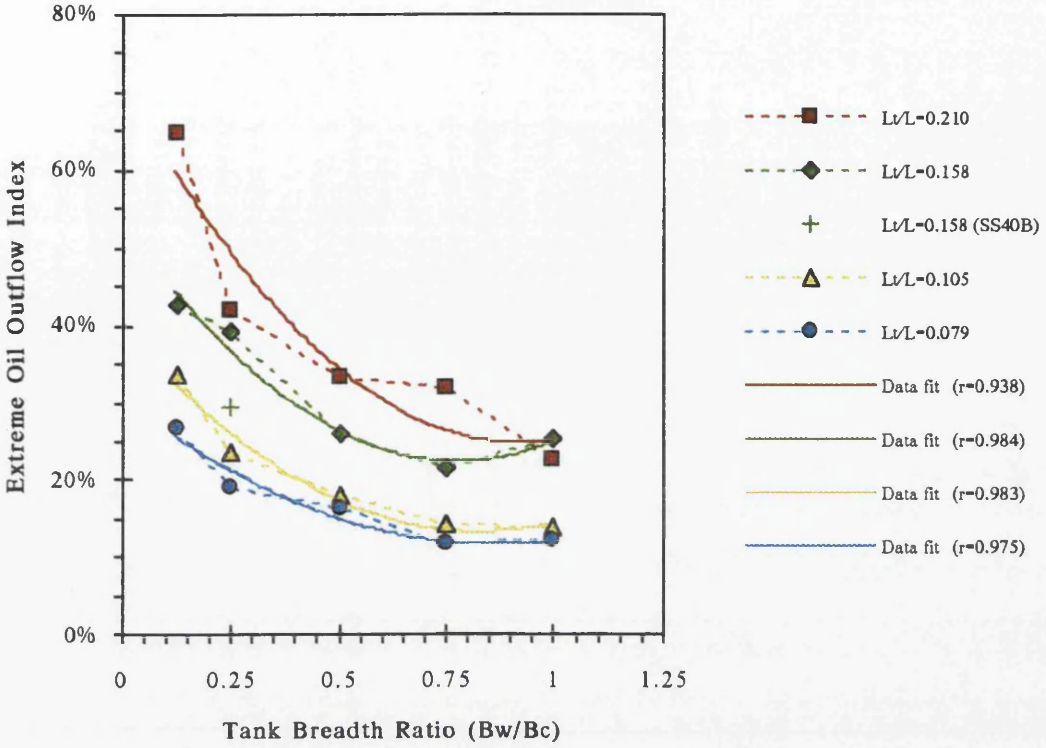

Figure D.10: Effect of Tank Breadth Ratio on Extreme Oil Outflow.

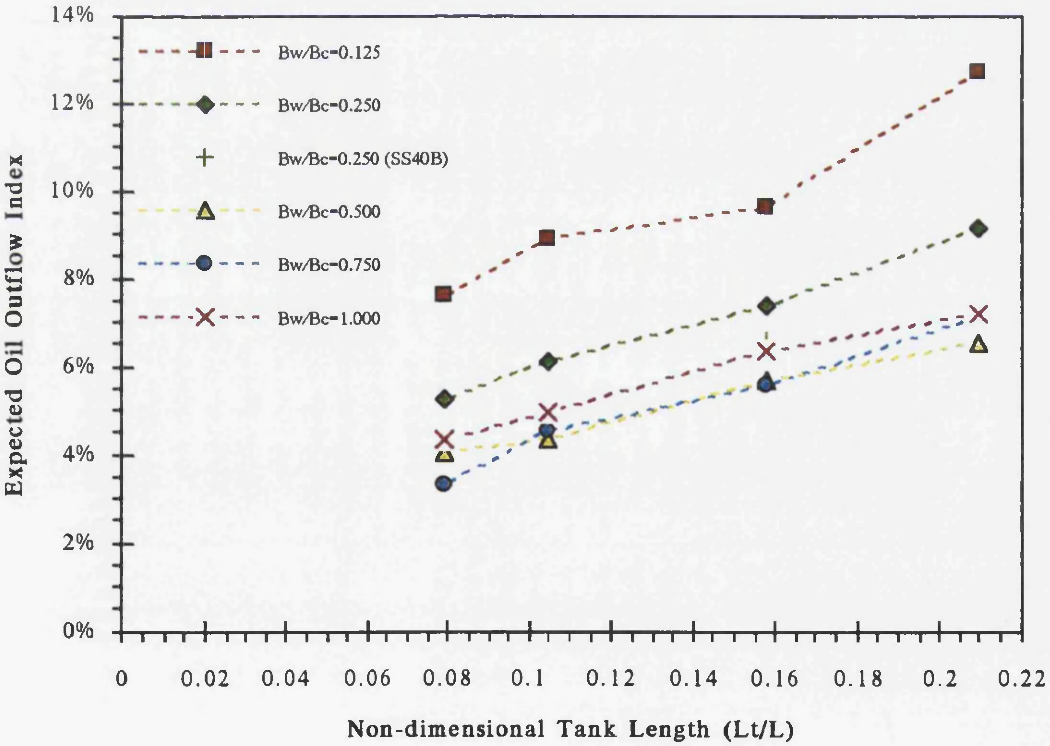

Figure D.11: Effect of Tank Length and Tank Breadth Ratio on Expected Oil Outflow.

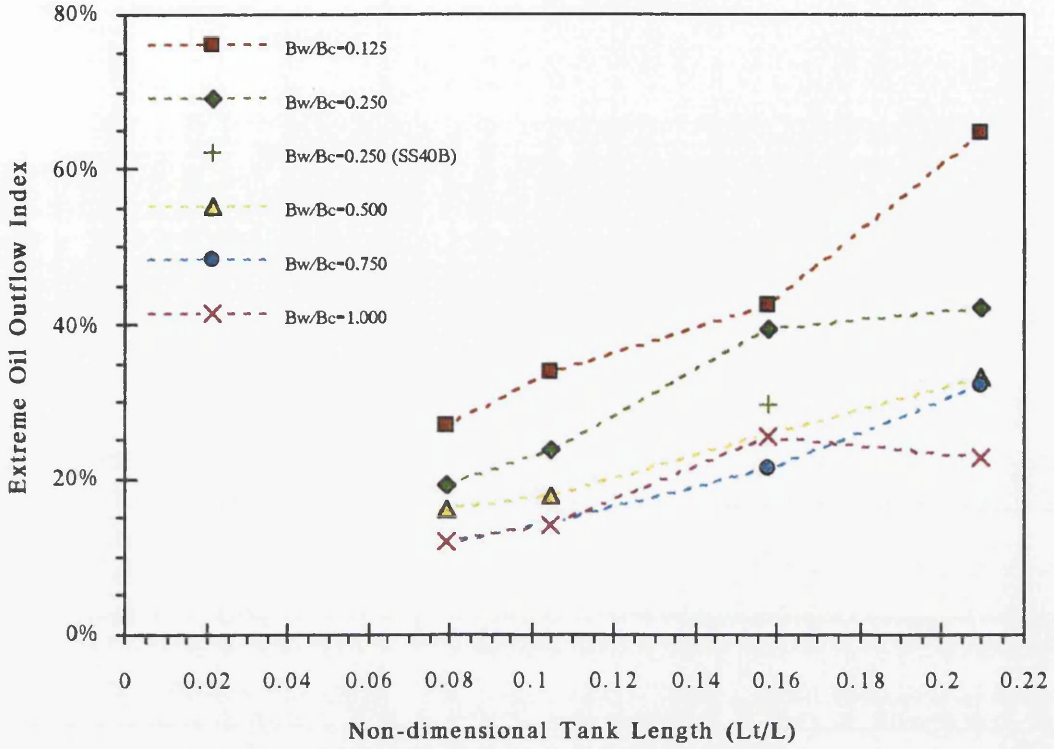

Figure D.12: Effect of Tank Length and Tank Breadth Ratio on Extreme Oil Outflow.

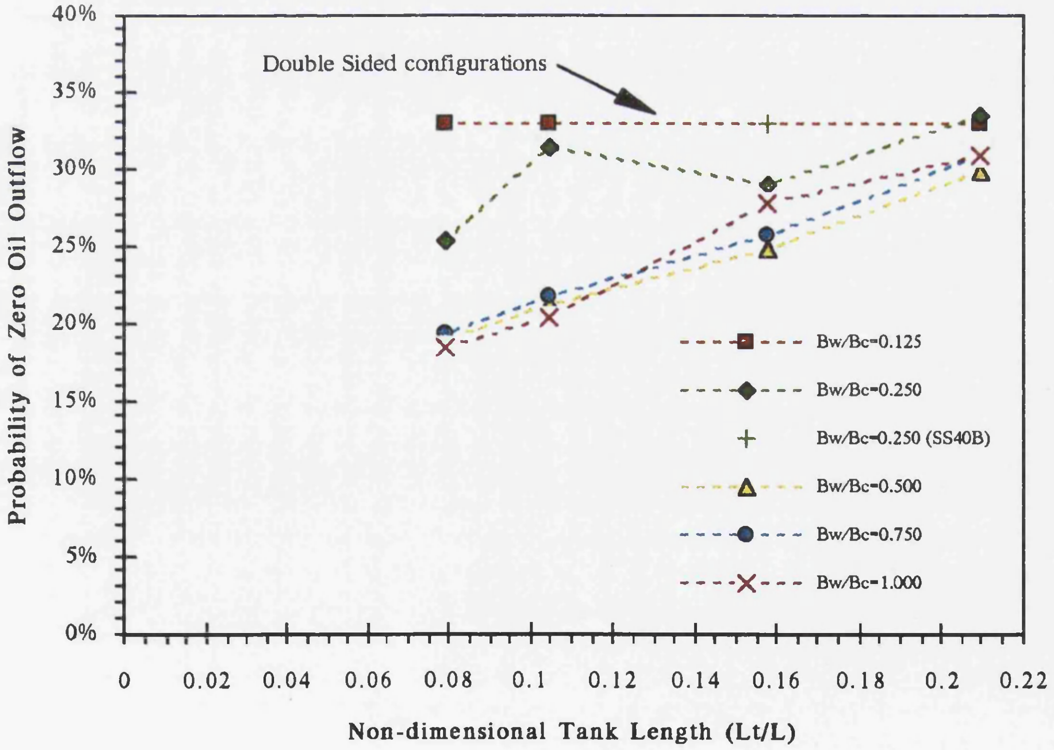

Figure D.13: Effect of Tank Length on the Probability of Zero Oil Outflow under constant Tank Breadth Ratio.

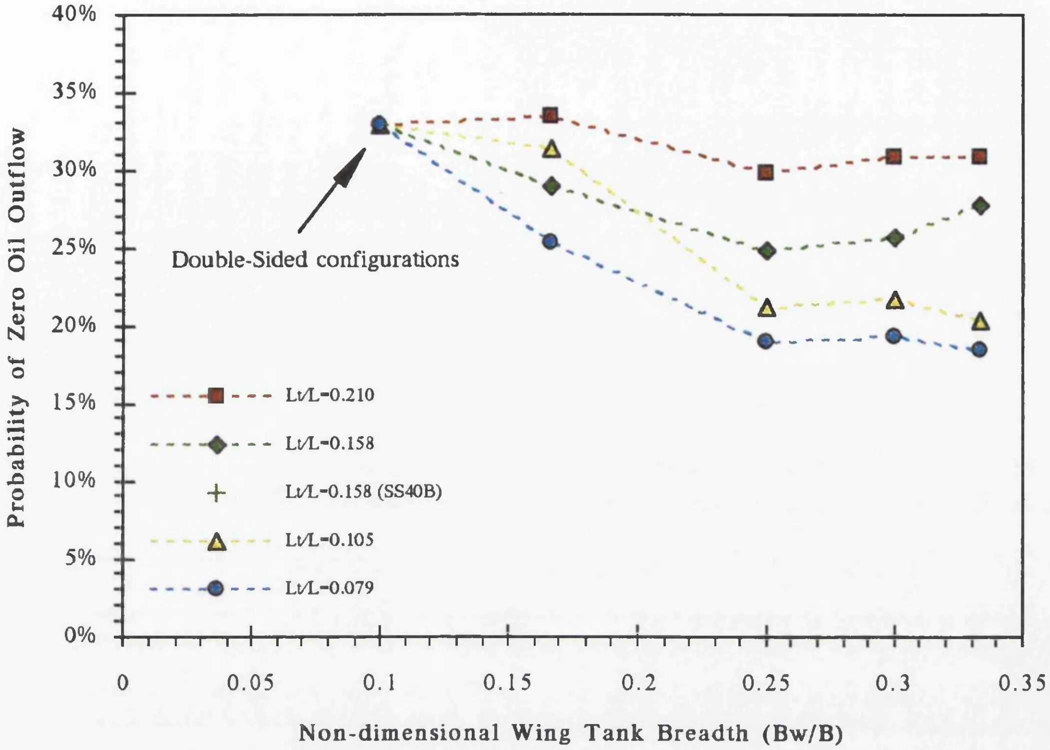

Figure D.14: Effect of Wing Tank Breadth on the Probability of Zero Oil Outflow under constant Tank Length.

D.1.2 DOUBLE-HULL ARRANGEMENTS

	Cargo	Cargo Tank Volume			
Code	Capacity	(m^3)	index	Bds/B	Vdb/Vds
DH0L1	205458	48213	23.47%	0.074	0.497
DH1L1	205458	24106	11.73%	0.074	0.497
DH2L1	205632	16071	7.82%	0.074	0.497
DH0L2	205727	48226	23.44%	0.057	1.034
DH1L2	205727	24113	11.72%	0.057	1.034
DH2L2	205901	16076	7.81%	0.057	1.034
DH0L3	205962	48233	23.42%	0.038	2.155
DH1L3	205962	24116	11.71%	0.038	2.155
DH2L3	206355	16078	7.79%	0.038	2.155
DH0U1	205458	48213	23.47%	0.074	0.497
DH1U1	205458	24106	11.73%	0.074	0.497
DH2U1	205632	16071	7.82%	0.074	0.497
DH0U2	205727	48226	23.44%	0.057	1.034
DH1U2	205727	24113	11.72%	0.057	1.034
DH2U2	205901	16076	7.81%	0.057	1.034
DH0U3	205962	48233	23.42%	0.038	2.155
DH1U3	205962	24116	11.71%	0.038	2.155
DH2U3	206355	16078	7.79%	0.038	2.155
DH0S1	205458	48213	23.47%	0.074	0.497
DH1S1	205458	24106	11.73%	0.074	0.497
DH2S1	205632	16071	7.82%	0.074	0.497
DH0S2	205727	48226	23.44%	0.057	1.034
DH1S2	205727	24113	11.72%	0.057	1.034
DH2S2	205901	16076	7.81%	0.057	1.034
DH0S3	205962	48233	23.42%	0.038	2.155
DH1S3	205962	24116	11.71%	0.038	2.155
DH2S3	206355	16078	7.79%	0.038	2.155

Table D.3: Tank arrangement particulars.

	Potential Oil Outflow					Corrected			
	Expected value		Extreme value		Probability of	Probability of	Maximum Oil Outflow		
Code	(m^3)	index	(m^3)	index	Zero Outflow	Zero Outflow	(m^3)	index	Probability
DH0L1	22616	11.01%	93525	45.52%	27.97%	25.69%	139619	67.95%	1.53E-06
DH1L1	13159	6.40%	52999	25.80%	27.96%	25.68%	139619	67.95%	2.61E-05
DH2L1	9860	4.80%	42432	20.63%	27.96%	25.70%	93079	45.26%	1.53E-06
DH0L2	24311	11.82%	91298	44.38%	25.07%	23.06%	139658	67.89%	2.03E-06
DH1L2	14052	6.83%	52708	25.62%	25.07%	23.06%	139658	67.89%	2.03E-06
DH2L2	10673	5.18%	50722	24.63%	25.07%	23.08%	93105	45.22%	2.03E-06
DH0L3	23995	11.65%	86931	42.21%	20.01%	18.42%	139677	67.82%	4.57E-06
DH1L3	15288	7.42%	58553	28.43%	20.00%	18.41%	139677	67.82%	2.20E-05
DH2L3	11467	5.56%	50825	24.63%	20.00%	18.44%	93118	45.13%	4.57E-06
DH0U1	23382	11.38%	95152	46.31%	27.96%	25.68%	139619	67.95%	7.97E-04
DH1U1	14166	6.89%	63507	30.91%	27.96%	25.68%	139619	67.95%	2.76E-05
DH2U1	10880	5.29%	44515	21.65%	27.96%	25.70%	93079	45.26%	1.85E-04
DH0U2	24258	11.79%	94128	45.75%	25.08%	23.06%	139658	67.89%	8.33E-04
DH1U2	16212	7.88%	64433	31.32%	25.08%	23.06%	139658	67.89%	2.66E-05
DH2U2	11323	5.50%	52435	25.47%	25.08%	23.08%	93105	45.22%	1.80E-04
DH0U3	25521	12.39%	90830	44.10%	20.01%	18.42%	139677	67.82%	8.94E-04
DH1U3	15838	7.69%	60293	29.27%	20.00%	18.41%	139677	67.82%	2.66E-05
DH2U3	12084	5.86%	52296	25.34%	20.00%	18.44%	93118	45.13%	1.80E-04
DH0S1	23061	11.22%	95293	46.38%	27.97%	25.69%	139619	67.95%	7.60E-04
DH1S1	12792	6.23%	52998	25.80%	27.96%	25.68%	139619	67.95%	2.61E-05
DH2S1	10732	5.22%	45032	21.90%	27.96%	25.70%	93079	45.26%	1.76E-04
DH0S2	24805	12.06%	89099	43.31%	25.07%	23.06%	139658	67.89%	6.37E-05
DH1S2	13701	6.66%	52684	25.61%	25.07%	23.06%	139658	67.89%	2.03E-06
DH2S2	11657	5.66%	51563	25.04%	25.07%	23.08%	93105	45.22%	1.37E-05
DH0S3	25534	12.40%	89951	43.67%	20.01%	18.42%	139677	67.82%	7.40E-04
DH1S3	16599	8.06%	59880	29.07%	20.00%	18.41%	139677	67.82%	2.20E-05
DH2S3	12542	6.08%	50375	24.41%	20.00%	18.44%	93118	45.13%	1.49E-04

Table D.4: Oil Outflow results.

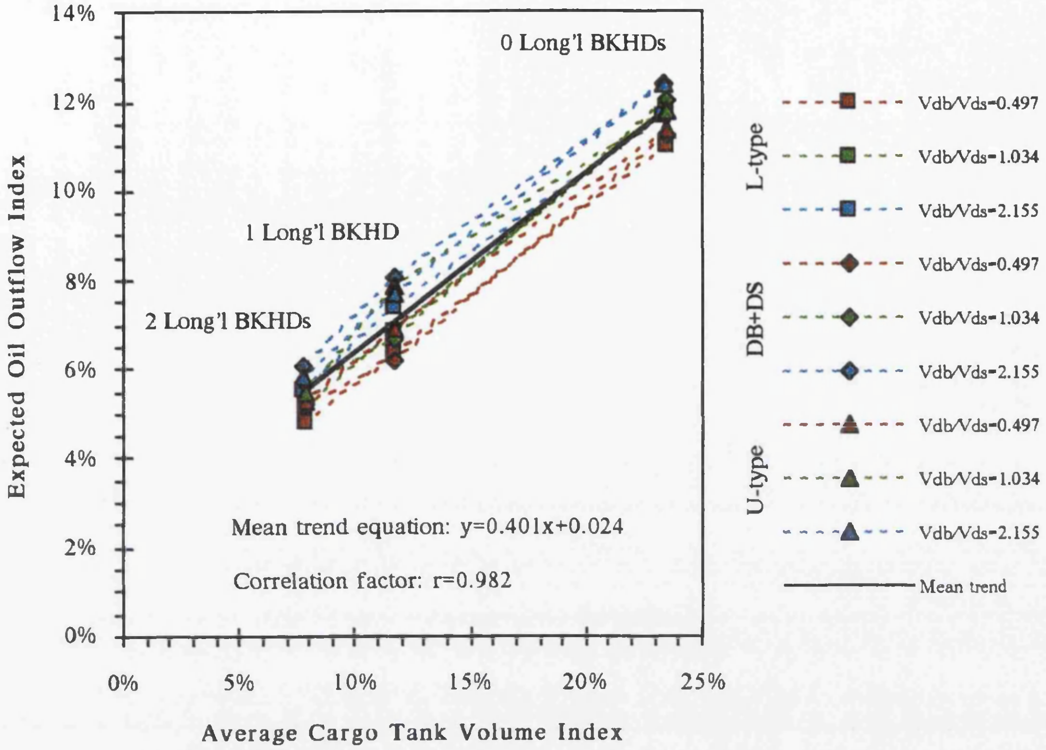

Figure D.15: Effect of Average Cargo Tank Volume on Expected Oil Outflow.

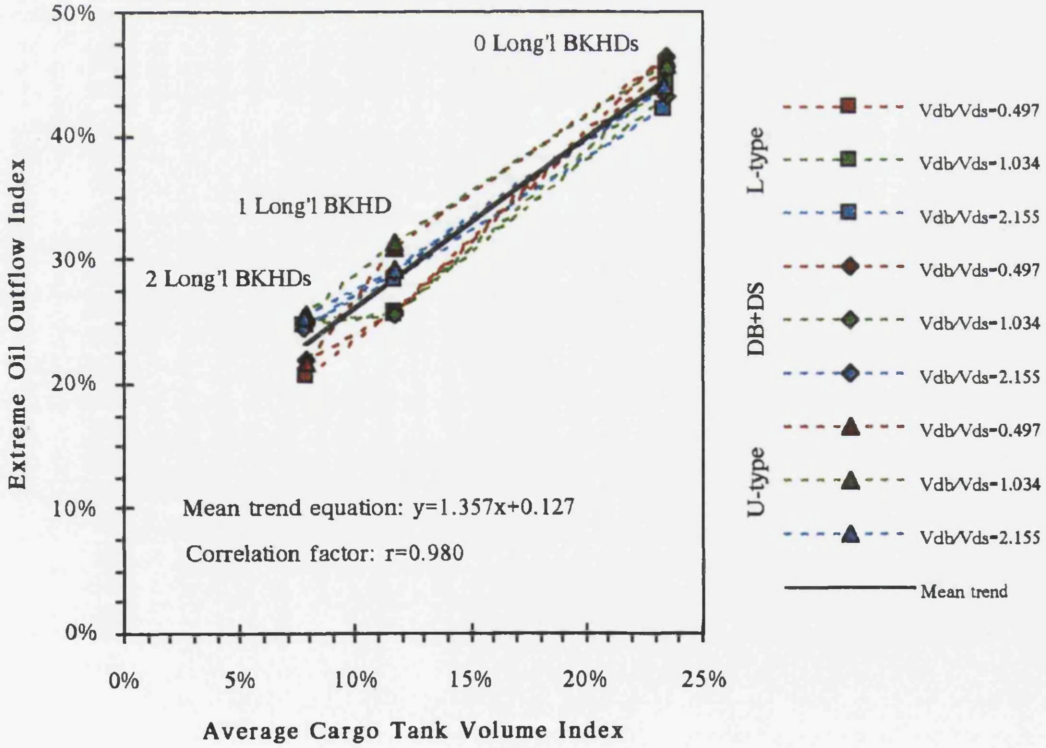

Figure D.16: Effect of Average Cargo Tank Volume on Extreme Oil Outflow.

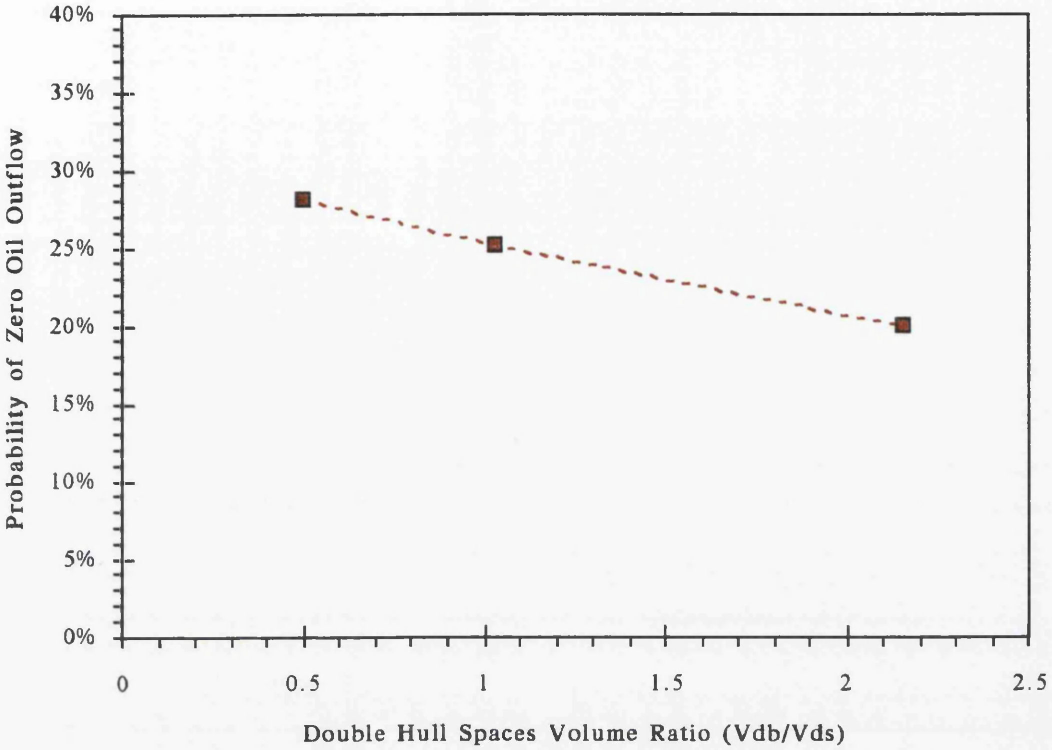

Figure D.17: Effect of distribution of water ballast, between double sides and double bottom, on the Probability of Zero Oil Outflow.

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D.1.3 MID-DECK ARRANGEMENTS

Code	Cargo Capacity	Tank Volume				Tank Volume index			
		Upper	Lower	Mean	Average*	Upper	Lower	Mean	Average*
MDHN1	223722	12600	36000	24300	24300	5.63%	16.09%	10.86%	10.86%
MDMN1	223722	24300	24300	24300	24300	10.86%	10.86%	10.86%	10.86%
MDLN1	223722	36000	12600	24300	24300	16.09%	5.63%	10.86%	10.86%
MDHN0	223722	12600	36000	24300	24300	5.63%	16.09%	10.86%	10.86%
MDMN0	223722	24300	24300	24300	24300	10.86%	10.86%	10.86%	10.86%
MDLN0	223722	36000	12600	24300	24300	16.09%	5.63%	10.86%	10.86%
MDHU1	223722	6300	36000	16200	21150	2.82%	16.09%	7.24%	9.45%
MDMU1	223722	12150	24300	16200	18225	5.43%	10.86%	7.24%	8.15%
MDLU1	223722	18000	12600	16200	15300	8.05%	5.63%	7.24%	6.84%
MDHU0	223722	6300	36000	16200	21150	2.82%	16.09%	7.24%	9.45%
MDMU0	223722	12150	24300	16200	18225	5.43%	10.86%	7.24%	8.15%
MDLU0	223722	18000	12600	16200	15300	8.05%	5.63%	7.24%	6.84%
MDHF1	223722	6300	18000	12150	12150	2.82%	8.05%	5.43%	5.43%
MDMF1	223722	12150	12150	12150	12150	5.43%	5.43%	5.43%	5.43%
MDLF1	223722	18000	6300	12150	12150	8.05%	2.82%	5.43%	5.43%
MDHF0	223722	6300	18000	12150	12150	2.82%	8.05%	5.43%	5.43%
MDMF0	223722	12150	12150	12150	12150	5.43%	5.43%	5.43%	5.43%
MDLF0	223722	18000	6300	12150	12150	8.05%	2.82%	5.43%	5.43%

Note: (Average*) refers to the average volume of one upper and one lower tanks.

Table D.5: Tank arrangement particulars.

Code	Potential Oil Outflow				Probability of Zero Outflow	Maximum Oil Outflow		
	Expected value		Extreme value					
	(m^3)	index	(m^3)	index		(m^3)	index	Probability
MDHN1	20709	9.26%	93943	41.99%	32.95%	141106	63.07%	1.83E-04
MDMN1	16326	7.30%	62212	27.81%	32.87%	142149	63.54%	1.97E-04
MDLN1	16850	7.53%	57041	25.50%	32.84%	141471	63.24%	1.78E-04
MDHN0	20717	9.26%	93941	41.99%	32.84%	141106	63.07%	1.83E-04
MDMN0	16385	7.32%	62806	28.07%	32.85%	142149	63.54%	1.97E-04
MDLN0	16705	7.47%	56020	25.04%	32.84%	141471	63.24%	1.78E-04
MDHU1	18229	8.15%	82277	36.78%	32.90%	141106	63.07%	6.78E-06
MDMU1	12922	5.78%	54264	24.26%	32.85%	142149	63.54%	7.29E-06
MDLU1	11301	5.05%	50868	22.74%	32.85%	141471	63.24%	6.60E-06
MDHU0	19120	8.55%	86390	38.61%	32.84%	141106	63.07%	6.78E-06
MDMU0	13013	5.82%	47729	21.33%	32.84%	142149	63.54%	7.29E-06
MDLU0	10872	4.86%	50365	22.51%	32.84%	141471	63.24%	6.60E-06
MDHF1	10131	4.53%	43344	19.37%	32.96%	141106	63.07%	6.78E-06
MDMF1	9366	4.19%	38842	17.36%	32.87%	142149	63.54%	7.29E-06
MDLF1	9783	4.37%	42394	18.95%	32.84%	141471	63.24%	6.60E-06
MDHF0	10143	4.53%	43348	19.38%	32.84%	141106	63.07%	6.78E-06
MDMF0	9242	4.13%	38986	17.43%	32.84%	142149	63.54%	7.29E-06
MDLF0	9450	4.22%	41677	18.63%	32.84%	141471	63.24%	6.60E-06

Table D.6: Oil Outflow results.

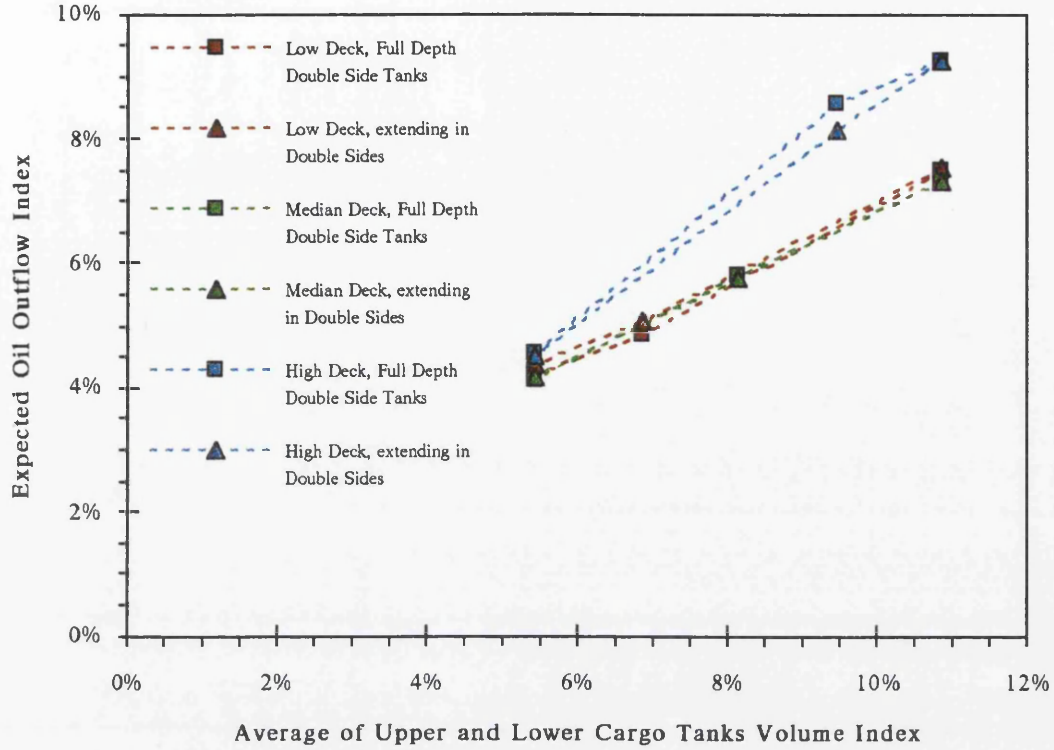

Figure D.18: Effect of Average Cargo Tank Volume on Expected Oil Outflow.

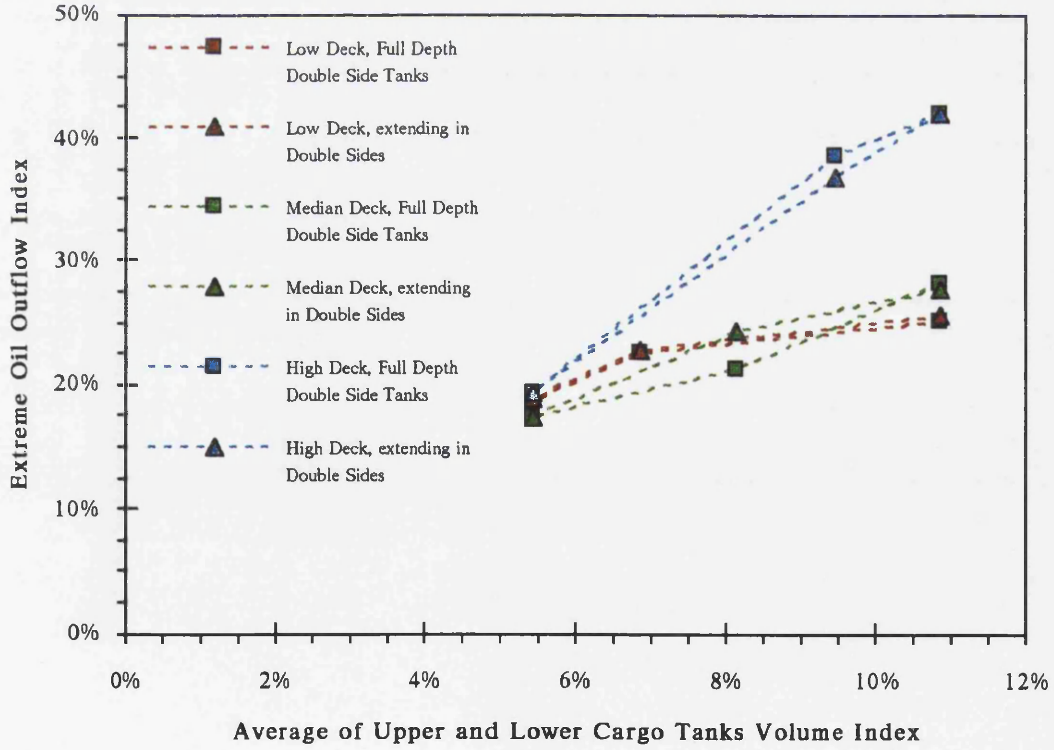

Figure D.19: Effect of Average Cargo Tank Volume on Extreme Oil Outflow.

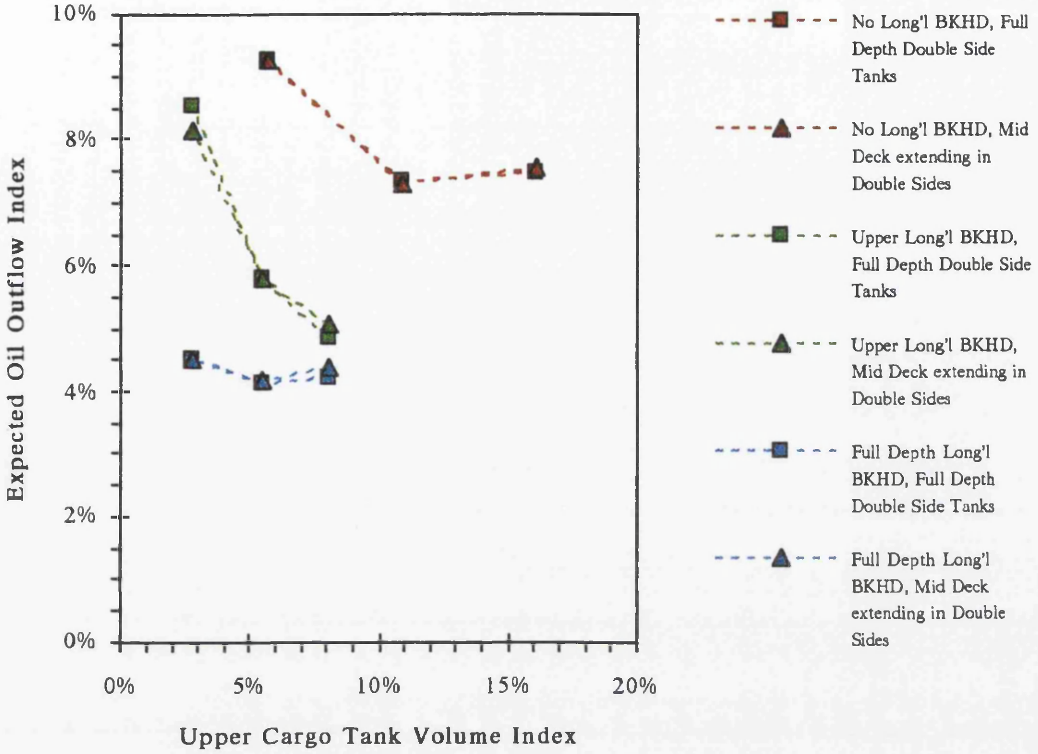

Figure D.20: Effect of Upper Cargo Tank Volume on Expected Oil Outflow.

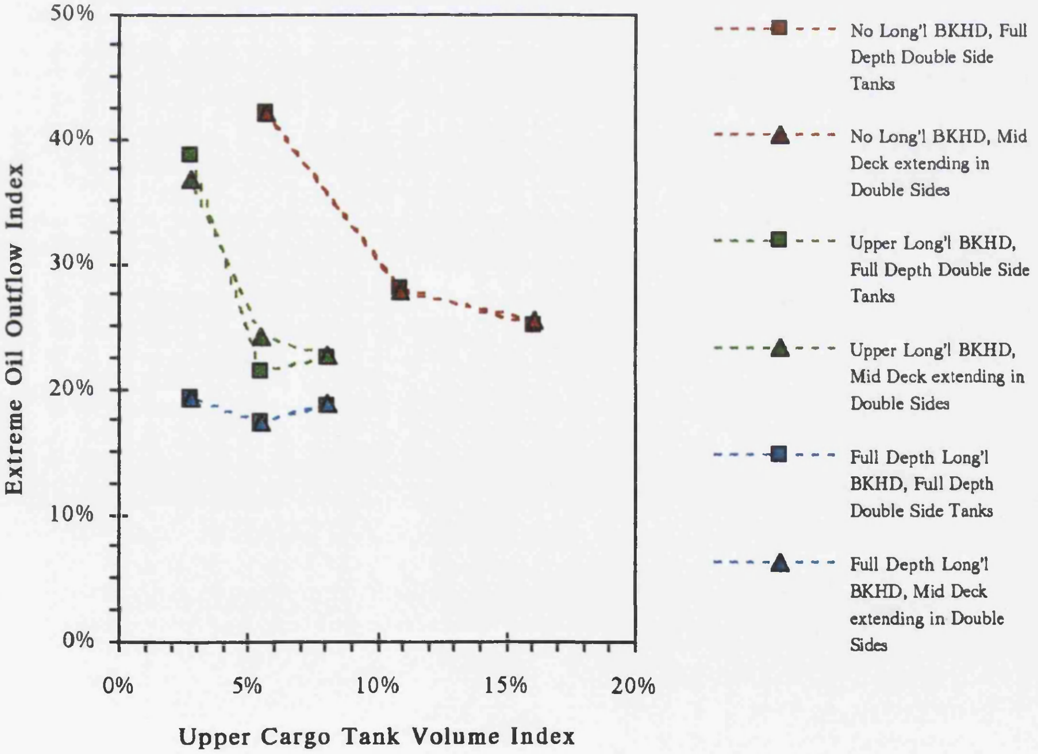

Figure D.21: Effect of Upper Cargo Tank Volume on Extreme Oil Outflow.

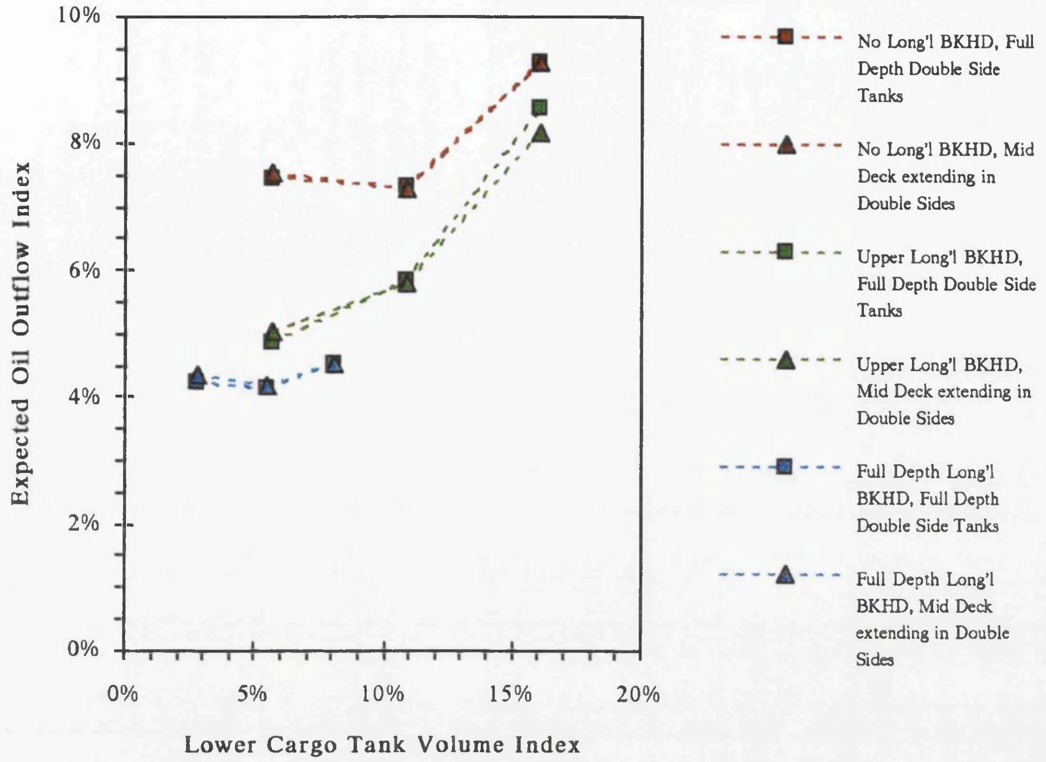

Figure D.22: Effect of Lower Cargo Tank Volume on Expected Oil Outflow.

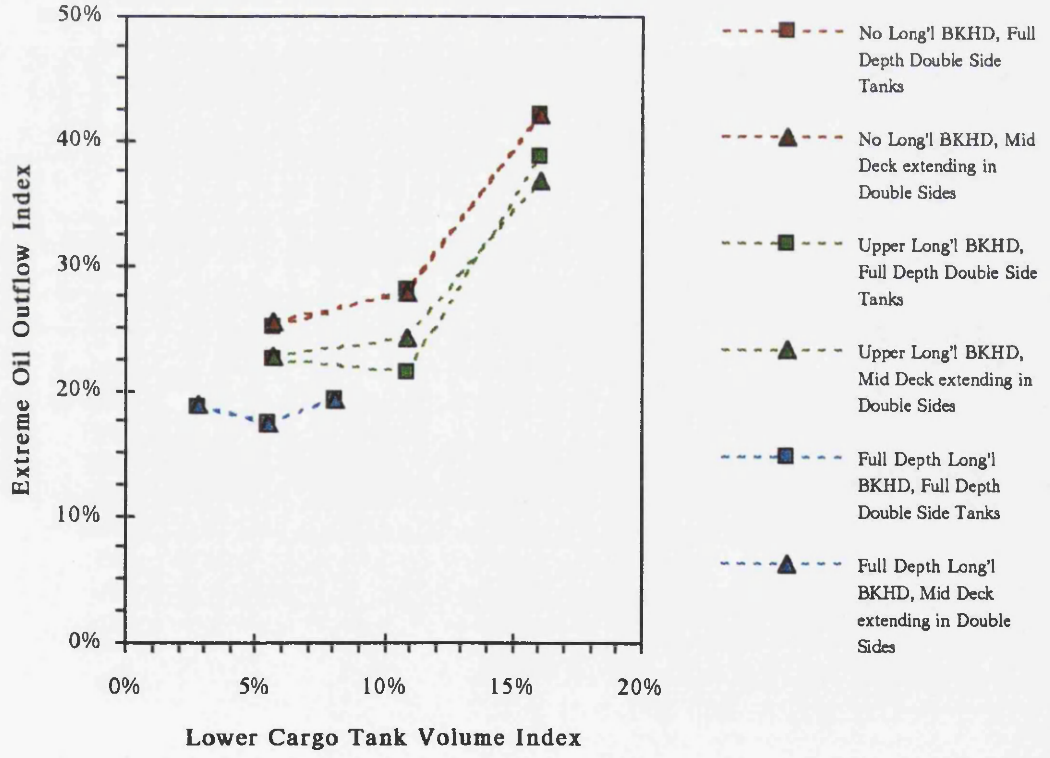

Figure D.23: Effect of Lower Cargo Tank Volume on Extreme Oil Outflow.

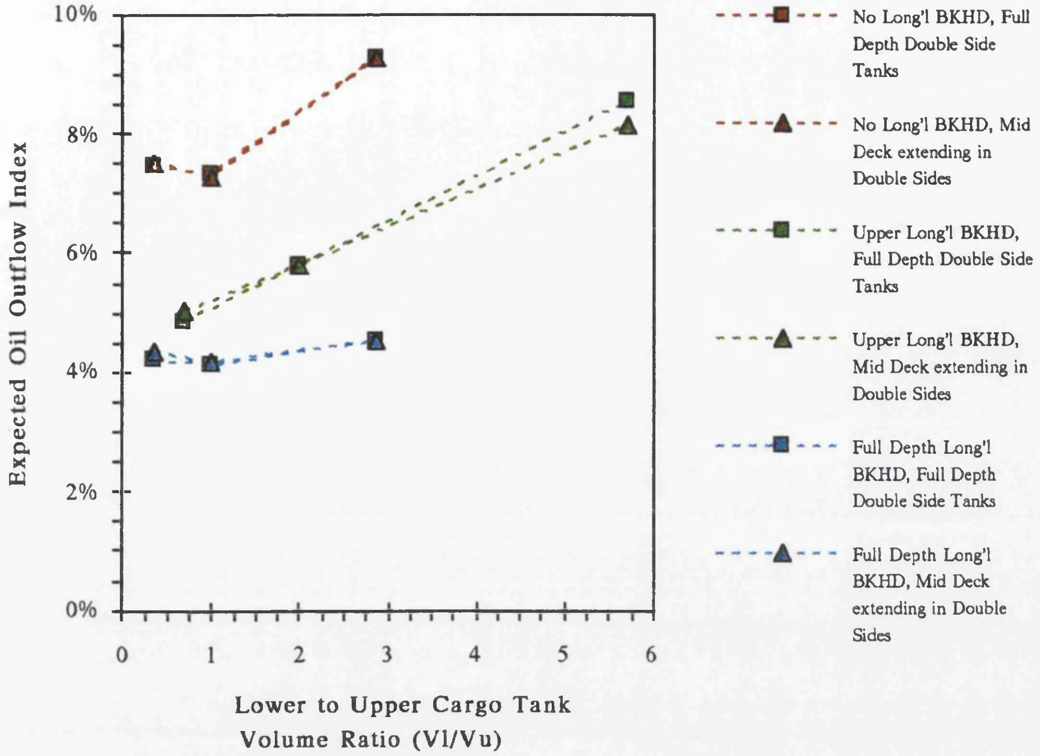

Figure D.24: Effect of relative size of Lower and Upper Cargo Tanks on Expected Oil Outflow.

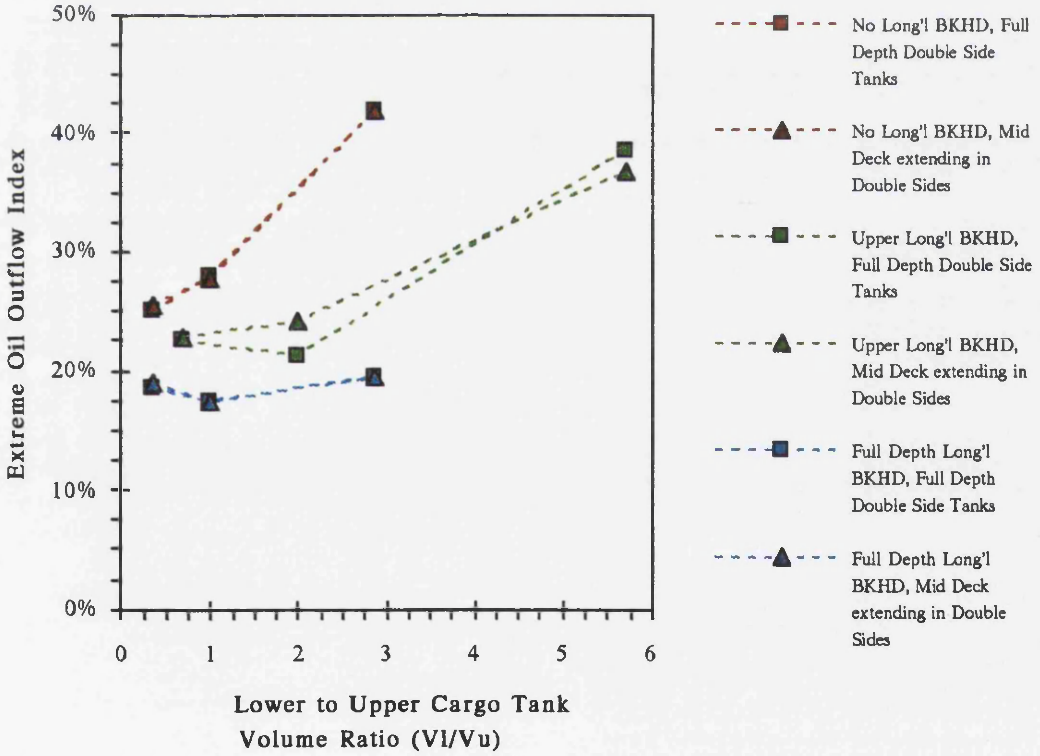

Figure D.25: Effect of relative size of Lower and Upper Cargo Tanks on Extreme Oil Outflow.

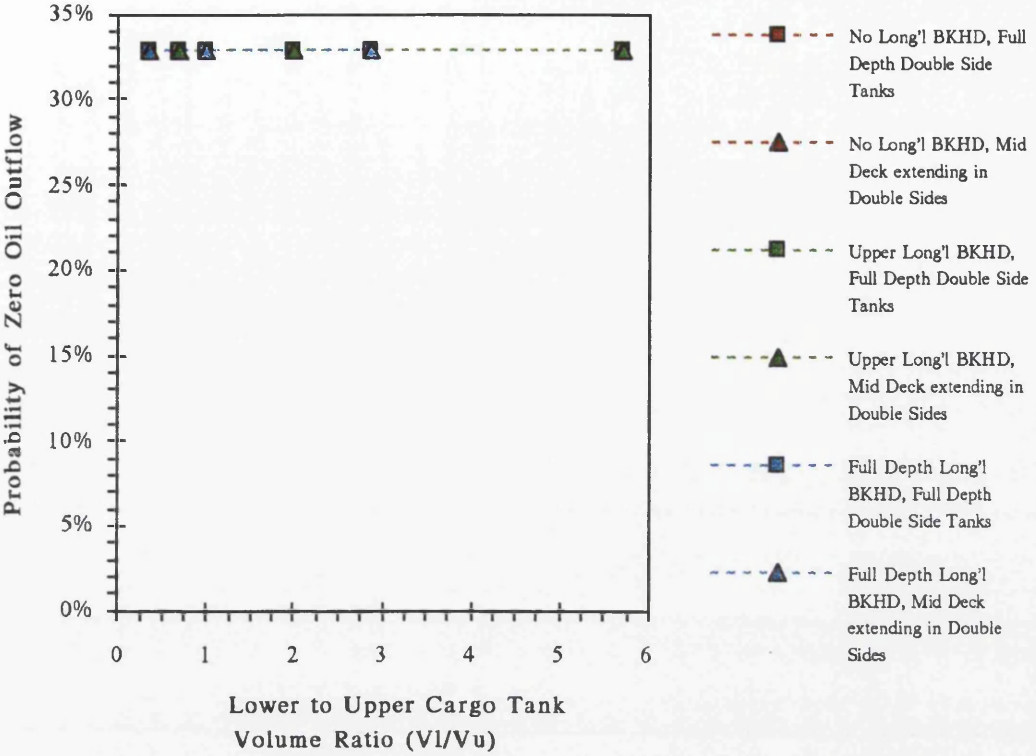

Figure D.26: Effect of relative size of Lower and Upper Cargo Tanks on the Probability of Zero Oil Outflow.

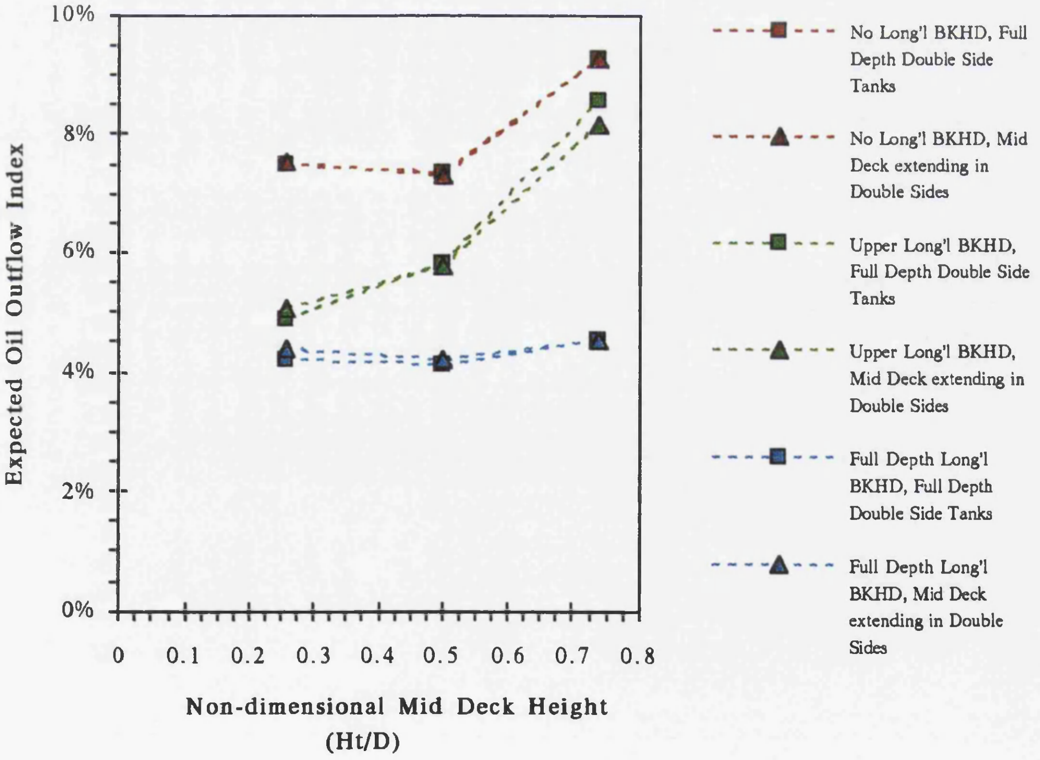

Figure D.27: Effect of mid-deck position on Expected Oil Outflow.

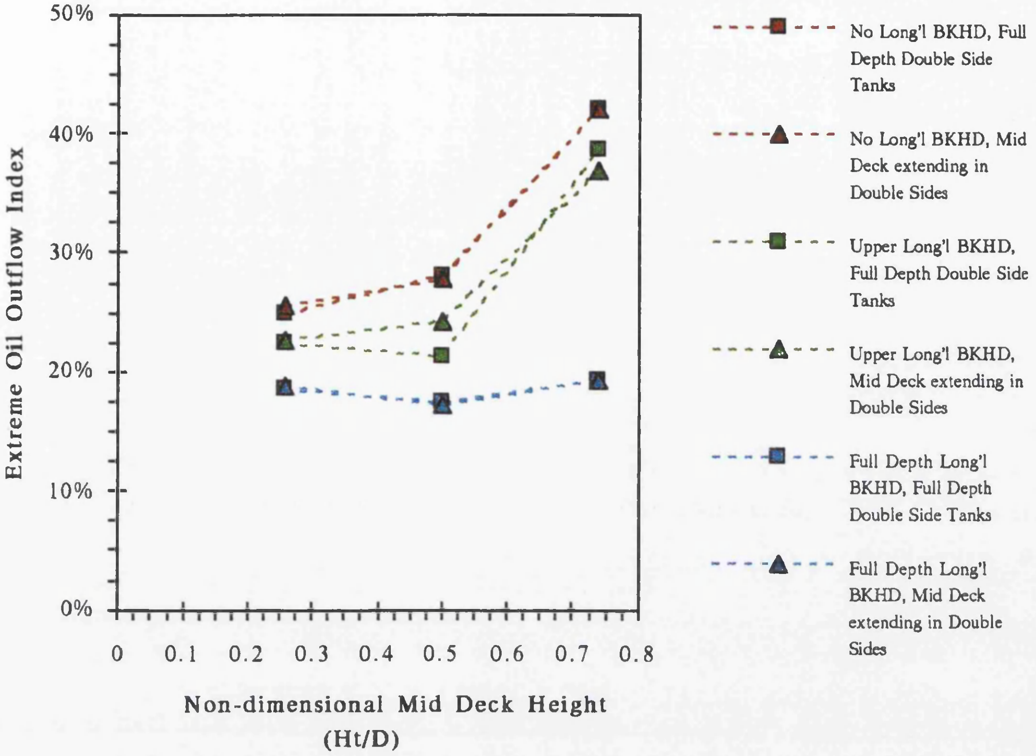

Figure D.28: Effect of mid-deck position on Extreme Oil Outflow.

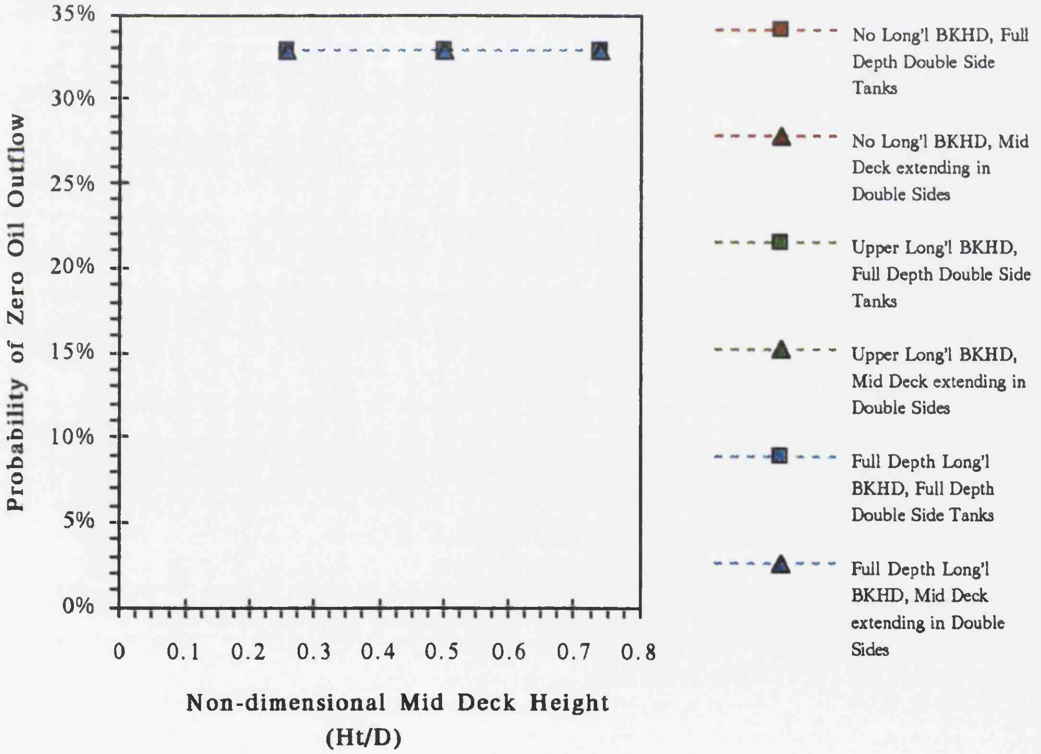

Figure D.29: Effect of mid-deck position on the Probability of Zero Oil Outflow.

D.2 COMPARISON OF DIFFERENT TANKER CONCEPTS

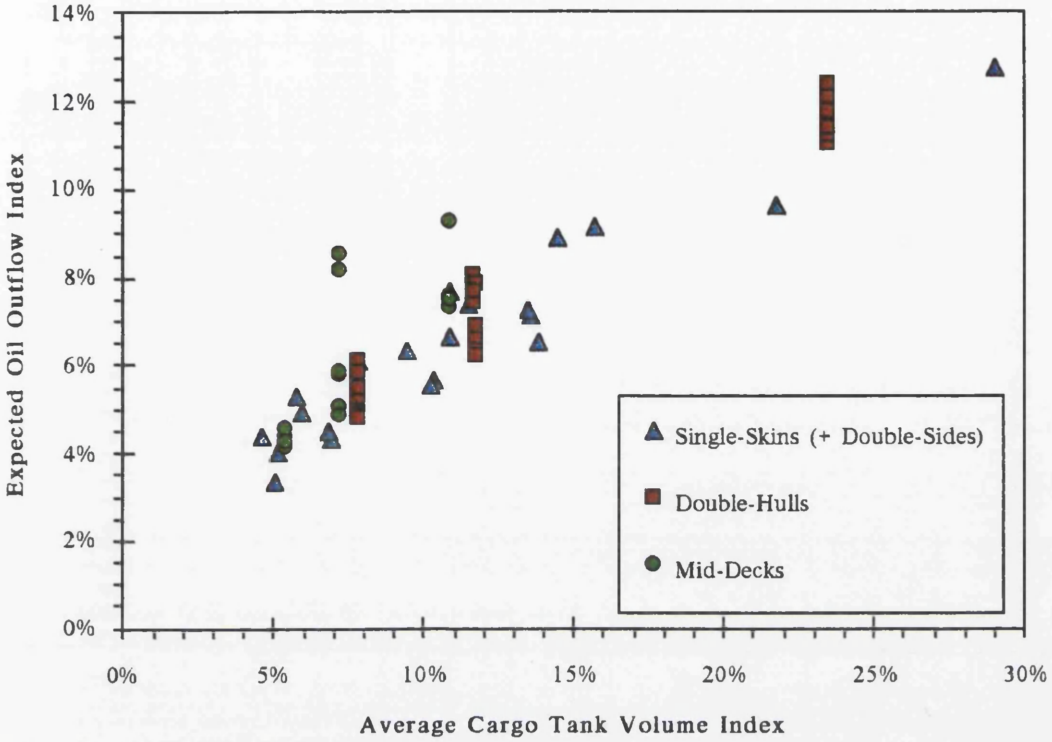

Figure D.30: Comparative performance of Single-Skin, Double-Hull and Mid-Deck arrangements in terms of Expected Oil Outflow.

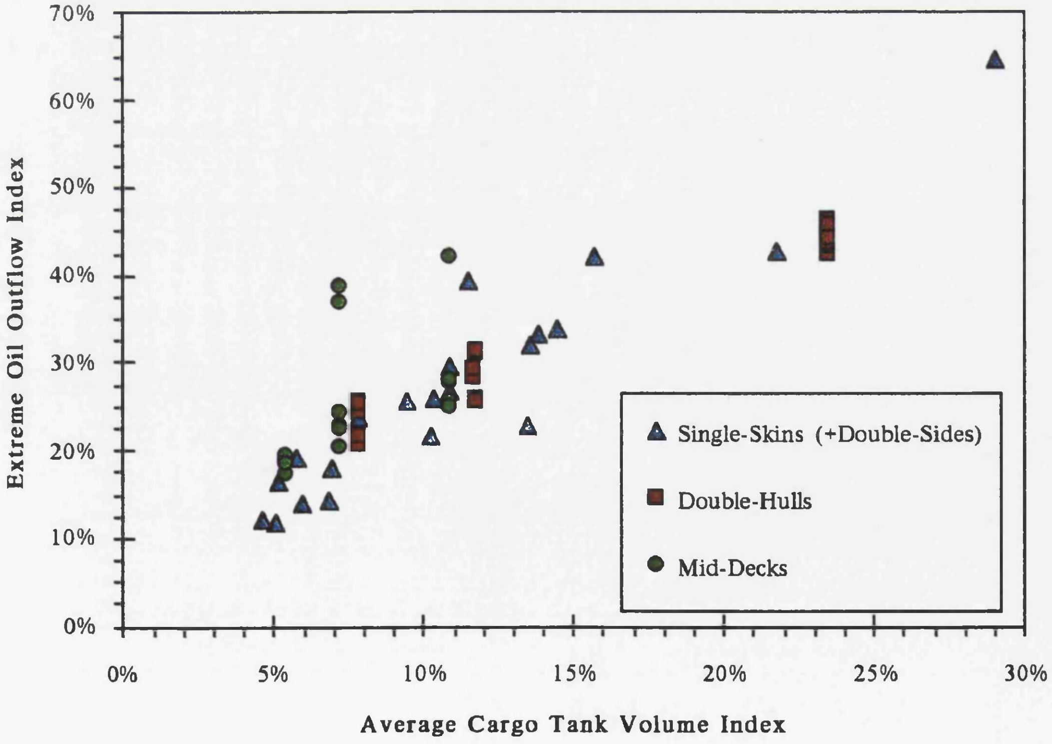

Figure D.31: Comparative performance of Single-Skin, Double-Hull and Mid-Deck arrangements in terms of Extreme Oil Outflow.

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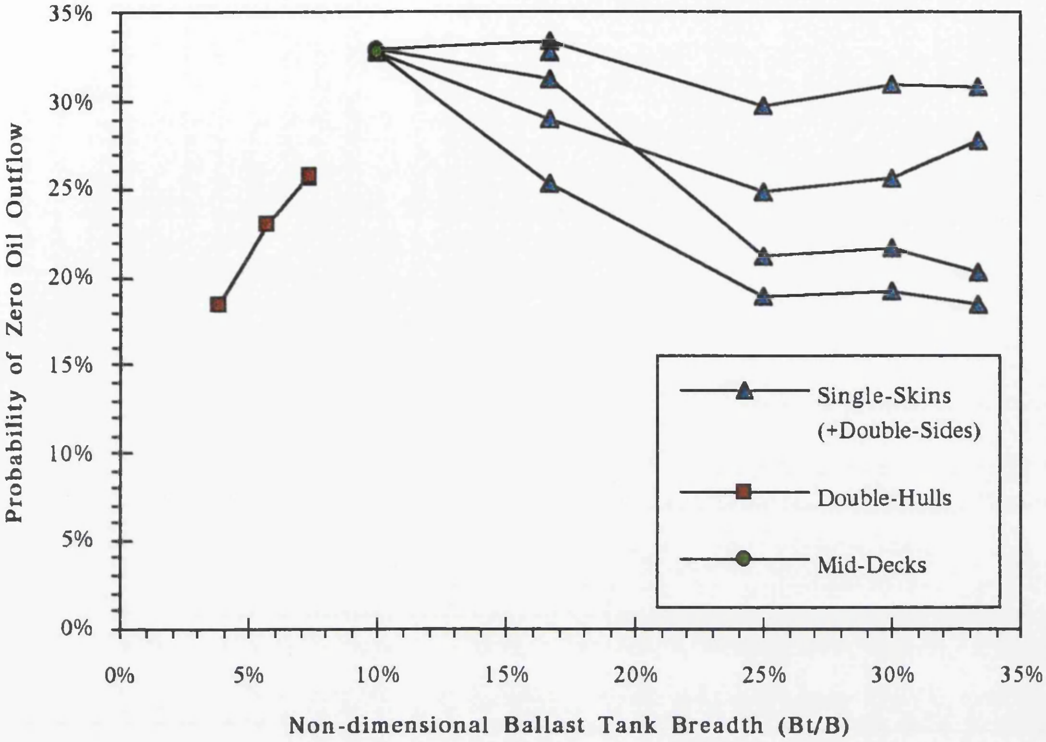

Figure D.32: Comparative performance of Single-Skin, Double-Hull and Mid-Deck arrangements in terms of the Probability of Zero Oil Outflow.

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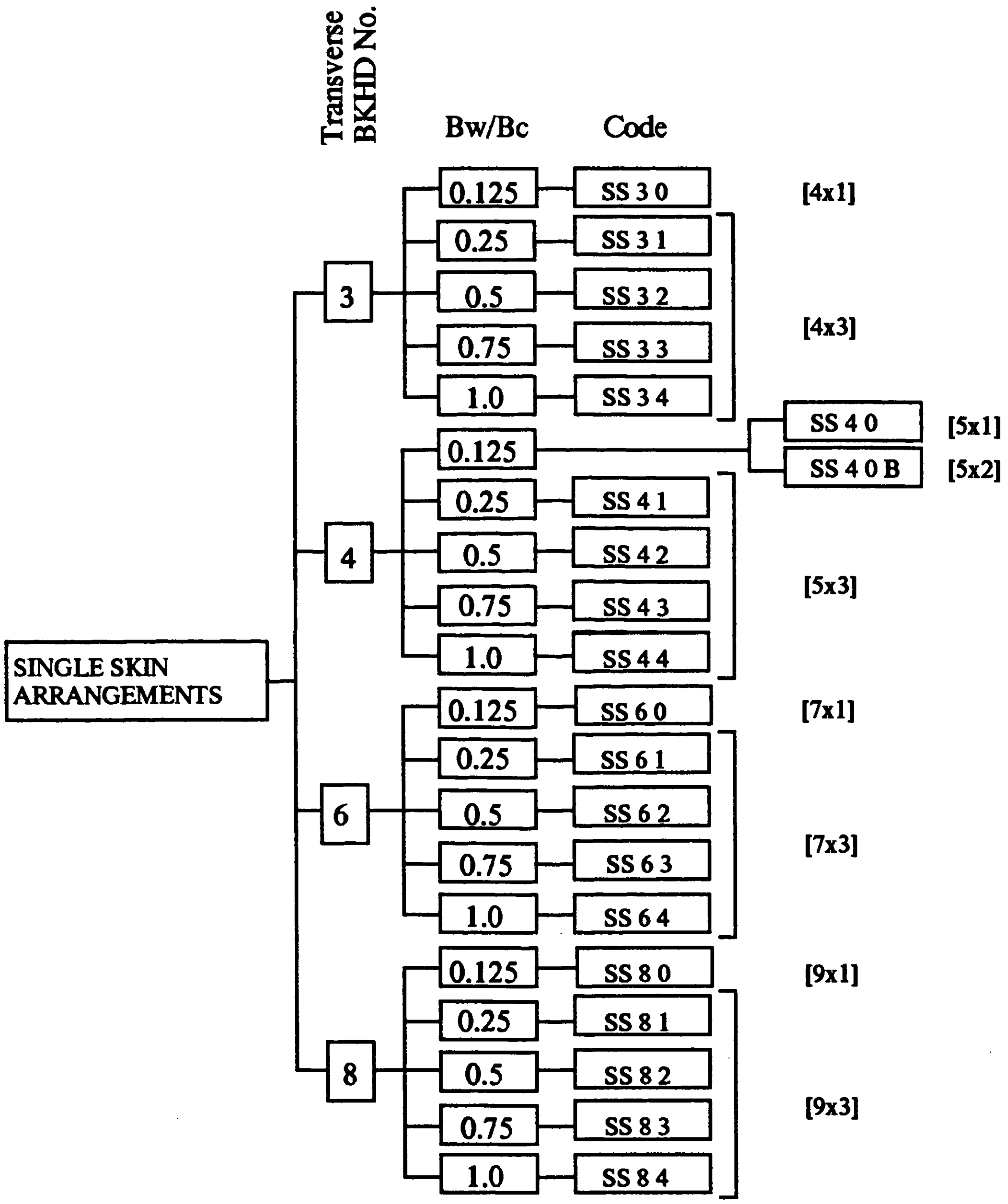
D.3 OIL OUTFLOW CHARTS

D.3.1 SINGLE-SKIN ARRANGEMENTS WITH WING BALLAST TANKS



Note: Code "0" indicates a double-sided arrangement

Figure D.33: Variations of Single-Skin arrangements and corresponding codes.

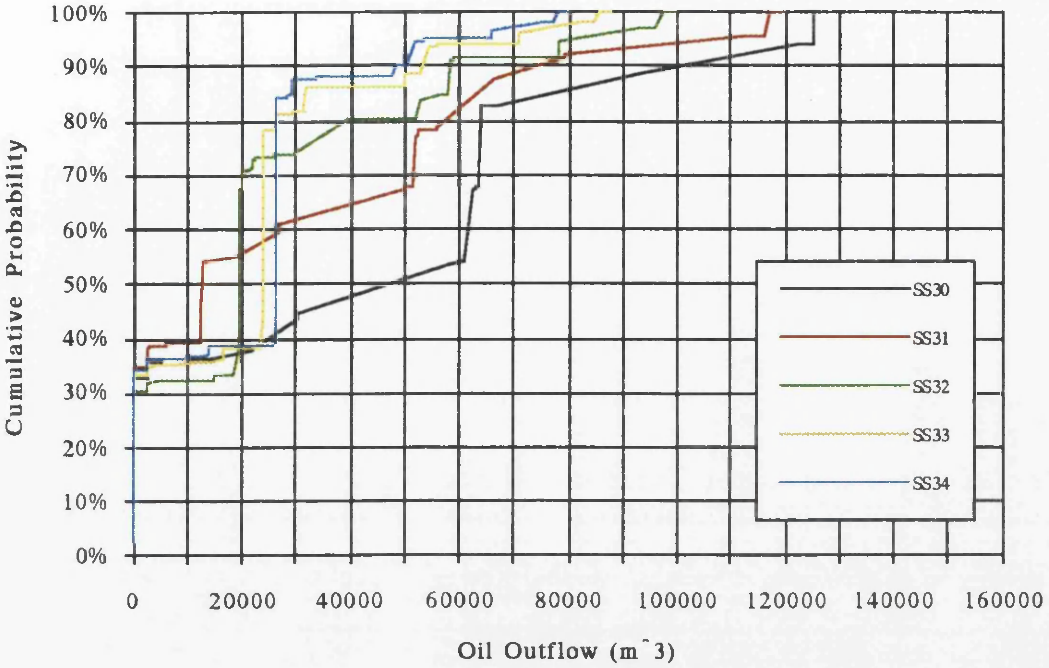


Figure D.34: Comparison of configurations with 3 transverse bulkheads.

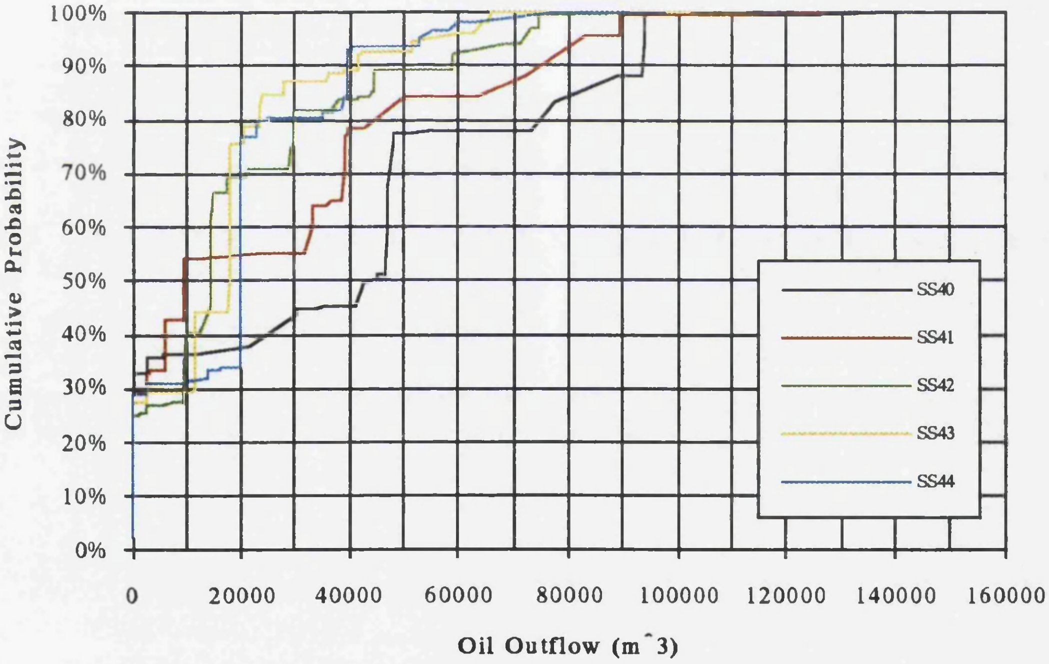


Figure D.35: Comparison of configurations with 4 transverse bulkheads.

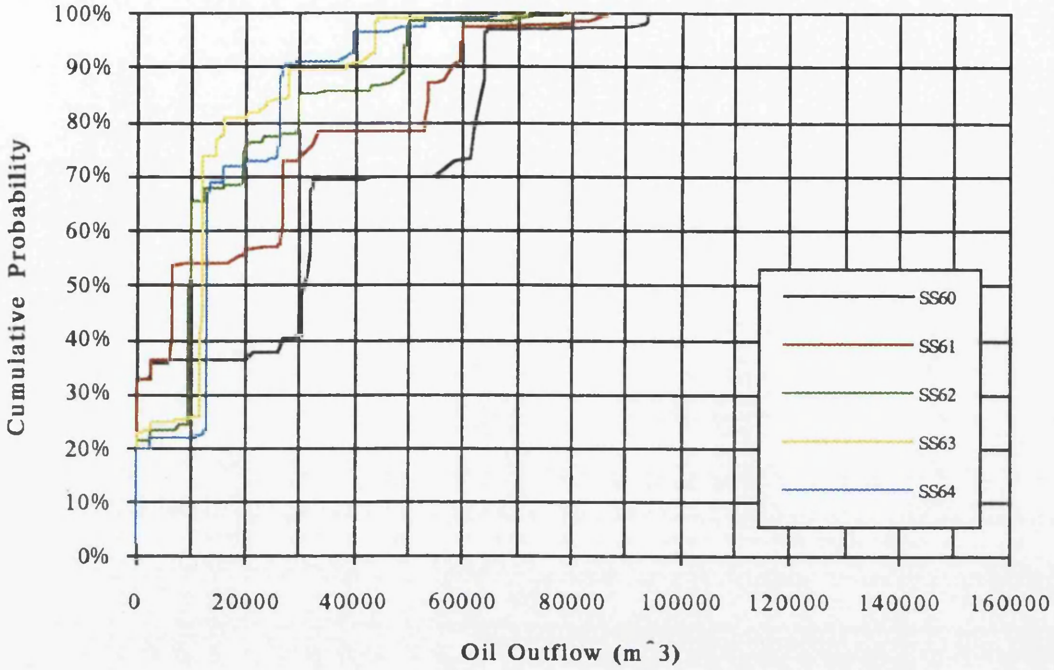


Figure D.36: Comparison of configurations with 6 transverse bulkheads.

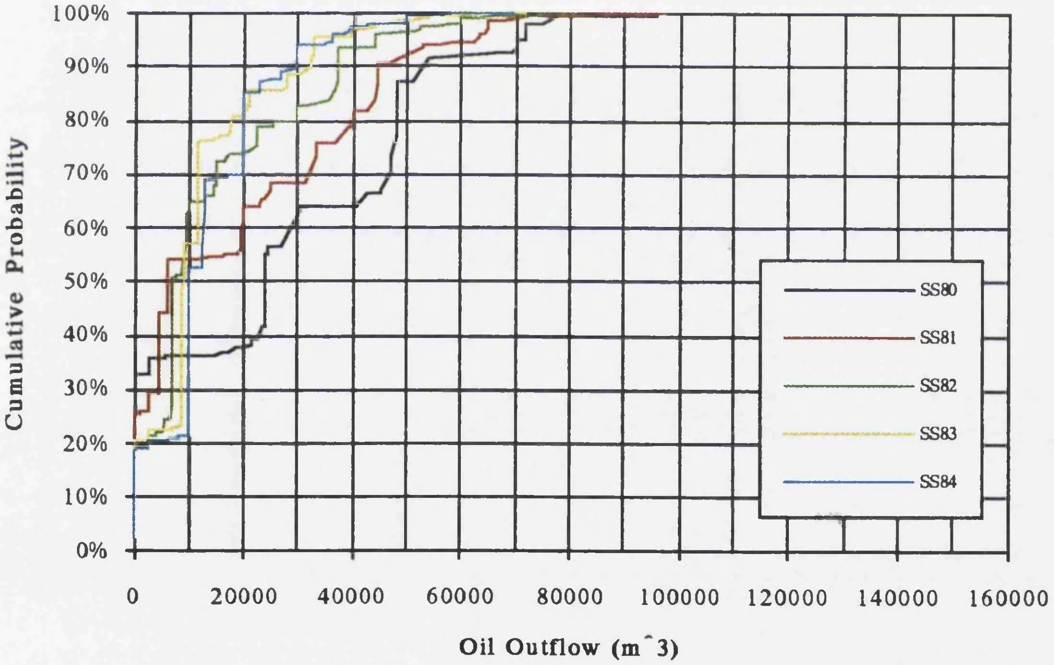


Figure D.37: Comparison of configurations with 8 transverse bulkheads.

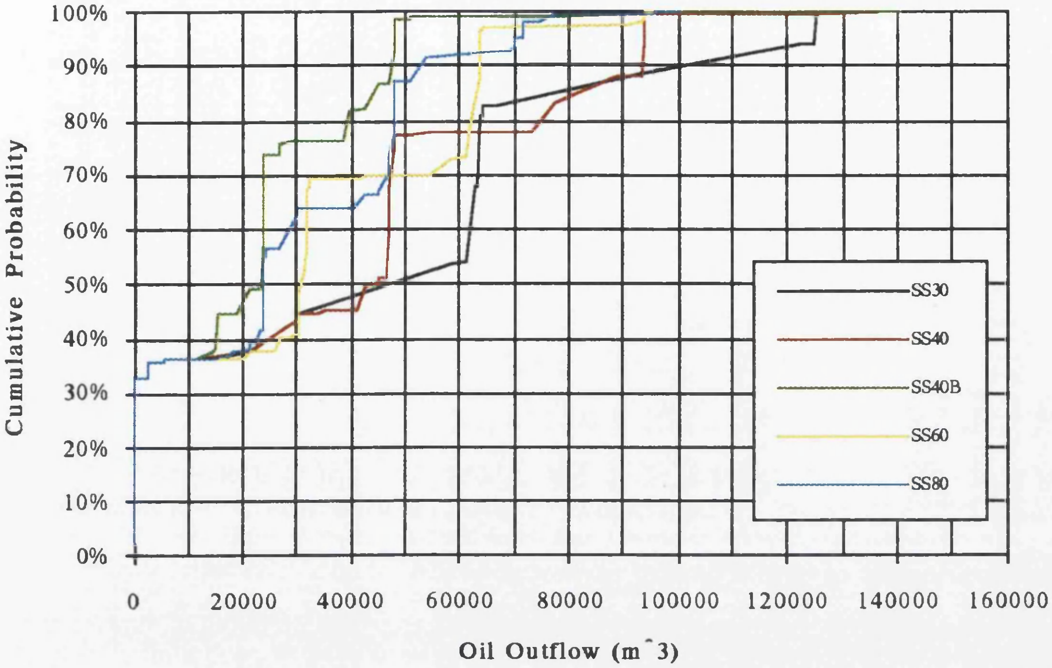


Figure D.38: Comparison of configurations with double-sides or with Tank Breadth Ratio equal to 0.125 .

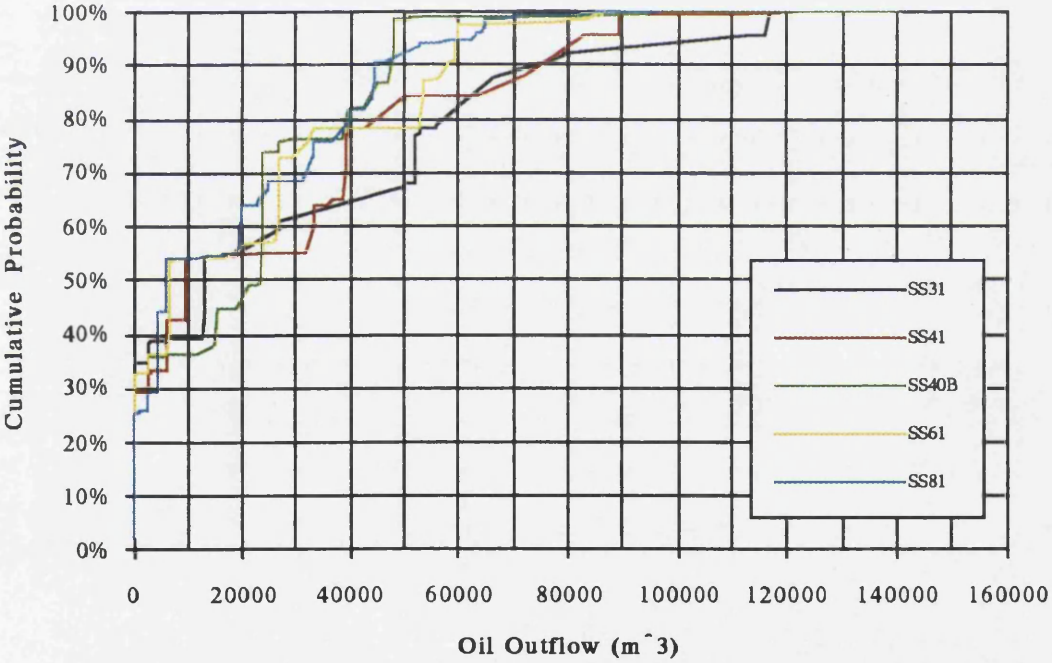


Figure D.39: Comparison of configurations with Tank Breadth Ratio equal to 0.250 .

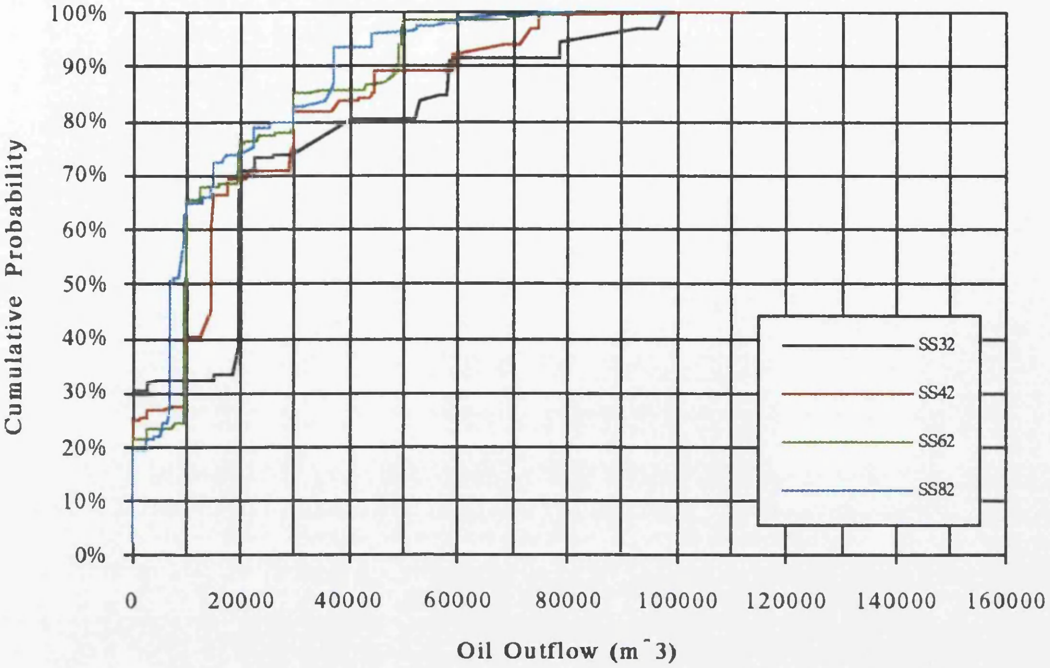


Figure D.40: Comparison of configurations with Tank Breadth Ratio equal to 0.500 .

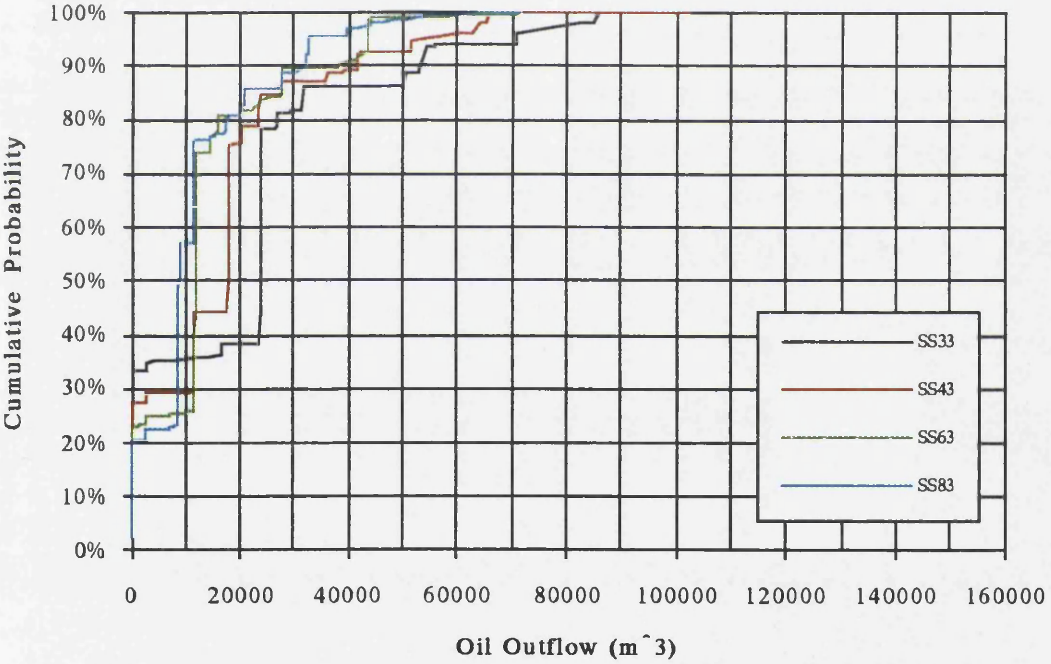


Figure D.41: Comparison of configurations with Tank Breadth Ratio equal to 0.750 .

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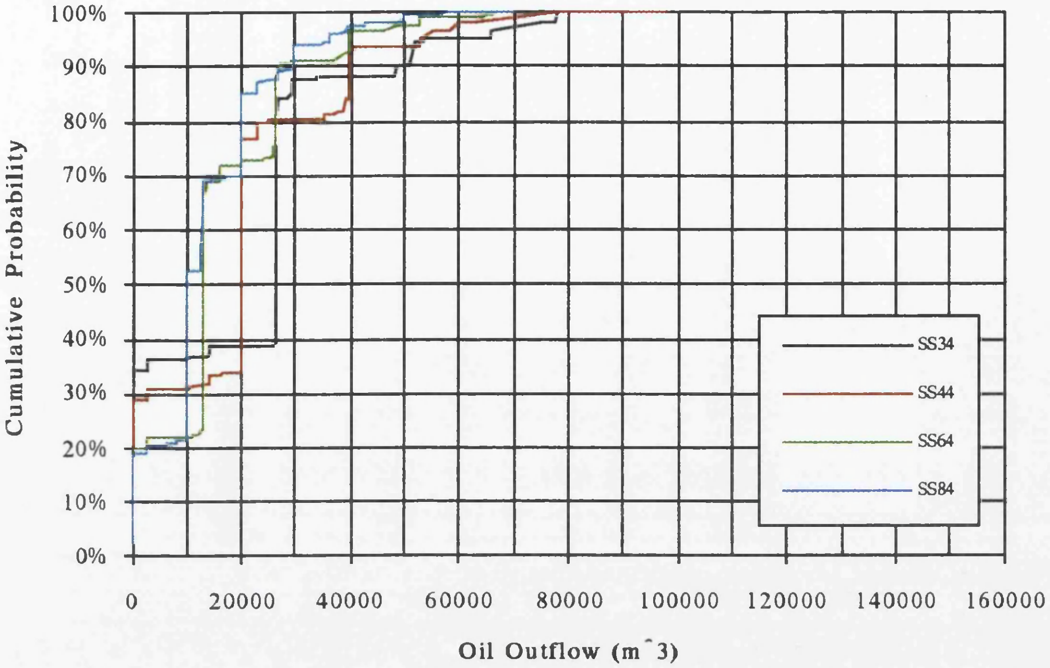
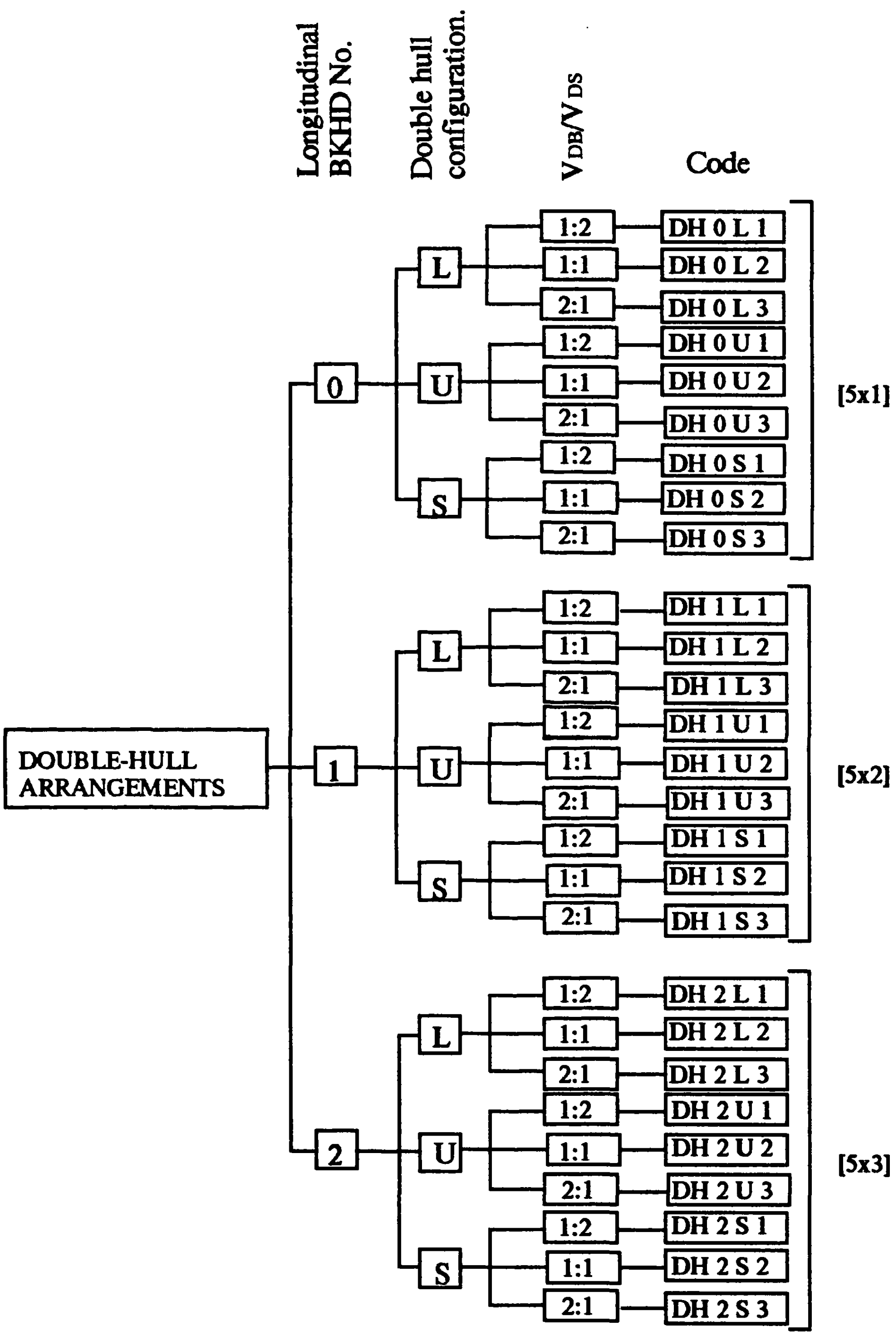


Figure D.42: Comparison of configurations with Tank Breadth Ratio equal to 1.000 .

D.3.2 DOUBLE-HULL ARRANGEMENTS



Note: L, U, S identify the double hull space configuration.
S= Double Bottom + Double Sides.

Figure D.43: Variations of Double-Hull arrangements and corresponding codes.

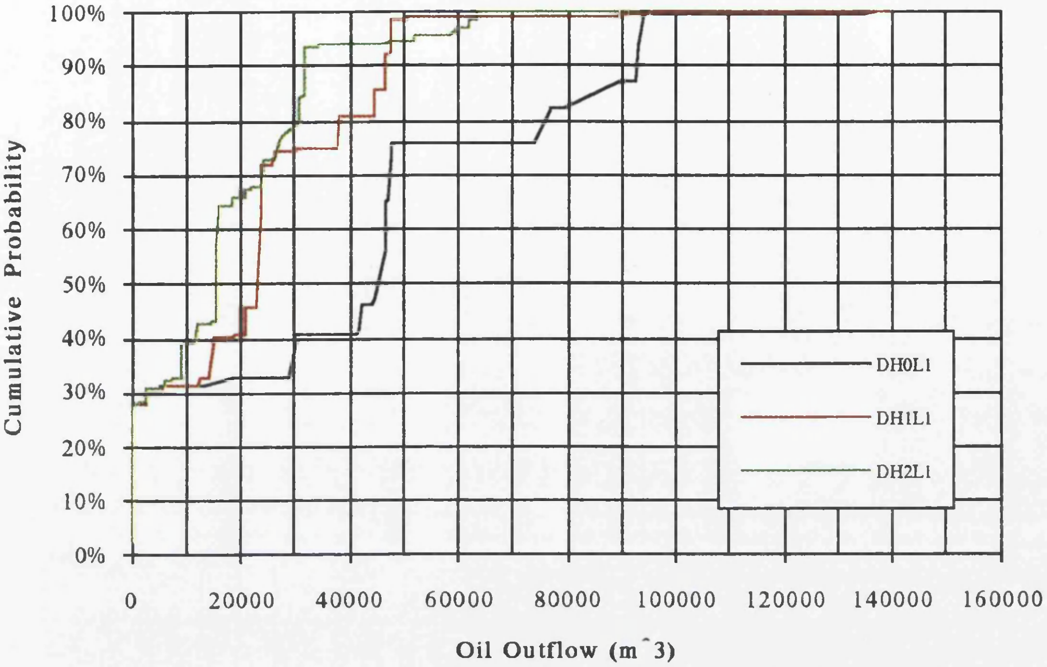


Figure D.44: Effect of number of longitudinal bulkheads in arrangements with L-shaped water ballast tanks - Case 1: V_{DB}/V_{DS} =0.497

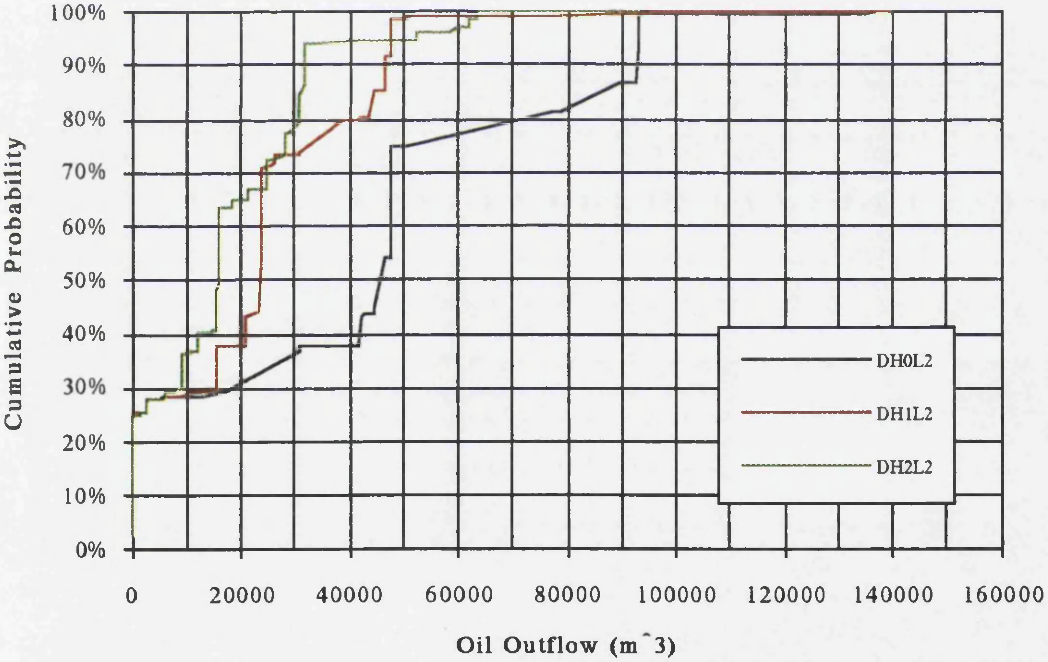


Figure D.45: Effect of number of longitudinal bulkheads in arrangements with L-shaped water ballast tanks - Case 2: V_{DB}/V_{DS} =1.034

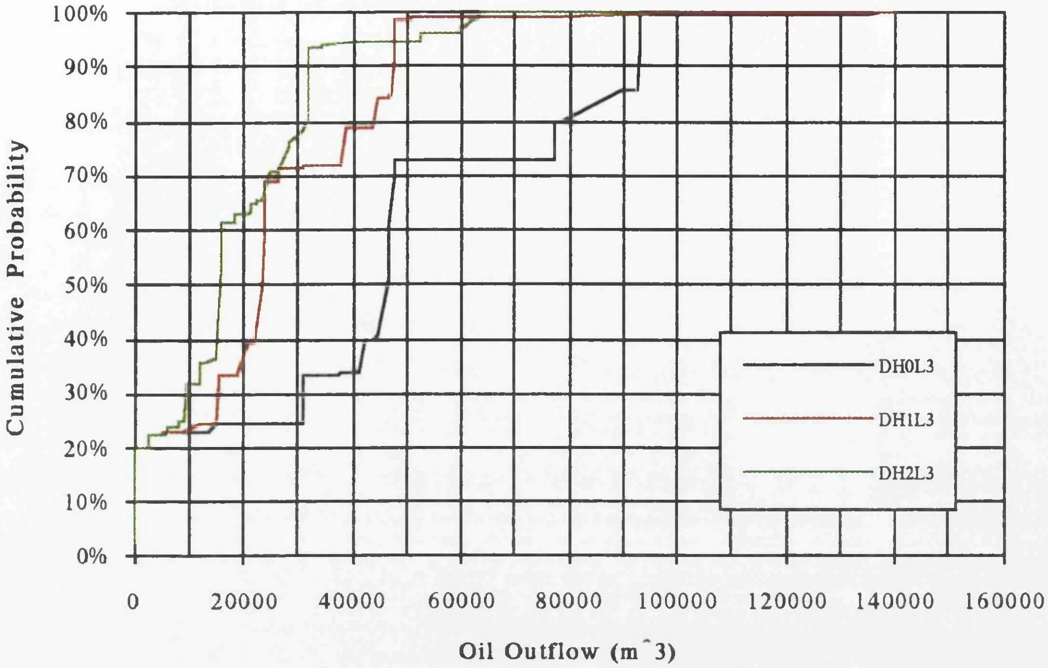


Figure D.46: Effect of number of longitudinal bulkheads in arrangements with L-shaped water ballast tanks - Case 3: V_{DB}/V_{DS} =2.155

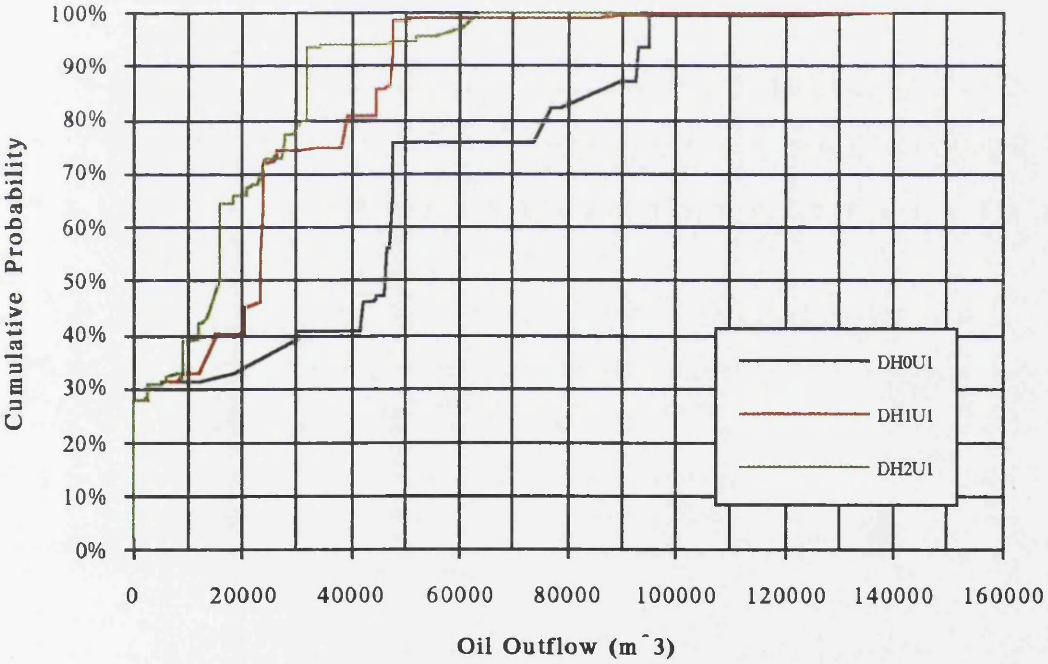


Figure D.47: Effect of number of longitudinal bulkheads in arrangements with U-shaped water ballast tanks - Case 1: V_{DB}/V_{DS} =0.497

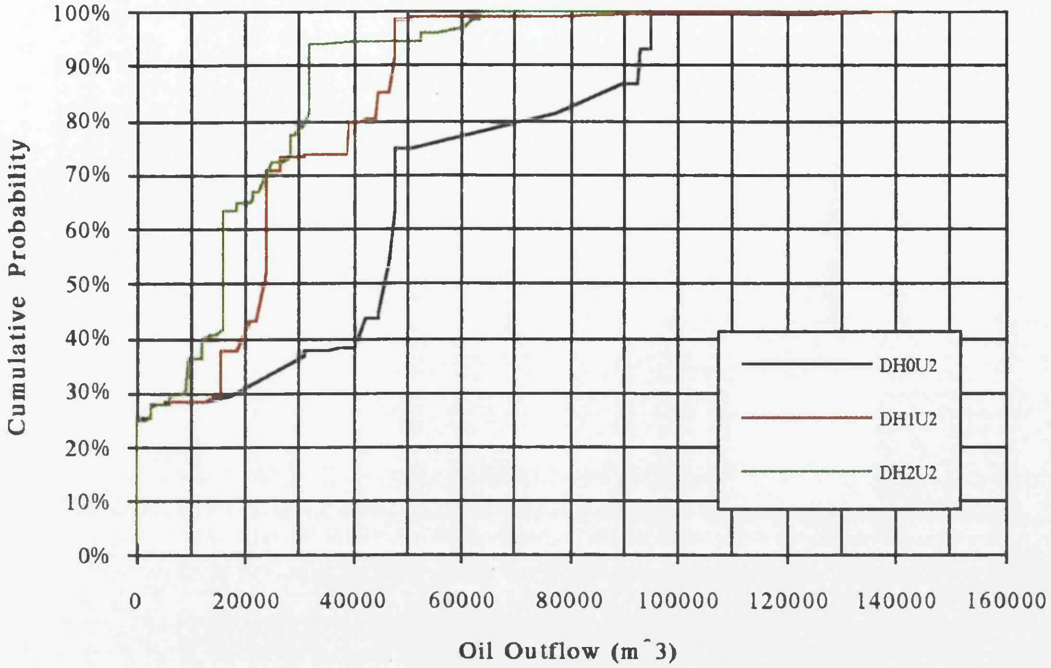


Figure D.48: Effect of number of longitudinal bulkheads in arrangements with U-shaped water ballast tanks - Case 2: V_{DB}/V_{DS} =1.034

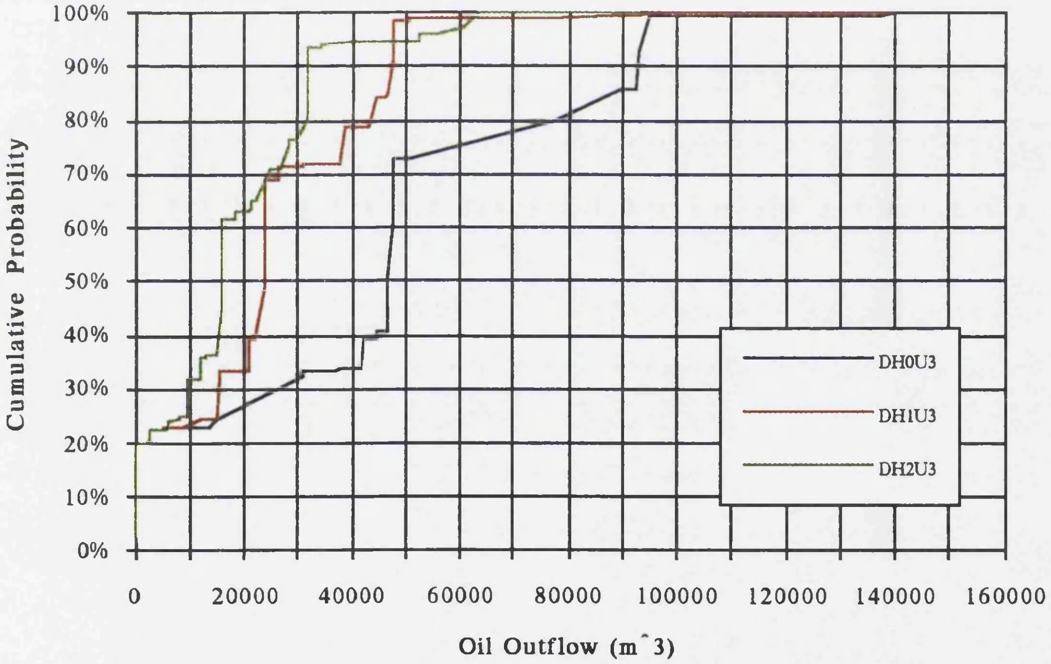


Figure D.49: Effect of number of longitudinal bulkheads in arrangements with U-shaped water ballast tanks - Case 3: V_{DB}/V_{DS} =2.155

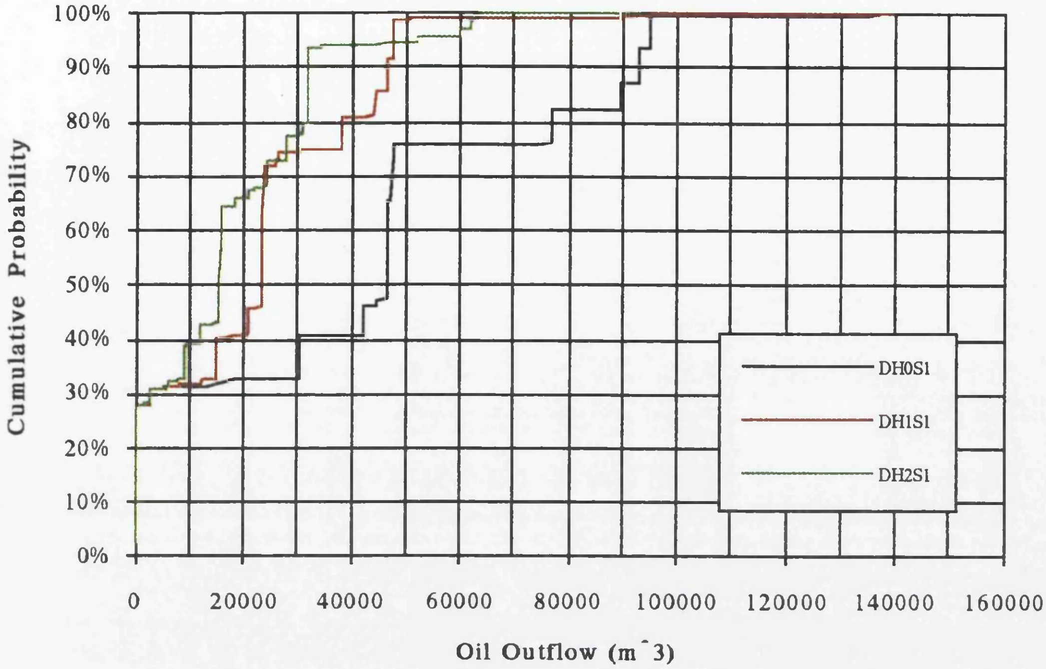


Figure D.50: Effect of number of longitudinal bulkheads in arrangements with separate double-side and double-bottom water ballast tanks - Case 1: V_{DB}/V_{DS} =0.497

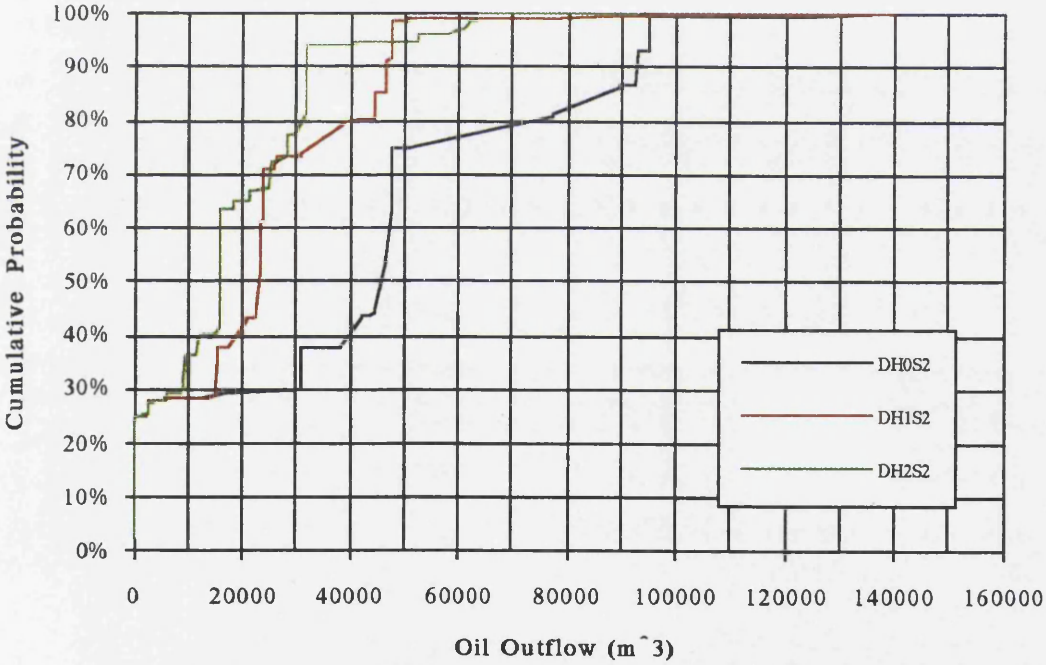


Figure D.51: Effect of number of longitudinal bulkheads in arrangements with separate double-side and double-bottom water ballast tanks - Case 2: V_{DB}/V_{DS} =1.034

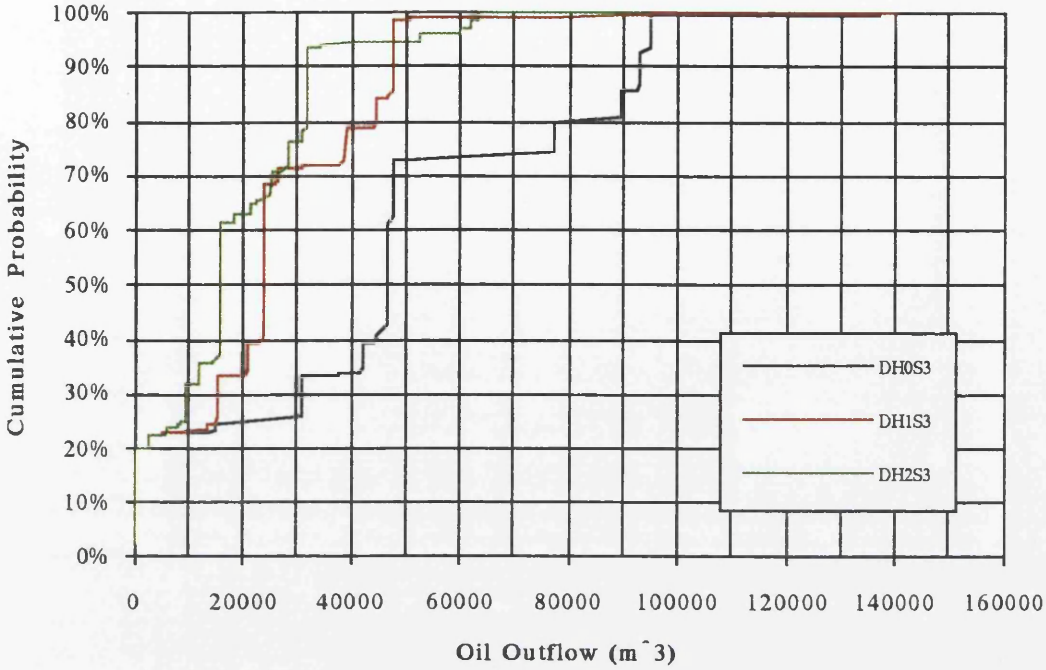


Figure D.52: Effect of number of longitudinal bulkheads in arrangements with separate double-side and double-bottom water ballast tanks - Case 3: V_{DB}/V_{DS} =2.155

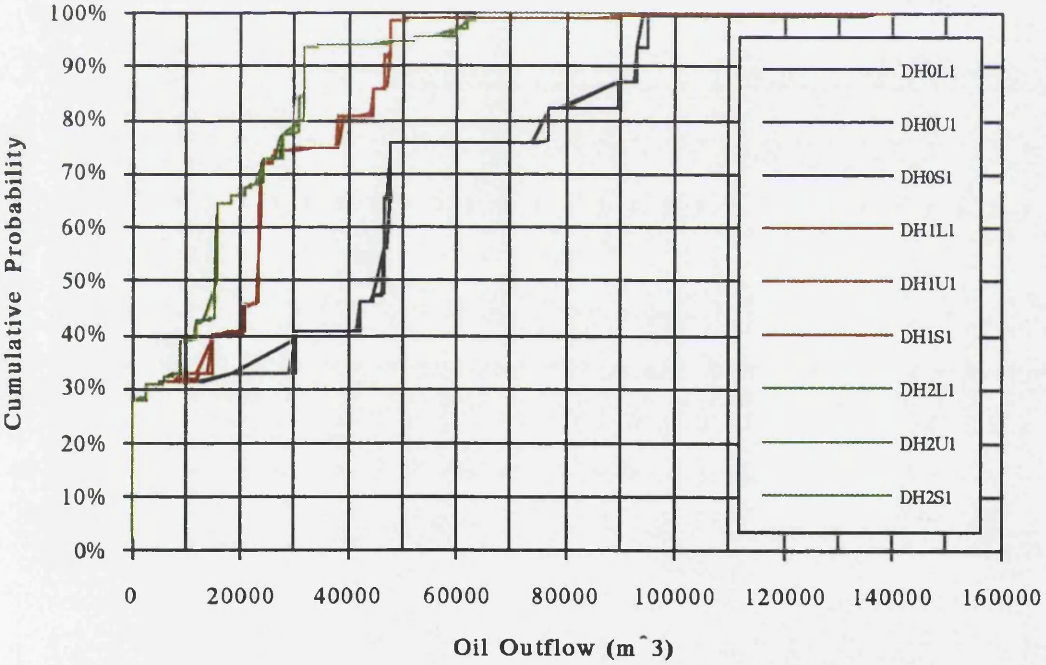


Figure D.53: Comparison of different water ballast tank configurations for arrangements with 0, 1 and 2 longitudinal bulkheads - Case 1: V_{DB}/V_{DS} =0.497

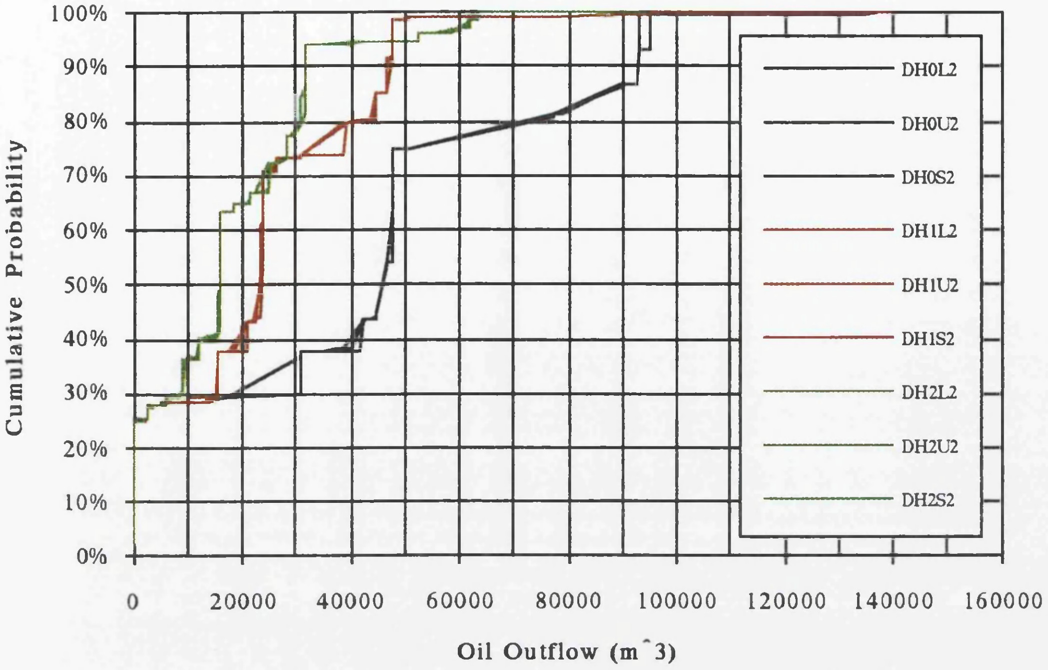


Figure D.54: Comparison of different water ballast tank configurations for arrangements with 0, 1 and 2 longitudinal bulkheads - Case 2: V_{DB}/V_{DS} =1.034

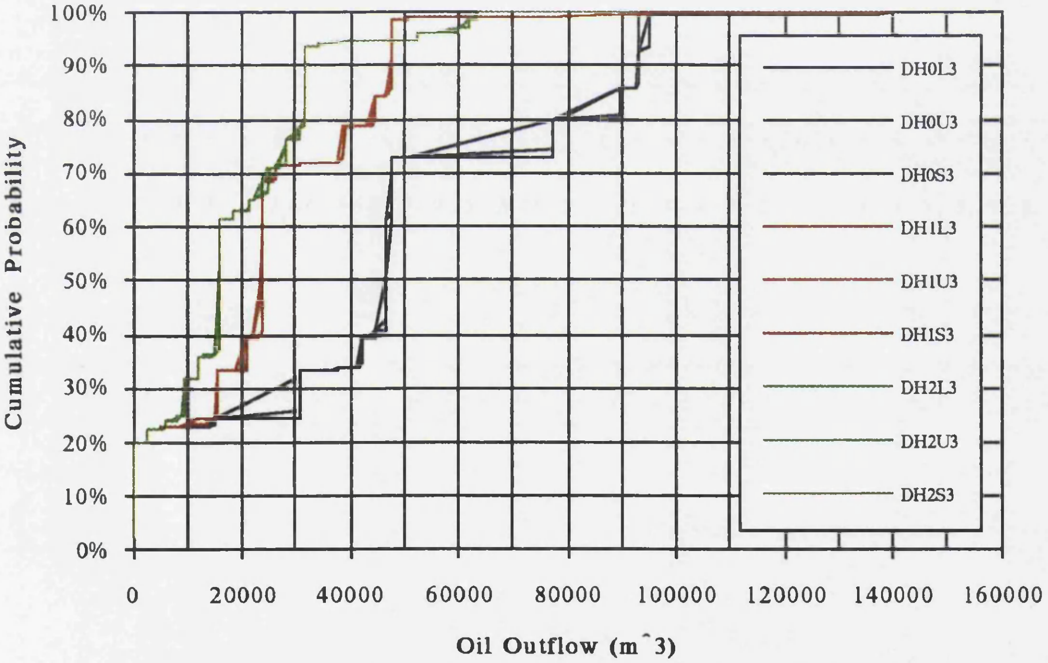


Figure D.55: Comparison of different water ballast tank configurations for arrangements with 0, 1 and 2 longitudinal bulkheads - Case 3: V_{DB}/V_{DS} =2.155

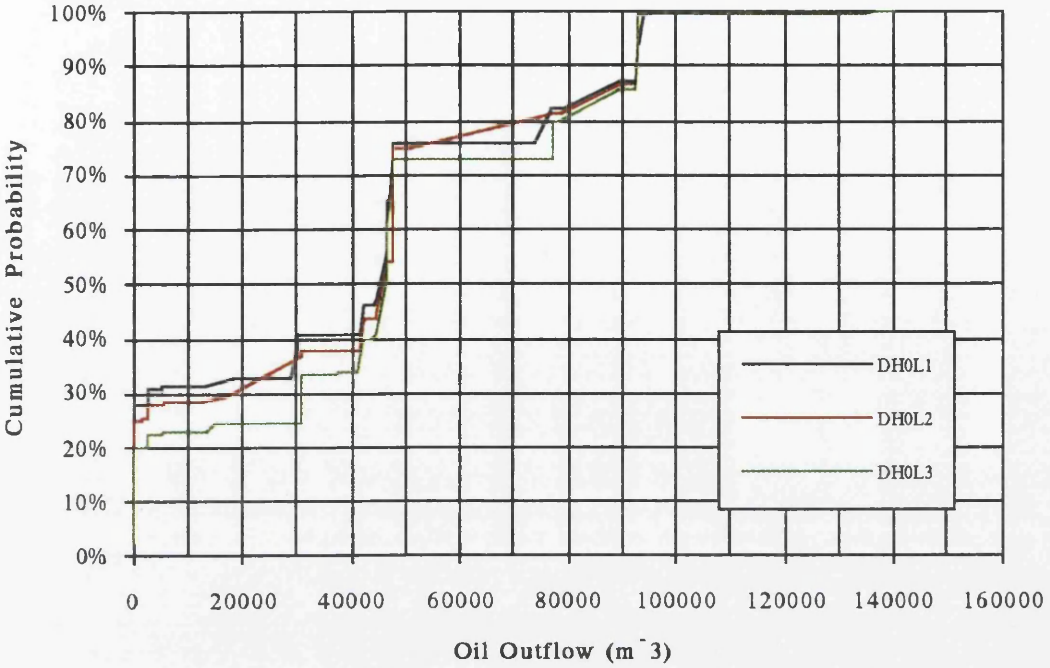


Figure D.56: Effect of V_{DB}/V_{DS} ratio in arrangements without longitudinal subdivision and with L-shaped water ballast tanks.

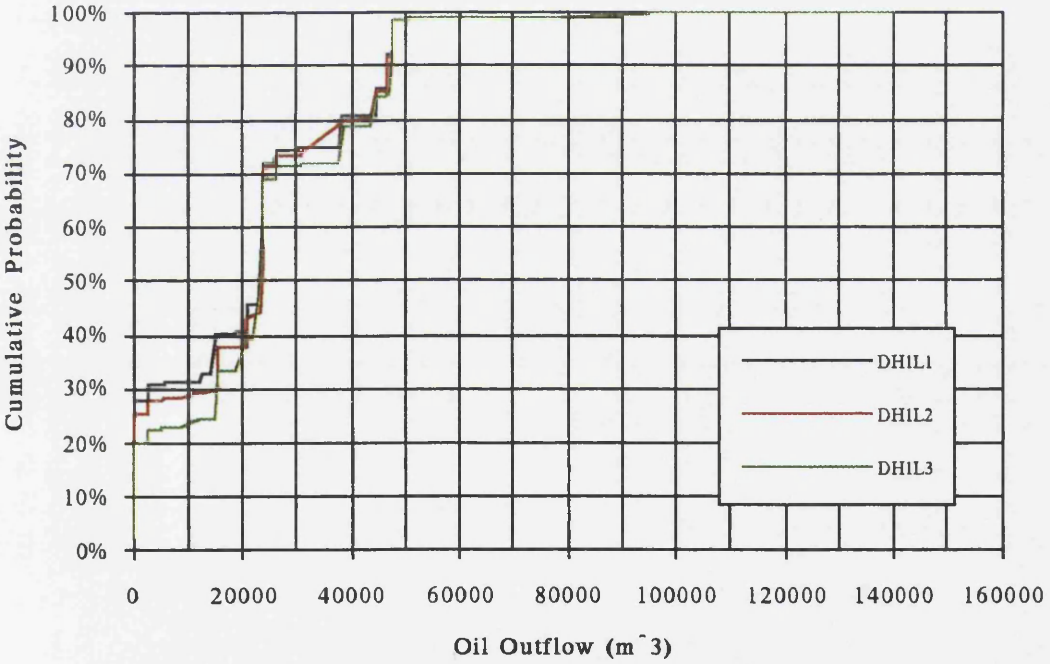


Figure D.57: Effect of V_{DB}/V_{DS} ratio in arrangements with a centreline longitudinal bulkhead and with L-shaped water ballast tanks.

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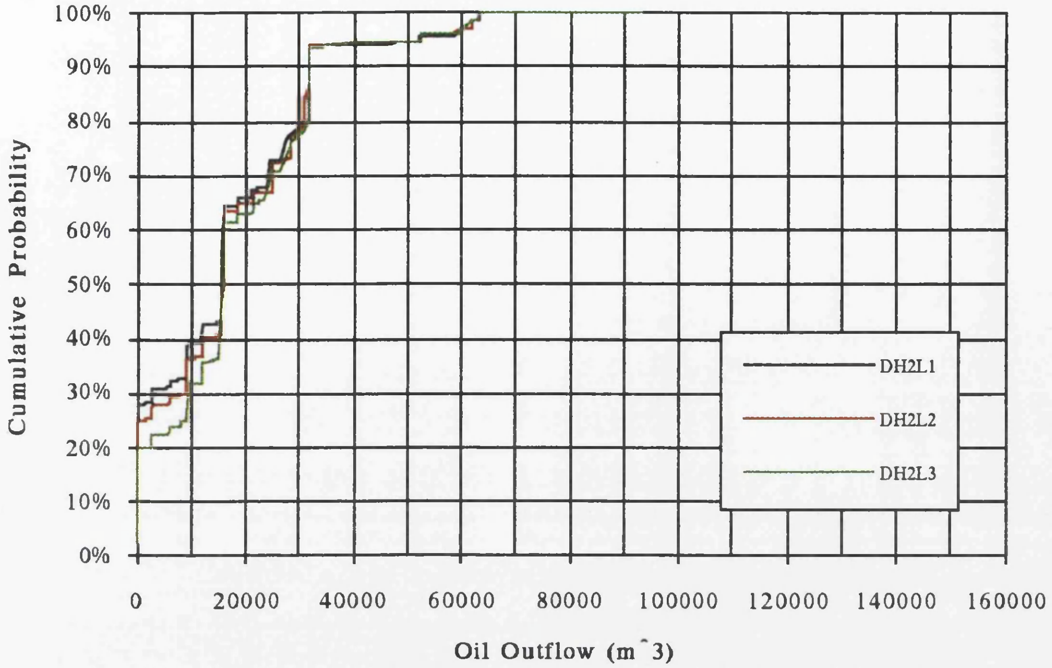


Figure D.58: Effect of V_{DB}/V_{DS} ratio in arrangements with two longitudinal bulkheads and with L-shaped water ballast tanks.

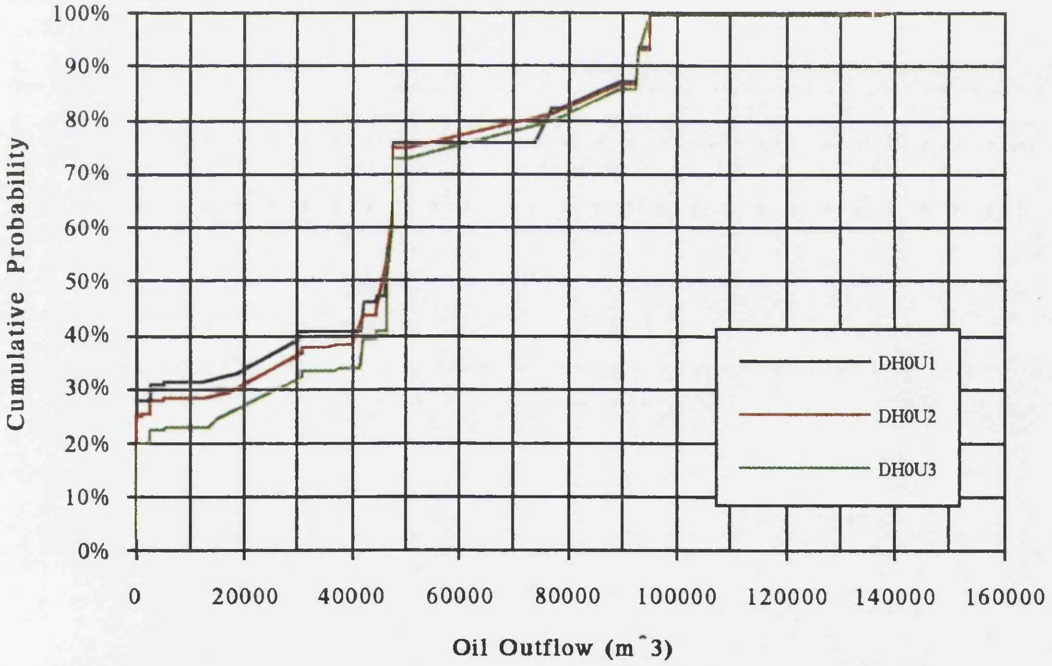


Figure D.59: Effect of V_{DB}/V_{DS} ratio in arrangements without longitudinal subdivision and with U-shaped water ballast tanks.

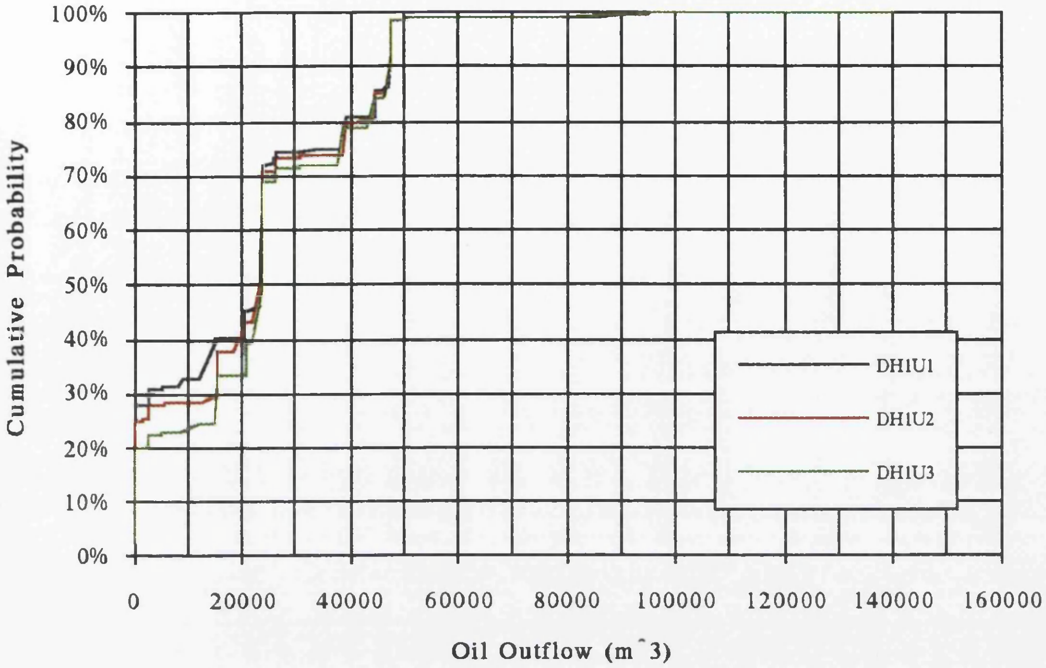


Figure D.60: Effect of V_{DB}/V_{DS} ratio in arrangements with a centreline longitudinal bulkhead and with U-shaped water ballast tanks.

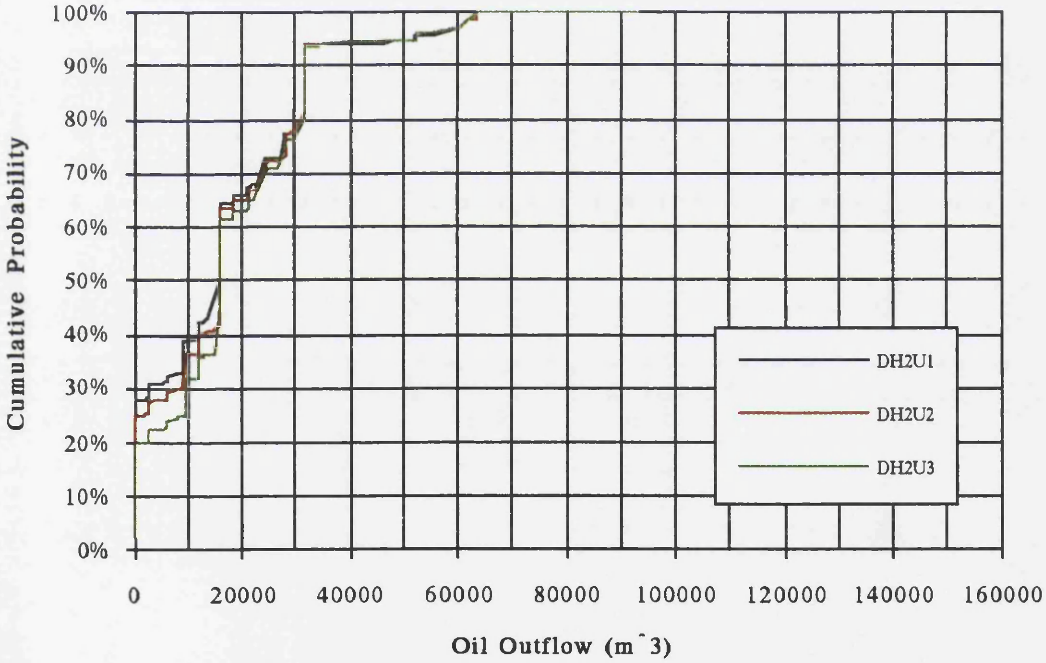


Figure D.61: Effect of V_{DB}/V_{DS} ratio in arrangements with two longitudinal bulkheads and with U-shaped water ballast tanks.

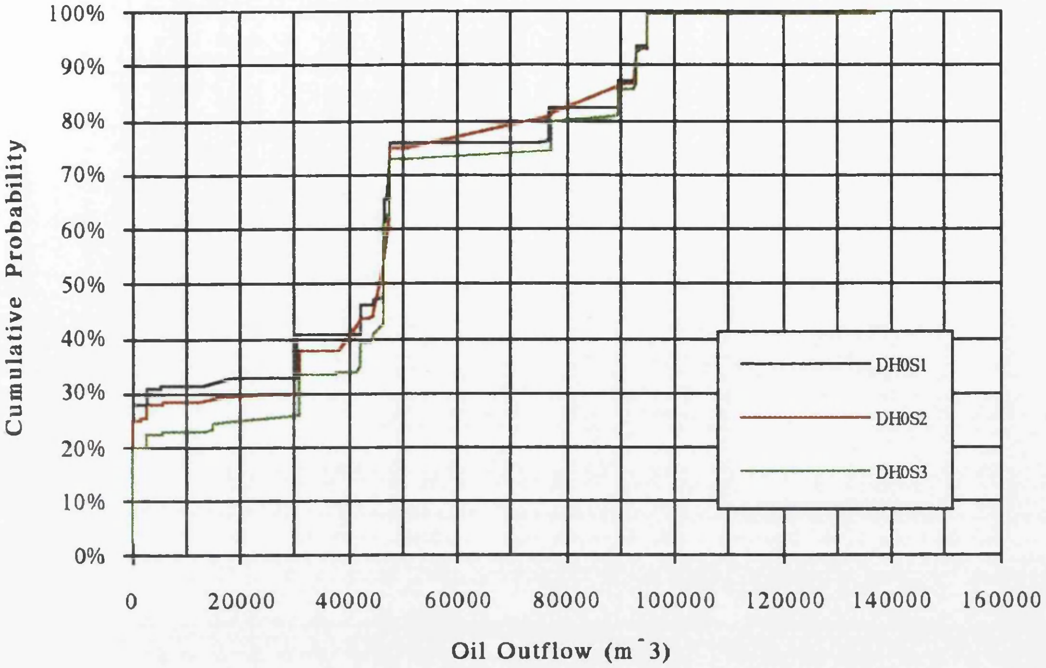


Figure D.62: Effect of V_{DB}/V_{DS} ratio in arrangements without longitudinal subdivision and with separate double-side and double-bottom water ballast tanks.

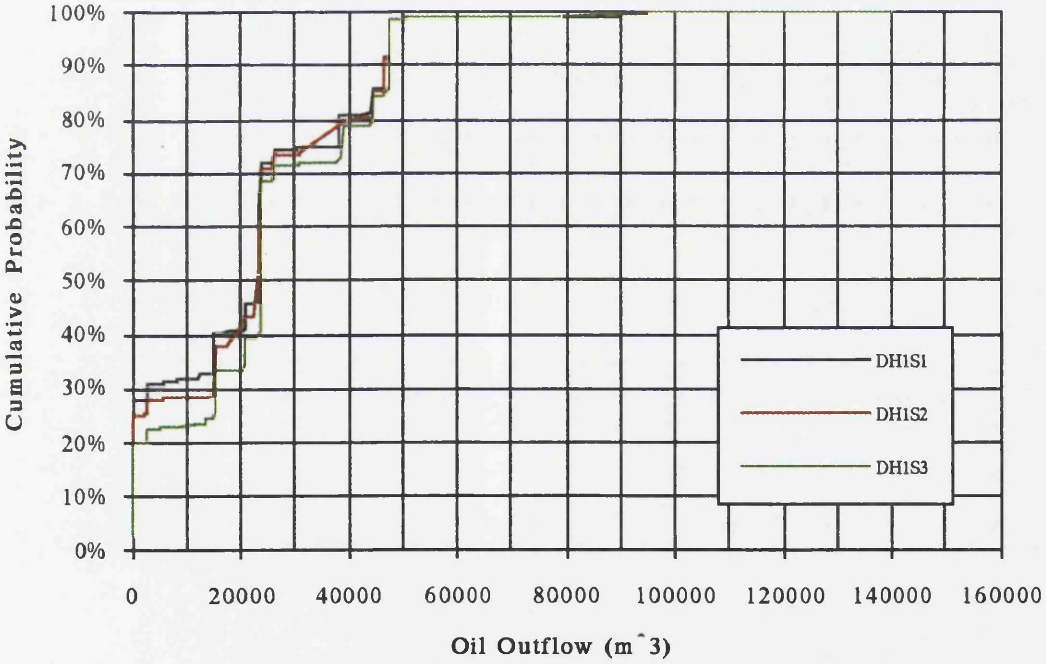


Figure D.63: Effect of V_{DB}/V_{DS} ratio in arrangements with a centreline longitudinal bulkhead and with separate double-side and double-bottom water ballast tanks.

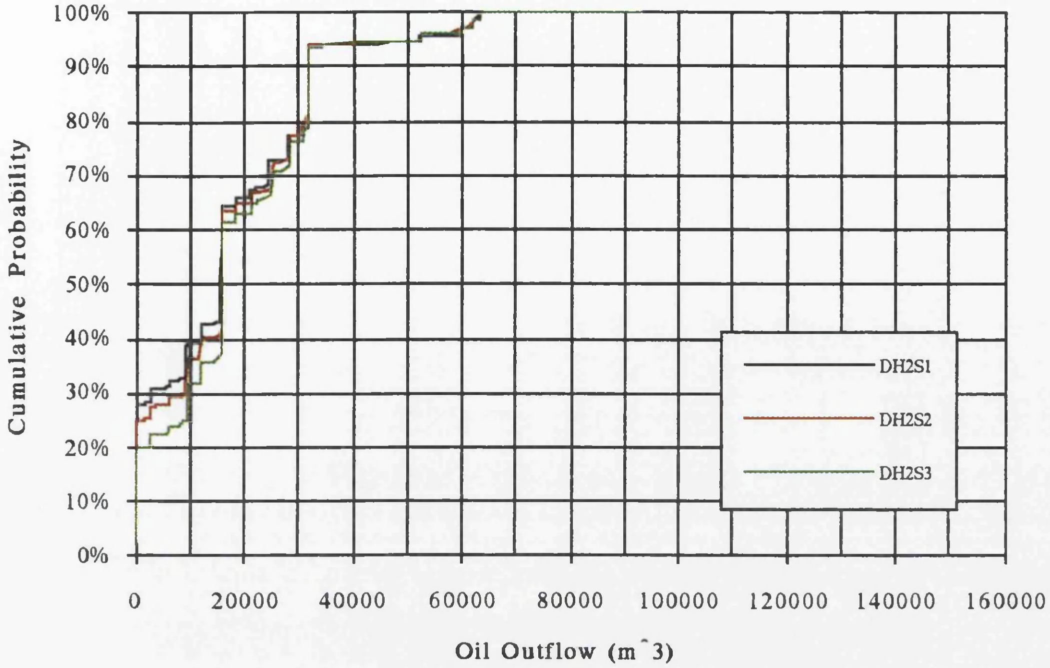
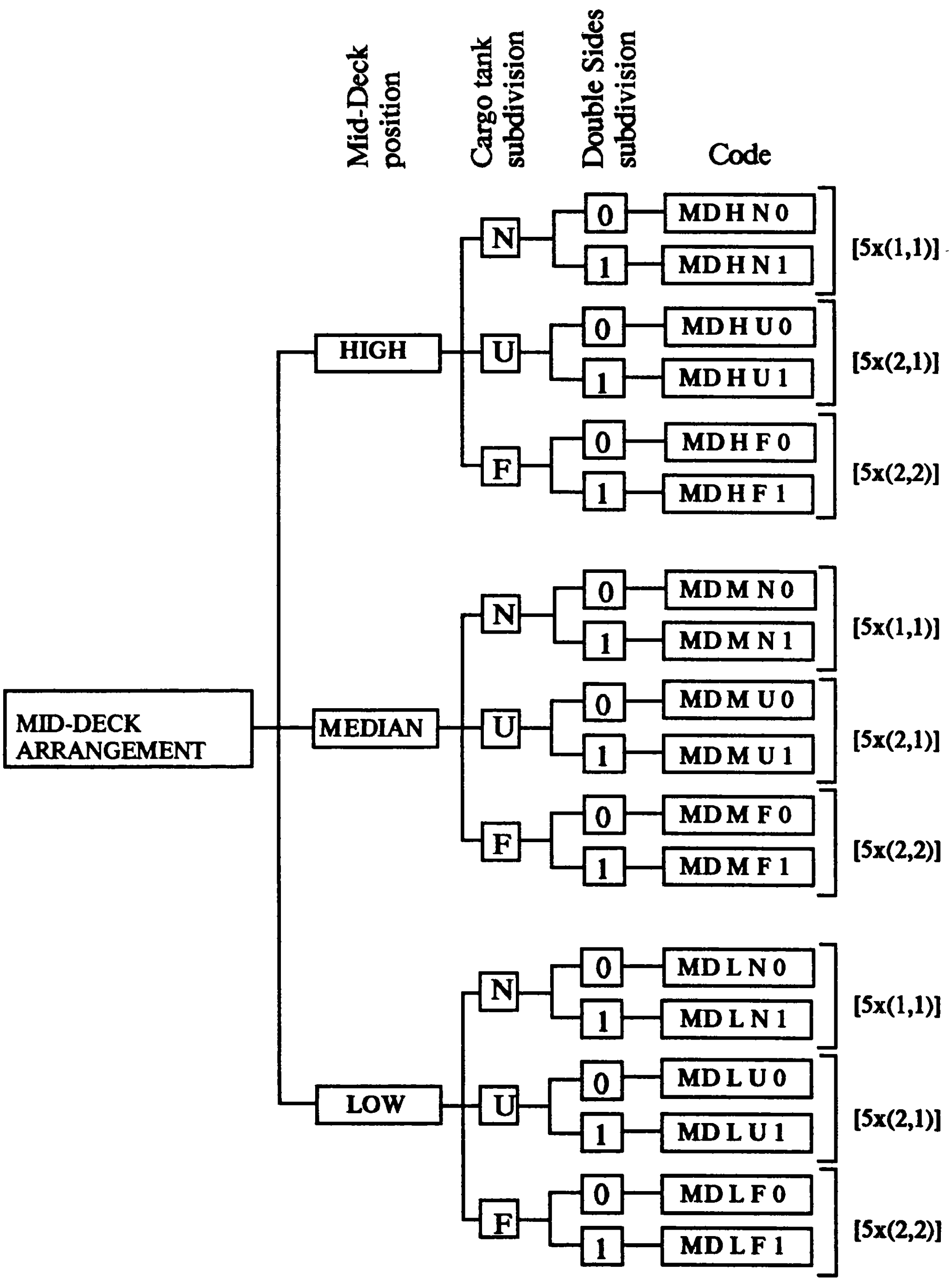


Figure D.64: Effect of V_{DB}/V_{DS} ratio in arrangements with two longitudinal subdivision and with separate double-side and double-bottom water ballast tanks.

D.3.3 MID-DECK ARRANGEMENTS



Note: N= No Long'l BKHD,
U= Long'l BKHD in upper cargo tanks only,
F= Full depth Long'l BKHD.

0= Full height Double Sides,
1= Horizontally subdivided Double Sides.

Figure D.65: Variations of Mid-Deck arrangements and corresponding codes.

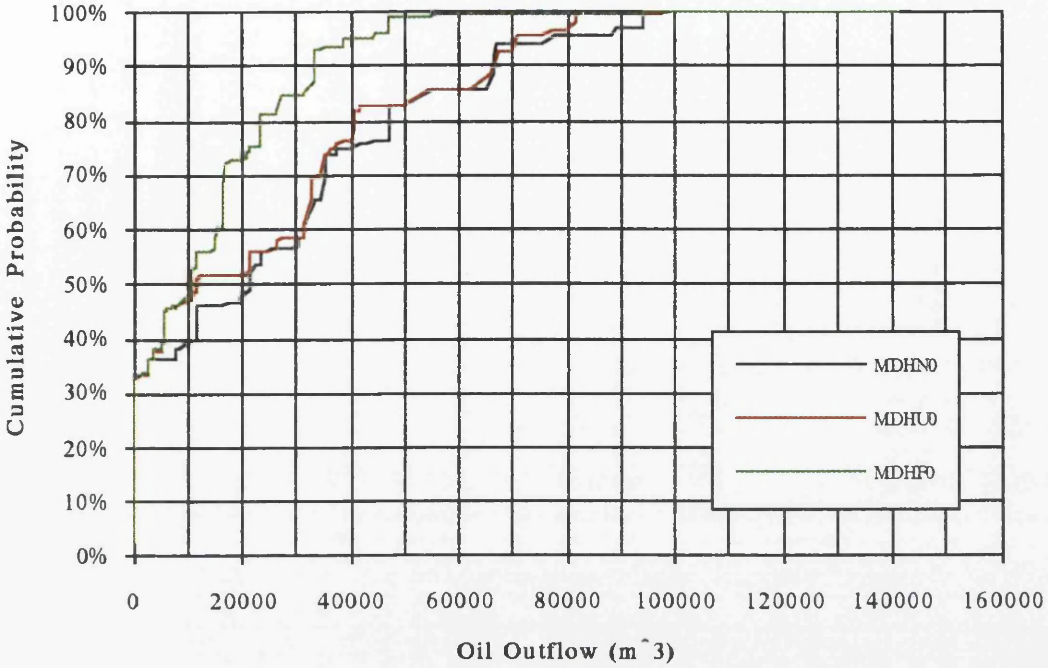


Figure D.66: Effect of longitudinal subdivision in configurations with high mid-deck position.

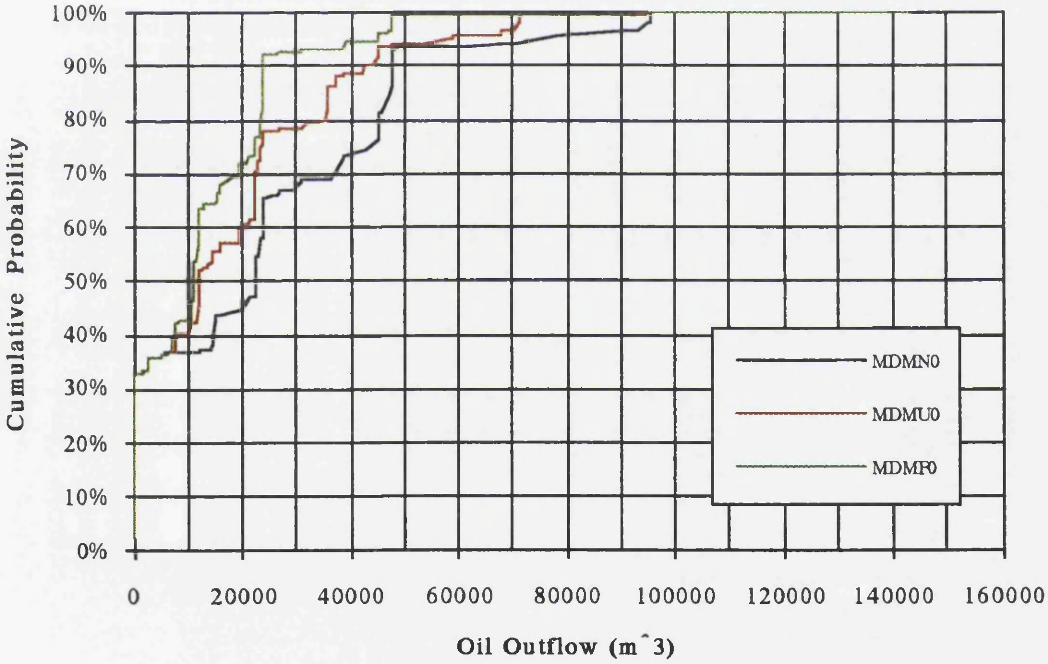


Figure D.67: Effect of longitudinal subdivision in configurations with median mid-deck position.

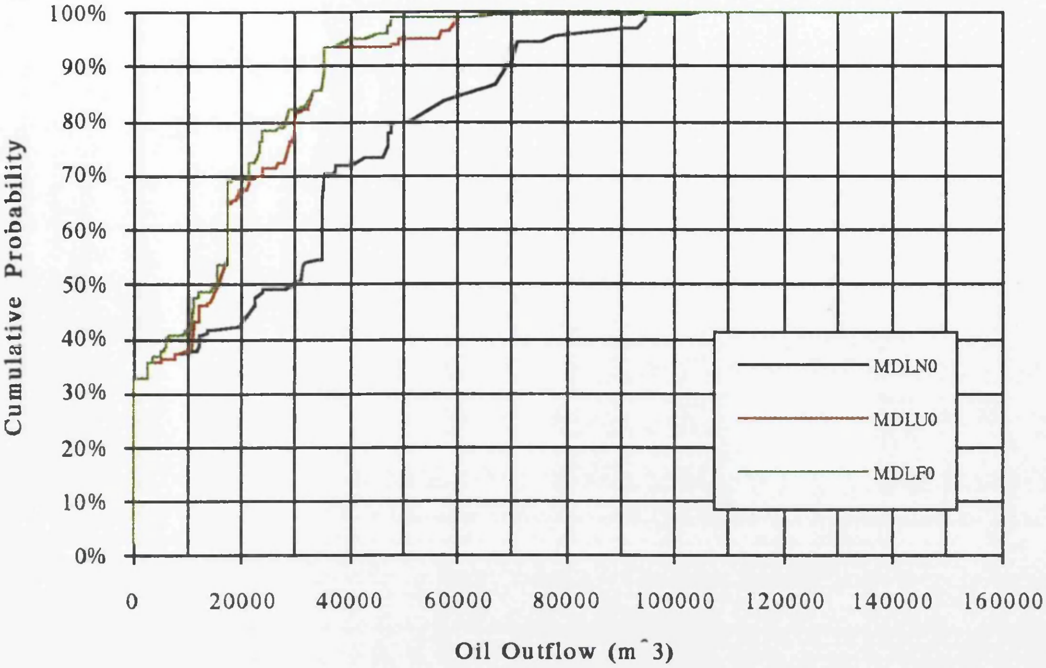


Figure D.68: Effect of longitudinal subdivision in configurations with low mid-deck position.

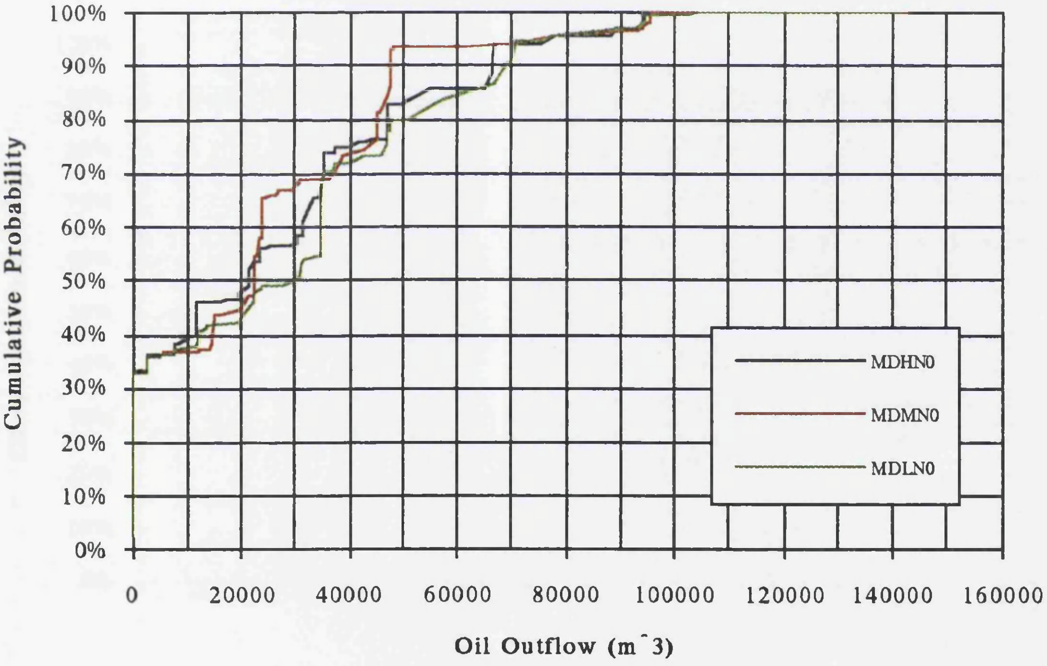


Figure D.69: Effect of mid-deck position in arrangements without longitudinal subdivision.

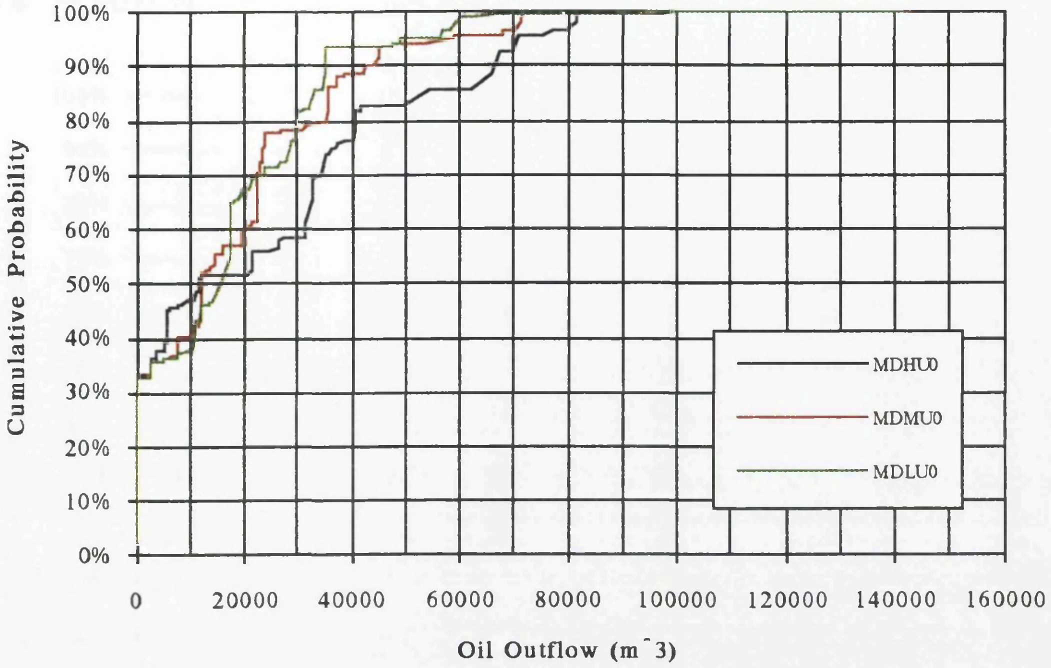


Figure D.70: Effect of mid-deck position in arrangements with a centreline longitudinal bulkhead in the upper cargo spaces only.

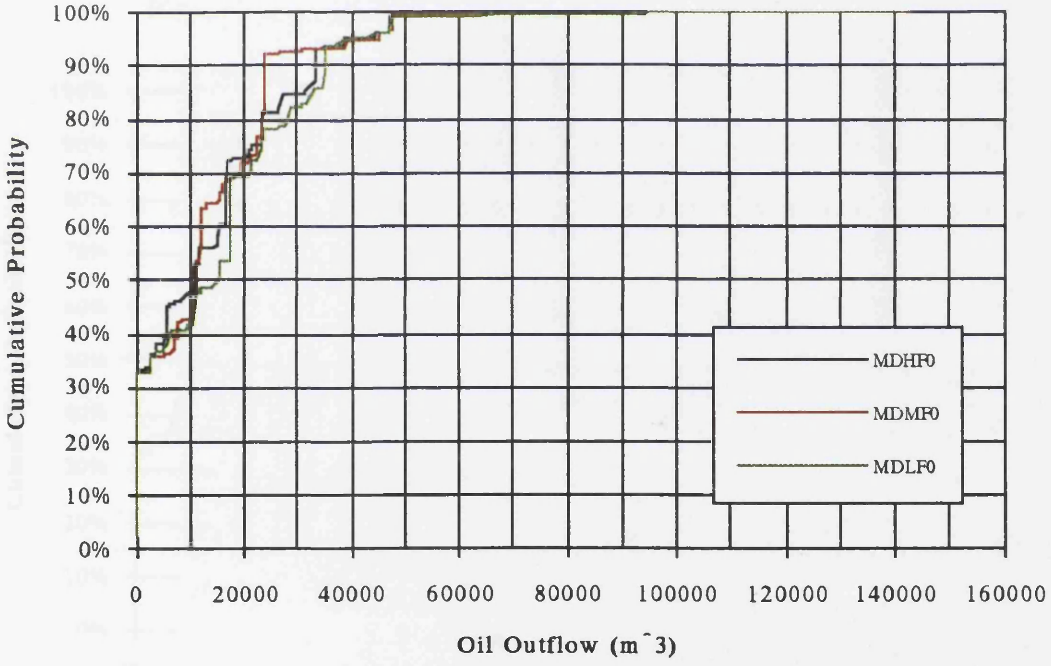


Figure D.71: Effect of mid-deck position in arrangements with a full-depth centreline longitudinal bulkhead.

D.3.4 HORIZONTAL VS. LONGITUDINAL SUBDIVISION

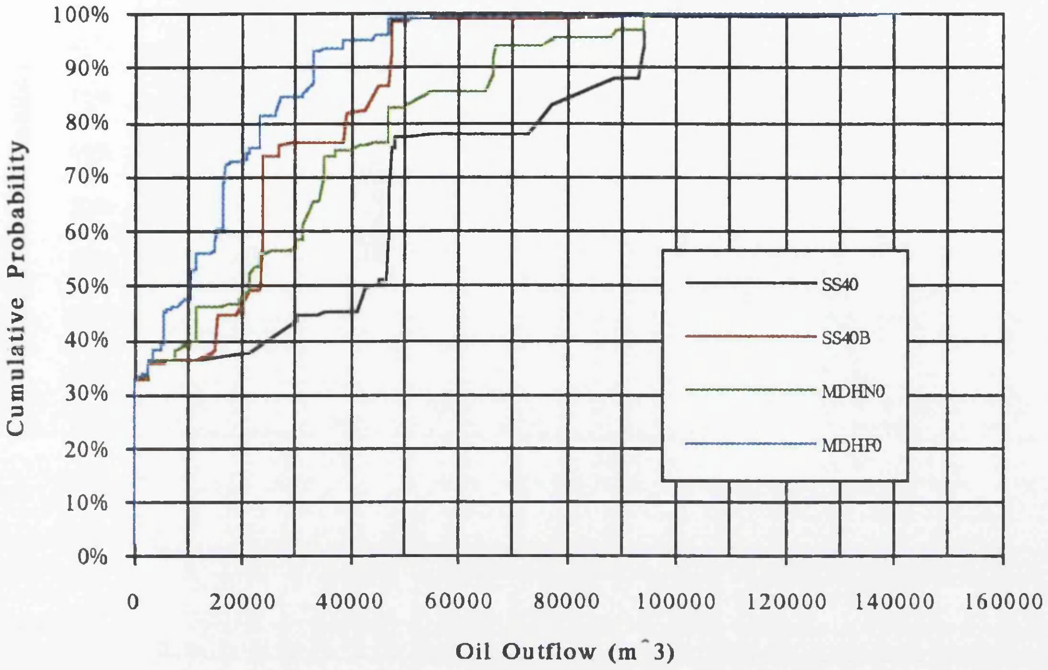


Figure D.72: Comparison of horizontal and longitudinal subdivision - Case 1: High mid-deck position.

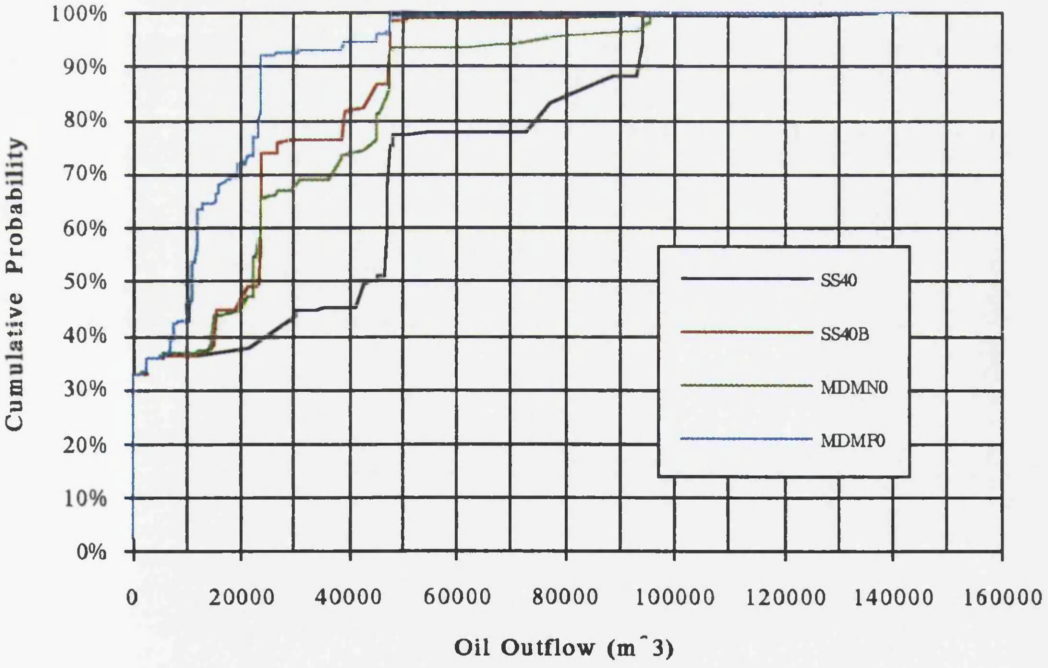


Figure D.73: Comparison of horizontal and longitudinal subdivision - Case 2: Median mid-deck position.

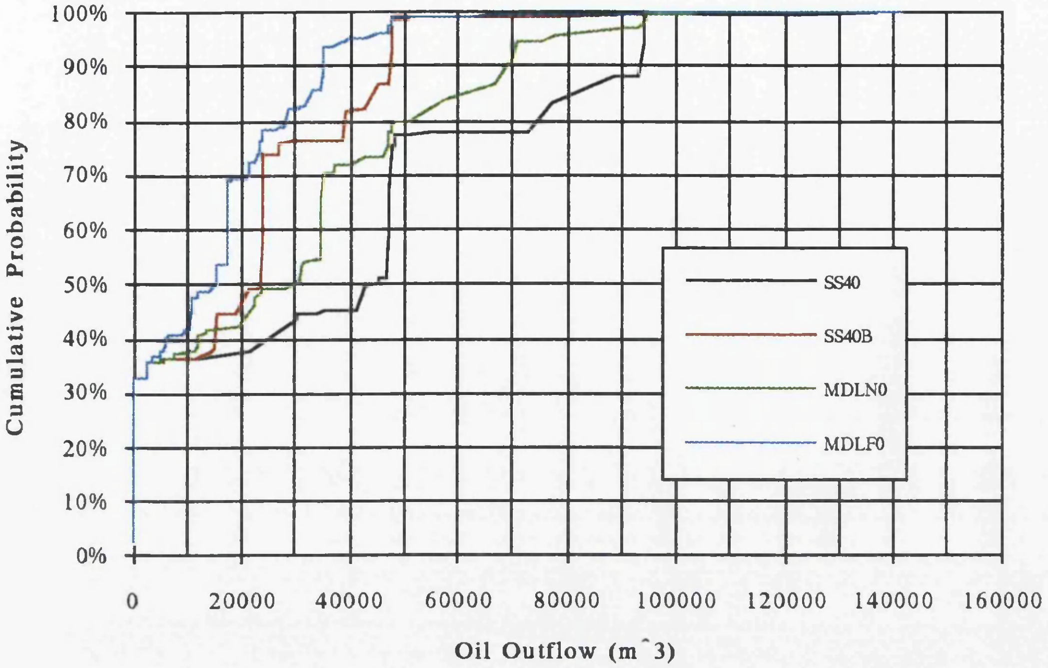


Figure D.74: Comparison of horizontal and longitudinal subdivision - Case 3: Low mid-deck position.

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