A Framework for Assessing the Environmental Performance of Tankers in Accidental Groundings and Collisions

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Abstract

Recent international and domestic regulatory actions have resulted in significant changes to oil tanker designs and intensified attention being paid to analytical methods for predicting the performance in accidental groundings and collisions. The paper proposes a rational framework for evaluating designs considering the costs of pollution, oil outflow characteristics and enhanced structural performance. Current analytical methods do not adequately account for variations in various ship design characteristics. These variations include wing tank and double bottom dimensions, certain aspects of cargo block subdivision, and structural arrangement of double bottoms. Further, current methods do not account for the non-linear unit costs of oil spills. This paper integrates the environmental effects of accidental pollution with the oil outflow characteristics of various ship designs to arrive at a rational method for using cost-benefit analysis to determine optimal tanker designs. The results summarized in this paper represent the work of an ad hoc panel convened under the SNAME Technical and Research Program.

1 INTRODUCTION

The ship design process requires balancing numerous variables in order to achieve an optimal solution. The international and domestic regulations are some of the boundary conditions that must be satisfied within this optimization process. The vast majority of such regulations related to ship design are prescriptive in nature, which are “generally conservative and rigid”.[1] Performance standards, on the other hand, tend to allow greater design flexibility, “while maintaining adequate safety and pollution performance.” [1]

Current international regulations for oil tankers intended to minimize pollution from oil tankers from accidental side and bottom damage, is one example of a prescriptive standard. While such standards are relatively straightforward in their application, new oil outflow calculation techniques have demonstrated [2] that these regulations need to be revised. The replacement of some of these prescriptive standards, with those that are more performance oriented, is a principal goal of the work that is presented in this paper.

Computing oil outflow from a tanker that has been involved in a grounding or collision is based upon applying an assumed extent of damage and calculating the oil outflow based on physical hydrostatic and “quasi-hydrodynamic” principles. The International Maritime Organization (IMO) has developed the guidelines for approving alternatives to the new tanker construction requirements [3]. These guidelines contain a rigorous methodology to compute the oil outflow in accidental groundings and collisions and provides for the development of a “pollution prevention index” for comparison with a series of “reference” double hulls. This index includes three characteristics of the oil outflow performance of any tanker, namely, probability of zero outflow, mean outflow, and extreme outflow (these terms are defined and discussed in detail in the next section).
During the development of these guidelines the importance of these parameters was realized, however, the relative importance of these characteristics was determined in an arbitrary manner. This was, in part, due to the fact that the variation in the environmental effects of a “unit spill” as a function of spill size, was not included in the formulation for the “pollution prevention index”.

Furthermore, the assumed extents of damage that are used in the guidelines are based upon actual data from compiled from various collisions and grounding incidents[4][5], all of which were single hull tankers. This data was compiled by the classification societies at IMO’s request, from sources including LR, ABS, DnV, ClassNK, RI. This data was derived from casualties to oil tankers, chemical tankers, OBOs, OROs of 30,000 tonnes deadweight and above, for the period 1980 to 1990.

Finally, the oil outflow calculation methodology in the guidelines, in part because of the necessary rigor required for a careful comparison of alternative tanker designs, is quite complex. For the purpose of comparing alternative designs this direct (and complex) method is acceptable. Indeed, due to its importance IMO maintained review authority in the regulations for considering alternatives¹. However, for routine regulatory design applications (as opposed to relatively infrequent applications for evaluating regulatory alternatives), a simplified methodology is preferable.

These primary reasons, namely, complexity of methodology, the need for a more rational basis for the development of an environmental index, and finally the recognition² that the extent of accidental damage is a function of structural arrangement, provided the fundamental motivation for the work presented in this paper.

The work of the panel, as presented in this paper, consists of three essential elements - (1) the development and refinement of a simplified oil outflow calculation methodology, (2) an analysis of the environmental effects of marine oil pollution, in terms of variation of unit spill values as a function of spill size, (3) and an investigation of structural performance of tankers during groundings.

This paper presents the work performed to study these three elements and suggests an analytical model for combining these three elements into a single framework.

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¹ Since IMO does not generally exercise any compliance authority, this action by IMO (review of technical calculations for compliance with regulations) was unusual, but necessary.

² Although this has been well recognized and documented, it is only recently that some tools such as DAMAGE [6] have been available.

2 IMGO GUIDELINE PROBABILISTIC OIL OUTFLOW METHODOLOGY

The IMO "Interim Guidelines for the Approval of Alternative Methods of Design and Construction of Oil Tankers Under Regulation 13F(5) of Annex I of MARPOL 73/78 [3], hereunder referred to as the IMO Guidelines, provides a probabilistic-based procedure for assessing the oil outflow performance of an alternative tanker design. The alternative design is compared to selected reference double hull design on the basis of a pollution prevention index.

A fully probabilistic evaluation of a specific vessel on a specific route would require development of the following conditional probabilities.

- The probability that the ship will encounter damage;
- The probability of the damage location and extent;
- The expected consequences (i.e. quantity of outflow).

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

The following sections provide an overview of the calculation methodology. The reader is referred to the example contained in the IMO Guidelines [3] and reference [7] for additional information on application of the IMO Guidelines, and references [8][9][10][11] for further background on probabilistic oil outflow calculations.

2.1 IMO Guideline Outflow Calculation Methodology

In this paper, the IMO Guideline calculation methodology is referred to as the DIRECT method, as it involves direct application of the IMO probability density distribution functions to the subject design. There are four main steps involved when applying the IMO Guidelines:

Step 1: Assemble Damage Cases

The IMO Guidelines contain probability density functions (pdf’s) describing the location, extent and penetration of side and bottom damage. These functions were derived from historical damage statistics for 52 collisions and 63 groundings of tankers 30,000 metric tons deadweight and above.

Side damage pdf’s are provided for the probability of the damage longitudinal location, longitudinal extent, transverse penetration, vertical location and vertical extent. Similarly, bottom damage includes evaluation of the longitudinal location, longitudinal extent, transverse location, transverse extent, and vertical penetration. The density scales are normalized by the ship length for longitudinal location and extent, by ship breadth for...
transverse location and extent, and by ship depth for vertical location and extent. The pdf variables are treated independently for the lack of adequate data to define their dependency.

Figure 1 contains the probability density function for the longitudinal extent of damage from grounding. The histograms represent statistical data collected by the classification societies [4][5] and the linear plot represents IMO's piece-wise linear fit of the data. The other pdfs are constructed in a similar manner.

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

Step 2: Calculate Oil Outflow

The next step is to compute the oil outflow associated with each unique side damage and bottom damage case. For side damage, total (100%) outflow is assumed for each damaged cargo tank. For bottom damage, oil loss is calculated based on pressure balance principles, assuming tide reductions of 0, 2 and 6 meters. The flooded volume of double bottom ballast tanks or voids located below breached cargo tanks retain up to 50% oil by volume. Breached cargo tanks which bound the outer shell have a minimum outflow of 1% of the cargo tank volume. This is intended to account for the expected oil loss at initial impact and through dynamic effects such as currents and waves.

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

Step 3: Calculate Oil Outflow Parameters

Three outflow parameters are computed:

- The probability of zero outflow, \( P_0 \), represents the likelihood that no oil will be released into the environment, given a collision or grounding casualty which breaches the outer hull. \( P_0 \) equals the cumulative probability of all damage cases without outflow.
- The mean outflow parameter, \( O_M \), is the non-dimensionalized mean or expected outflow, and provides an indication of a design’s overall effectiveness in limiting oil outflow. The mean outflow equals the sum of the products of each damage case probability and the associated outflow. \( O_M \) equals the mean outflow divided by the total quantity of oil onboard the vessel.
- The extreme outflow parameter, \( O_E \), is the non-dimensionalized extreme outflow, and provides an indication of the expected oil outflow from particularly severe casualties. The extreme outflow is the weighted average of the upper 10% of all casualties (i.e. all damage cases within the cumulative probability range from 0.9 to 1.0).

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

Step 4: Compute the Pollution Prevention Index “E”

Alternative designs are compared to reference double hull designs by substituting the outflow parameters for the reference design and the alternative design into the following formula:

\[
E = \frac{(0.5)(P_0) + (0.4)(0.01 + O_M) + (0.1)(0.025 + O_E)}{0.01 + O_M + 0.025 + O_E}
\]

\( P_0, O_M, \) and \( O_E \) are the oil outflow parameters for the alternative design, and \( P_{OR}, O_{OR}, \) and \( O_{ER} \) are the oil outflow parameters for the IMO reference ship of equivalent size.
Further Background to the IMO Guidelines

Development of the formula for “E” was an item of considerable discussion at IMO. It was recognized that the weighing factors for the outflow parameters should have a rational basis associated with the benefits of avoiding spills, and the relative financial and environmental impacts of smaller spills as compared to larger spills. However, IMO was unable to obtain such information, and it was necessary to develop “E” in a more arbitrary manner. Specifically, outflow calculations were carried out for a number of double hull and mid-deck tanker designs, all of which satisfied the requirements of the new MARPOL 13F regulations. The weighing factors were then selected to assure that the double hull and mid-deck concepts, both of which were deemed acceptable by IMO, would be in conformance with the guidelines.

The reference designs developed by IMO for assessing the equivalency of alternative designs all exhibit favorable accidental outflow performance. This was done intentionally, on the premise that alternative arrangements should perform as well as “good” double hull tankers.

Selection of the reference ships was based on the best judgment of the regulation’s developers, as time and resources did not allow for cost-benefit analyses of alternative reference designs. Recognizing that the longitudinal subdivision of cargo tanks has a major influence on the oil outflow in case of inner hull penetration, all of the IMO reference double hull designs have at least one oiltight longitudinal bulkhead within the cargo tanks.

A SIMPLIFIED PROBABILISTIC OIL OUTFLOW CALCULATION METHODOLOGY

Current hypothetical outflow and tank size requirements for oil tankers are contained in Regulations 22-24 of Annex I of MARPOL 73/78. Recognizing that these regulations do not effectively assess the environmental performance of double hull tankers, IMO instructed its BLG (Bulk Liquids and Gases) Sub-Committee to develop a new accidental oil outflow regulation modeled after the probabilistic methodology contained in the IMO Guidelines.

Rigorous application of the probabilistic oil outflow methodology contained in the IMO Guidelines is a calculation intensive effort. Although suitable for evaluating alternative designs and unique tankage configurations, the BLG working group tasked with developing the new regulation felt that a regulation applicable to all tanker newbuildings would be better served by an approach which is easier to apply. The first and revised drafts [12][13] of the proposed new “Accidental Oil Outflow” regulation contains a simplified approach to calculating oil outflow. The reader is referred to reference [14] for further information on this simplified calculation procedure.

SIMPLIFIED Outflow Calculation Methodology

This SIMPLIFIED methodology applies the same probability density functions and many of the assumptions contained in the DIRECT conceptual approach described in the IMO Guidelines. The significant differences between the two methods are as follows:

Step 1: Assemble Damage Cases

The primary difference is in the assessment of damage cases. Rather than determining each unique damage case and its associated probability, in the SIMPLIFIED approach the probability of damaging each cargo tank is calculated. This is the probability that a tank will be breached, either alone or in combination with other tanks, and equals the sum of the probabilities for all of the unique damage cases which involve that particular cargo tank.

For application of the SIMPLIFIED method, the probability distribution functions have been converted into tables which indicate the probability that the damage is bounded on one side by a given longitudinal, vertical or transverse plane. For example, the function \( p_d(d) \) is the probability that damage is restricted to less than \( d \), the normalized damage location, given \( g(y) \), the probability density distribution of extent of damage, \( h(x) \), the probability density distribution of location, and \( c \), the maximum extent of damage.

\[
P_b = \int_0^c \int_0^{d-y/2} g(y) \cdot h(x) \, dx \, dy
\]

Similarly, \( p_d(d) \) is the probability that damage is restricted to more than \( d \). These equations are repeated for all of the damage probability calculations. For the cases involving penetration they simplify to single integral equations.

To obtain the probability that a region bounded by \( d_1 \) below and \( d_2 \) above is damaged, one finds:

\[
p = 1 - p_d(d_1) \cdot p_d(d_2)
\]

Note that this probability includes all damages which include the region, not just those that damage that region alone. To determine the probability of damage for a region in three-dimensional space the appropriate probabilities in each dimension are multiplied together reflecting the independence between the IMO distributions. To simplify the calculation process, the extreme boundaries of the compartment are used.
Step 2: Calculate Oil Outflow

Consistent with the **DIRECT** analysis approach, 100% outflow for all cargo tanks sustaining side damage is assumed, and outflow from bottom damage is calculated at various tidal conditions based on hydrostatic pressure differentials. However, the **SIMPLIFIED** method differs from the **DIRECT** method in its treatment of oil “capture” by the double bottom tanks.

When two or more cargo oil tanks are located above a double bottom tank, the oil “captured” by the double bottom tank is proportioned between the cargo oil tanks in proportion to their respective capacities. That is, the portion of captured oil applicable to a given cargo tank is taken as the volume of that tank divided by the volume of all affected cargo oil tanks. This is a necessary simplification as the specific damaged compartments associated with each unique damage case are not determined with the **SIMPLIFIED** approach.

In the first draft of the proposed “Accidental Oil Outflow” regulation, all double bottom tanks located below a given cargo tank were assumed to be effective in capturing oil. At its April, 1997 meeting, BLG modified this provision to limit credit taken for oil “capture” to only one double bottom tank per cargo tank. This was done to so that the **SIMPLIFIED** approach would provide conservative (higher mean outflow) results as compared to the **DIRECT** approach.

For example, for the single-tank-across arrangement (ARRGT “B” of Figure 5), some damage cases will involve breaching of the cargo tank and only one ballast tank, and some cases will involve both ballast tanks. If the **SIMPLIFIED** approach assumes both ballast tanks are damaged, it will over-estimate capture and under-estimate outflow. By assuming only one of the ballast tanks is damaged, the **SIMPLIFIED** approach will tend to slightly over-estimate outflow.

Step 3: Calculate Oil Outflow Parameters

For the **SIMPLIFIED** approach, the mean outflow is calculated by summing the products of the probability of damaging each cargo tank and the oil outflow associated with that cargo tank.

The probability of zero outflow is computed by treating the cargo block as a single tank. If \( P_{CB} \) is the probability of breaching the cargo block, then the probability of zero outflow \( P_0 \) (i.e. the probability of breaching the outer hull but not spilling any oil) is: \( P_0 = 1 - P_{CB} \). When the wing tank or double bottom dimensions are not uniform over the length of the cargo block, the proposed regulation allows for application of correction factors.

The extreme outflow parameter cannot be calculated with this **SIMPLIFIED** methodology. The extreme outflow parameter represents the weighted average of the largest spills. Since the distribution of spills by size is not known, there is no means for evaluating outflow relative to spill size.

Step 4: Compute the Pollution Prevention Index

Work on establishing the performance standard for the proposed “Accidental Oil Outflow” regulation is in its early stages. It is intended that an IMO Intersessional Correspondence Group will solicit and review proposals for an index during 1997, and that these issues will be dealt with at the next BLG meeting scheduled for the Spring of 1998.

3.2 Assembling Damage Cases: A Simple Example

The two different approaches used for assigning probabilities and computing the outflow parameters are best illustrated by a simple example (see Figure 2).

![Image of single-hulled barge](image)

**Figure 2: Plan View of Single-Hulled Barge**

**DIRECT** Method: Application of the probability density functions for side damage yields twelve unique compartment groupings with their associated probabilities as shown in Table 1.

<table>
<thead>
<tr>
<th>Unique Groupings</th>
<th>Probability</th>
<th>Cumulative Probability</th>
<th>Oil Outflow (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 + CO3 + CO4</td>
<td>0.0004</td>
<td>1.0000</td>
<td>7,000</td>
</tr>
<tr>
<td>WB1 + CO2 + CO3</td>
<td>0.0033</td>
<td>0.9966</td>
<td>5,000</td>
</tr>
<tr>
<td>CO2 + CO3</td>
<td>0.0628</td>
<td>0.9934</td>
<td>5,000</td>
</tr>
<tr>
<td>CO3 + CO4</td>
<td>0.0628</td>
<td>0.9334</td>
<td>5,000</td>
</tr>
<tr>
<td>CO3 + CO4 + WB5</td>
<td>0.0033</td>
<td>0.8706</td>
<td>5,000</td>
</tr>
<tr>
<td>CO3</td>
<td>0.1839</td>
<td>0.8673</td>
<td>3,000</td>
</tr>
<tr>
<td>WB1 + CO2</td>
<td>0.0633</td>
<td>0.6834</td>
<td>2,000</td>
</tr>
<tr>
<td>CO2</td>
<td>0.1032</td>
<td>0.6201</td>
<td>2,000</td>
</tr>
<tr>
<td>CO4</td>
<td>0.1032</td>
<td>0.5169</td>
<td>2,000</td>
</tr>
<tr>
<td>CO4 + WB5</td>
<td>0.0633</td>
<td>0.4137</td>
<td>2,000</td>
</tr>
<tr>
<td>WB1</td>
<td>0.1752</td>
<td>0.3504</td>
<td>0</td>
</tr>
<tr>
<td>WB5</td>
<td>0.1752</td>
<td>0.1752</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: **DIRECT** Side Damage Evaluation

Two of the groupings result in no outflow, each of which have a probability of occurrence of 0.1752. The probability of zero outflow equals their cumulative probability, or 0.3504. Summing the products of the

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5
outflows and probabilities of occurrence for each unique grouping gives the mean outflow of 1,878 m$^3$. Similarly, taking the weighted average for the groupings with a cumulative probability above 0.90 gives an extreme outflow of 5,009 m$^3$.

SIMPLIFIED Method: Application of the probability tables contained in the proposed “Accidental Oil Outflow” regulation [8] yields the probabilities of damaging the cargo tanks shown in Table 2. Summing the products of the outflows and probabilities of damaging the respective cargo tanks gives the mean outflow of 1,879 m$^3$.

As previously noted, the extreme outflow cannot be determined with the SIMPLIFIED approach as the distribution by spill size is not available.

<table>
<thead>
<tr>
<th>Cargo Tanks</th>
<th>Probability of Damaging Cargo Tank</th>
<th>Oil Outflow (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>0.233</td>
<td>2,000</td>
</tr>
<tr>
<td>CO3</td>
<td>0.316</td>
<td>3,000</td>
</tr>
<tr>
<td>CO4</td>
<td>0.233</td>
<td>2,000</td>
</tr>
</tbody>
</table>

Mean Outflow = 1,879 m$^3$

Table 2: SIMPLIFIED Side Damage Evaluation

If the entire cargo block consisting of cargo tanks CO2, CO3, and CO4 are considered as a single compartment, application of the probability tables [13] gives a probability of breaching the cargo block $P_{CB} = 0.6493$. The probability of zero outflow is therefore: $P_{O} = 1 - P_{CB} = 0.3507$.

As illustrated in this simple example, computation effort is significantly reduced with the SIMPLIFIED approach. For a double hull tanker with a 5-long by 2-wide cargo tank arrangement plus two slop tanks, the SIMPLIFIED method requires analysis of twelve tanks. In comparison, with the DIRECT approach there are typically 100 to 200 unique groupings for side damage, and 400 to 700 unique groupings for bottom damage. Another advantage of the SIMPLIFIED method is that it does not require development of specialized computer code, and its straightforward procedures should enable designers to obtain repeatable results.

4 EVALUATION OF DOUBLE HULL TANKER DESIGNS

A parametric series of 210 double hull tanker variations was developed and analyzed to gain a better understanding of the following:

- The influence of internal sub-division (i.e. additional longitudinal and transverse bulkheads within the cargo block) on projected outflow from collisions and groundings.
- The effectiveness of the current hypothetical outflow and tank size regulations in assuring a consistent level of environmental performance.
- The relationship between the intact stability and oil outflow performance of typical double hull tankers.
- The relative impact of the simplifying assumptions inherent in the proposed accidental outflow regulation.

This double hull tanker outflow analysis was developed under the sponsorship of the United States Coast Guard. Results are summarized in this section of the paper. Further details are provided in reference [15].

4.1 Ship Designs Analyzed

Four sizes of crude oil carriers were evaluated:
- PANAMAX approximately 41,000 DWT
- AFRAMAX approximately 98,000 DWT
- SUEZMAX approximately 145,000 DWT
- VLCC approximately 291,000 DWT

These four sizes of tankers are identified throughout this report as 41K DWT, 98K DWT, 145K DWT, and 291K DWT respectively. For each size, five variations of double bottom depth and wing tank width were modeled. For each of the double bottom and wing tank variations, ten or eleven different cargo tank arrangements were evaluated. These selected arrangements are presented in Table 3. All of the designs of a given size have identical cargo deadweight.

<table>
<thead>
<tr>
<th>DWT</th>
<th>Double Bottom Depth (m) x Wing Tank Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41K</td>
<td>2.0 X 2.0 2.0 X 3.0 2.5 X 2.5 3.0 X 2.0 3.0 X 3.0</td>
</tr>
<tr>
<td>98K</td>
<td>2.0 X 2.0 2.0 X 3.0 2.5 X 2.5 3.0 X 2.0 3.0 X 3.0</td>
</tr>
<tr>
<td>145K</td>
<td>2.0 X 2.0 2.0 X 3.0 2.5 X 2.5 3.0 X 2.0 3.0 X 3.0</td>
</tr>
<tr>
<td>291K</td>
<td>2.0 X 2.0 2.0 X 4.0 3.0 X 3.0 4.0 X 2.0 4.0 X 4.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DWT</th>
<th>Cargo Tank Arrangement (No. of Tanks Long’l x No. Tanks Across)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41K</td>
<td>8X1 7X1 6X1 5X1 4X1 6X2 5X2 4X2 5X3 4X3</td>
</tr>
<tr>
<td>98K</td>
<td>8X1 7X1 6X1 5X1 7X2 6X2 5X2 4X2 5X3 4X3</td>
</tr>
<tr>
<td>145K</td>
<td>10X1 9X1 8X1 7X1 8X2 7X2 6X2 5X2 6X3 5X3 4X3</td>
</tr>
<tr>
<td>291K</td>
<td>9X2 8X2 7X2 6X2 7X3 6X3 5X3 4X3 6X4 5X4 4X4</td>
</tr>
</tbody>
</table>

Table 3: Evaluated Designs

These designs extend beyond the range of configurations acceptable under current regulations. This was intentionally done recognizing that the current hypothetical outflow and tank size regulations may not be reliable indicators of accidental outflow performance, and some designs which do not meet these requirements might have good outflow characteristics.

Typical tankage arrangements are shown in Figures 3 and 4. When the number of cargo tank transverse
bulkheads is seven or less (i.e. up to six cargo tanks long), ballast tanks were aligned with the fore and aft bounds of the cargo tanks. For instance, the 6X1, 6X2, and 6X3 cargo tank arrangements all have 6X2 ballast tank arrangements. When the number of cargo tanks bulkheads exceeds seven, a 5X2 or 6X2 ballast tank arrangement was used with some the ballast tanks extending longitudinally over two cargo tanks.

![Figure 3: Typical 6X2 Cargo Tank Arrangement](image1)

![Figure 4: Typical 8X1 Cargo Tank Arrangement](image2)

Longitudinal wing bulkheads were arranged to maintain the designated wing tank width and double bottom height as far as practical. Typically, the wing tank clearances are maintained at the appropriate values at the ends of cargo tanks. In keeping with normal design practice, an effort was made to limit the number of knuckles in the longitudinal bulkhead. Therefore, clearances typically increase above the designated values below the waterline and toward the middle of the fore and aft cargo tanks.

Consistent with present practice, the "single tank across" 41K DWT designs were arranged with upper hopper tanks to control free surface in the loaded condition (see ARRGT "A" of Figure 5). All other designs maintain vertical sides in way of the upper portions of the wing bulkheads (see ARRGT "B" through ARRGT "E" of Figure 5).

Lines representative of modern practice for single screw tankers with bulbous bows were developed for each design. A block coefficient of about 0.81 was used for all designs. To accommodate variations in the double hull dimensions while maintaining constant cargo volume, the ship dimensions were proportionately adjusted while holding the length/beam, beam/depth, and length/depth ratios constant. Principal particulars of the designs are summarized in Table 4. The drafts for each design were determined based on a full load condition with the cargo oil at 98% capacity and a density of 0.85 MT/m3, and 50% consumables.

Raking bottom damage calculations in accordance with MARPOL Regulation 13F(6) were run for each
Calculations were carried out for the full load condition. To satisfy this regulation, a "U" type ballast tank was provided on the 7X2 and 8X2 arrangements of 291K DWT tankers fitted with 4m wing tanks and double bottoms. All other arrangements satisfy the raking damage criterion with "L" ballast tanks only.

<table>
<thead>
<tr>
<th>Ships DWT</th>
<th>Cargo DWT (M.Tons)</th>
<th>LBP</th>
<th>Beam (m)</th>
<th>Depth (m)</th>
<th>Draft (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41K</td>
<td>39,600</td>
<td>170.25-178.20</td>
<td>30.96-32.20</td>
<td>17.03-17.82</td>
<td>10.44-11.14</td>
</tr>
<tr>
<td>98K</td>
<td>96,200</td>
<td>235.20-242.05</td>
<td>41.80-43.02</td>
<td>19.80-20.38</td>
<td>13.27-13.84</td>
</tr>
<tr>
<td>145K</td>
<td>141.80</td>
<td>257.70-264.00</td>
<td>46.86-48.00</td>
<td>23.43-24.00</td>
<td>16.10-16.55</td>
</tr>
<tr>
<td>291K</td>
<td>287.00</td>
<td>311.00-324.50</td>
<td>56.55-59.00</td>
<td>30.34-31.66</td>
<td>20.85-22.28</td>
</tr>
</tbody>
</table>

Table 4: Principal Characteristics

4.2 Oil Outflow Calculations

All of the ships were evaluated in accordance with the following criteria:

- Regulations 22-24 of Annex I of MARPOL 73/78, hypothetical outflow and tank size requirements.
- Conceptual approval methodology contained in the "Interim Guidelines for the Approval of Alternative Methods of Design and Construction of Oil Tankers Under Regulation 13F(5) of Annex I of MARPOL 73/78 [3], herein referred to as the DIRECT approach.
- "Accidental Oil Outflow" regulation currently under development at IMO [13], herein referred to as the SIMPLIFIED method.

Designs were also evaluated per the new intact stability regulation for tankers, Regulation 25A of Annex I of MARPOL 73/78.

Herbert Engineering Corp.'s HECSALV software was used to carry out the DIRECT and SIMPLIFIED outflow calculations, as well as the stability analysis. Outflow analysis results for the DIRECT and SIMPLIFIED methods are presented in Appendix A, Table A-1 and Table A-2 respectively.

4.3 Comparison of Designs

The graphs in Figures 6 through 8 illustrate some of the results of the outflow analyses. The selected graphs were considered representative of the results. Figure 6 illustrates the effect of longitudinal and transverse subdivision for the 2.5m X 2.5m double bottom/wing tank values for each vessel size (3m X 3m for the 291K DWT). Figures 7 and 8 show the impact of double bottom depth and wing tank width on the probability of zero outflow and mean outflow, respectively.

Longitudinal sub-division has a significant influence on mean outflow. In particular, introduction of a centerline bulkhead nearly halves the projected outflow. Even when additional transverse bulkheads are added to "single-tank-across" designs, projected outflow remains much higher.
as compared to designs with one or two internal longitudinal bulkheads. For example, the mean outflow for the 98K DWT design with a 6X2 cargo tank configuration is 53% of the 6X1 design mean outflow value, and 63% of the 8X1 design mean outflow value.

There is a diminishing return in reduction of mean outflow when adding bulkheads. As seen in Figure 6, adding transverse bulkheads to the 41K DWT class continues to reduce mean outflow, but the decrease in mean outflow is more significant going from 4 to 5 tanks longitudinally than from 5 to 6 tanks. Similarly, adding a centerline bulkhead greatly reduces the mean outflow, but a smaller decrease in mean outflow is exhibiting when adding a 2nd longitudinal bulkhead within the cargo tanks. Note that changing the internal sub-division has no effect on the probability of zero outflow, because the distance to penetrate the cargo block has not been altered.

Double bottom and wing tank dimensions influence both the probability of zero outflow and the mean outflow, as shown in Figures 7 and 8.

Increasing the double bottom and wing tank dimensions has a significant influence on both the probability of zero outflow and the mean outflow. For the 145K DWT, increasing from a 2mX2m double bottom/wing tank size to a 3mX3m double bottom/wing tank size increases the $P_0$ by 8%, from 79% to 86%. Alternately, given a collision or grounding, the 2mX2m double bottom/wing tank arrangement is 33% more likely to spill cargo than the 3mX3m double bottom/wing tank arrangement. For the same pair of vessels, the mean outflow is reduced about 25%.

For the present method of calculating outflow, increasing the wing tank width has more of an impact on the pollution prevention index, $E$, than increasing the double bottom depth. This is for a number of reasons. Increasing the wing tank width decreases the $P_0$ and therefore the mean outflow for side damage. As there is no capture for side damage, the mean outflow is substantially higher than for bottom damage. Since side damage results account for 40% of the total outflow parameters, this can be very significant. Also, the increase in ballast volume increases the potential capture volume, reducing outflow in the grounding cases. Additionally, the increase in double bottom depth has three effects on outflow. It not only increases the $P_0$ and capture volume for the tanks, but also increases the hydro-balanced outflow because the height of the cargo has increased, offsetting some of the benefit.

It was noted during the study that in comparing double hull vessels, the mean outflow parameter is an excellent indicator of $E$. While $P_0$ is an important outflow parameter, especially when discussing alternative tankers, the spread in $P_0$ for this study was not as large as that for the mean outflow.

### 4.4 MARPOL Outflow Analysis

For each design, hypothetical outflow calculations were run in accordance with MARPOL Regulation I/22-23, and tank lengths were evaluated per Regulation I/24. Some or all of the designs with the following configurations failed to satisfy Regulations I/22-24:

<table>
<thead>
<tr>
<th>Design</th>
<th>Governing Regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>41K DWT</td>
<td>4X1, 4X2, 4X3, 5X1</td>
</tr>
<tr>
<td>98K DWT</td>
<td>5X1, 6X1</td>
</tr>
<tr>
<td>145K DWT</td>
<td>7X1, 8X1</td>
</tr>
<tr>
<td>291K DWT</td>
<td>6X2, 7X2, 8X2, 9X2, 4X3</td>
</tr>
</tbody>
</table>

The MARPOL I/22-24 criterion does not assure consistent levels of outflow performance amongst different designs. The deterministic approach taken for defining longitudinal extent does not properly account for the increased probability of penetrating a transverse bulkhead as the spacing between transverse bulkheads is reduced. As a result, a 5X2 cargo tank arrangement and a 10X1 cargo tank arrangement are considered comparable.
under this criterion, whereas the 5X2 arrangement is a much better design with respect to outflow from collisions and groundings as shown on Table A-1 (Appendix A).

Additionally, the tank length criterion ignores the positive effects of longitudinal sub-division, and is not a good indicator of outflow performance. This is shown in Figure 6, where the 145K DWT 4X3 cargo tank arrangement has good outflow parameters, but doesn’t meet the tank length criteria.

4.5 Intact Stability Analysis

The intact stability characteristics of each design were evaluated in accordance with the "PROPOSED NEW MARPOL REGULATION I/25A" [Ref. 2]. A density of 0.85 M.Tons/m$^3$ was assumed for all cargo oil. All cargo oil and ballast tanks were simultaneously loaded to levels which provided the lowest overall metacentric height. Fuel oil and other consumables were set to 50% of capacity. Consistent with the proposed regulations, slack free surface values were applied for all tanks.

Designs which fail to meet the proposed intact stability criterion tend to be the designs with the highest projected mean outflow. All of the single tank across designs failed to meet I/25A and had poor outflow performance. The exception to this is that both the 291K DWT 7X2 & 8X2 cargo tank arrangements fail to meet I/25A due to the U-ballast tank, but both have fair outflow performance.

4.6 DIRECT & SIMPLIFIED Outflow Calculation Methods Comparison

One of the considerations in replacing the DIRECT method with the SIMPLIFIED method is the calculation of an index, E, without the extreme outflow parameter. To determine the effect of Q on E, a modified pollution prevention index designated “E50” was calculated. For the index E50, the extreme outflow term has been dropped and the weighing factor for the mean outflow term increased from 0.4 to 0.5.

\[ E50 = \frac{(0.5)(P_0)}{P_{OR}} + \frac{(0.5)(0.01 + O_{MR})}{0.01 + O_M} \]

For the DIRECT calculation, all of the E values are within 0.01 of the corresponding E50 values indicating that, at least for purpose of comparing double hull tanker designs, the extreme outflow calculation can be omitted without significantly influencing accuracy.

In Figure 9, the probabilities of zero outflow obtained from the DIRECT calculation approach are compared to those from the SIMPLIFIED methodology. The mean deviation and standard deviation are also given in the plot.

While the agreement is very close for the 41K and 98K DWT designs, slightly greater scatter is observed for the 145K and 291K DWT vessels. This is because the "three-tank-across" arrangement (see ARRGT "D" in Figure 5) has damage cases breaching the centerline cargo tank and P/S ballast tanks. For the larger designs, the volume of the ballast tanks is sufficient to fully capture the oil outflow from the cargo tank. In accordance with the 13F Guideline procedures, the DIRECT calculation approach assumes no outflow for these damage cases. An argument can be made that some outflow is likely regardless of the capture capability of the double bottom tanks. If a small outflow is assumed for all cases that penetrate cargo tanks, the probability of zero outflow values from the SIMPLIFIED and DIRECT methods would all be within 0.01.

Figure 10 provides a comparison of the mean outflow parameters obtained with the SIMPLIFIED and DIRECT methodologies.

As compared to the probability of zero outflow, agreement for the mean outflow results are not as consistent, with the SIMPLIFIED values falling both above and below the DIRECT values. This is primarily
due to assumptions for double bottom capture, which are necessarily less rigorous with the *SIMPLIFIED* approach.

For example, for the single-tank-across arrangement (ARRGT "B" of Figure 5), some damage cases will involve breaching of the cargo tank and only one ballast tank. The *SIMPLIFIED* approach always assumes both tanks are damaged, and therefore tends to over-estimate capture and under-estimate outflow.

Excellent agreement between the two calculation approaches is obtained for designs which have a one-to-one relationship between ballast tanks and cargo tanks (for example, a 5X2 cargo tank arrangement located in line with a 5X2 ballast tank arrangement). For these designs, the mean deviation is -0.00013 and the standard deviation is 0.00015.

### 5 ENVIRONMENTAL EFFECTS OF ACCIDENTAL POLLUTION

While the probability of zero outflow and the expected outflow of a particular ship design are crucial factors in the assessment of the relative performance of various tanker designs, the next logical step in such an assessment is a cost-benefit analysis to estimate the relative value in terms of a common metric (i.e., dollars). This section of the paper presents the methodology used to conduct an illustrative cost-benefit analysis based on five of the 210 designs examined in the oil outflow model. A cost-benefit framework provides a superior methodology for assessing relative tanker performance because it allows the estimated avoided costs of environmental damage to be compared with the estimated incurred costs of a particular design.

The cost-benefit portion of this analysis is divided into four steps: (1) develop cost estimates for four environmental categories based on varying locations and spill sizes; (2) develop costs as a function of spill size to summarize the results of the various cost estimates; (3) combine the cost equations with the oil outflow probabilities to develop design-specific avoided environmental costs; (4) compare the design-specific avoided environmental costs with the relative costs of construction and operation of each design to identify the designs with the highest benefit-cost ratio.

#### Cost Categories

For this analysis, four categories of spill costs were estimated: natural resource damages, clean-up costs, third-party losses, and the value of lost product. The methodology and data used to develop a set of spill costs for each of these categories is described below.

#### Natural Resource Damage Costs

For smaller spills (i.e., those of 100,000 gallons or less), Natural Resource Damages (NRDs) were estimated using the U.S. Department of Interior’s (DOI’s) *Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM)*. The NRDAM also is comprised of a series of linked sub-models and databases that calculate the damages to a natural resource based on the costs to restore the injured resource, when restoration is appropriate, and the compensable values of lost uses of the resource prior to restoration or natural recovery. The model contains a physical fates sub-model, a biological effects sub-model, a restoration sub-model, and a compensable value sub-model. A geographical information system (GIS) provides spatially gridded environmental and biotic information to the sub-models.

The NRDAM contains geographic, environmental, biological, physical-chemical, and toxicological data for 470 substances and a broad range of environments. The NRDAM also contains specific data on price levels, values for wildlife and recreational activities and restoration costs for ten separate provinces of U.S. waters: Acadian, Arctic, Californian, Carolinian, Columbian, Fjord, Louisianian, Pacific Insular, Virginian, and West Indian. The ten provinces are further divided into 77 distinct geographical areas. The model contains specific biological data for these 77 geographical areas, each of which may contain up to 21 ecological habitat types. To manage this information, the NRDAM uses a fixed grid system illustrating the entire area covered by the model. Each grid consists of an array of 50 by 50 cells. Each cell is coded by land versus water and habitat type. Smaller scale grids are used for areas representing more complex environments, such as near shore areas and wetland areas, while larger scale grids are used for less complex areas, such as off-shore areas. The large amount of data requires that information be generalized; the specific biological, geographic, and environmental data are averaged over each grid cell.

Most of the data required by the model to quantify environmental injury and estimate the economic damages are contained within the model’s databases. However, the user of the NRDAM is required to provide the following incident-specific information to the model:
(1) type of oil spilled;
(2) quantity of oil spilled;
(3) date of release;
(4) duration of release;
(5) latitude and longitude of release point;
(6) a wind time series;
(7) background and/or tidal currents.

For the current study, data were extracted from a database of Oil Spills that occurred between 1975 and 1996 in U.S. water that was assembled by the Coast Guard and edited by the National Academy of Science as part of National Research Council (NRC) research. This dataset contained the latitude and longitude of each spill, the quantity spilled, and the date of the release. In most cases, no actual NRDs were assessed for the spills in the database so it was necessary to estimate the potential NRDs using the NRDAM.

To perform this analysis, data on several additional model parameters were collected or assumed. Only crude oil spills were included in the analysis and the simplifying assumption that each spill consisted of North Slope Crude was used. In each case, the duration of the spill was assumed to be 24 hours with no cleanup occurring during that 24-hour period. Two databases of geographically gridded, geostrophic wind and background current data obtained from the National Center for Atmospheric Research were used to supplement the NRDAM’s internal databases.

Because of model limitations and the unique nature of NRDs associated with very large spills, only spills contained in the database of 100,000 gallons or less were run through the model. Further, the NRDAM generates very small NRD damages for spills of less than 1,000 gallons (e.g., less than $100 in total NRDs). For this reason, a geographically diverse sample of 80 spills falling between 1,000 and 100,000 gallons were modeled using the NRDAM.

For each of the 80 spills run through the NRDAM, damages based on restoration costs and the value of lost direct uses of the resource prior to restoration or natural recovery were estimated. The following types of direct use values and restoration costs are captured by the model:

- Fisheries consumptive use values (commercial, recreational, and subsistence);
- Wildlife consumptive use values (i.e., hunting);
- Wildlife non-consumptive use values (i.e., wildlife viewing);
- Restocking costs; and
- Direct restoration costs of affected habitats;
- Recreational use values (beach use and boating).

Restoration and restocking costs are not included when the cost of such activities exceeds ten times the reduction in damages (i.e., reduction in lost use-values) resulting from the restoration actions. The model does not account for lost non-use values resulting from the release or discharge. In addition, for purposes of this analysis, no beach closures were included in the cost estimates, which likely underestimates the total NRDs associated with spills in the 1,000 to 100,000 gallon range.

For spills greater than 100,000 gallons, historical data on NRDs were used to supplement the database of model-generated costs. These costs together were used to develop a cost function for NRDs.

**Clean-up Costs**

For purposes of this study, clean-up refers to the activities immediately following a spill event which are designed to contain and control the spill, such as the mobilization of response equipment and personnel. Companies assume responsibility for internal response costs and for external expenses, such as response contractors and equipment, government expenditures, and other operations. Clean-up costs borne by the government for such operations...
up costs do not include long-term restoration of the affected environment.

Clean-up costs used in the current analysis were extracted from U.S. Mineral Management Service data. The 76 spills contained in this dataset ranged from 168 gallons to 185 million gallons and occurred in various locations around the world between 1976 and 1990.

**Third-Party Costs**

Oil spills not only impact the environment, but often also have serious adverse economic effects on local recreation and tourism, industry, fisheries, and other third parties. OPA 90 language is vague concerning a spiller’s financial liability for economic losses suffered by third parties as a result of an oil spill. Section 1002(b)(2)(E) of OPA 90 makes each responsible party liable for “…damages equal to the loss of profits or impairment of earning capacity due to the injury, destruction, or loss of real property, personal property, or natural resources, which shall be recoverable by any claimant.”

The legal trend in judgments against spillers for third-party claims has been against compensation for economic losses unless the plaintiff suffers direct physical harm. Thus, the majority of third party claims against a spill for economic losses resulting from a release are dismissed since they do not involve direct physical harm to the third party. Claims for economic losses suffered by commercial fishing, however, are generally exempt from this interpretation. In the case of Exxon Valdez, for example, the Ninth Circuit Court of Appeals dismissed claims against Exxon from third parties (e.g., seafood wholesalers, processors, and cannery workers) other than commercial fisherman.

For this analysis, data collected by the International Oil Pollution Compensation Fund (IOPC) was used to estimate third-party costs. Costs reported in the IOPC report are divided into seven categories:

- clean-up;
- fishery-related;
- tourism-related;
- farming-related;
- other loss of income;
- other damage to property; and
- environmental damage.

All of the above costs, excluding clean-up and environmental costs, were combined into a single third-party estimate. The resulting third-party costs likely underestimate the total third-party damages because litigation costs are not included in the compensations paid by the fund. However, this underestimate may be off-set in the overall cost analysis by the potential for double counting between the NRD values generated by the NRDAM for fisheries and the compensations paid by the IOPC related to damages to fisheries.

**Lost Product Costs**

The value of lost product was included in the analysis only to allow for a full accounting of the magnitude of total spill costs. The value of lost product is based on the aggregate wholesale cost of the spilled commodity. For example, the value of spilled oil could be estimated by multiplying the spill volume by the current wholesale price for oil. For the current study, the estimated average world market price for crude ($0.57 per gallon) was used.

**Development of Oil Spill Cost Functions**

For each of the four cost categories discussed above, a separate cost equation was developed that generates a unit spill value as a function of the spill size. The methods used to develop these cost functions varied slightly across the different cost categories, but in general linear or non-linear regression techniques were used to find a “best fit” curve for the modeled or historical data. The specific approaches for each cost category and the resultant cost curves are presented below.

**Natural Resource Damage Cost Function**

Per gallon costs for NRDs vary greatly depending upon the size and location of the spill. Unit costs for spills of less than 100,000 gallons tend to increase in the interval between 1,000 and 20,000 gallons. In the interval between 20,000 and 100,000 gallons, unit NRDs generally are expected to decrease with increasing spill size. A non-linear regression was used to fit a curve to the NRDAM-modeled total costs as a function of spill size. The best fit equation was:

---

6 Based on 1997 Energy Information Administration world crude oil price data.

---

5 Union Oil Co. v. Oppen, 501 F.2d 558 [1974].
**NRD costs for spills of less than 100K Gallons**

\[
NRD \text{ costs for spills of less than 100K Gallons} = \frac{18642}{82156} \cdot e^{\frac{Gallons}{18642}}
\]

Figure x below illustrates the functional form of this equation.

**Figure x: Predicted NRD Unit Costs for Spills Under 100K Gallons**

Historical data from larger spills indicates that NRDs tend to rise with spill costs. NRD costs for a few of these larger spills were published in a 1993 U.S. Department of Energy report.⁹ Specifically, NRD values were reported for the following spills:

- **Amazon Venture**, a 500,000 gallon spill which resulted in NRDs of approximately 0.27 per gallon;
- Exxon Arthur Kill, a 567,000 gallon spill, which resulted in estimated NRDs of approximately $3.15 per gallon; and
- **Exxon Valdez**, a 10.8 million gallon spill, which resulted in NRDs of approximately $100 per gallon.

Based on these historical NRDs, one would expect unit NRD costs to continue to decrease with spill size up to the 500,000 gallon level. For the current analysis, this expectation was incorporated into the cost equation by interpolating from the 100,000 gallon level modeled in the NRDAM down to the Amazon Venture’s 500,000 gallon total spill cost, such that:

\[
NRD \text{ costs for spills 100K to 500K gallons (1995$)} = 0.152 \cdot Gallons + 60478
\]

For spills larger than 500,000 gallons, a second interpolation of total spill costs was performed up to the 567,000 gallon Arthur Kill spill. This same line was then continued to extrapolate the total NRD costs of larger spills, such that:

\[
NRD \text{ costs for spills greater than 500K gallons (1995$)} = 24.604 \cdot Gallons - 12165739
\]

The Exxon Valdez spill was excluded from the interpolation/extrapolation because it is generally considered to be an anomalous case. The combined unit cost function for the larger spills (i.e., those greater than 100,000 gallons) is presented in Figure xx, below.

**Figure xx: NRD Unit Cost Function for Spills Larger Than 100K Gallons**

The data upon which the cost curve for the larger spills is based is very limited, and therefore, is somewhat speculative. Nonetheless, there appears to be an implicit punitive multiplier that is applied to larger spills that causes the unit values to increase with increasing spill volumes. Further research on the NRD cost effects of increasing spill sizes in the larger spill size categories is needed to provide a more definitive estimate of these costs.

**Clean-up Cost Function**

A similar approach was used for developing total cleanup cost functions. As with the NRD costs, the unit cleanup costs are highly dependent upon the volume of oil spilled. Also as with the NRD costs, there is a definite break in the unit cost trend between smaller and larger spills. The total cost to spill size relationship of smaller spills (i.e., those of less than 2 million gallons) can be described using a log-linear equation of the form:

\[
\text{Cleanup costs for spills less than 2 million gallons} = \frac{10^{2.223 + 0.716 \cdot Gallons}}{}
\]
The functional form of this equation converted to unit values is presented in Figure x, below.

**Figure x: Unit Cleanup Costs for Spills Under 2 Million Gallons**

As can be seen from the figure, unit cleanup costs fall dramatically over the first 100,000 gallons spilled. Across the 100,000 to 2 million gallon interval, unit costs remain relatively flat. Above 2 million gallons (see Figure x, below), however, unit costs have historically risen up to approximately the 10 million gallon spill size and have then gradually fallen as spill size increased. A non-linear regression was used to model the relationship of total costs to spill size for these larger spills, as follows:

\[
\text{Cleanup costs for spills greater than 2M gallons} =\]

\[
10^{[-80.006 + 207.922 \cdot \text{Gallons} - 28.90 \cdot \log(\text{Gallons})]}
\]

The functional form of this equation for estimating total costs converted to unit costs is presented in Figure x, below.

**Figure x: Unit Cleanup Costs for Spills Larger than 2 Million Gallons**

The increase in costs between 2 million and 10 million gallons is likely due to the greatly increased resources needed to respond to very large spills. The decrease above that volume is likely due primarily to the limitation on available response resources. That is, 10 million gallons may represent a maximum response in terms of manpower and equipment deployed, so that above that volume some unit cost efficiencies are realized at very large spills.

**Third-Party Cost Function**

As discussed earlier in the paper, third-party costs are an area of considerable uncertainty because of the ambiguity involved in the definition of this cost category. Based on the IOPC dataset, we were, however, able to fit a curve to the third-party costs with reasonable confidence. A single function was used to describe the relationship between oil spill volume and unit third-party costs, such that:

\[
\text{Third-party costs per gallon} = \frac{0.240 - 0.54 \log(\text{Gallons})}{10^{1 - 0.515 \log(\text{Gallons}) + 0.068 \cdot \log(\text{Gallons})}}
\]

The functional form for this equation is presented in Figures x and x, below. Figure x presents the third-party costs associated with spill sizes of 50,000 gallons and less, while Figure x presents larger spills. Two graphs are used simply for clarity of presentation.

Based on this analysis, third-party unit costs appear to increase sharply for spills up to approximately 7,000 gallons and then fall off sharply in the interval of 7,000 to 20,000 gallons. These costs continue to decrease through approximately 300,000 gallons and then slowly increase for larger spills.

**Figure x: Unit Third-party Costs for Spills of Less than 50,000 gallons**
Lost Product Cost Function

As discussed above, the unit cost of lost product is a constant that does not vary as a function of spill size. Thus, the average world crude price of $0.57 per gallon results in a constant function as presented in Figure x.

Combination of Spill Unit Values with Oil Outflow Calculations

[NEED PLOT FOR TOTAL]

The cost functions presented above were next combined with the probability distribution functions that were generated by the oil outflow modeling. While 210 separate ship designs were modeled in the outflow analysis, for purposes of illustration and clarity, the cost benefit analysis was limited to eight alternative designs -- four double hull and four mid-deck -- and one low-cost reference ship that was used to create relative measures of performance.

Spill costs were combined with the cumulative distribution functions (CDFs) generated by the oil outflow to generate a mean environmental cost weighted by the probability of occurrence of various spill events. To do this, the total volume of each spill modeled with the oil outflow model was used as the independent variable in each of the cost equations presented in the previous section. These costs were then added to arrive at a single environmental cost for each possible spill condition for a particular ship design. Spill costs were adjusted to 1995 dollars before they were combined into a single value. Each possible spill event (i.e., gallons spilled) was then multiplied by the individual case probability of that spill event occurring. This procedure is illustrated in Figure x.
Oil Outflow of Single Spill Event
\[ = 12,625,469 \text{ gallons} \]

Using this value as the independent variable in the cost equations, we generate:

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleanup Cost</td>
<td>$965,940,825</td>
</tr>
<tr>
<td>NRD Cost</td>
<td>$298,477,366</td>
</tr>
<tr>
<td>Third-Party Cost</td>
<td>$8,633,942</td>
</tr>
<tr>
<td>Lost Product Cost</td>
<td>$7,196,517</td>
</tr>
<tr>
<td>Tot Environmental Cost</td>
<td>$1,280,248,650</td>
</tr>
</tbody>
</table>

The modeled probability for this size spill for this tanker design is 0.015. This probability is multiplied by the total environmental cost to generate a probability-weighted environmental cost:

\[
$1,280,248,650 \times 0.015 = $19,203,730
\]

This probability weighting is repeated for each modeled spill event for a given ship design. The summation of these probability-weighted costs across all possible spill events generates a design-specific mean environmental cost.

For each ship design, four separate oil outflow probability distributions were combined with the cost equations (as illustrated above). The four probability distributions -- corresponding to side damage, bottom damage with no tide, bottom damage with a 2m tide, and bottom damage with a 6m tide -- were then combined in a manner consistent with IMO’s mean outflow calculations. Specifically,

\[
0.4 S + 0.6 (0.4 B_1 + 0.5 B_2 + 0.1 B_3)
\]

where,

- \( S \) = the weighted mean environmental cost associated with side damage for a particular ship design
- \( B_1 \) = the weighted mean environmental cost associated with bottom damage for a particular ship assuming no tide
- \( B_2 \) = the weighted mean environmental cost associated with bottom damage for a particular ship assuming a 2m tide
- \( B_3 \) = the weighted mean environmental cost associated with bottom damage for a particular ship assuming a 6m tide.

Cost-Benefit Analysis of Tanker Performance

Following the estimation of a single probability-weighted mean environmental cost for each ship, we conducted a cost-benefit analysis (CBA) to compare the relative performance of eight alternative ship designs.

The CBA consisted of three stages: (1) an estimate of ship design present value costs; (2) an estimate of ship design present value environmental benefits; and (3) a comparison of the costs to the benefits.

Estimation of Present Value Ship Design Costs

Capital and annual ship design costs were taken from a recent study conducted by Herbert Engineering Corporation (HEC) for the U.S. Coast Guard.\(^7\) Capital costs were incurred in the first year and annual operating costs were incurred each year over an assumed 25-year tanker operating life. These costs were then discounted at a real rate of seven percent to arrive at a present value ship design cost. All design costs in the HEC study were expressed as an incremental cost increase relative to a low-cost reference ship.

Estimation of Present Value Ship Design Environmental Benefits

In order to arrive at a present value environmental benefit, it was necessary to estimate the probability that a spill from a particular ship would occur in a particular year. For this purpose, the annual probability of a ship being involved in a grounding or collision was assumed to be 0.0042 casualties/ship year based on an analysis of historical spill data conducted by Herbert Engineering Corp.\(^7\)

This annual probability of a casualty was then multiplied by the probability-weighted mean environmental cost for each year of the assumed 25-year operating life of a tanker. This stream of expected benefits (expressed as avoided costs) was then discounted using a seven percent real discount rate to arrive at the present value environmental benefits of each of the eight designs.

The present value environmental benefits for the eight alternative designs were then compared with the reference ship such that environmental benefits were expressed as incremental benefits relative to the low-cost reference ship. This conversion to a relative present value benefit allowed for direct comparison with the present value capital and operating costs described above.

Comparison of Present Value Costs and Benefits
Once the present value costs and benefits for the low-cost reference ship and the eight alternative designs were estimated, the next step in the analysis was to compare the costs and benefits to identify the design with the highest benefit to cost ratio. Figure x presents the results of the CBA for the eight alternative designs.

Figure x: Comparison of Relative Present Value Costs and Benefits for 25 Double Hull Tanker Designs

<table>
<thead>
<tr>
<th>Tanker Design</th>
<th>Relative Mean Outflow (Gallons Avoided)</th>
<th>Relative Cost of Design (Delta from Least Cost Design of its Class)</th>
<th>Cost Per Gallon Avoided</th>
<th>Expected Spill Cost Avoided</th>
<th>Benefit Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFRAMAX 5X2 2X2</td>
<td>486,737</td>
<td>$361,924</td>
<td>$0.74</td>
<td>$2,576,531</td>
<td>7.12</td>
</tr>
<tr>
<td>AFRAMAX 6X2 2X2</td>
<td>550,136</td>
<td>$655,141</td>
<td>$1.19</td>
<td>$2,830,873</td>
<td>4.32</td>
</tr>
<tr>
<td>AFRAMAX 6X1 2X2</td>
<td>112,739</td>
<td>$234,895</td>
<td>$2.08</td>
<td>$575,639</td>
<td>2.45</td>
</tr>
<tr>
<td>AFRAMAX 7X1 2X2</td>
<td>204,024</td>
<td>$469,074</td>
<td>$2.29</td>
<td>$1,006,014</td>
<td>2.15</td>
</tr>
<tr>
<td>AFRAMAX 5X2 3X3</td>
<td>625,045</td>
<td>$2,979,027</td>
<td>$4.77</td>
<td>$2,901,444</td>
<td>0.97</td>
</tr>
<tr>
<td>AFRAMAX 6X2 3X3</td>
<td>668,328</td>
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<td>$575,639</td>
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<td>1.83</td>
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<td>$1,164,596</td>
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<td>$716,751</td>
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As can be seen in the figure, the use of cost-benefit analysis adds a unique perspective to the determination of optimal performance. Take, for example, a comparison of the double hull ships presented above. Based solely on a comparison of avoided mean outflow, one would identify the AFRAMAX 6X1 2X2 configuration as the optimal performer. If one were to carry the analysis a step further to consider benefits as the incremental cost per gallon spilled, one would select this same design. However, when the CBA component is added to the analysis, the clear choice in terms of the cost-benefit ratio is the AFRAMAX 5X2 2X2 configuration.
Ship discrete variables:
Type (SH,DH,ID/DS,DB,DS)
LBP, B, D
Displacement
L or T stiffened, b, t , stiffener

Grounding:
Probabilities:
Type of bottom (rock, sand, mud)
Type of obstruction (narrow rock, pinnacle, hard/soft)
Pdf’s:
Ship speed
Ship trim
Height of obstruction above BL
Eccentricity of obstruction
Tip/edge angle
Edge radius/width
Slope/inclination angle

Monte Carlo Simulation

Regression Analysis

DAMAGE

Grounding joint pdf’s for location, longitudinal, vertical and transverse extent of damage

Joint pdf parametrics for location and extent of damage

Figure 11: Method for Estimating Damage pdf’s
6 STRUCTURAL PERFORMANCE OF TANKER BOTTOMS DURING ACCIDENTAL GROUNDING

6.1 Current Methodology

A major shortcoming in IMO’s current hypothetical oil outflow calculation methodology [6] is that it does not consider the effect of structural design or crashworthiness on damage extent. The primary reason for this exclusion is that no definitive theory or data exists to define this relationship.

The Interim Guidelines [6] use probability density functions (pdf’s) to describe extent of damage. These pdf’s are based on a statistical analysis conducted by Lloyd’s Register in support of the IMO Comparative Study on Tanker Design [7]. They are applied identically to all tankers, and do not consider individual ship structural characteristics.

It is logical and essential that crashworthiness be considered in oil outflow calculations, but sufficient data does not exist to adequately predict damage extent as a function of ship structural design. An analytical method is required to define the relationship between structural design and damage extent. A method which considers crashworthiness must be sensitive to at least the basic parameters defining unique structural designs while maintaining sufficient generality and simplicity to be applied by working engineers in a regulatory context for a ship in worldwide operation. It should not require detailed finite element analysis or be limited to a single accident scenario.

6.2 Proposed Method for Estimating Damage pdf’s

Figure 11 illustrates a scheme for developing a set of parametric equations which define the pdf’s for damage extent in grounding as a function of independent variables defining the ship and ship structural design [8]. A similar methodology can be applied to collision, and this will be addressed in subsequent work.

Probabilities for bottom type, obstruction type, and pdf’s for ship speed, ship trim and bottom/obstruction characteristics are postulated based on expert opinion and sensitivity analysis. These pdf’s are applied in a Monte Carlo simulation to select discrete values for each of the external grounding variables (ship speed, trim, rock elevation, eccentricity, tip radius and tip angle). Assumed input pdf’s with the actual values selected in the Monte Carlo simulation are shown in Figures 12 through 14. Each point in these figures represents a fraction of the 1000 points selected in each simulation run.
Using these values and a discrete set of parameters describing the ship and ship structural design, extent of damage is calculated using the program DAMAGE [5]. This process is repeated for the same ship characteristics until pdf's for extent of damage are developed, and then repeated for a series of ship parameters. The final pdf's are reduced to parametric form using regression analysis resulting in mathematical expressions for damage extent pdf’s as a function of ship structural design characteristics.

6.3 DAMAGE [5]

In order to consider the effect of structural design or crashworthiness on damage extent, it is necessary to model the interaction between local structural damage and global ship motion. The variety of structural details and potential accident scenarios makes this difficult. The computational model DAMAGE developed at MIT by Professor Tomasz Wierzbicki, under the Joint MIT-Industry Project on Tanker Safety, provides an efficient solution to this problem.

In this model, the ship hits ground with some initial kinetic energy, and as this energy is dissipated, the ship comes to rest.

\[ \alpha \text{ = rock tip angle} \]
\[ r \text{ = rock tip radius} \]

![Figure 15: Rock Characteristics](image)

Perhaps one of the most difficult aspects of the project is determining what a “typical” grounding rock looks like. There are an infinite number of possible rock shapes and reef formations. During the first two years of the Tanker Safety Project, the primary focus of research was on a sharp vertical wedge-type rock. As the project progressed, a more general type of grounding obstacle was necessary. A cone-shaped rock with varying cone apex angle and tip radius as shown in Figure 15 was chosen.

The primary mechanisms of energy dissipation in the rock grounding case are:

1. A change in potential energy of the ship and surrounding water.
2. Friction between the ground and hull.
3. Deformation and fracture of the hull.

Initially, the ship is assumed to be on a straight course with a known velocity and trim. The rock is narrow compared with the beam of the ship. It is at some distance, the rock eccentricity, to port or starboard of the ship’s centerline, and at some height, the rock elevation, above the ship’s baseline. During grounding, the grounding reaction induces heave, roll and pitch motion on the ship, and eventually causes the ship to stop.

Initially, the rock causes lifting of the ship, accompanied by large plastic deformation without fracture. As the rock approaches midship, the force becomes larger, and eventually the shell plating may rupture. First principles of mechanics and plasticity theory, without strong dependence on empirical relations, are used to predict damage forces and extent. DAMAGE is not a finite element program. The two basic damage mechanisms modeled are superfolding and supertearing. Damage forces and extent at any timestep are calculated in a closed-form solution.

DAMAGE models the grounding event as a series of stepwise incremental displacements resulting from the rock’s interaction with the ship structure and global ship motion. At each step, the rock’s penetration and resulting reaction force are calculated. Static equilibrium of global ship forces and local damage forces is assumed. This timestepping proceeds until the forward motion of the ship is stopped. When the calculation is completed, the heave, pitch, rock penetration, structural reaction force and plating status (rupture/no rupture) is known at each step.

6.4 Input Structural Parameters

In the current study, sensitivity analysis and Monte Carlo simulation has only been accomplished for the representative MARPOL single hull tanker shown in Figure 16. Damage results from this analysis are compared to the single hull pdf’s from the Interim Guidelines [6] in Figures 17 through 20. Analysis is ongoing for a representative double hull tanker which should provide an interesting contrast to the single hull results. Ultimately, calculations will be repeated for a matrix of ship parameters over the full range of potential ship and structural characteristics. The final pdf’s will be reduced to parametric form using regression analysis to provide mathematical expressions for damage extent pdf’s as a function of ship structural design characteristics.
Discussion of Damage pdf’s

Damage results for the single hull test case are presented in Figures 17 through 20. Interim Guideline pdf’s [6] derived from the Lloyds’s analysis are also shown. As can be seen, longitudinal location matches the Lloyd’s data extremely well with only a small bias towards the forward cargo block bulkhead. Extent of damage matches well except that DAMAGE results predict raking damage running the full length of the cargo block while the Interim Guideline pdf predicts a maximum damage length of 0.8L. The DAMAGE pdf seems very reasonable, but must be validated. If necessary, input pdf’s for ship trim and height of obstruction may be used to adjust DAMAGE results to match the Lloyds data. An additional set of sensitivity runs is in progress to better understand this difference, and consider potential adjustments.

Match-up for damage penetration and transverse extent is fair, but DAMAGE results indicate fewer very shallow penetrations, and no damage with transverse extent spanning the entire beam of the ship. Vertical
penetration and transverse extent are very sensitive to rock geometry pdf’s and no soft ground or broad transverse ridge bottom conditions are considered in the DAMAGE model. This may account for these differences, and these conditions should be included in subsequent versions of the model.

6.6 Future Work and Structural Performance Implementation in IMO Regulation

The preliminary work and proposed methodology for relating extent of damage pdf’s to structural design demonstrates the feasibility of this approach. This analysis must next be extended to consider side damage due to collision, and to develop parametric equations relating basic structural design parameters to damage extent. This includes further sensitivity analysis to select important design parameters effecting grounding and collision structural performance.

Ultimately, parametric equations relating important structural parameters to damage extent will be derived. It is expected that these parameters will include basic single and double hull structural attributes such as plating thickness, stiffener size, stiffener spacing, double bottom depth and wing tank width. These simple attributes adequately describe standard double hull and mid-deck geometry, but will not adequately define unique designs.

The first step in revising and harmonizing tanker design regulation will be to incorporate a performance requirement based on the SIMPLIFIED outflow method and a rational environmental index into MARPOL Annex 1. It is hoped that this work can be completed at BLG 3. This revision will be based on the current pdf’s for damage extent. Once this is completed, serious work can begin on including crashworthiness in the outflow calculations and regulation. This could be accomplished over the next three to five years.

One viable plan for future regulation is to support two approaches for evaluating tanker performance:

1. A standard approach for typical double hull and mid-deck designs. This would incorporate the SIMPLIFIED method for estimating outflow using standard parametric equations for damage extent based on standard structural attributes.

2. A detailed approach which would include the DIRECT method for estimating outflow and allow finite element or other validated analysis techniques to be used for estimating damage extent pdf’s. This second approach would require detailed guidelines to define basic assumptions and requirements for analysis.

7 AN APPROACH TO DEVELOPING AN ENVIRONMENTAL INDEX COMBINING THE SIMPLIFIED OIL OUTFLOW CALCULATION METHODOLOGY AND THE ENVIRONMENTAL EFFECTS

In order to apply the SIMPLIFIED method results (probability of zero outflow, $P_0$, and mean outflow, $O_M$) directly to calculate a probability-weighted environmental cost, it is necessary to derive an outflow pdf based on these parameters. An outflow pdf cannot be obtained directly from SIMPLIFIED method results. To derive a standard form for this pdf, the following procedure was applied to the DIRECT method damage case results:

1. Damage case outflows, $O$, were normalized with total ship cargo volume, $C$, resulting in non-dimensional outflow, $x = O/C$.

2. Side damage and tidal case probabilities were multiplied by the appropriate case weighing factors, ie. 0.4S, 0.6(4)B, 0.6(5)B and 0.6(1)B, resulting in specific probabilities for each case.

3. Non-dimensional mean outflow given outflow, $\mu$, was calculated for each case. This is the probability-weighted mean of all non-dimensional outflows greater than zero. This mean can also be calculated using the SIMPLIFIED method. $\mu = O_M/(1-P_0)$

4. A single generic pdf($x,P_0,\mu$) was derived using regression analysis to model the DIRECT method pdf’s for oil outflow given outflow. The area under this pdf is equal to $(1-P_0)$ and the mean is equal to $\mu$.

Although not complete for the entire 210 ship data set, this process was completed for a number of double hull and mid-deck designs. It was found that a standard Rayleigh distribution provided an excellent fit to the DIRECT method results for all double hull cases and a good fit for mid-deck designs. Cumulative distribution functions comparing actual and calculated results for representative double hull and mid-deck designs are shown in Figures 1 and 2.
Using zero outflow, $P_0$, and non-dimensional mean outflow given outflow, $\mu$, calculated from a SIMPLIFIED analysis, the non-dimensional outflow given outflow pdf is:

$$pdf(\chi, P_0, \mu) := \frac{1}{A \cdot \mu^2} \left(1 - P_0\right) \chi e^{-\frac{x^2}{A \cdot \mu^2}}$$

where $A = \frac{2}{\pi}$.

Applying this generic pdf, the probability-weighted environmental cost is:

$$\text{Cost} := \int_0^1 p(\chi, P_0, \mu) \cdot \text{cost}( C \cdot \chi) \, d\chi$$

where $\text{cost}(\chi)$ is the total unit cost for outflow, $\chi$.

If $p(\chi, P_0, \mu)$ and $\text{cost}(\chi)$ are known functions, the expression for probability-weighted environmental cost can be integrated directly, and environmental cost can be expressed as a function of zero outflow, $P_0$, and mean outflow given outflow, $\mu$.

The following is an example of the above method as applied to 6 SUEZMAX designs with varying cargo block subdivision and double hull dimensions:

$$A := \frac{2}{\pi}$$

$$A = 0.637$$

$$x := 0, 0.01..0.4$$

$$n := 1..6$$

$$\frac{145000}{85} \cdot m^3 = 4.506 \cdot 10^7 \cdot \text{gal}$$

<table>
<thead>
<tr>
<th>Design</th>
<th>Outflow Size (m$^3$)</th>
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<tr>
<td>6X2 (3x3)</td>
<td>145k</td>
<td>6X2 (3x3) 145k</td>
</tr>
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<td>145k</td>
<td>5X2 (3x3) 145k</td>
</tr>
<tr>
<td>5X2 (2x2)</td>
<td>145k</td>
<td>9X1 (3x3) 145k</td>
</tr>
<tr>
<td>5X2 (2x2)</td>
<td>145k</td>
<td>9X1 (2x2) 145k</td>
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data := \[
\begin{bmatrix}
170588.2353 & 0.8318 & 2163.46 \\
170588.2353 & 0.767 & 2922.52 \\
170588.2353 & 0.8302 & 2426.48 \\
170588.2353 & 0.765 & 3277.38 \\
170588.2353 & 0.83148 & 3272.96 \\
170588.2353 & 0.7676 \\
\end{bmatrix}
\]
\]
\[
\text{totGal}_n := \frac{\text{data}_{n,1} \cdot m^3}{\text{gal}}
\]
\[
\text{totGal}_1 = 4.5
\]
\[
\begin{bmatrix}
490024.5 & 17386079 & -9.45 \times 10^8 \\
-39.3557 & -23.4838 & 388.62067 \\
.002615 & 1.52 \times 10^{-5} & -2.45 \times 10^{-5} \\
\end{bmatrix}
\]
\[
a := \begin{bmatrix}
-6.9 \times 10^{-8} & 2.11 \times 10^{-12} & 7.79 \times 10^{-13} \\
9.51 \times 10^{-13} & -4.16 \times 10^{-10} & -1.34 \times 10^{-20} \\
-6.63 \times 10^{-18} & 2.18 \times 10^{-26} & 1.20 \times 10^{-28} \\
1.84 \times 10^{-23} & -3.78 \times 10^{-34} & -4.46 \times 10^{-37} \\
\end{bmatrix}
\]
\[
P_{0_n} := \text{data}_{n,2}
\]
\[
\mu_n := \frac{\text{data}_{n,3}}{(1 - \text{data}_{n,2}) \cdot \text{data}_{n,1}}
\]
\[
c(n, x) := \begin{cases} 
1 \text{ totGal}_n \leq 100000, & \sum_{i=1}^{7} a_{i,1} \cdot (\text{totGal}_n \cdot x)^{i-1}, \\
0 & \text{totGal}_n > 20000000
\end{cases}
\]
\[
\text{COST} := \begin{bmatrix}
3.232 \times 10^7 \\
4.26 \times 10^7 \\
3.998 \times 10^7 \\
5.283 \times 10^7 \\
6.77 \times 10^7 \\
8.843 \times 10^7 \\
\end{bmatrix}
\]

Remember to add discussion on the reasonable test for validity of this approach. The test would be a comparison of the rankings using this approach with the rankings using the DIRECT approach (see WW’s table in Section 6).

8 A PROPOSED ENVIRONMENTAL INDEX - AN APPROACH TO SELECTING THE “REFERENCE” INDEX

The following multi step process:

- 4 best cost ships by combining the DIRECT cumulative distribution functions (CDFs) with the cost functions.

Clearly, these designs are “best” from the combined influence of effective subdivision in the cargo tanks and the highest values of double side widths and double bottom depths. The “choice” of these vessels does not include any consideration of design or operating costs.

AFRAMEX 6x2, 3x3
PANAMAX 6x2, 2.5x2.5
SUEZMAX 6x2, 3x3  
VLCC 6x3, 4x4

• 4 best CBAs by combining the effects of the value of oil not spilled together with the costs of design and operation of the vessel. As discussed in Section 6, this provides a unique perspective regarding the relative performance of designs.

  These designs are:

  AFRAMAX 5x2, 2x2  
PANAMAX 5x2, 2x2  
SUEZMAX 6x2, 2x2  
VLCC 5x3, 3x3

The effects of increased costs due to a higher degree of subdivision within the cargo block, combined with wider and deeper inner hull spaces leads to a different “choice” of vessels.

• 4 best from HEC study of CB using mean and ship construction and operating costs.

  This is similar to the above approach, however, the environmental effects of oil outflow are considered only in terms of mean outflow, without consideration of the variation of unit spill costs as a functions of spill size. This approach is based on quantifying the “extra (construction and operating) costs per cubic meter of oil not spilled.”

  The “selected” designs are:

  AFRAMAX 6x2, 2x2  
PANAMAX 5x2, 2x2  
SUEZMAX 6x2, 2.5x2.5  
VLCC 5x3, 3x3

• Select 4 ships (based on AJB’s output)

  SUEZMAX 6x2, 3x3 (standard too high? - see AJB’s MATHCAD file COST145k.MCD)

    [Need other ships to be run through AJB’s model to pick the other 3 designs]

• Fit curve/Linearly interpolate between index points

9  RECOMMENDATIONS FOR FURTHER STUDIES

There are many simplifying assumptions inherent in the calculation procedure for the probabilistic analysis of oil outflow from groundings and collisions. Research is required to assess the sensitivity of these assumptions to the final results, and to refine the methodology where appropriate. The following topics need further studies.

   The probability density functions (for the extents of damage) are applied independently. In reality, some correlation is expected. For instance, it is not realistic to assume the maximum longitudinal extent of damage (generally caused by raking damage) with occur simultaneously with the maximum transverse penetration (generally caused by a "t-bone" collision).

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

   The probability of experiencing a collision or grounding was applied equally for all designs, although some variation is expected amongst different services. For instance, an FPSO or a VLCC used for offshore lightering will have a different probability of grounding as compared to a coastal tanker.

   Weight estimates were developed through comparison to a limited number of existing designs. If a designer can reduce costs for a particular design through further optimization of structure, this will influence the net benefits for that design.

   Cost estimates assume ship construction at internationally competitive prices. For ships constructed for the Jones Act trades, the higher construction costs will impact the cost to benefit ratios.

   The reduction in accidental oil outflow was the only benefit included when developing the net benefits. There may be other benefits (and perhaps some detrimental effects) associated with changes to a tanker’s configuration. For instance, designs which could potentially become unstable were identified in this study, but the possible consequences on oil outflow or vessel operations were not considered. Similarly, no attempt was made to quantify possible improvements in tank access and structural reliability that might be realized with wider wing tanks or deeper double bottom tanks.

   Benefits were defined as the reduction in annual outflow. Neither the relative size of the spill nor the probability of zero outflow were considered when determining benefits.

   Only crude oil carriers 40,000 DWT and above were investigated in this study. Smaller tankers and barges should be investigated in the future.

10  CONCLUSION

A rational framework for quantifying the pollution prevention performance of tankers in accidental groundings and collisions, has been developed. The
significant ship design parameters that influence this performance have been discussed. A method has been proposed for combining the oil outflow characteristics of ship designs with the environmental effects of pollution. Finally, a recommendation is made for a performance based standard that combines the considerations for cost effectiveness, with the need for a high standard of pollution prevention.

Further, this paper further suggests areas of future study for a more mature, robust and technologically advanced approach to evaluating the pollution prevention characteristics of tanker design.

11 REFERENCES

APPENDIX A: OUL OUTFLOW CALCULATION RESULTS

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### Bold - fails to meet proposed Intact Stability Regulation I/25A

### Bold - fails to meet MARPOL 73/78 Regulations I/22-24 Hypothetical Outflow and Tank Size Criteria
<table>
<thead>
<tr>
<th></th>
<th>41K DWT (CO = 39,600 MT at 0.85 MT/m^3)</th>
<th>98K DWT (CO = 96,200 MT at 0.85 MT/m^3)</th>
<th>145K DWT (CO = 141,800 MT at 0.85 MT/m^3)</th>
<th>291K DWT (CO = 287,000 MT at 0.85 MT/m^3)</th>
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<td>10x1: <strong>0.86</strong> 0.95 0.93 0.90 0.99</td>
<td>9x2: <strong>0.92</strong> 1.07 1.09 0.97 1.17</td>
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<td>Prob. of zero outflow P_o</td>
<td>0.83 0.86 0.86 0.86 0.89</td>
<td>0.79 0.82 0.82 0.82 0.85</td>
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**Bold** fails to meet MARPOL 73/78 Regulation 25A - Intact Stability Criterion

- fails to meet MARPOL 73/78 Regulations 22-24 Hypothetical Outflow and Tank Size Criteria

Table A-2: SIMPLIFIED Oil Outflow Analysis Results
APPENDIX B

Charter of the SNAME Ad Hoc Panel

Background  IMO has developed analytical models for computing accidental oil outflow from tankers involved in groundings, strandings and collisions. Other environmental/economic models also exist to determine the environmental costs associated with accidental marine spills. These two types of models may be simplified and combined to create a framework for quantifying the environmental performance of tanker designs. Some initial steps are being taken towards this end in the form of studies, the results of which will be presented at the MARIENV '95 conference in September 95 (Tokyo).

Panel Goal  The task of the panel will be to critically evaluate the framework and in a decision paper for an international audience, develop a simplified measure to quantify tanker accidental oil outflow performance.

Schedule  
2. Initial Report - January 1996, for possible submission to the newly formed IMO subcommittee on Bulk Liquids and Gases (BLG) - BLG 1 March 1996.

Suggested Panel Membership Guidelines

1. SNAME members only, limited exceptions for special situations like overseas corresponding members.
2. Diverse group - operators, owners, designers, builders, regulators, environmentalists, transportation economists.
3. Active participation (technical analyses, data collection, reviewing information) will be required.
4. Participation will be entirely voluntary (similar to any T&R panel membership).

SNAME T&R Ad hoc panel process
The SNAME T&R Steering Committee, recognizing the need and the opportunity for the Society to provide technical input to problems of a topical nature had approved the formation of two “ad hoc” panels (the first on ro-ro safety, and the second on tanker intact stability). These two panels have been extremely successful, and the final results of the work of these two panels have been presented in Society journals and conferences.

In early 1995, some SNAME members felt the need for a third T&R ad hoc panel to study issues related to the accidental oil outflow from tankers. Accordingly, a panel charter was drafted and considered by the SNAME T&R Steering Committee at the full meeting of the Committee. The Committee approved the formation of the panel with Jaideep Sirkar as the Chairman.

The formation of the panel, and open invitations to serve on the panel was announced by the Chairman of the T&R Steering Committee, Thomas Mackey. The panel was formed and started its work in late summer 1995.

The following chronology notes significant dates in the work of the panel:

- **May 17, 1995** - Panel charter considered and approved by the T&R Steering Committee.
- **May-September, 1995** - Various announcements regarding formation of panel, including September 18, 1995 memo from Thomas Mackey to all SNAME Section Chairs and Regional V.P.s announcing formation of panel, and inviting participation.
- **October 4-5, 1995** - First Meeting of Panel, Washington D.C.
- **October 2, 1996** - Second Meeting of Panel, New York, NY.
- **October 2, 1996** - T&R Steering Committee approves panel proposal for T&R funding.
- **January 24, 1997** - Third Meeting of Panel, Cambridge, MA.

Oil Spill Data 1975-1996, the Coast Guard, edited by the National Academy of Science, National Research Council for NRC research.


