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SSC-424

EVALUATION OF ACCIDENTAL OIL SPILLS FROM BUNKER TANKS (PHASE I)

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2003

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EVALUATION OF ACCIDENTAL OIL SPILLS FROM BUNKER TANKS (PHASE I)

Recent collision, allision and grounding incidents in environmentally sensitive waters have raised public and industry awareness of the risk of oil spills from the bunker tanks of large freighters. Cargo ships do not have any requirements for protective location of bunker tanks, except that fuel oil tanks must be located aft of the collision bulkhead. Bunker oil, the generic term for the fuel used to power the vessel, is typically stored in tanks along the side shell and in the double bottom. In a collision or grounding accident, tanks in these locations are vulnerable to damage that would result in an oil spill.

Data for bunker spills in US, Canadian and international waters, for the last 15 years, provide statistics establishing the volume and frequency of these spills. For freighters greater than 1,600 GRT, structural integrity failures account for 3 % (in US waters) to 7 % (in US, Canadian and International waters) of the number of bunker oil spill incidents, and 29 % (in US waters) to 61 % (in US, Canadian and International waters) of the bunker oil volume spilled.

This report develops a probabilistic oil outflow methodology based on IMO guidelines and draft regulations. Performance is measured in terms of a non-dimensional mean oil outflow parameter (O_M). The method is then applied to calculate outflow for 25 different cargo ships (10 tankers, 6 containerships, 5 bulkers and 4 others), typical of vessels in US and Canadian waters. The results indicate a wide variation in performance in the fleet. Tank location with respect to the shell plating is a primary factor with location along the length as a secondary contributing factor. Modifying tank size and arrangements to achieve improved outflow performance may be possible. Improved performance comes with additional construction cost since the better performing bunker tank arrangements do not have tanks against the shell plating.

PAUL J. PLUTA
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

Recent collision, allision and grounding incidents, in environmentally sensitive waters, have raised public and industry awareness of the risk of oil spills from the bunker tanks of large cargo vessels. Cargo vessels do not have any requirements for protective location of bunker tanks, except that fuel oil tanks must be located aft of the collision bulkhead. Bunker oil, the generic term for the fuel used to power the vessel, is typically stored in tanks along the side shell and in the double bottom. In a collision or grounding accident, tanks in these locations are vulnerable to damage that would result in an oil spill.

Data for bunker spills in US, Canadian and international waters, for the last 15 years, provide statistics establishing the volume and frequency of these spills. For freighters greater than 1,600 GRT, structural failures accounted for 3 percent (in US waters) to 7 percent (in US, Canadian and International waters) of the number of bunker oil spill incidents, and 29 percent (in US waters) to 61 percent (in US, Canadian and International waters) of the bunker oil volume spilled.

This report develops a probabilistic oil outflow methodology based on IMO guidelines and draft regulations. Performance is measured in terms of a non-dimensional mean oil outflow parameter (O_M). The method is then applied to calculate outflow for 25 different cargo vessels (10 tankers, 6 containerships, 5 bulkers and 4 others), typical of vessels in US and Canadian waters. The results indicate a wide variation in performance in the fleet. Tank location with respect to the shell plating is a primary factor with location along the length as a secondary contributing factor. Modifying tank size and arrangements to achieve improved outflow performance may be possible. Improved performance will come at an additional cost, since the construction cost is generally greater for the better performing bunker tank arrangements that do not have tanks against the shell plating.

A detailed plan for a phase II study is presented. Depending on the results of phase II, it may be beneficial to implement a performance standard for bunker oil outflow for new bunker tank arrangements and designs.

17. Key Words oil spill, ship construction, ship building costs, tanker ships, accidents, bunker fuel, construction guideline, collision, grounding, allision, freighter, bulk carrier, oil pollution	18. Distribution Statement Distribution is available to the public through: National Technical Information Service U.S. Department of Commerce Springfield, VA 22151 Ph. (703) 487-4650

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CONVERSION FACTORS

(Approximate conversions to metric measures)

To convert from	To	Function	Value
LENGTH			
inches	Meters	divide	39.3701
inches	Millimeters	multiply by	25.4000
feet	Meters	divide by	3.2808
VOLUME			
cubic feet	cubic meters	divide by	35.3149
cubic inches	cubic meters	divide by	61,024
SECTION MODULUS			
inches^2 feet	centimeters^2 meters	multiply by	1.9665
inches^2 feet	centimeters^3	multiply by	196.6448
inches^3	centimeters^3	multiply by	16.3871
MOMENT OF INERTIA			
inches^2 feet^2	centimeters^2 meters^2	divide by	1.6684
inches^2 feet^2	centimeters^4	multiply by	5993.73
inches^4	centimeters^4	multiply by	41.623
FORCE OR MASS			
long tons	Tonne	multiply by	1.0160
long tons	Kilograms	multiply by	1016.047
pounds	Tonnes	divide by	2204.62
pounds	Kilograms	divide by	2.2046
pounds	Newtons	multiply by	4.4482
PRESSURE OR STRESS			
pounds/inch^2	Newtons/meter^2 (Pascals)	multiply by	6894.757
kilo pounds/inch^2	mega Newtons/meter^2 (mega Pascals)	multiply by	6.8947
BENDING OR TORQUE			
foot tons	meter tons	divide by	3.2291
foot pounds	kilogram meters	divide by	7.23285
foot pounds	Newton meters	multiply by	1.35582
ENERGY			
foot pounds	Joules	multiply by	1.355826
STRESS INTENSITY			
kilo pound/inch^2 inch$^{1/2}$(ksi$\sqrt{\text{in}}$)	mega Newton MNm$^{3/2}$	multiply by	1.0998
J-INTEGRAL			
kilo pound/inch	Joules/mm^2	multiply by	0.1753
kilo pound/inch	kilo Joules/m^2	multiply by	175.3
TEMPERATURE			
Degrees Fahrenheit	Degrees Celsius	subtract	32
		& divide by	1.8

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EXECUTIVE SUMMARY

Recent collision and grounding incidents, in environmentally sensitive waters and coastal areas, have raised public and industry awareness of the risk of oil spills from the bunker tanks of large freighters. Cargo vessels, such as tankers, bulk carriers, containerships, RO-RO's, cruise ships and other large commercial vessels, do not have any requirements placed on the location of bunker oil tanks, other than the MARPOL requirement that they must be located aft of the collision bulkhead. Bunker oil, the generic term for the fuel used to power and operate the vessel, is typically stored in tanks located along the side shell and in the double bottom. In a collision or grounding accident, bunker oil tanks in these locations are more vulnerable to damage that would result in an oil spill.

Examination of the data for bunker oil spills in US, Canadian and international waters, for the last 15 years, provides statistics establishing the volume and frequency of spills from bunker oil tanks. For freighters of greater than 1,600 GRT (excluding tankers), the bunker oil spill incident data were categorized as either a structural failure or as an operational failure. Structural failures are the type of failure that would be most affected by protective tank location or outflow performance requirements that may be developed in the future.

In US waters, structural failures accounted for 3 percent of the number of bunker spill incidents and 29 percent of the bunker spill volume from freighters. Worldwide, structural failures accounted for 7 percent of the spill incidents and 61 percent of the spill volume from freighters. In the overall context of marine oil spill volume in US waters, freighters accounted for 4 percent of the total from all sources in the post-OPA 90 time period from 1992-1997. Structural failures accounted for less than half of this spill volume or less than 2 percent of the total marine spill volume.

In a recent SNAME technical paper (Michel & Winslow, 2000), a probabilistic oil outflow procedure was used to assess the effectiveness of alternative bunker tank arrangements. This probabilistic methodology was further developed and documented in this report. The procedure is based on the International Maritime Organization (IMO) guidelines and draft regulations for evaluating accidental outflow for new tankers. Performance is measured in terms of a non-dimensional mean oil outflow parameter (O_M). The methodology was then applied in calculations of hypothetical bunker oil outflow for 25 different cargo vessels typical of those calling in US and Canadian waters.

The results of the probabilistic oil outflow analysis on the 25 vessels indicate a wide variation in performance in the existing fleet. Tank location with respect to the shell was a primary factor, with location along the length as a secondary contributing factor. Modifying tank size and arrangements to achieve improved outflow performance is undoubtedly possible. Improved outflow performance, however, will come at an additional cost since the relative cost is greater for arrangements that do not have bunker tanks against the shell plating.

Further study is needed, and a detailed plan for a phase II study was developed. It is recommended that the phase II study be conducted for a parametric series of vessel designs. The study should include outflow analysis for varying bunker tank arrangements and a cost benefit analysis. This will assist in the development of a rationally-based performance standard for oil outflow from bunker tanks in the event of a collision or grounding.

1.0 INTRODUCTION

The objective of this study was to assess the risk of oil spills from 'bunker' oil tanks of cargo vessels in the event of collision, allision and grounding; and evaluate alternatives to mitigate this risk. Hereafter, collisions and allisions are referred to jointly as 'collisions'. The term 'bunker' is used here in the general sense, as the fuel carried on board and used to power and operate a cargo vessel. The term 'cargo vessel' is intended to include tankers, containerships, bulkers, cruise ships, RO-RO's and other commercial cargo vessels of a size arbitrarily chosen as greater than 1,600 Gross Registered Tons (GRT). The term 'freighter' is intended to include all such vessels other than tankers and tank barges.

A review of historical data for spills from freighters in US water contained in a recent SNAME technical paper (Michel & Winslow, 2000) found that the spill rate for freighters was relatively low compared to tank barges and tankers. Following enactment of the Oil Pollution Act of 1990 (OPA 90), the spill volume from tankers decreased dramatically, effectively increasing the contributing fraction of the freighter oil volume spilled. Recently, freighter spills from 'collision' and grounding accidents (*Kure*, 1997 and *New Carissa*, 1999) have affected environmentally sensitive areas. This has moved the US Congress to initiate debate on the need for enhanced regulations concerning the carriage of bunker oil on commercial vessels.

There are currently no requirements for protectively locating bunker tanks within freighters. Regulation 13F of MARPOL 73/78 requires all new tankers above 5,000 DWT to have a double hull, a mid-deck, or an alternative arrangement approved by IMO. OPA 90 mandates double hull construction for all new tank vessels calling in US waters. However, both regulations apply only to cargo oil tanks, and any bunker fuel oil tanks located within the cargo tank length. The cargo tank length extends from the aft-most cargo tank boundary to the forward most cargo tank bulkhead. Since tankers typically have their bunker oil tanks arranged on each side of the engine room, these tanks can be located adjacent to the shell.

The work related to investigating the risk of bunker spills has been divided into two phases. The current work, phase I, includes:

- ☐ An assessment of US, Canadian and international data on the frequency and volume of spills from bunker tanks,
- ☐ Further development of a probabilistic oil outflow analysis methodology based on IMO guidelines and draft regulations (originally used in the SNAME technical paper by Michel & Winslow, 2000),
- ☐ Application of the method to a selection of freighters in a range of sizes and types typical of the vessels that frequent US and Canadian ports,
- ☐ A review of the relative costs of the bunker tank arrangements for these vessels,
- ☐ Development of a plan for a proposed phase II study where the data and methods prepared in phase I can be used to do a cost benefit analysis of possible new requirements for minimizing bunker tank oil spills.

2.0 ASSESSMENT OF BUNKER OIL SPILL DATA

2.1 BUNKER OIL SPILL DATA

Information related to accidental spills of bunker oils from marine vessels was collected to assess the quantity and frequency of bunker oil spills from cargo vessels. Bunker oil is the fuel carried on board and used to power and operate a freighter or other marine vessel. Common names for bunker fuels considered in this study include marine diesel oil, marine diesel medium, heavy fuel oil, residual fuel, bunker C, and fuel oil No. 2, No. 5 or No. 6. Crude oil spill data was not collected. The focus of this data search was on obtaining data for bunker oil spills resulting from structural failures of bunker tank boundaries for larger freighters typical of those calling in US and Canadian waters. These structural failures result from collisions, groundings, or 'other' structural failures that lead to spillage of bunker oil into the water. The 'other' structural failures includes leakage from cracking of the bunker oil tank boundary hull plating due to any reason (including structural fatigue cracking, poor structural details, or overloading of hull girder). Spills caused by structural failures are most likely to be affected by any new protective tank location or outflow performance requirements.

Upon review of the available data for tankers, it was determined that there was no practical way to separate spills of bunker oils carried as cargo, from spills of bunker oils used to fuel and operate the vessel. Bunker oil spills from tankers were therefore kept as a separate category. Data for tankers spilling crude oil cargoes were not included.

Data were collected for all types of marine bunker oil spills from all types of vessels in US, Canadian and international waters, by Dr. Etkin of Environmental Research Consulting. Fifteen years of data spanning from 1985-1999 were obtained and evaluated. The data sets for 1999 were not complete at the time of the search but relevant portions were included. This time frame provides sufficient data, to show the effect of implementing the Oil Pollution Act of 1990 (OPA 90).

For the 15-year period, data were collected for 10,579 marine spills of bunker oil for all types of vessels. The total volume spilled was 421,074 cubic meters. Figure 1 shows a breakdown of the volume and number of spills. Freighters greater than 1,600 GRT were indicated to be the source of 13 percent of the spill volume from 32 percent of the spill incidents.

2.1.1 US Bunker Oil Spill Data

Base data for US spills were obtained through the USCG MSIS Casualty Database, the National Response Center Database, and the Tanker Advisory Center. The information was collected in two groups, the first, for spills from all vessels other than tankers, and the second, for bunker spills associated with tankers. The non-tanker related set accounted for 9,740 spills while the tankers account for 367 bunker oil spills over the 15-year period. The records include all reported spills, including spills as small as a few gallons.

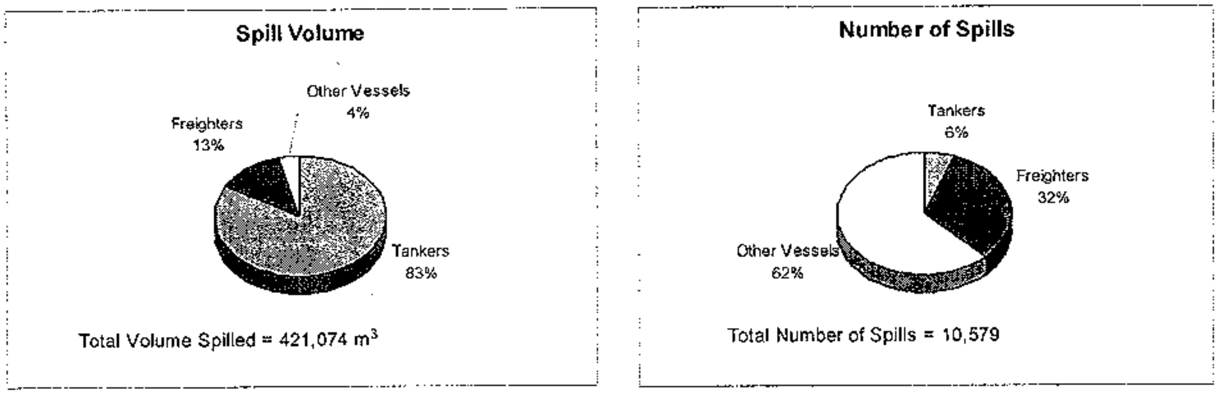


Figure 1 - US, Canadian and International Marine Bunker Oil Spills for 1985 to 1999

The data were inclusive of all spill types including operational spills (i.e. hose ruptures, accidental tank overflows, etc.) as well as spills related to structural failures. Operational failures were considered to include bunker oil spills associated with fueling operations (fuel hose break, tank overflow/overfill, inattention while fueling, valve malfunction) as well as weather related sinkings, operations in a war zone, capsizing and other miscellaneous spill causes.

Figure 2 shows a breakdown of the volume and number of spills gathered for bunker oil spills in US waters. For the 15-year period, data were collected for 10,107 US marine spills of bunker oil for all types of vessels. The total volume spilled was 19,632 cubic meters. Freighters greater than 1,600 GRT were indicated to be the source of 41 percent of the spill volume from 31 percent of the spill incidents.

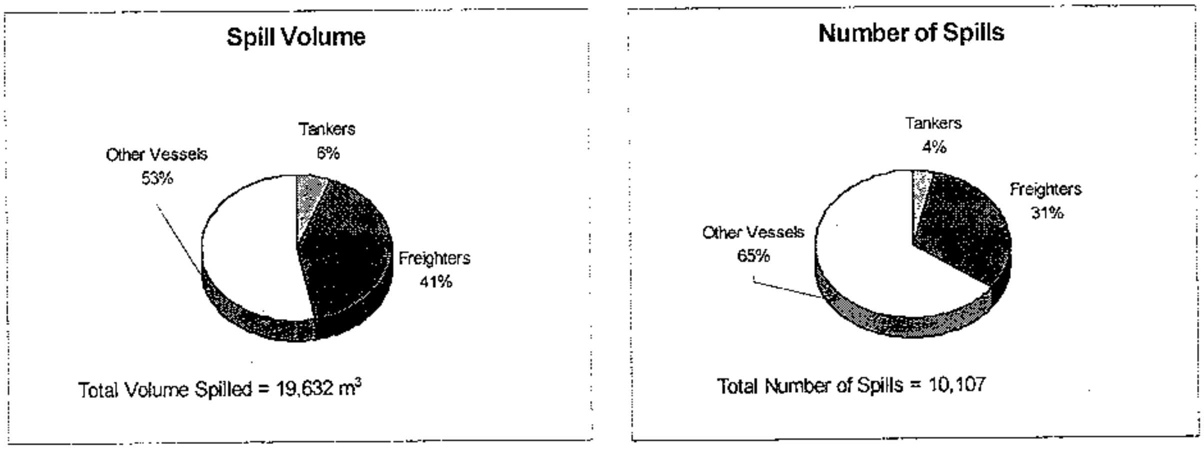


Figure 2 - US Marine Bunker Oil Spills for 1985 to 1999

2.1.2 International Bunker Oil Spill Data

International spills were generally not as extensively documented as the US spills, in the available databases. Most of the data contained in the databases does not include spills under 10,000 gallons (about 40 m^3). Base data for the international spills were developed from

Environmental Research Consulting's Database, Cutter Information Corporation's *Annual Statistical Summaries*, International Maritime Organization's GESAMP report on oil output and other published reports, *Oil Spill Intelligence Reports*, and the Tanker Advisory Center. Data related to bunker oil spills in Canadian waters were included in this database.

The information was collected in two groups, the first, for non-tanker related spills, accounted for 239 incidents, and the second, for the tanker related bunker oil spills, accounted for 233 incidents. The records include all spill types including operational spills (i.e. hose ruptures, etc.) and spills due to structural failures.

Figure 3 shows a breakdown of the volume and number of bunker oil spills in international waters (excluding the US). For the 15-year period, data were collected for 472 marine spills of bunker oil for all types of vessels. The total volume spilled was 401,442 cubic meters. Freighters greater than 1,600 GRT were indicated to be the source of 11 percent of the spill volume from 42 percent of the spill incidents.

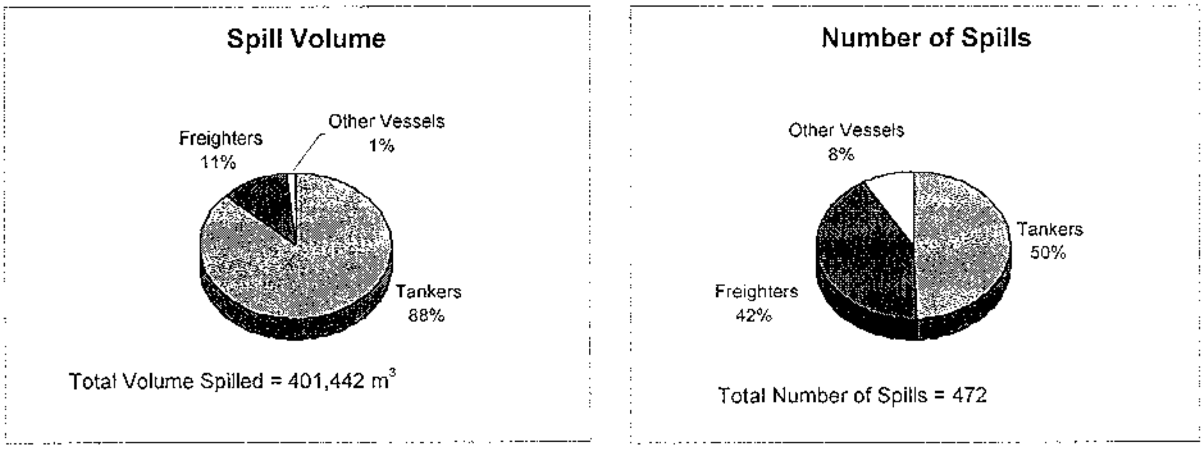


Figure 3 - International (excluding US) Marine Bunker Oil Spills for 1985 to 1999

2.2 BUNKER OIL SPILL DATA ANALYSIS

The information was analyzed to provide answers to two specific questions. What was the frequency of bunker oil spills associated with failure of the structural integrity of the bunker oil tanks for freighters of greater than 1,600 GRT? And, what was the quantity spilled in relation to these failures? These questions were answered by first focusing on the spill incidents for freighters in the collected data and sorting the data records for causes related to structural failures of the bunker oil tank boundaries. Tanker data were not included, as noted before, since it was not possible to determine from the spill data whether the spill source was the vessel's own bunker oil tanks or the vessel's cargo tanks.

The data for freighters were sorted into two categories, structural failures and operational failures, as defined previously. The results of this categorization are shown in Figures 4 and 5. Figure 4 shows the breakdown of the spills from freighters of greater than 1,600 GRT in US waters. Freighters were the source of 3,170 bunker oil spills with a total of 9,493 cubic meters spilled. Structural failures account for only 3 percent of the number of spills but were the source of 29 percent of the volume of bunker oil spills from freighters in US waters.

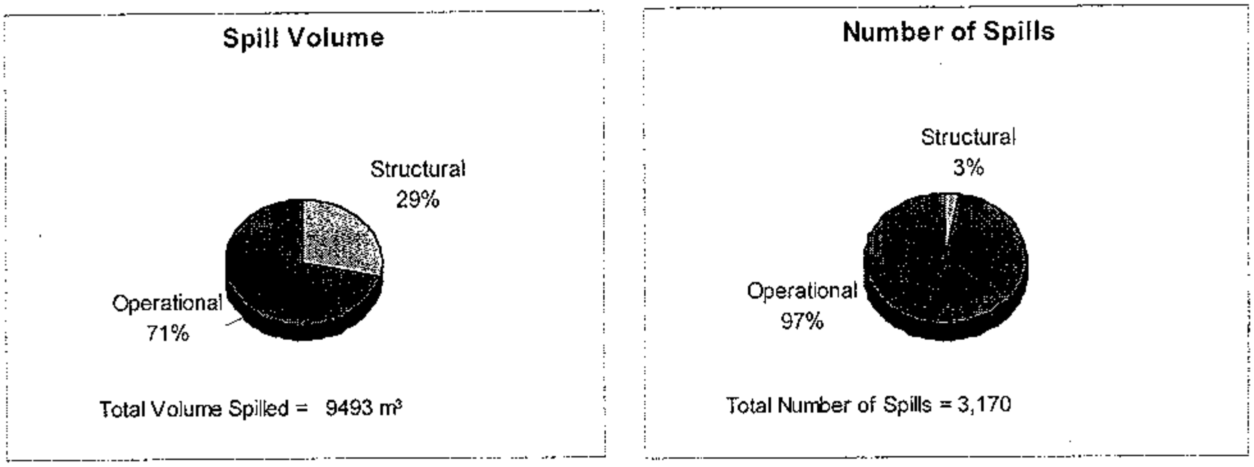


Figure 4 - Bunker Oil Spills in US Waters for Freighters

Figure 5 adds the Canadian and International data to the US data for freighters greater than 1,600 GRT. Worldwide, freighters were the source of 3,369 bunker oils spills with a total of 55,349 cubic meters spilled. Structural failures account for only 7 percent of the number of spills, but were the source of 61 percent of the volume of bunker oil spills reported from freighters around the world for 1985 to 1999.

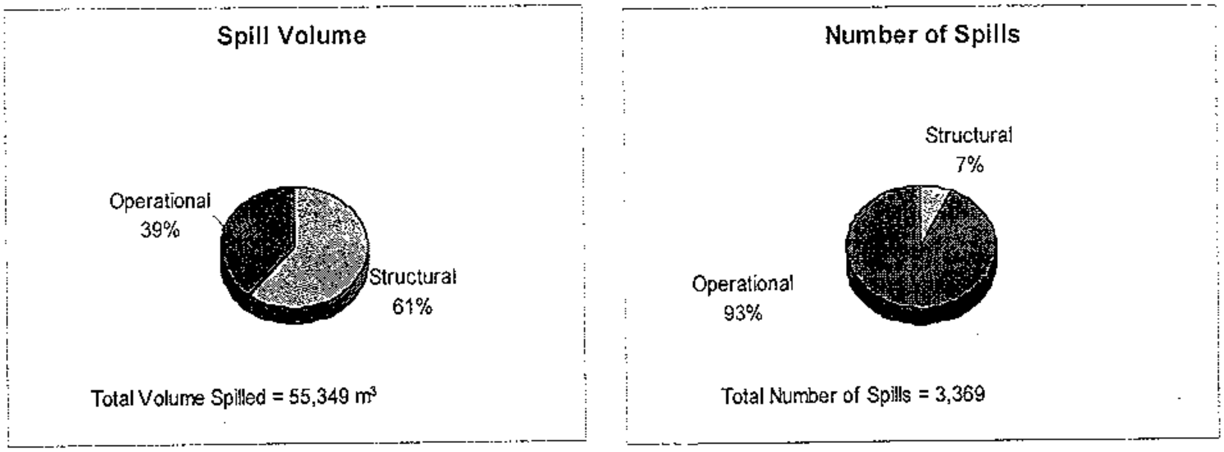


Figure 5 - Bunker Oil Spills in US and International Waters for Freighters

For freighters in US waters the average spill size was about 3 m^3 per spill. This value was significantly lower then the 230 m^3 per international spill. As noted earlier, the reason for the difference was attributed to the variation in data collection methods. The US records include spills as small as a few gallons and the international data only contains larger spill records.

The frequency of structural failures of freighter bunker oil tanks and the volume of the associated bunker oil spills are shown in Figures 6 and 7, by year, for the time period of 1985 to 1999. Note that the 1999 records were incomplete due to the timing of the data search. Figure 6 shows the number of spills and the volume spilled from freighter structural failure incidents in US waters. The data does not include any tanker related incidents, but it is interesting to note the significant drop in the number of spills per year, after the Oil Pollution Act of 1990 went into effect.

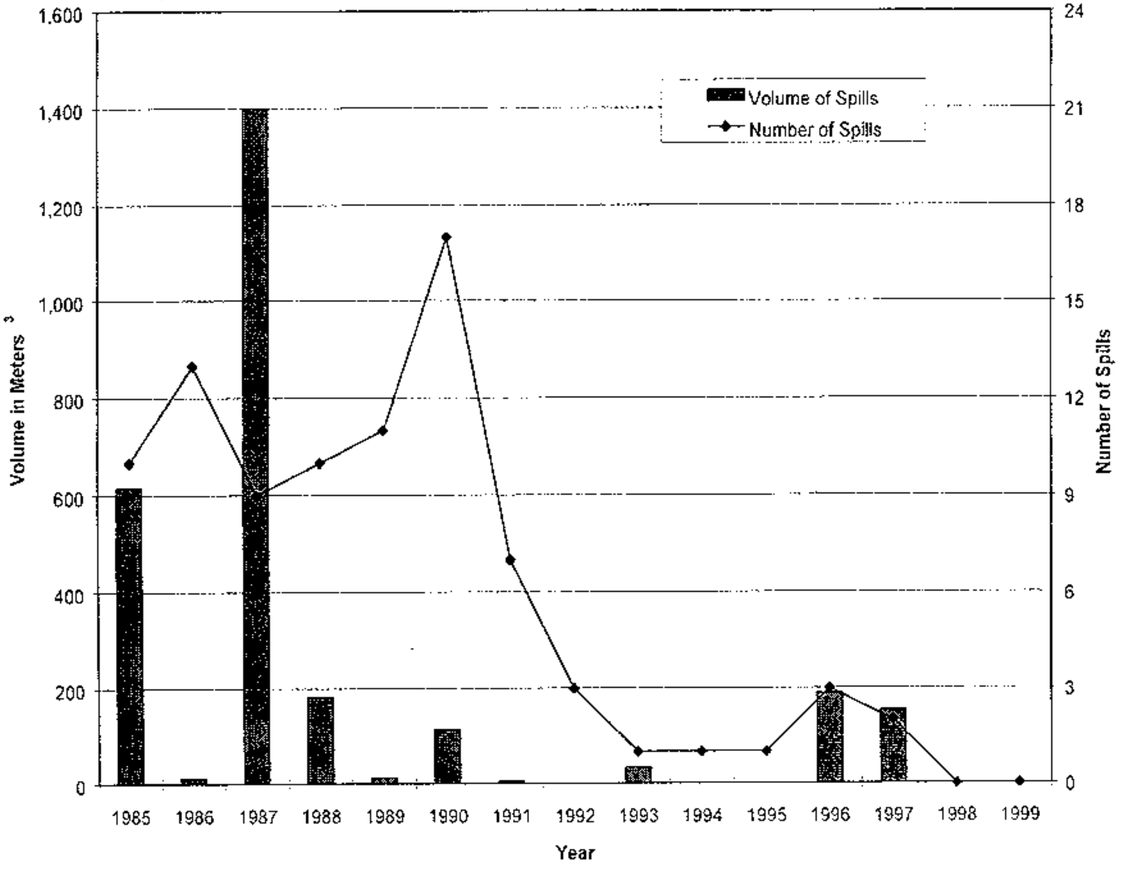


Figure 6 - Frequency and Volume of Bunker Oil Spills in US Waters from Structural Failures in Freighters

Figure 7 shows the number of spills and the associated volumes for freighter structural failure incidents in waters outside of the US from 1985 to 1999. The data shows that the average annual spillage from structural incidents was about 2000 m^3. The trend in the number of such spills seems to be increasing slightly, with the last four years prior to 1999, at or above 12 incidents per year. The years prior to 1995 showed an average of less than 9 incidents per year. However, the international database was not as complete a representation of worldwide spills as the US database and care must be taken when drawing conclusions.

In Tables 1 and 2, the freighter structural failure spill category was sorted by cause. The data were broken out for spills due to allisions, collisions, groundings and 'other' structural related causes. Table 1 contains the records for spills from freighters in US waters and Table 2 contains the records for spills in international waters (including Canada but without the US).

Figure 8 provides a combined summary of the cause data for US and international waters, for the volume and number of spills associated with the freighter structural failure category. Grounding and collision account for more than 50 percent of the incidents and almost 80 percent of the spill volume.

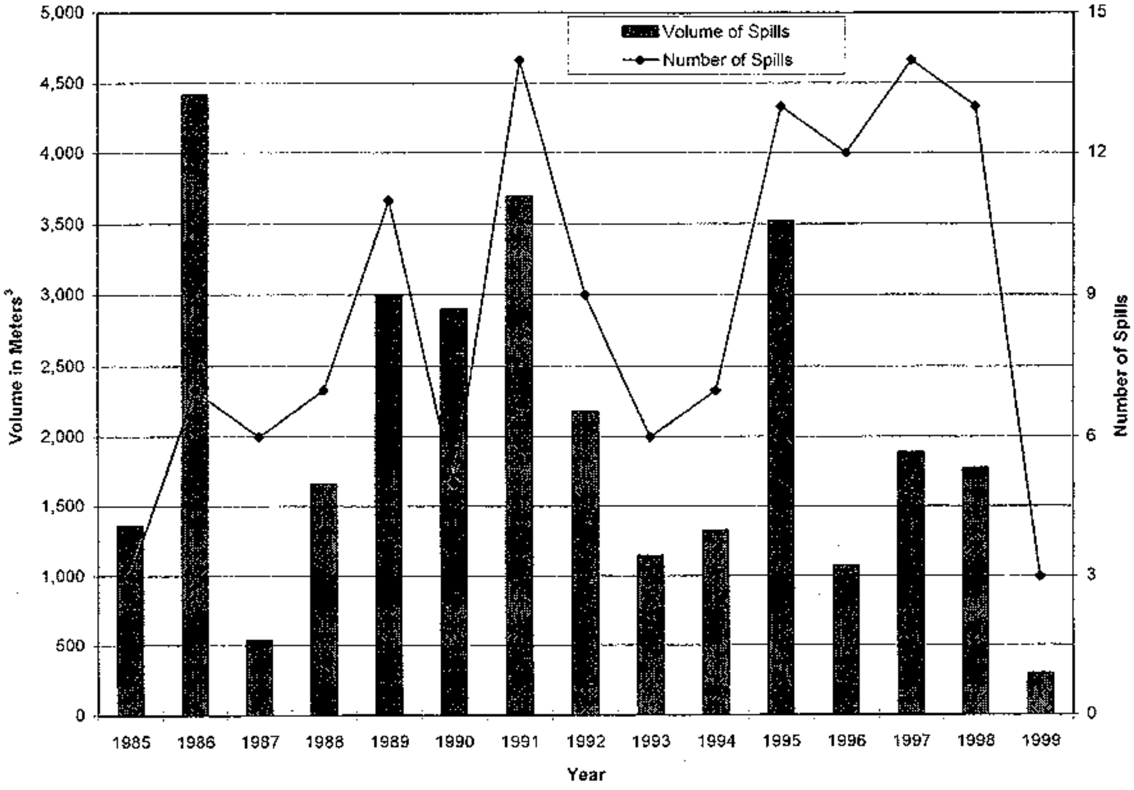


Figure 7 - Frequency and Volume of Bunker Oil Spills Outside of US Waters from Structural Failures in Freighters

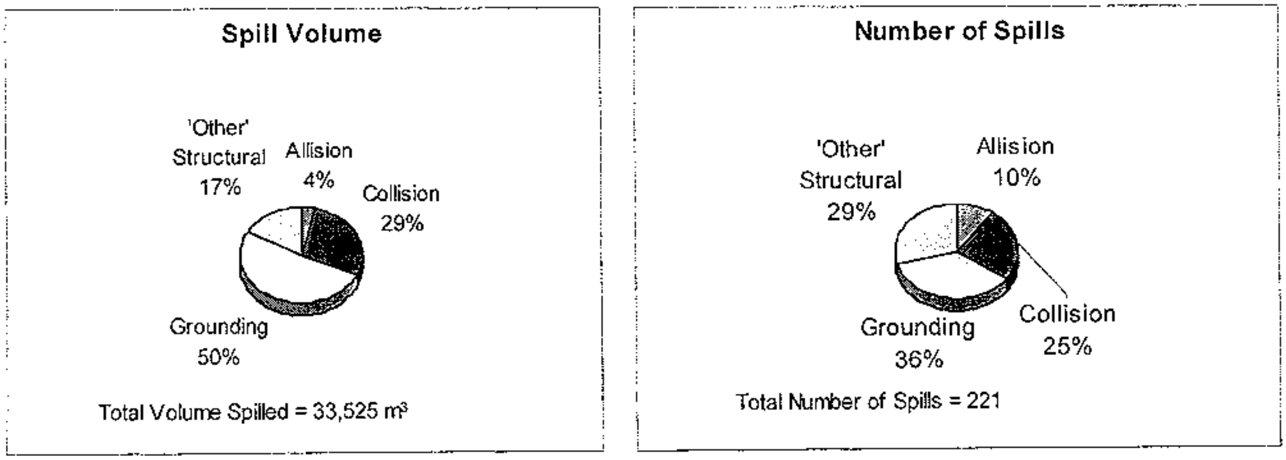


Figure 8 - Bunker Oil Spills from Structural Failures in US and International Waters for Freighters

	Total Vessels US							
	Allision		Collision		Grounding		Structural	
	#	Volume (m^3)	#	Volume (m^3)	#	Volume (m^3)	#	Volume (m^3)
1985	0	0	0	0	5	615	5	1
1986	0	0	3	1	2	1	8	10
1987	0	0	2	1,397	0	0	7	2
1988	0	0	3	0.06	1	6	6	177
1989	0	0	1	0.04	3	9	7	2
1990	0	0	6	55	2	29	9	31
1991	0	0	1	2	2	0.45	4	3
1992	1	0.01	0	0	1	0.04	1	0.06
1993	0	0	1	34	0	0	0	0
1994	0	0	0	0	0	0	1	0.38
1995	0	0	0	0	1	0.19	0	0
1996	2	189	0	0	1	0.004	0	0
1997	1	3	0	0	1	151	0	0
1998	0	0	0	0	0	0	0	0
1999	0	0	0	0	0	0	0	0
TOTAL	4	192	17	1,489	19	812	48	226

Table 1 - Freighter Structural Failure Related Bunker Oil Spills in US Waters

	Total Vessels International w/o US							
	Allision		Collision		Grounding		'Other' Structural	
Year	#	Volume (m^3)	#	Volume (m^3)	#	Volume (m^3)	#	Volume (m^3)
1985	0	0	0	0	3	1,359	0	0
1986	1	49	2	1,772	4	2,597	0	0
1987	0	0	3	179	3	363	0	0
1988	0	0	4	715	3	946	0	0
1989	2	254	1	545	7	2,200	1	1
1990	1	38	1	110	1	1,836	2	917
1991	5	281	2	121	3	785	4	2,511
1992	2	145	3	946	4	1,094	0	0
1993	1	49	2	416	3	681	0	0
1994	0	0	5	1,046	2	282	0	0
1995	0	0	4	1,703	5	981	4	838
1996	0	0	6	238	5	836	1	1
1997	1	1	2	130	9	1,547	2	212
1998	3	150	3	185	5	556	2	886
1999	2	46	0	0	1	254	0	0
TOTAL	18	1,013	38	8,107	58	16,318	16	5,366

Table 2 - Freighter Structural Failure Related Bunker Oil Spills in International Waters w/o US

2.3 BUNKER OIL TANK SPILL DATA ASSESSMENT SUMMARY

Accidental spill data for bunker oil from marine vessels have been collected for the period from 1985 to 1999 for over 10,500 spill incidents including 472 incidents in international waters. The worldwide bunker oil spill volume for all vessel types was 421,074 m^3 for this time period. Freighters of greater than 1,600 GRT were involved in about 32 percent of the incidents and accounted for 13 percent of the spill volume worldwide (including US, Canadian and international data). Tankers were counted separately since there was no practical way to separate the bunker oil carried as cargo from the vessel's own bunker oil fuel. Tankers accounted for 6 percent of the incidents and 83 percent of the bunker oil spill volume worldwide. The remaining 62 percent of the incidents and 4 percent of the volume were attributed to the 'other' vessel category (tugs, fishing vessels, small craft, etc.).

In US waters, for the same time period, only 19,632 m^3 of bunker oils were spilled for all vessel types. Freighters of greater than 1,600 GRT accounted for 41 percent of the volume and 31 percent of the incidents. Tankers accounted for 6 percent of the volume and 4 percent of the incidents in US waters. The remaining 53 percent of the volume and 65 percent of the bunker spill incidents were from the 'other' vessel category.

Further review of the performance of freighters in bunker oil spills in US waters indicates that almost 30 percent of the volume spilled involved a bunker tank structural failure. These failures include spills from 'collisions', groundings and 'other' structural failures. When the data for waters outside the US were added, structural failures account for about 61 percent of the bunker oil spill volume from freighters and 7 percent of the incidents. Of this spill volume, 83 percent comes from incidents involving 'collisions' and groundings.

In US waters, bunker spills due to structural failure in freighters averaged about 389 m^3/per year for the period of 1985-1990. Following the implementation of OPA 90, the volume dropped to about 42 m^3/year during the period from 1991-1999.

In order to maintain a proper perspective, it is important to note that the volume of bunker oil spilled from freighters represents 4 percent of the oil spill volume in US waters, from all sources from 1992-1997 (Michel & Winslow, 2000). Considering that over the longer term of the full data set, 30 percent of freighter spills were due to a structural failure (Figure 4), then one could extrapolate that the spill volume affected by a change in design approach (protectively locating bunker tanks, etc.), would be less then 2 percent of the US oil spill volume for the same post OPA 90 time period.

However, a number of recent spills have demonstrated that even relatively small spills can lead to a significant impact to the environment and sizable cleanup costs (Michel & Winslow, 2000). The frequency and volume of these spills could be reduced by incorporating design methodologies and practices that locate bunker oil tanks in freighters in protected locations (from collision or grounding damage), by incorporating a double hull bunker tank configuration, or by locating tanks using a performance-based, probabilistic approach.

3.0 PROBABILISTIC OIL OUTFLOW ANALYSIS

A methodology for probabilistic oil outflow analysis from bunker tanks was developed and then exercised on a set of ships typical of those calling in US and Canadian waters. The *Accidental Outflow Performance Guideline Related to Spills from Bunker Tanks* (hereafter referred to as the "Simplified Approach") is given in Appendix A. A second set of calculations utilizing the computer program HECSALV (hereafter referred to as the "Direct Approach") were performed for validation purposes.

3.1 PROBABILISTIC OIL OUTFLOW METHODOLOGY

3.1.1 Overview of IMO Probabilistic Oil Outflow Regulations

IMO has adopted interim guidelines that describe the procedures for obtaining approval of alternative tanker designs to the double hull standard (IMO, 1997). These guidelines employ a rigorous probabilistic approach for computing the oil outflow in accidental groundings and collisions, and provide for the calculation of a "pollution prevention index" for comparison with a series of "reference" double hulls. This index incorporates three characteristics of the oil outflow performance of any tanker: the probability of zero outflow, mean outflow, and extreme outflow.

- The *probability of zero outflow* represents the likelihood that no oil will be released into the environment, given a collision or grounding casualty which breaches the outer hull.
- The *mean outflow parameter* is the non-dimensionalized mean or expected outflow.
- The *extreme outflow parameter* is the non-dimensionalized extreme outflow, and provides an indication of the expected oil outflow from particularly severe casualties.

The determination of damage cases and their associated probabilities of occurrence was achieved through direct application of a set of probability density distribution functions (pdf's), which were derived from tanker accident statistics. The evaluation of a tanker design with this methodology is a calculation intensive effort. Although such a sophisticated approach was considered necessary for evaluating the possible complexities of alternative arrangements, IMO is pursuing a simplified outflow analysis approach to replace the current hypothetical outflow regulations 22-24 of MARPOL. The latest version of this new draft regulation was published as BLG5/WP4, "Proposed MARPOL Annex I Regulation 22: Accidental Oil Outflow Performance" (IMO, 2000).

The primary difference between the IMO interim guidelines and the draft Regulation 22 is in the assessment of damage cases. With the IMO guidelines, all possible combinations of damaged compartments together with their probabilities of occurrence were determined. For the simplified approach presented in draft Regulation 22, 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. The simplified approach contained in draft Regulation 22 provides for calculation of only the mean outflow parameter, and therefore tanker designs would be compared on this basis alone. It is assumed that the double hull provisions of MARPOL Regulation 13F assure adequate protection against the likelihood of spills, and therefore evaluation of the probability of zero outflow is not necessary.

The simplified approach to oil outflow presented in draft Regulation 22 is straightforward and can readily be carried out on a spreadsheet. References (Michel et al, 1996 and Sirkar et al, 1997) provide further background on the assumptions and calculation procedures.

3.1.2 Probabilistic Oil Outflow Analysis for Bunker Tanks (Simplified Approach)

The methodology for performing the bunker outflow calculations is briefly explained herein. The detailed description is contained in Appendix A. The basis of the algorithms for the bunker tank analysis was derived from the draft IMO MARPOL Annex I Regulation 22, "Accidental Oil Outflow Performance" (IMO, 2000). Similar to the draft MARPOL regulation, the bunker spill analysis assesses environmental performance based on a non-dimensional mean oil outflow parameter (O_M). The principal changes made to the IMO draft regulation to suit application to bunker tanks were as follows:

a) The Bunker Outflow Guideline was applied only to fuel tanks, and only to tanks greater than 100 m^3 in size. As discussed in Appendix B, ships with less than 100 m^3 of bunkers are typically under 50 meters in length. This study concentrates on larger cargo vessels. However, it is recognized that vessels with bunker tanks less than 100m^3 (26,416 gallons) in capacity can pose a significant risk to the environment, and may merit further consideration in the future.

b) Whereas tankers were evaluated at their full load draft, the bunker spill analysis was carried out at a partial loadline draught, equal to the lightship draft plus 60 percent of the difference between the lightship draught and the loadline draught.

c) The nominal density of the bunker oil was taken as 1.0 t/m^3.

d) Whereas tankers were assumed to have a nominal 0.05 bar inert gas pressure on the tops of the tanks, the bunker tanks were assumed to be at atmospheric conditions.

e) The Tanker Outflow Criterion allows reduction in outflow for cargo oil that may be entrapped within the double hulls. This was not accounted for in the Bunker Outflow Guideline.

f) The "Table of probabilities for side damage" presented in paragraph (8)(c) of the performance guideline (Appendix A) was developed from probability density functions based on historical cargo ship collision data. Appendix B provides background information related to the derivation of these functions. Historical damage data were not available for cargo ship groundings, and therefore the "Table of probabilities for bottom damage" presented in paragraph (9)(c) of the performance guideline was taken directly from draft IMO MARPOL Annex I Regulation 22. This table was based on casualty statistics for tankers only, and should be updated when data for cargo ship groundings become available.

g) A target level for the mean outflow parameter standard presented in paragraph (3) of the performance guideline (Appendix A) was tentatively set to 0.04.

The probability distributions for damage extents of the side and the bottom of the hull were prepared in tabular form. These tables were applied against the extreme boundaries of each bunker tank (i.e., the aft most bound, the forward most bound, the closest point to the side shell, etc.), to calculate the probability of damage penetrating into the bunker tank. It was assumed that side damage results in total oil outflow and bottom damage results in oil loss based on hydrostatic properties. The product of a tank's probability of damage and the associated outflow were summed across all tanks to obtain the mean outflow.

Each of the tanks was evaluated with respect to probabilistic bottom and side damage. Outflow for bottom damage was computed for two conditions, a 0.0 meter tidal change and a 2.5 meter tidal drop. The aggregated mean oil outflow from bottom damage was determined by adding 70 percent of the mean outflow with a 0 m tide and 30 percent of the mean outflow calculated for a minus 2.5 m tide. The mean outflow parameter was determined by adding 40 percent of the mean outflow for side damage (m^3) and 60 percent of the mean outflow for bottom damage (m^3) and dividing by the total volume of bunker oil (m^3).

3.1.3 Probabilistic Oil Outflow Analysis for Bunker Tanks (Direct Approach)

The Herbert Engineering Corp. computer program HECSALV enables direct application of probability density distribution functions to a vessel's compartmentation. Calculations were run on HECSALV directly applying the pdf's described in Appendix B. All other assumptions were as defined in the performance guideline presented in Appendix A. The mean outflow parameters were then calculated using this approach.

3.2 BUNKER TANK OIL OUTFLOW ANALYSIS

Twenty-five vessels were analyzed. The vessels were representative of those calling in US and Canadian waters. The bunker tank oil outflow analysis found that the Simplified Approach (Appendix A), provided results that were not significantly different than the mean oil outflow values developed with the computer program HECSALV and the Direct Approach. The results of both sets of analyses are discussed below.

3.2.1 Vessel Selection

A selection of vessels that encompassed a cross section of those calling in US and Canadian waters was required. The vessels needed to be representative of the types and sizes of vessels and additionally, representative of the variety of bunker tank arrangements currently in service.

The vessels chosen included 10 tankers (2 x VLCC, 3 x Suezmax, 2 x Aframax, & 3 x Panamax); 6 container ships (1 x Post- Panamax, 2 x Panamax, & 3 x Feedership); 5 Bulk carriers (1 x Capesize, 1 x Panamax, and 3 x Handysize); and 4 other vessels (1 x LNG carrier, 1 x Livestock carrier, 1 x RO/RO vessel, & 1 x Cruise ship). Descriptions of the bunker tank arrangements are included in Appendix C, and schematics of the tank arrangements are shown in Figures 9 to 12.

Table 3 provides more detailed information concerning the ships selected for this study.

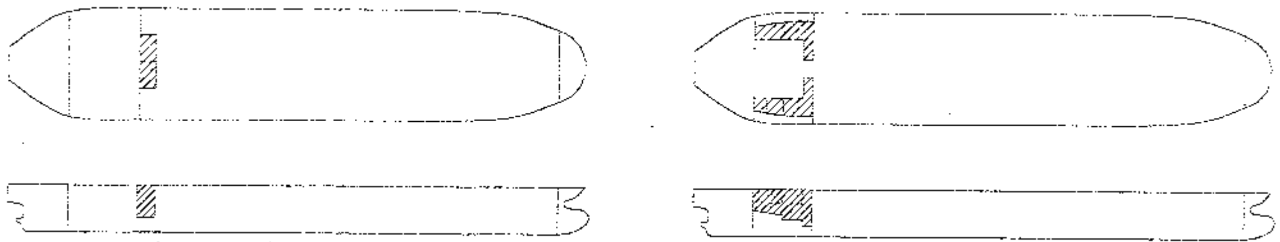
ID #	Ship Type	Deadweight (M.Tons)	No. of Bunker Tks >100 m3 in volume	Bunker Tk Capacity (98% Full) (m3)
T1	Tanker (Panamax)	46,000	2	1,070
T2	Tanker (Aframax)	82,000	5	2,312
T3	Tanker (Suezmax)	121,000	6	4,528
T4	Tanker (Suezmax)	151,000	6	4,074
T5	Tanker (VLCC)	300,000	7	8,759
T6	Tanker (VLCC)	306,000	8	7,896
T7	Tanker (Panamax)	40,000	3	1,892
T8	Tanker (Panamax)	37,000	3	2,211
T9	Tanker (Aframax)	85,000	5	2,849
T10	Tanker (Suezmax)	136,000	5	4,659
C1	Containership (Post-Panamax)	55,000	16	7,801
C2	Containership (Panamax)	36,000	12	5,253
C3	Containership (Panamax)	29,000	8	2,838
C4	Containership (Feedership)	11,000	4	933
C5	Containership (Feedership)	25,000	12	4,043
C6	Containership (Feedership)	15,000	8	2,293
O1	LNG Carrier	72,000	9	7,020
O2	Livestock Carrier	23,000	13	3,229
O3	Ro-Ro Vessel	28,000	9	8,314
O4	Cruise Ship	9,000	10	2,560
B1	Bulk Carrier (Capesize)	161,000	4	4,728
B2	Bulk Carrier (Handysize)	28,000	5	1,633
B3	Bulk Carrier (Handysize)	25,000	3	1,379
B4	Bulk Carrier (Panamax)	45,000	8	2,437
B5	Bulk Carrier (Handysize)	31,000	3	338

Table 3 - Description of Selected Vessels

3.2.2 Oil Outflow Results

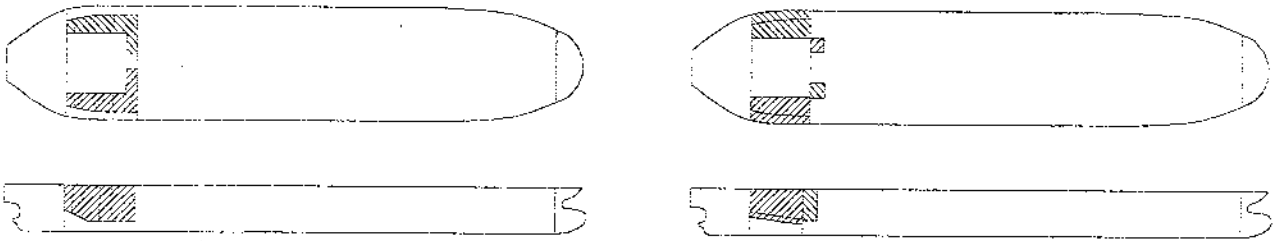
Results from the proposed methodology and direct approach using HECSALV are presented. The mean oil outflow parameter from the two methods are summarized, along with the probability of zero outflow obtained through the direct approach.

A spreadsheet was developed, based on the algorithms contained in the Simplified Approach (Appendix A), to calculate the mean oil outflow associated with each vessel chosen for the study. A sample calculation is contained in Appendix D.



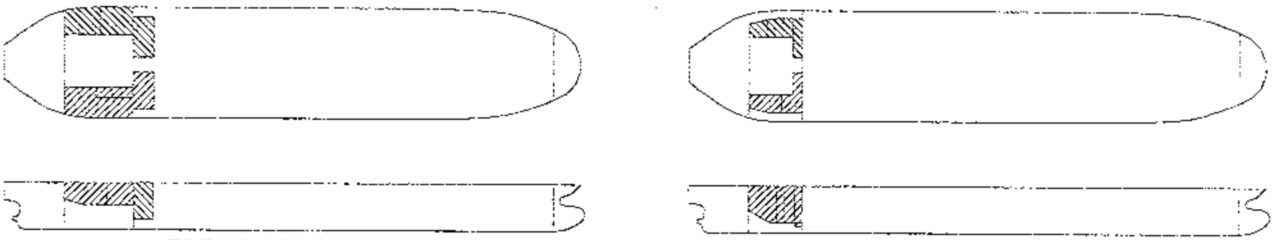
T1 Tanker (Panamax)

T2 Tanker (Aframax)



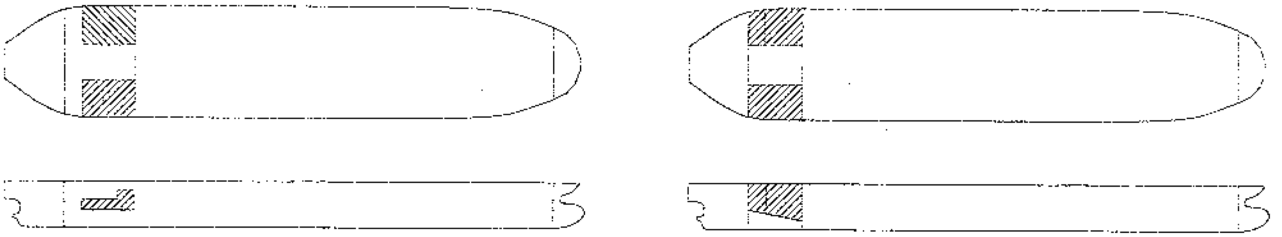
T3 Tanker (Suezmax)

T4 Tanker (Suezmax)



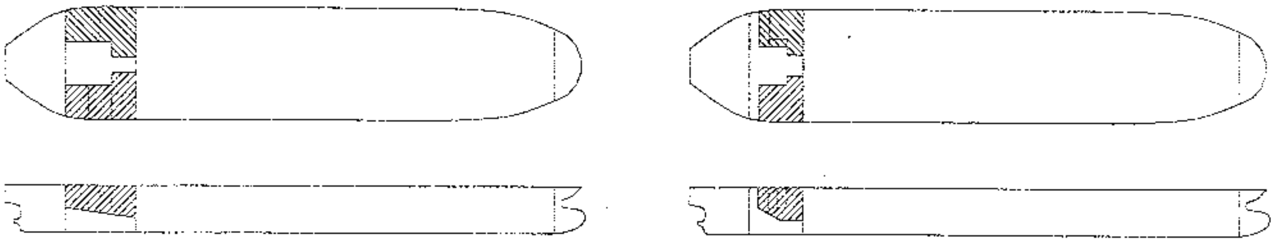
T5 Tanker (VLCC)

T6 Tanker (VLCC)



T7 Tanker (Panamax)

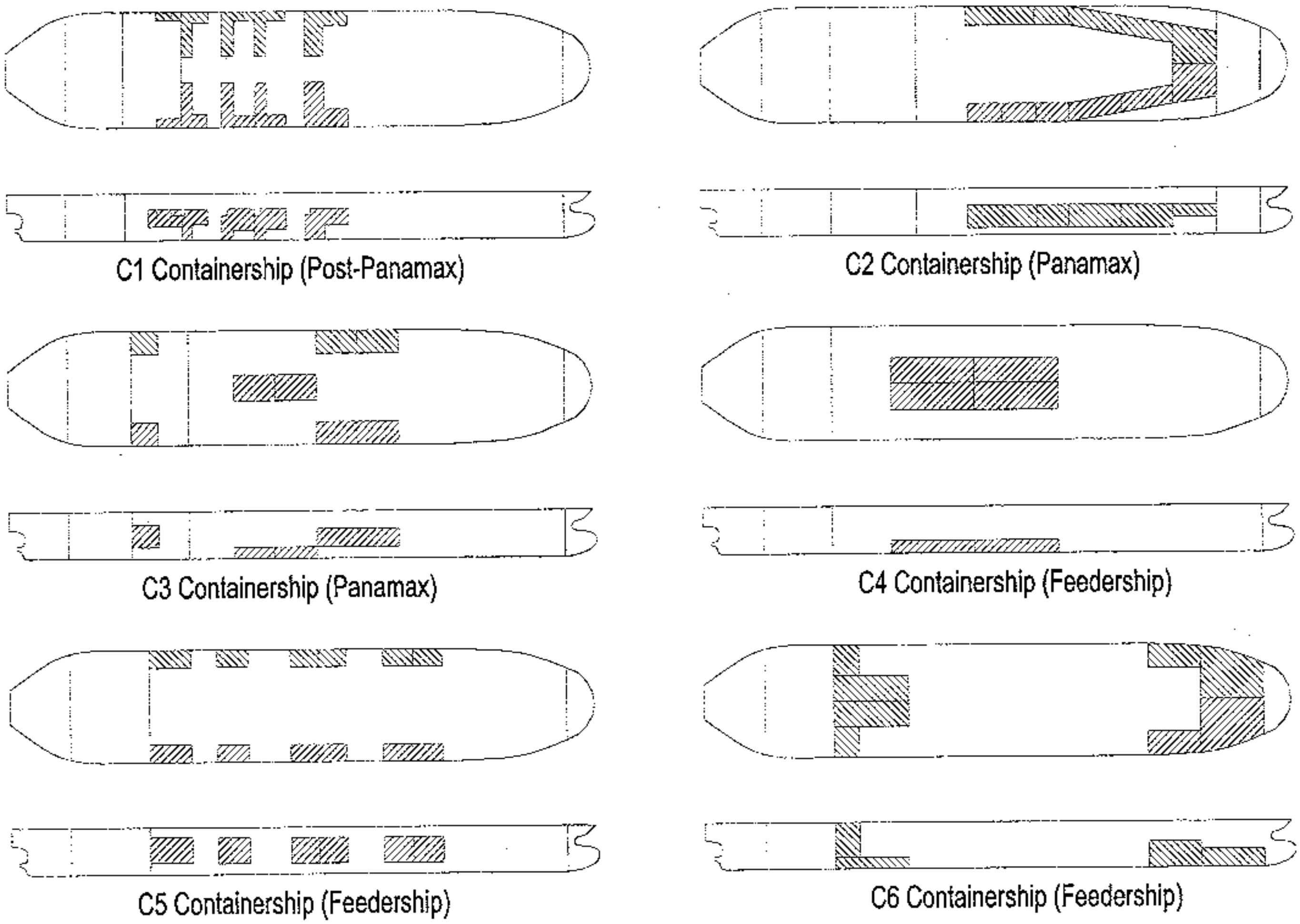
T8 Tanker (Panamax)



T9 Tanker (Aframax)

T10 Tanker (Suezmax)

Figure 9 - Schematics Of Bunker Tank Arrangements (1 of 4)



C1 Containership (Post-Panamax)

C2 Containership (Panamax)

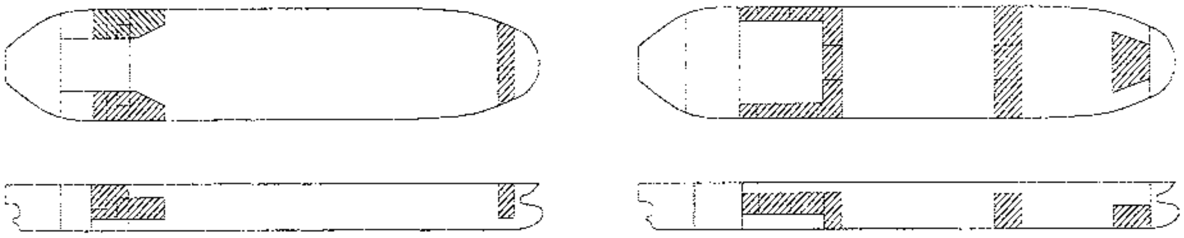
C3 Containership (Panamax)

C4 Containership (Feedership)

C5 Containership (Feedership)

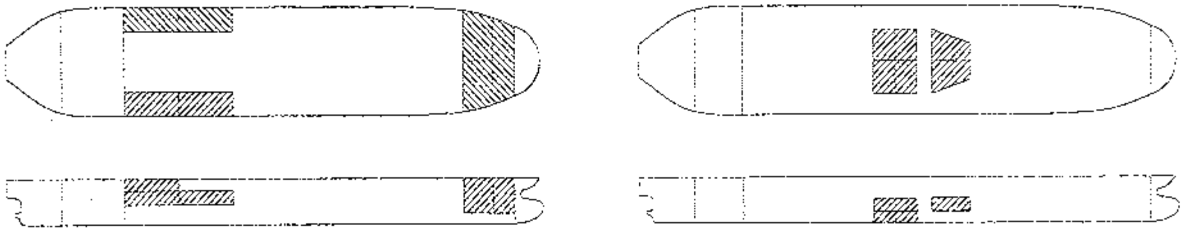
C6 Containership (Feedership)

Figure 10 - Schematics Of Bunker Tank Arrangements (2 of 4)



O1 LNG Carrier

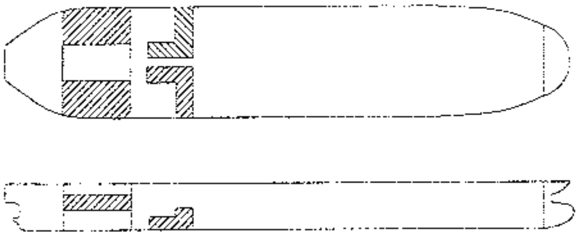
O2 Livestock Carrier



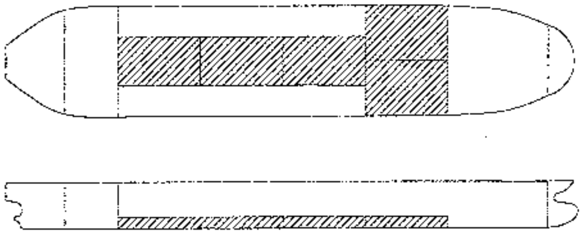
O3 Ro-Ro Vessel

O4 Cruise Ship

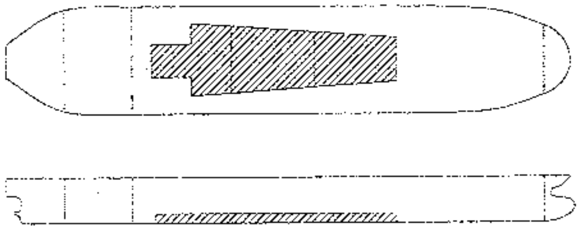
Figure 11 - Schematics Of Bunker Tank Arrangements (3 of 4)



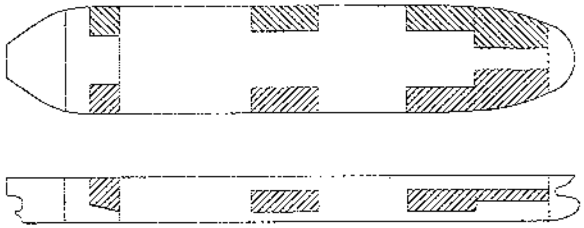
B1 Bulk Carrier (Capesize)



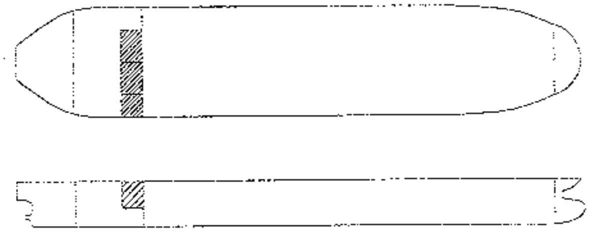
B2 Bulk Carrier (Handysize)



B3 Bulk Carrier (Handysize)



B4 Bulk Carrier (Panamax)



B5 Bulk Carrier (Handysize)

Figure 12 - Schematics Of Bunker Tank Arrangements (4 of 4)

A summary of the mean oil outflows versus deadweight for each vessel type is provided in Figure 13. The results of the simplified oil outflow analysis are provided in tabular format in Table 4 below.

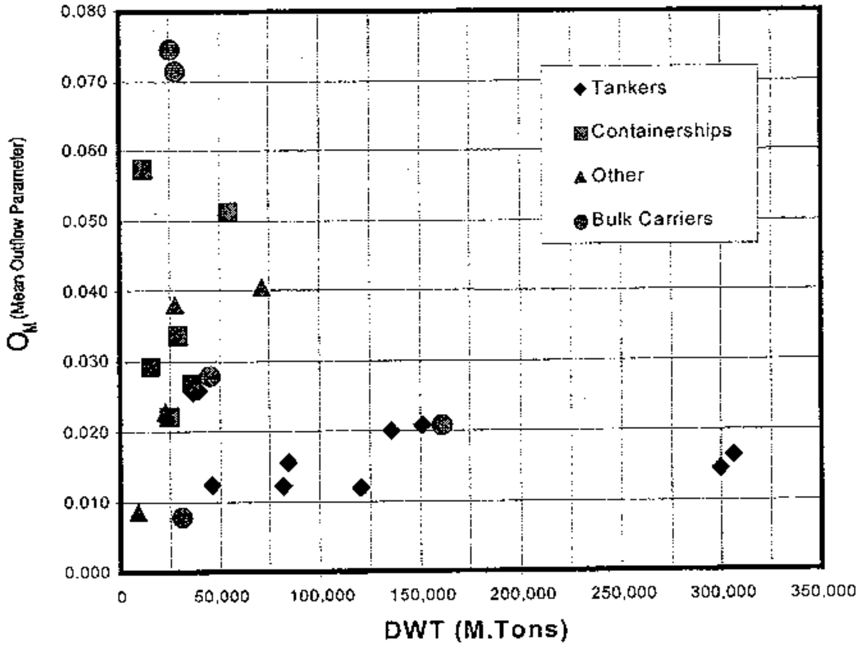


Figure 13 - Mean Oil Outflow versus DWT (Simplified Approach)

ID #	Ship Type	Deadweight M.Tons	Fuel Oil Capacity at 98% Filling M.Tons	Mean Outflow m^3	O_M	Average by Ship Type O_M
T1	Tanker (Panamax)	46,000	1,070	13.3	0.012	0.018
T2	Tanker (Aframax)	82,000	2,312	28.7	0.012	
T3	Tanker (Suezmax)	121,000	4,528	54.4	0.012	
T4	Tanker (Suezmax)	151,000	4,074	84.9	0.021	
T5	Tanker (VLCC)	300,000	8,759	127.4	0.015	
T6	Tanker (VLCC)	306,000	7,896	130.1	0.016	
T7	Tanker (Panamax)	40,000	1,892	48.9	0.026	
T8	Tanker (Panamax)	37,000	2,211	56.4	0.026	
T9	Tanker (Aframax)	85,000	2,849	44.5	0.016	
T10	Tanker (Suezmax)	136,000	4,659	93.1	0.020	
C1	Containership (Post-Panamax)	55,000	7,801	400.8	0.051	0.037
C2	Containership (Panamax)	36,000	5,253	142.2	0.027	
C3	Containership (Panamax)	29,000	2,838	95.7	0.034	
C4	Containership (Feedership)	11,000	933	53.7	0.058	
C5	Containership (Feedership)	25,000	4,043	90.2	0.022	
C6	Containership (Feedership)	15,000	2,293	67.4	0.029	
O1	LNG Carrier	72,000	7,020	284.9	0.041	0.028
O2	Livestock Carrier	23,000	3,229	74.0	0.023	
O3	Ro-Ro Vessel	28,000	8,314	316.5	0.038	
O4	Cruise Ship	9,000	2,559	22.2	0.009	
B1	Bulk Carrier (Capesize)	161,000	4,728	98.9	0.021	0.041
B2	Bulk Carrier (Handysize)	28,000	1,633	117.0	0.072	
B3	Bulk Carrier (Handysize)	25,000	1,379	103.0	0.075	
B4	Bulk Carrier (Panamax)	45,000	2,437	68.3	0.028	
B5	Bulk Carrier (Handysize)	31,000	338	2.7	0.008	

Table 4 - Results of Proposed Oil Outflow Analysis (Simplified Approach)

The results of the proposed methodology were checked against the results of HECSALV to ensure that the simplified method was not significantly different than the direct calculation. The mean outflows determined both by the proposed methodology and the HECSALV direct computation are provided in Table 5. As shown in the far right hand column, the two approaches are generally in good agreement.

	Analysis per Proposed Criterion Mean Outflow in m^3			Direct Application of PDF's Mean Outflow in m^3			Discrepancy between Simplified & Direct Analyses		
ID #	Side	Bottom	Combined	Side	Bottom	Combined	Side	Bottom	Combined
T1	20.8	8.3	13.3	21.0	8.3	13.4	-0.5%	0.0%	-0.2%
T2	71.7	0.0	28.7	92.5	0.0	37.0	-22.5%	0.0%	-9.0%
T3	136.0	0.0	54.4	144.0	0.0	57.6	-4.4%	0.0%	-1.8%
T4	203.9	5.5	84.9	202.0	7.0	85.0	1.2%	-0.9%	-0.1%
T5	318.6	0.0	127.4	328.5	0.0	131.4	-2.8%	0.0%	-1.1%
T6	324.4	0.5	130.1	368.1	0.5	147.5	-13.8%	0.0%	-5.5%
T7	122.3	0.0	48.9	115.0	0.0	46.0	9.6%	0.0%	3.8%
T8	122.4	12.5	56.4	123.0	18.3	60.2	-0.7%	-6.6%	-4.2%
T9	111.2	0.0	44.5	109.0	0.0	43.6	1.9%	0.0%	0.8%
T10	230.7	1.4	93.1	227.7	2.7	92.7	1.6%	-0.7%	0.2%
C1	319.4	455.0	400.8	280.0	379.6	339.8	12.6%	24.2%	19.6%
C2	286.3	46.1	142.2	274.0	43.8	135.9	5.9%	1.1%	3.0%
C3	118.2	80.7	95.7	103.7	79.8	89.4	12.7%	0.8%	5.6%
C4	8.0	84.1	53.7	3.8	96.6	59.5	11.3%	-33.5%	-15.6%
C5	176.7	32.5	90.2	177.0	28.0	87.6	-0.2%	2.8%	1.6%
C6	67.7	67.3	67.4	62.0	71.4	67.6	6.2%	-4.5%	-0.2%
O1	518.1	129.5	284.9	512.0	168.2	305.7	2.2%	-13.8%	-7.4%
O2	109.2	50.5	74.0	106.0	56.2	76.1	2.5%	-4.4%	-1.6%
O3	706.3	56.7	316.5	710.0	58.7	319.2	-1.1%	-0.6%	-0.8%
O4	12.4	28.8	22.2	8.0	30.4	21.4	4.3%	-1.6%	0.8%
B1	188.6	39.1	98.9	187.4	38.4	98.0	0.6%	0.4%	0.5%
B2	7.4	190.0	117.0	6.0	196.9	120.5	2.2%	-10.5%	-5.4%
B3	7.3	166.9	103.0	5.8	167.2	102.6	2.6%	-0.5%	0.7%
B4	151.6	12.7	68.3	156.0	14.5	71.1	-4.5%	-1.8%	-2.9%
B5	6.7	0.0	2.7	7.2	0.0	2.9	-3.3%	0.0%	-1.3%

Note: Discrepancy = ((OUTFLOW MEAN(criterion)-OUTFLOW MEAN(direct))/(0.04)(C)
where C is the capacity of the fuel tanks at 98% filling,
(0.04)(C) is the assumed permissible mean outflow per the performance guidelines of Appendix A.
This approach was used, as sometimes O_M is a very small number. Comparing the two mean outflow values directly can be misleading.

Table 5 - Comparison of Mean Oil Outflow Analyses Methods

3.2.3 Oil Outflow Discussion

The oil outflow parameter (O_M) varies as a function of bunker oil tank arrangement. Most designs have bunker oil tanks located adjacent to the shell. These are, of course, more vulnerable to damage than double-hulled tanks. The risk of penetrating a tank during a collision, allision, or grounding tends to increase with area of the side shell bounding the tank. Also, tanks located forward and tanks located adjacent to the bottom shell are particularly vulnerable. A discussion of the resulting outflow parameters by ship type follows. The schematics of the tank arrangements are provided in Figures 9-12.

An average mean oil outflow parameter of 0.018 was obtained for the Tankers (refer to Table 4), which is considerably less than values for the other ship types. Four of the ten tankers had double-hulled bunker tanks. These all performed well, with O_M values between 0.012 and 0.016. Also, modern tankers have their bunker tanks located in the upper portions of the engine room.

This aft location was less susceptible to side damage, and their relatively high position within the hull protected these tanks from grounding damage.

For the Containerships examined, the average mean oil outflow parameter was 0.037. The bunker oil tanks in the Containerships examined were of all shapes and sizes and at numerous locations throughout the vessel. The containerships tended to have tanks located in either wings or double bottoms, distributed about the amidships region. The tanks tended to have a relatively large surface area bounding the shell, increasing their vulnerability.

For the Other Vessel types, the average mean oil outflow parameter was 0.028. Vessel O4 (Cruise Ship) had the smallest value at 0.009. This was the result of only a small percentage of the bunker oil tanks having contact with the shell of the vessel, and may not be representative of cruise ships in general. The remainder of the vessels examined in the group had their bunker oil tanks located on the side shell and bottom shell, which resulted in larger O_M values.

The Bulk Carrier group had the largest average mean oil outflow parameter at 0.041, but had the widest range of results. The lowest mean oil outflow value for all of the vessels in this investigation was the result of 0.008 for B5. With the exception of one small starboard tank, the bunker oil was stored clear of the hull plating. The Capesize bulk carrier, B1 also exhibited a relatively good performance (O_M=0.021), as her bunker tanks were located in the engine room. Bulk carriers B2 and B3 had the highest mean outflow parameters in this study, at 0.072 and 0.075 respectively. In both of these vessels, all of the bunker oil was stored in large bottom tanks, spanning over 50 percent of the vessel length and 70 percent of the breadth.

4.0 RELATIVE COSTS OF BUNKER TANK CONFIGURATION

Standard design practices and design considerations lead to different bunker tank arrangements for different ship types. Even so, there is variation within the ship types as well. For the vessels that were reviewed in the preceding oil outflow analysis, the following applies:

- Tankers: In modern tankers, the HFO tanks are usually arranged in one or two pairs of wing tanks on each side of the engine room subdivision bulkheads (see tanker arrangements, Tankers 'T1' through 'T10' in Figure 9). This allows for short piping runs, and avoids passing HFO piping through ballast and cargo tanks. The double-hulled spaces forward of the engine room are dedicated to cargo oil, maximizing cargo cubic. Several of the tankers in this review include double hulls for the engine room bunker tanks.
- Containerships: Most commonly, the majority of HFO is allocated to wing tanks outboard of the cargo holds. These tanks are distributed longitudinally through the midship region, such that bunkering or consuming bunker oil does not significantly alter trim or stability (see Containerships 'C1' through 'C6' in Figure 10). Of the sample ships included in the outflow calculations, double bottom tanks were also used in the vessels labeled, C3, C4 and C6. Additionally, there will be some bunker oil storage in engine room wing tanks.
- Other Vessels: This group includes an LNG carrier, a RO-RO, a passenger vessel and a livestock carrier (Figure 11). The LNG carrier was arranged in a similar manner to the bulk carriers and tankers, with the bunker tanks arranged around the engine room. The RO-RO and the livestock carrier were also similarly arranged, with deep tanks forward and wing tanks aft, just forward of the engine space. The passenger vessel uses deep tanks forward and double bottom and deep tanks aft.
- Bulk Carriers: Capesize bulk carriers usually carry their bunker oil in engine room wing tanks in a similar manner to the tankers. For the smaller Handysize or Panamax ships, HFO was most commonly allocated to center double bottom tanks. Alternatively, bulk carriers may have HFO in the outboard double bottom/wing tanks, or arranged in deep tanks forward in combination with engine room tanks (see Bulk Carriers 'B1' through 'B5' in Figure 12).

The vessels in this study therefore include a variety of combinations of double bottom, cargo hold wing, deep tank and engine room wing tanks as bunker tanks. For a given required bunker oil capacity (derived from an owners requirement), the bunker tanks were sized and arranged by a designer or shipyard to meet the operational needs (trim and stability) and to minimize construction costs (piping runs and structural boundaries).

The relative costs for each type of bunker tank configuration are difficult to quantify since each vessel is designed to meet the individual owners needs. The cost of differing approaches to tank arrangements is not necessarily apparent from a simple switching of volumes from one area of the ship to another. For example, if double bottom and wing tanks were eliminated as possible locations for bunker tanks, and all bunker oil had to be carried in internal deep tanks, then the vessel's length may need to be increased. This change in length would be needed to maintain the same cargo capacity (especially for a container vessel) and would increase the cost of the vessel significantly.

In terms of a qualitative relative cost, primarily based on the extent of tank boundary structure, the double bottom tank is essentially 'free' space. The structural design rules require the use of a double bottom structure in cargo vessels (now including new tankers in accordance with OPA 90). Since the volume is required, it makes sense to use it as either a ballast or a bunker oil tank.

The side wing tanks in the cargo block of a container ship or a bulk carrier are also relatively 'free' spaces for bunker oil or ballast tanks. The volume outboard of the inboard face of the main deck box girder in a container ship (or the similar space in bulk carrier) can be closed off with a longitudinal bulkhead for a relatively low cost solution (may already be enclosed, if in a bulk carrier).

Engine room wing tanks will have a similar cost to that of the side wing tanks (an additional advantage is shorter piping runs to the engine room). The cost of a port and starboard pair of longitudinal tank bulkheads would need to be considered. This arrangement is more common for the new tankers where the engine room width requirement is significantly less than the beam of the vessel. Of note is that some of the new tankers (tanker 1, 2, 3 and 6 in the outflow analysis) have double hull arrangements for the engine room wing tanks already installed. In calculation of the oil outflow, better results were achieved with double hull installation. For tanker 2, the addition to the new construction acquisition cost was estimated to be about $500k for double hulled engine room bunker tanks. This cost was based on an estimated 210 tonnes of added steel ($700/tonne) at 50 man hours per tonne and $35 per hour. Shipyard labor and productivity rates vary widely around the world, but this approximates the order of magnitude for this application.

Inboard deep tanks will cost relatively more than other alternatives. At least two longitudinal and one transverse bulkhead would be needed. Depending on the depth of the tank a new tank top may also be installed to enclose the tank volume. Deep tanks are often located forward (for trim) and therefore may require relatively longer piping runs.

In conclusion, the relative costs for alternative tank arrangements range from double bottom tanks as least expensive (most desirable), to wing tanks and then inboard deep tanks as most expensive. From the bunker oil outflow point of view, the opposite is true, as the tanks on the shell are least desirable. A more rigorous cost-benefit analysis is recommended to better assess these trade-offs.

5.0 CONCLUSIONS

An examination of the data for bunker oil spills in US, Canadian and international waters, for the last 15 years, provided statistics establishing the volume and frequency of spills from bunker oil tanks. For freighters of greater than 1,600 GRT (excluding tankers), the bunker oil spill incident data were categorized as either a structural failure (primarily due to collision or grounding) or as an operational failure. The spills as a result of structural failures are of interest as these would be the most affected by requirements for protective tank locations or oil outflow performance requirements. Worldwide, structural failures accounted for 7 percent of the number of bunker oil spill incidents and 61 percent of the bunker oil volume spilled. In US waters, structural failures accounted for 3 percent of the incidents and 29 percent of the bunker oil spill volume. To put this in perspective, the volume of bunker oil spilled from freighter incidents involving structural failures accounted for less then 2 percent of the total oil spilled in US waters from all sources from 1992-1997.

A probabilistic oil outflow methodology, based on IMO guidelines and draft regulations for evaluating accidental outflow for new tankers, was developed for use in evaluation of freighter bunker oil spill performance. Performance was measured in terms of a non-dimensional mean oil outflow parameter (O_M). The methodology was then applied in calculations of bunker oil outflow for 25 different cargo vessels (10 tankers, 6 containerships, 5 bulk carriers and 4 others), typical of vessels calling in US and Canadian waters.

The results of the probabilistic oil outflow analysis on the 25 vessels indicate a wide variation in bunker oil outflow performance in the existing fleet. Tank location with respect to the shell was a critical factor. The location along the vessels length, the distance of double-hulled tanks from the shell, and the size of the tanks were all contributing factors to outflow performance. Modifying tank size and arrangements to achieve improved outflow performance may be possible. Improved outflow performance will generally come at an additional cost since, in most cases, the relative cost is greater for the better performing bunker tank arrangements.

Additional study is needed to further develop the cost benefit relationship of improving bunker oil spill performance of freighters. A detailed plan for a phase II study was developed and is included in the following section. It is recommended that the phase II study be conducted for a parametric series of designs. The study would include outflow analysis for varying bunker tank arrangements and a cost benefit analysis. This will assist in the development of a rationally-based performance standard for mitigating oil outflow from bunker tanks in the event of a collision or grounding.

6.0 PHASE II - SCOPE OF WORK

Objective: The objective of the phase II study is to: a) establish the relative risk of bunker spills from freighters, tankers, and small vessels, and compare the spill frequency and spill volume to total oil inputs into the oceans; and, b) perform cost-benefit analyses on a parametric series of tanker, containership, and bulk carrier designs. This information is needed by policy makers, if a minimum performance standard related to accidental spills from bunker tanks is to have a rational foundation.

Scope of Work:

1) Further review of historical spill data:
   Analyze the US spill data for the period since 1991 to better understand the relative inputs from various types of vessels. This study should include the following:
   a) Review the actual spill incidents of bunkers to determine whether the spillage would have been mitigated by double-hulling the tanks, or locating the tanks in a less vulnerable location (i.e. clear of the double bottom, in the aft body regions, etc.). This investigation will help establish the total oil spillage from bunker tanks that could theoretically be avoided through implementation of structural measures such as double-hulling.
   b) Assess the impact on the historical projection of bunker spillage of legislation which has been enacted but not yet fully in force, such as ISM and STCW. Forecast the impact on bunker spillage of expected increases in vessel traffic in future years.
   c) Based on 1a) and 1b) above, establish a baseline of projected oil spillage to be applied in the cost benefit analysis.
   d) Spills from small vessels (tugs, fishing boats, etc.) comprise a large percentage of the total bunker spillage. These should be analyzed to better understand the causes of this spillage. Regulations intended to mitigate spillage in larger vessels may not be directly applicable to smaller craft.
   e) To put spillage from bunker tanks in a broader perspective, compare the historical spill data from bunker tanks with spills from all vessels (including tankers and tank barges), and also with total oil inputs into US waters (including land sources, natural seepage, etc.).
2) Review of current design practices:
   Investigate current bunker tank design practices, concentrating on vessels constructed during the 1990's:
   a) Analyze existing designs for vessels built since 1990 to determine the current practices for locating tanks (i.e. the percentage of ships with all tanks double-hulled, the percentage of ships with at least 50 percent of bunkers double-hulled, the percentage of ships with double bottom bunker tanks, the percentage of ships with bunkers located in the forward ¼ length, etc.). Perform this analysis for crude oil

carriers, product tankers, containerships, bulk carriers, passenger ships, tugboats, and fishing boats. Breakdown data by the size of vessels when appropriate.

   b) Investigate technical and operational considerations related to alternative bunker tank arrangements. For instance, containerships frequently distribute bunkers along the ship's side centered about the LCB, so there is little change in trim and KG as the bunkers are consumed. What would be the impact of relocating these tanks aft? Consideration should be given to safety issues, available space for allocating bunkers, stability and strength implications, etc.

3) Perform cost-benefit analysis:
   Investigate current bunker tank design practices, concentrating on vessels constructed during the 1990's:

   a) Develop a parametric series of designs with varying bunker tank arrangements. Investigate three sizes each of tankers, containerships, and bulk carriers.

   b) Review the methodology as developed in this report for assessing oil outflow from bunker tanks, and revise as appropriate.

   c) Calculate the expected mean outflow in accordance with the probabilistic methodology for each design developed in step 3a).

   d) Determine the relative costs of the designs developed in step 3a).

   e) Compute the cost per "barrel of oil spillage avoided" for each design developed in step 3a). Costs should include construction costs, any impact on operational costs, and avoided costs (e.g. avoided clean-up costs, damage to vessel, lost cargo, etc.).

4) Assess overall impact of possible bunker spill performance standards:
   Investigate the impact on spillage in US waters and overall costs of alternative performance requirements:

   a) Assess three alternative performance levels: O_M=0.015 (roughly equivalent to requiring double-hulling), O_M=0.25, and O_M=0.40.

   b) For each performance level given in step 4a), determine the total oil spillage avoided. The spill baseline calculated in step 1c), the current design practices from step 2a), and the anticipated reductions in spillage determined in step 3c) are inputs into the calculation.

   c) For each performance level given in step 4a), determine the total cost differential.

   d) Combine data from steps 4b) and 4c) to determine the overall cost per barrel of oil spillage avoided, for the three levels of performance.

5) Propose possible performance standards applicable to small vessels (tug boats, fishing boats, etc.)

7.0 REFERENCES

1) Michel, Keith and Winslow, Thomas. " Cargo Ship Bunker Tanks: Designing to Mitigate Oil Spillage" Marine Technology and SNAME News, Oct. 2000, Vol. 37.No. 4 (ISSN 0025-3316), pg. 191-9.

2) Etkin, Dagmar S. "US and Worldwide Bunker Spills," CD ROM: Environmental Research Consulting, Dated May 31, 2000

3) IMO, "MARPOL Annex I Appendix 8: 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", MARPOL 73/78 Consolidated Edition, 1997.

4) IMO, "Proposed MARPOL Annex I Regulation 22: Accidental Oil Outflow Performance", contained in BLG5/WP4, dated June 28, 2000.

5) Sirkar et al, "A Framework for Assessing the Environmental Performance of Tankers in Accidental Groundings and Collisions", SNAME TRANSACTIONS, 1997.

6) Michel, Moore, & Tagg, "A Simplified Methodology for Evaluating Alternative Tanker Configurations," *Journal of Marine Science and Technology, Volume 1 Number 4, SNAJ,* September 1996

7) USCG Report, "Subdivision and Damage Stability Harmonization Study, Technical Support to the Harmonization of Rules and Design Rationale Project (HARDER), Casualty Data Analysis", May 2000.

Appendix A - Accidental Outflow Performance Guideline Related to Spills from Bunker Tanks

(1) Applicability:

(a) This guideline is applicable to all new vessels having *oil fuel* or bunker tank(s) that exceed 100 m^3 in capacity.

(b) "oil fuel" means any oil used as fuel in connection with the propulsion and auxiliary machinery of the ship in which such oil is carried.

(2) For the purpose of this guideline, the following definitions shall apply:

(a) "Load line draught (d_S)" is the vertical distance, in meters, from the molded baseline at mid-length to the waterline corresponding to the summer freeboard to be assigned to the ship.

(b) "Partial load line draught (d_P)" is the lightship draught plus 60 percent of the difference between the light ship draught and the load line draught d_S.

(c) "Waterline (d_B)" is the vertical distance, in meters, from the molded baseline at mid-length to the waterline corresponding to 30 percent of the depth D_S.

(d) "Breadth (B_S)" is the greatest molded breadth of the ship, in meters, at or below the deepest load line draught (d_S).

(e) "Breadth (B_B)" is the greatest molded breadth of the ship, in meters, at or below the waterline d_B.

(f) "Depth (D_S)" is the molded depth, in meters, measured at mid-length to the upper deck at side.

(g) "Length (L)" and "deadweight (DW)" are as defined in MARPOL Annex I regulations 1(18) and 1(22).

(3) The level of protection against oil pollution in the event of collision or grounding shall be assessed on the basis of the mean oil outflow parameter as follows:

$[O_M \leq 0.04]$

Note: This value is used for illustrative purposes in this report. Further analysis and consideration is needed before selecting an appropriate level for O_M.

where:

O_M = mean oil outflow parameter.

(4) The following general assumptions shall apply when calculating the mean oil outflow parameter:

(a) Where this regulation refers to *oil fuel tanks*, it shall be understood to include tanks exceeding 100 m^3 in capacity intended for the carriage of oil fuel or bunker oil.

(b) The ship shall be assumed loaded to the partial load line draught d_P without trim or heel.

(c) All oil fuel oil tanks shall be assumed loaded to 98 percent of their volumetric capacity.

(d) The nominal density of the oil fuel (ρ_n) shall generally be taken as 1,000 kg/m^3. If the density of the oil fuel is specifically restricted to a lesser value, the lesser value may be applied.

(c) For the purposes of these outflow calculations, the permeability of each oil fuel tank shall be taken as 0.99, unless proven otherwise.

(5) The following assumptions shall be used when combining the oil outflow parameters:

(a) The mean oil outflow shall be calculated independently for side damage and for bottom damage and then combined into the non-dimensional oil outflow parameter O_M, as follows:

$$O_M = (0.4\ O_{MS} + 0.6\ O_{MB}) / C$$

where:

O_{MS} = mean outflow for side damage, in m^3.
O_{MB} = mean outflow for bottom damage, in m^3.
C = total volume of oil fuel, in m^3, at 98 percent tank filling.

(b) For bottom damage, independent calculations for mean outflow shall be done for 0 m and 2.5 m tide conditions, and then combined as follows:

$$O_{MB} = 0.7\ O_{MB(0)} + 0.3\ O_{MB(2.5)} \quad (m^3)$$

where:

$O_{MB(0)}$ = mean outflow for 0 m tide condition; and,
$O_{MB(2.5)}$ = mean outflow for minus 2.5 m tide condition, in m^3.

(6) The mean outflow for side damage O_{MS} shall be calculated as follows:

$$O_{MS} = \sum_{1}^{n} P_{S(i)} O_{S(i)} \qquad (m^3)$$

where:

i = represents each oil fuel tank under consideration;
n = total number of oil fuel tanks;
$P_{S(i)}$ = the probability of penetrating oil fuel tank i from side damage, calculated in accordance with (8)(a); and;
$O_{S(i)}$ = the outflow, in m^3, from side damage to oil fuel tank i, which is assumed equal to the total volume in oil fuel tank i at 98 percent filling.

(7) The mean outflow for bottom damage shall be calculated for each tidal condition as follows:

(a) $$O_{MB} = \sum_{1}^{n} P_{B(i)} O_{B(i)} \qquad (m^3)$$

where:

i = represents each oil fuel tank under consideration;
n = total number of oil fuel tanks;
$P_{B(i)}$ = the probability of penetrating oil fuel tank i from bottom damage, calculated in accordance with (9)(a); and;
$O_{B(i)}$ = the outflow from bottom damage to oil fuel tank i, in m^3, calculated in accordance with (7)(b)

For calculation of $O_{MB(2.5)}$, $O_{B(i)}$ shall be the oil outflow after tidal change.

(b) The oil outflow $O_{B(i)}$ for each oil fuel or bunker tank shall be calculated based on pressure balance principles, in accordance with the following assumptions:

(i) The ship shall be assumed stranded with zero trim and heel, with the stranded draught prior to tidal change equal to the partial load line draught d_P.

(ii) The oil fuel level after damage shall be calculated as follows:

$$h_F = \{(d_P + t_C - Z_l)(\rho_S) / \rho_n$$

where:

h_F = the height of the oil fuel surface above Z_l, in m;
t_C = the tidal change, in m. Reductions in tide shall be expressed as negative values;
Z_l = the height of the lowest point in the oil fuel tank above baseline, in m;

ρ_S = density of seawater, to be taken as 1,025 kg/m^3; and;
ρ_n = nominal density of the oil fuel, as defined in (4)(d).

(iii)For oil fuel tanks bounded by the bottom shell, unless proven otherwise, oil outflow $O_{B(i)}$ shall be taken not less than the volume of the tank up to a height of 1.0 m above the lowest point in the tank Z_l, or one-half the depth of the tank, $(Z_l + Z_u)/2$, whichever is less.

(8) The probability P_S of breaching a compartment from side damage shall be calculated as follows:

(a) $P_S = P_{SL}\ P_{SV}\ P_{ST}$

where:

$P_{SL} = (1 - P_{Sf} - P_{Sa})$ = probability the damage will extend into the longitudinal zone bounded by X_a and X_f;
$P_{SV} = (1 - P_{Su} - P_{Sl})$ = probability the damage will extend into the vertical zone bounded by Z_l and Z_u; and
$P_{ST} = (1 - P_{Sy})$ = probability the damage will extend transversely beyond the boundary defined by y.

(b) P_{Sa}, P_{Sf}, P_{Sl}, and P_{Su} shall be determined by linear interpolation from the table of probabilities for side damage provided in (8)(c), and P_{Sy} shall be calculated from the formulas provided in (8)(c), where:

P_{Sa} = the probability the damage will lie entirely aft of location X_a/L;
P_{Sf} = the probability the damage will lie entirely forward of location X_f/L;
P_{Sl} = the probability the damage will lie entirely below the tank;
P_{Su} = the probability the damage will lie entirely above the tank; and
P_{Sy} = the probability the damage will lie entirely outboard of the tank.

Compartment boundaries X_a, X_f, Z_l, Z_u and y shall be developed as follows:

X_a = the longitudinal distance from the aft terminal of L to the aft most point on the compartment being considered;
X_f = the longitudinal distance from the aft terminal of L to the foremost point on the compartment being considered;
Z_l = the vertical distance from the moulded baseline to the lowest point on the compartment being considered;
Z_u = the vertical distance from the moulded baseline to the highest point on the compartment being considered; and,
y = the minimum horizontal distance measured at right angles to the centerline between the compartment under consideration and the side shell.

In way of the turn of the bilge, y need not be considered below a distance h above base line, where h is the lesser of B/10, 3 m, or the top of the tank.

(c) Table of probabilities for side damage

X_a/L	P_{Sa}	X_f/L	P_{Sf}	Z_l/D_S	P_{Sl}	Z_u/D_S	P_{Su}
0.00	0.000	0.00	0.973	0.00	0.000	0.00	0.968
0.05	0.021	0.05	0.931	0.05	0.000	0.05	0.952
0.10	0.059	0.10	0.888	0.10	0.001	0.10	0.931
0.15	0.101	0.15	0.846	0.15	0.003	0.15	0.905
0.20	0.143	0.20	0.803	0.20	0.007	0.20	0.873
0.25	0.186	0.25	0.761	0.25	0.013	0.25	0.836
0.30	0.228	0.30	0.718	0.30	0.021	0.30	0.789
0.35	0.271	0.35	0.676	0.35	0.034	0.35	0.733
0.40	0.313	0.40	0.633	0.40	0.055	0.40	0.670
0.45	0.356	0.45	0.591	0.45	0.085	0.45	0.599
0.50	0.398	0.50	0.548	0.50	0.123	0.50	0.525
0.55	0.441	0.55	0.506	0.55	0.172	0.55	0.452
0.60	0.483	0.60	0.463	0.60	0.226	0.60	0.383
0.65	0.526	0.65	0.420	0.65	0.285	0.65	0.317
0.70	0.568	0.70	0.375	0.70	0.347	0.70	0.255
0.75	0.612	0.75	0.323	0.75	0.413	0.75	0.197
0.80	0.662	0.80	0.263	0.80	0.482	0.80	0.143
0.85	0.721	0.85	0.195	0.85	0.553	0.85	0.092
0.90	0.787	0.90	0.120	0.90	0.626	0.90	0.046
0.95	0.862	0.95	0.043	0.95	0.700	0.95	0.013
1.00	0.945	1.00	0.000	1.00	0.775	1.00	0.000

P_{Sy} shall be calculated as follows:

$P_{Sy} = (7.0 - 25.0\ y/B_S)\ (y/B_S)$ for $y/B_S \leq 0.1$

$P_{Sy} = 0.45 + \{2.18182 - (y/B_S)/0.55\}\ \{(y/B_S) - 0.1\}$ for $0.1 < y/B_S \leq 0.65$

P_{Sy} is not to be taken greater than 1.

(9) The probability P_B of breaching a compartment from bottom damage shall be calculated as follows:

(a) $P_B = P_{BL}\ P_{BT}\ P_{BV}$

where:

$P_{BL} = (1 - P_{Bf} - P_{Ba})$ = probability the damage will extend into the longitudinal zone bounded by X_a and X_f;

$P_{BT} = (1 - P_{Bp} - P_{Bs})$ = probability the damage will extend into the transverse zone bounded by Y_p and Y_s; and

$P_{BV} = (1 - P_{Bz})$ = probability the damage will extend vertically above the boundary defined by z.

(b) P_{Ba}, P_{Bf}, P_{Bp}, and P_{Bs}, shall be determined by linear interpolation from the table of probabilities for bottom damage provided in (9)(c), and P_{Bz} shall be calculated from the formulas provided in (9)(c), where:

P_{Ba} = the probability the damage will lie entirely aft of location X_a/L;
P_{Bf} = the probability the damage will lie entirely forward of location X_f/L;
P_{Bp} = the probability the damage will lie entirely to port of the tank;
P_{Bs} = the probability the damage will lie entirely to starboard of the tank; and
P_{Bz} = the probability the damage will lie entirely below the tank.

Compartment boundaries X_a, X_f, Y_p, Y_s, and z shall be developed as follows:

X_a and X_f are as defined in (8)(b);

Y_p = the transverse distance from the port-most point on the compartment located at or below the waterline d_B, to a vertical plane located B_B /2 to starboard of the ship's centreline;
Y_s = the transverse distance from the starboard-most point on the compartment located at or below the waterline d_B, to a vertical plane located B_B /2 to starboard of the ship's centreline; and,
z = the minimum value of z over the length of the compartment, where, at any given longitudinal location, z is the vertical distance from the lower point of the bottom shell at that longitudinal location to the lower point of the compartment at that longitudinal location.

(c) Table of probabilities for bottom damage

X_a/L	P_{Ba}
0.00	0.000
0.05	0.002
0.10	0.008
0.15	0.017
0.20	0.029
0.25	0.042
0.30	0.058
0.35	0.076
0.40	0.096
0.45	0.119
0.50	0.143
0.55	0.171
0.60	0.203
0.65	0.242
0.70	0.289
0.75	0.344
0.80	0.409
0.85	0.482
0.90	0.565
0.95	0.658
1.00	0.761

X_f/L	P_{Bf}
0.00	0.969
0.05	0.953
0.10	0.936
0.15	0.916
0.20	0.894
0.25	0.870
0.30	0.842
0.35	0.810
0.40	0.775
0.45	0.734
0.50	0.687
0.55	0.630
0.60	0.563
0.65	0.489
0.70	0.413
0.75	0.333
0.80	0.252
0.85	0.170
0.90	0.089
0.95	0.026
1.00	0.000

Y_p/B_B	P_{Bp}
0.00	0.844
0.05	0.794
0.10	0.744
0.15	0.694
0.20	0.644
0.25	0.594
0.30	0.544
0.35	0.494
0.40	0.444
0.45	0.394
0.50	0.344
0.55	0.297
0.60	0.253
0.65	0.211
0.70	0.171
0.75	0.133
0.80	0.097
0.85	0.063
0.90	0.032
0.95	0.009
1.00	0.000

Y_s/B_B	P_{Bs}
0.00	0.000
0.05	0.009
0.10	0.032
0.15	0.063
0.20	0.097
0.25	0.133
0.30	0.171
0.35	0.211
0.40	0.253
0.45	0.297
0.50	0.344
0.55	0.394
0.60	0.444
0.65	0.494
0.70	0.544
0.75	0.594
0.80	0.644
0.85	0.694
0.90	0.744
0.95	0.794
1.00	0.844

P_{Bz} shall be calculated as follows:

$$P_{Bz} = (14.5 - 67\ z/D_S)\ (z/D_S) \qquad \text{for } z/D_S \le 0.1,$$
$$P_{Bz} = 0.78 + 1.1\ \{(z/D_S) - 0.1\} \qquad \text{for } z/D_S > 0.1.$$

P_{Bz} is not to be taken greater than 1.

Appendix B - Derivations of Damage Probability Density Distributions

The IMO interim guidelines for obtaining approval of alternative tanker designs to the double hull standard (IMO, 1997) include probability density distribution functions for the following extents:

Side Damage	Bottom Damage
Longitudinal Location	Longitudinal Location
Longitudinal Extent	Longitudinal Extent
Transverse Penetration	Vertical Penetration
Vertical Extent	Transverse Location
Vertical Location	Transverse Extent

These functions are derived from historical damage statistics for 52 collisions and 63 groundings of tankers 30,000 metric tons deadweight and above. 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.

IMO is pursuing a simplified outflow analysis approach to replace the current hypothetical outflow regulations 22-24 of MARPOL. The latest version of this new draft regulation is published as BLG5/WP4, "Proposed MARPOL Annex I Regulation 22: Accidental Oil Outflow Performance" (IMO, 2000). This draft regulation applies the same pdf's as the interim guidelines, although they have been converted to tabular form to facilitate their use.

For the bunker spill guideline, it is preferable to utilize damage statistics representative of cargo vessels in general rather than only larger tank vessels.

The IMO passenger ship and dry cargo ship damage stability rules are based on damage statistics for 352 collisions. This original damage database has been augmented by collision data from Lloyd's Register Ship Repair Statistics, which contain a total of 133 records covering the period 1972-1982, and an additional 12 records from updated IMO statistics submitted to the SLF Sub-Committee since SLF 34. These data have been combined and analyzed in a report developed by the USCG (USCG, 2000).

The IMO cargo ship collision data contains records for longitudinal extent, longitudinal location, and transverse penetration only. The following approach is used to develop pdf's from the combined IMO/LR database for these three sets of damage statistics:

a) An analysis of existing cargo vessels indicated that ships below 50 meters in length typically have bunker tanks less than 100 m^3 in capacity. Therefore, ships under 50 m are culled from the IMO/LR database, resulting in elimination of 50 out of the 498 records.

b) The damage parameters (location along the hull, transverse penetration, and length of damage along the hull) are non-dimensionalized with respect to the appropriate ship dimensions (LBP or Beam).

c) The non-dimensionalized damage statistics are represented by piecewise linear distributions.

These pdf's are presented in Figures B.1, B.2 and B.3.

As cargo ship damage statistics are not available for vertical damage extent and location, the tanker pdf's are applied (see Figures B.4 and B.5). Similarly, cargo ship damage statistics are not available for groundings, and the tanker pdf's are applied for all five bottom damage pdf's (see Figures B.6 through B.10).

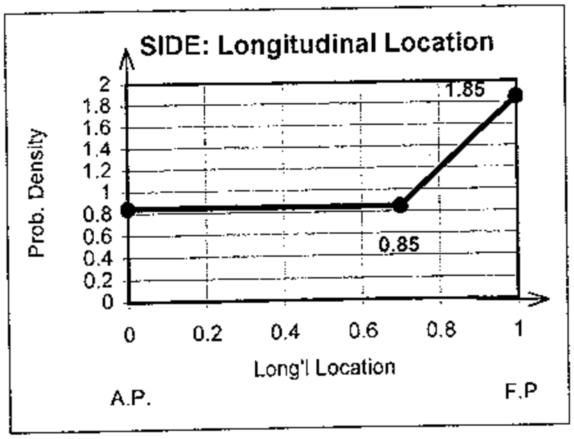


Figure B.1 - Side Damage: Long. Location

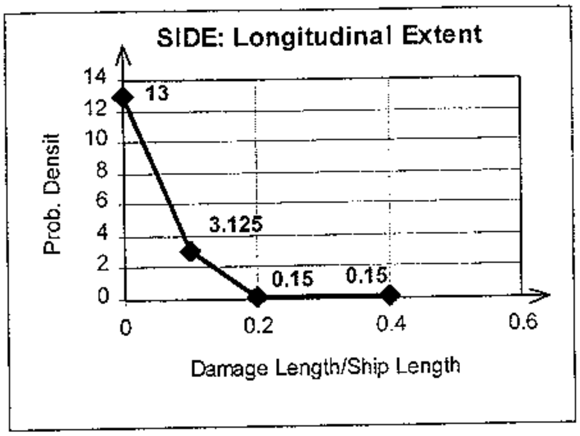


Figure B.2 - Side Damage: Long. Extent

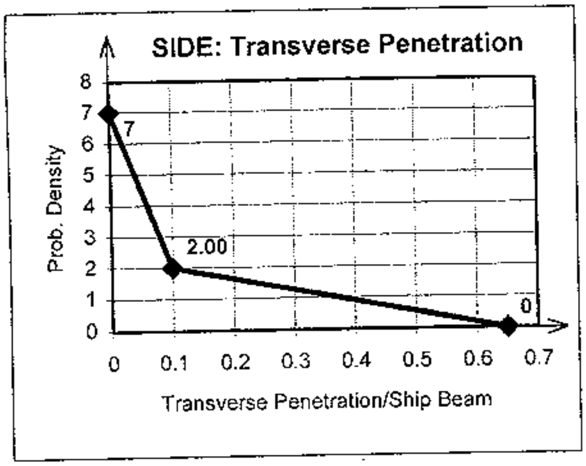


Figure B.3 - Side Damage: Trans. Penetration

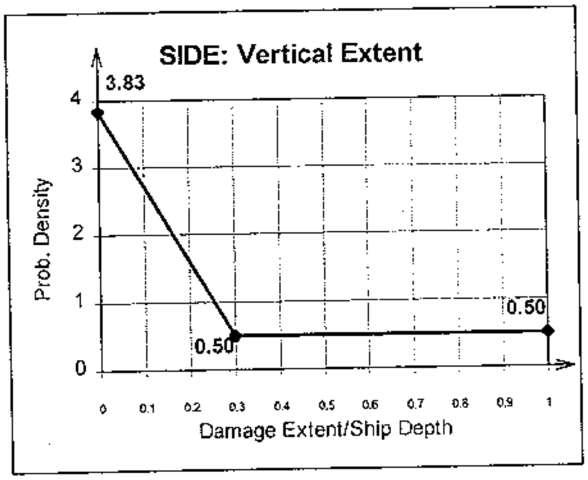


Figure B.4 - Side Damage: Vertical Extent

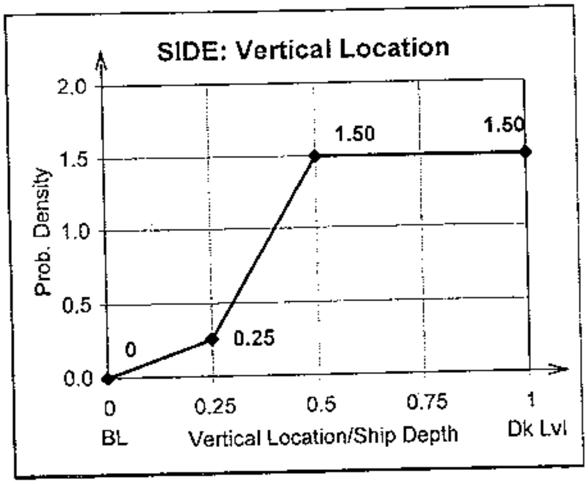


Figure B.5 - Side Damage: Vertical Location

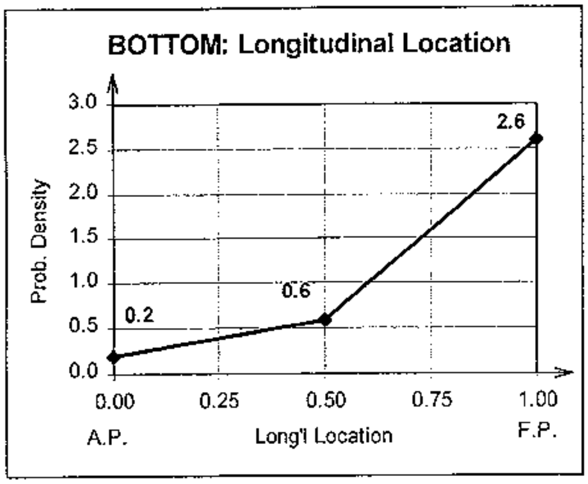


Figure B.6 - Bottom Damage: Long. Location

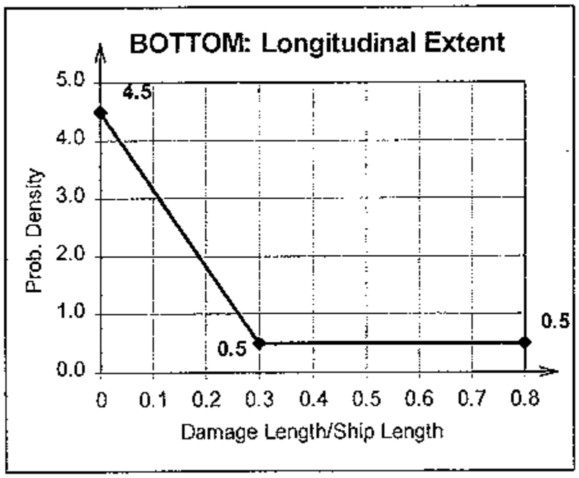


Figure B.7 - Bottom Damage: Long. Extent

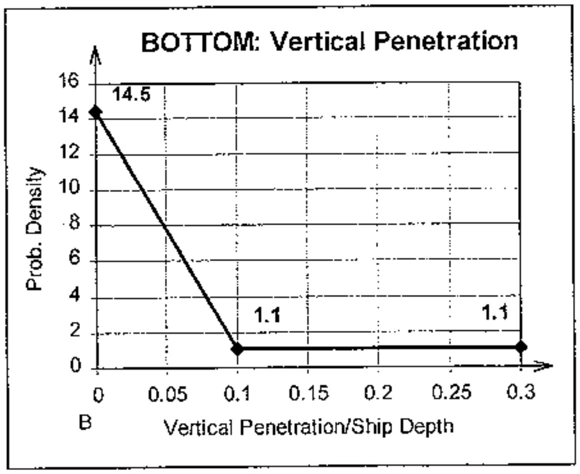


Figure B. 8 - Bottom Damage: Vertical Penetration

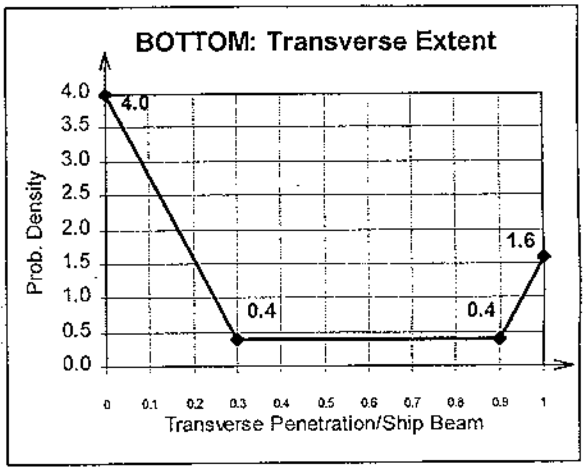


Figure B.9 - Bottom Damage: Trans. Extent

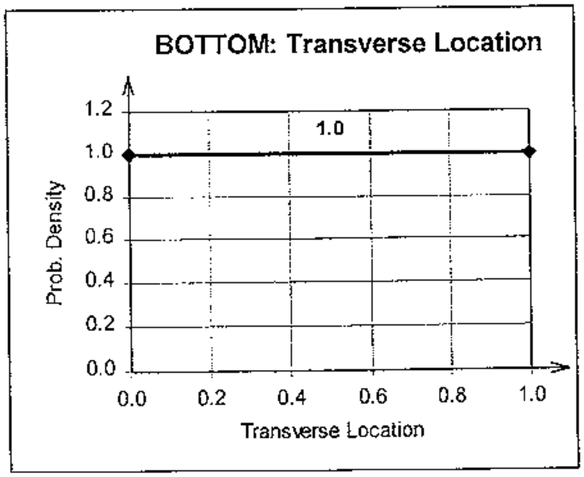


Figure B.10 - Bottom Damage: Transverse Location

Appendix C - Description of Bunker Tank Arrangements

The following describes the bunker tank arrangements on each of the selected vessels.

Tkr #1 Post OPA90 Double Hull 40K DWT Tanker:

There are 2 bunker fuel oil tanks, port and starboard. The tanks are double hulled off the side shell, adjacent at centerline, forward of the engine room, and aft of the slop tanks.

Tkr #2 80K DWT Post OPA90 Double Hull Tanker:

There are 4 bunker fuel tanks, all double hulled, with the #1 tanks forward and adjacent to the #2 tanks, port and starboard. There is one diesel oil tank, aft and adjacent to the #2S bunker fuel oil tank.

Tkr #3 150K DWT Post OPA90 Double Hull Tanker:

There are 4 bunker fuel tanks, all double hulled, with the #1 tanks forward and adjacent to the #2 tanks, port and starboard. There are two diesel oil tanks, both aft and adjacent to the #2S bunker fuel oil tank.

Tkr #4 Post OPA90 Double Hull 150K DWT Tanker:

There are 4 bunker fuel oil tanks, 2 port and 2 starboard. The outboard tanks are on the side shell and the outboard tanks protect the inboard tanks. In addition, there is a port and starboard pair of diesel oil tanks that are inboard, above the pump room, and forward of the engine room.

Tkr #5 Post OPA90 Double Hull 280K DWT Tanker:

There are 6 bunker fuel oil tanks, 4 of which are storage tanks, split 2 port and 2 starboard, and the other 2 are the service tank and settling tank, both starboard. The #1 FO tanks are forward of the other tanks, above and outboard of the pump room, double hulled from the hull. The #2 FO tanks are adjacent and aft of the #1s and are both on the hull. The service and settling tanks are built into the inboard side of the #2 S FO tank. There is also a diesel oil tank that is built into the after, upper part of #2 P FO, and it is bounded by the hull.

Tkr #6 Post OPA90 Double Hull 280K DWT Tanker:

There are 7 bunker fuel oil tanks, 4 of which are storage tanks, split 2 port and 2 starboard, and the other 3 are two settling tanks and 1 service tank, all port. All of the tanks are off the hull. The #1 FO tanks are forward of the other tanks, with the #2 FOs are adjacent and aft of the #1's. The service and settling tanks are built into the lower, forward, inboard side of the #2 P FO tank. There is also a diesel oil tank that is adjacent, inboard of the #1 FO P tank.

Tkr #7 Post OPA90 Double Hull 40K DWT Tanker with 3 bunker fuel oil Tanks:

HFO #1 P is in the engine room, built into the side shell, well above the bottom shell, extending the length of the engine room. HFO #1 S is also built into the side shell, well above the bottom shell, extending from the forward end of the engine room aft. Adjacent to the aft end of HFO #1 S is the Day Tank. The Day Tank is also built into the side shell, and extends from the aft end of the HFO #1 S to the aft end of the engine room.

Tkr #8 Post OPA90 Double Hull 80K DWT Tanker:

There are 2 bunker fuel oil tanks and 1 diesel oil tank. HFO #1 S is in the engine room, built into the side shell, above the bottom shell. On the port side, the HFO #1 P is in the engine room, built into the side shell, above the bottom shell. Built into the inboard, after end of HFO #1 P are the HFO service and settling tanks (not included in study). Adjacent and aft of the HFO #1 P tank is the DO Tank.

Tkr #9 Double Hull 150K DWT Tanker:

There are 4 bunker fuel oil tanks and 1 diesel oil tank. HFO #1 P is in the engine room, built into the side shell, well above the bottom shell. Aft and adjacent to the HFO #1 P is LSHFO tank. On the starboard side, HFO #2 S is built into the side shell, well above the bottom shell. Aft and adjacent is HFO #3 S and aft and adjacent to HFO #3 S is the DO tank.

Tkr #10 Double Hull 150K DWT Tanker:

There are 4 bunker fuel oil tanks and 1 diesel oil tank. HFO #1 S is in the engine room, built into the side shell, well above the bottom shell. HFO #1 P is in the engine room, built into the side shell, well above the bottom shell. Built into the inboard, after end of HFO #1 P are the HFO Service and HFO Settling tanks. Adjacent and aft of the HFO #1 P tank is the DO Storage Tank.

Cont #1 Post PANAMAX Containership:

There are a total of 14 bunker fuel oil tanks and 2 diesel oil tanks. There are 4 sets of fuel tanks port and starboard in way of the cargo holds. These tanks include the wing volumes adjacent to the hold, and extend inboard in way of the mid-cell structure between the holds. The remaining tanks are all in the machinery space. On the port and starboard sides, built adjacent to each other on the side shell, are (fwd to aft) HFO settling tank, DO service and the HFO storage tank. In addition, there are HFO service tanks built into the forward, upper portion of the HFO settling tanks, port and starboard.

Cont #2 PANAMAX Containership:

There are a total of 12 bunker fuel tanks, broken into 6 sets of adjacent port & starboard tanks. The forward deep tanks are forward of the cargo block, but the remainder of the tanks are in the cargo block. The deep tanks are off the hull, while the rest of the tanks are bounded by the hull.

Cont #3 PANAMAX Containership:

There are 6 bunker fuel tanks and 2 diesel tanks. There are 2 pairs of wing tanks forward (P&S) and they are adjacent and on the hull. Aft of that are 2 centerline double bottom tanks, on the hull, but not adjacent. Further aft is the pair of diesel oil wing tanks, port and starboard on the hull.

Cont #4 Coastal Containership:

There are 4 double bottom bunker fuel tanks, on the hull. The tanks are paired port and starboard and share a centerline bulkhead. The forward and aft pairs of tanks are adjacent.

Cont #5 Open Top Containership (slightly smaller than PANAMAX size):

There are 6 pairs of P&S wing tanks, all in the cargo block, all above the double bottom but on the side shell. The forward 2 pairs of tanks are adjacent fore and aft. Aft about 20 meters, there are another 2 pairs of tanks that are adjacent fore and aft. The remaining 2 pairs of tanks are not adjacent.

Cont #6 Containership (slightly smaller than PANAMAX size):

There are 4 pairs of P&S bunker fuel tanks. The forward most pair is on the hull, and share a centerline bulkhead. There is another pair of tanks immediately aft (and adjacent), but these tanks are wing tanks, so there is no common centerline bulkhead. In addition, these tanks are above the double bottom, on the side shell. At the aft end of the cargo block are 2 pairs of tanks, one pair of double bottom tanks, sharing a centerline bulkhead. The other pair are wing tanks that run about half the length of the double bottom fuel tanks. These wing tanks are above the double bottom height, their inboard distance off centerline is the same as the double bottom tanks outboard distance off centerline. Their forward boundary is approximately at the midpoint of the double bottom tanks.

Other #1 70K DWT LNG Tanker:

There are 7 bunker fuel oil tanks and 2 diesel oil tanks. There is one fuel tank forward of the cargo block, that extends side shell to side shell, above the double bottom. The rest of the tanks are all aft of the cargo block. There is a pair of FO wing tanks on the side shell. Adjacent on the aft end of the starboard FO wing tank is the FO Deep S (on the side shell), and the FO Settling S, which is built into the inboard side of the FO Deep S. On the aft end of the FO Deep S, there is a DO storage tank, that is on the side shell, and bounded fore and below by the FO Deep S tank. On the port side, aft of the FO Wing P, adjacent to it's aft end is the FO Deep P (on the side shell), and the FO Settling P, which is built into the inboard side of the FO Deep P. On the aft end of the FO Deep P is the DO Storage P, located on the side shell and bounded forward by the FO Deep P. The lower bound of DO Storage P is the FO Deep P.

Other #2 Livestock Carrier:

There are 13 bunker fuel tanks, 11 FO and 2 DO tanks. The Fwd Deep Tank is forward of the cargo block, bounded port, starboard and lower by the hull. Further aft is the set of three Deep Tank Forward port, center and starboard. The starboard tank is bounded by the bottom hull, and the side shell and on the port side is the Deep Tank Forward Center tank. The Deep Tank Forward Center tank is bounded by the Deep Tank Forward Starboard tank and the Deep Tank Forward Port tank and is above the pipe tunnel. Further aft is the set of Deep Tank Aft port, center and starboard tanks, similarly as the forward deep tanks. Adjacent on the aft end of the Deep Tank Aft Starboard tank is the FO #4 Wing Fwd Tank S, which is on the side shell, above the double bottom. Adjacent on the aft end of the FO #4 Wing Fwd Tank S, is the DO #4 Wing Aft Tank S, which is on the side shell, above the double bottom. Adjacent on the aft end of the DO #4 Wing Fwd Tank S, is the FO Settling Tank S, which is on the side shell, above the double bottom. Adjacent on the aft end of the Deep Tank Aft Port tank is the FO #4 Wing Fwd Tank P, which is on the side shell, above the double bottom. Adjacent on the aft end of the FO #4 Wing Fwd Tank P, is the DO #4 Wing Aft Tank P, which is on the side shell, above the double bottom.

Other #3 RO/RO Vessel:

There are 9 bunker fuel tanks, 8 FO tanks and 1 DO tank. The FO #1 Fwd extends from side shell to side shell, above the double bottom height. Adjacent on the aft end of the FO #1 Fwd are the FO #1 Aft P&S. These tanks extend from a common centerline bulkhead to the side shell. Much further aft are the remaining tanks. The FO #4 P&S are wing tanks above the double bottom and on the side shell. Directly aft of the FO #4 P&S are the FO #5 P&S, adjacent to the aft end. They are also wing tanks on the side shell above the double bottom. On the starboard side is the DO #5 S, which is a wing tank, bounded by the side shell and the FO #5 S on the bottom. On the port side is the upper FO #5 P, which is a wing tank, bounded by the side shell and the lower FO #5 P on the bottom.

Other #4 Passenger Ship:

There are 5 pairs of bunker fuel tanks on this ship. The fwd FO tanks share a centerline bulkhead and are above the double bottom and off the hull. Aft there is a cluster of the other 4 pairs of tanks. The FO #1s and #2s are double bottom tanks, with the pairs sharing a common centerline bulkhead and the #1 S and #2 S tanks as well as the #1 P and #2 P tanks share a transverse bulkhead. The tanks are bounded by longitudinal bulkheads. The FO #4s share a centerline bulkhead and the are built on top of the FO#1s. The FO #5s share a centerline bulkhead and the are built on top of the FO#2s and share a transverse bulkhead with the FO #4s.

Bulk #1 CAPESIZE Bulker:

Only 4 of the bunker fuel oil tanks are modeled for this study. There is a P&S pair of double bottom fuel tanks beneath the aft cargo hold. The forward portion of these tanks extend to the shell plating, about 8.5m off centerline. There is also a P&S pair of HFO tanks in the engine room, which is on the side shell and well above the baseline.

Bulk #2 28K DWT Bulker:

There are 5 double bottom bunker fuel tanks, beneath the cargo holds. FO #1 P&S are beneath Hold #2, and the FO tanks share a centerline bulkhead. FO #2 C is adjacent and aft of the #1's, on centerline, beneath Hold #3. FO #3 C is adjacent and aft of the FO #2 C, on centerline, beneath Hold #4. FO #4 C is adjacent and aft of the FO #3 C, on centerline, beneath Hold #5.

Bulk #3 25K DWT Bulker:

This ship has 3 double bottom bunker fuel tanks. All 3 tanks are bounded P&S by longitudinal bulkheads and the #2 FO tanks is bounded forward by the #1 FO and aft by the #3 FO tank.

Bulk #4 45K DWT Bulker:

There are 4 P&S pairs of bunker fuel tanks. The FO #1 P&S are on the side shell, well off centerline and above the baseline. FO #2 P&S are aft, adjacent of the #1 tanks, also on the side shell and above the bottom plating. FO #3 P&S are at midships, on the side shell, above the double bottom. FO #4 P&S are in the engine room, on the side shell.

Bulk #5 Great Lakes Bulker:

This ship has 2 bunker fuel oil and 1 diesel oil tank, all in the engine room and well above the baseline. The DO tank is on the side shell. The HFO S is adjacent and inboard of the DO tank. The HFO P is a mirror image about the centerline of the HFO S.

Appendix D - Sample Outflow Calculation

SIMPLIFIED Calculation of Outflow Parameters for Tanker T1

(for bunker tank evaluation)

General Data

LBP = 174.300 m (length between perpendiculars)
LWL = 182.500 m (length on WL at 85% Depth)
L_{AP} = 176.500 m (from rudder post to fwd stem at 85% Depth)
L = 176.500 m (length at defined in Regulation 1(18))
Beam = 32.200m (molded beam)
D_S = 19.200 m (molded depth)

d_S = 8.381 m (draft for bunker spill evaluation - measured above baseline)
12.200 m (draft to summer freeboard - measured above baseline)
2.653 m (lightship draft)

C = 1,070 m^3 (total volume of fuel oil at 98% filling)
ρ_C = 1.0000 MT/m^3 (nominal density of fuel oil)

B_S = 32.200 m (greatest molded breadth at or below dS)
B_B = 32.200 m (greatest molded breadth at or below dB)
d_B = 5.760 m (30% of D_S)

SW Density = 1.025 MT/m^3 (assumed seawater density)

Overpressure = 0.0000 Bar G (asumed inert gas pressure on bunker tanks)
g = 9.81 m/s^2 (gravitational constant)

Mean Oil Outflow Parameter		Mean Outflow m^3	Factor
Side Damage	O_{MS} =	20.8	0.4
Bottom Damage	O_{MB} =	8.3	0.6
		13.3	m^3
Mean Outflow Parameter	O_M =	**0.0125**	
Required	O_m =	**(to be developed)**	
Is O_M <= O_m ?		----	

Side Damage

Fuel Tank	98% Vol. m3	Xa m-AP	Xf m-AP	Zl m-BL	Zu m-BL	y m
FO P	535	34.990	37.840	2.150	19.571	16.100
FO S	535	34.990	37.840	2.150	19.571	3.461
	1,070.0					

Fuel Tank	Xa/L	Psa	Xf/L	Psf	Zl/Ds	Psl	Zu/Ds	Psu	y/Bs	Psy
FO P	0.1982	0.1415	0.2144	0.7909	0.1120	0.0015	1.0000	0.0000	0.5000	0.9591
FO S	0.1982	0.1415	0.2144	0.7909	0.1120	0.0015	1.0000	0.0000	0.1075	0.4649

Fuel Tank	P_{SL}	P_{SV}	P_{ST}	P_S	$O_{S(i)}$	$(P_S)(O_{S(i)})$	
FO P	0.0676	0.9985	0.0409	0.0028	535.0	1.5	
FO S	0.0676	0.9985	0.5351	0.0361	535.0	19.3	
					O_{MS} =	20.8	m^3

Bottom Damage

t_C Tidal Change m
0.0
-2.5

Fuel Tank	Y-Port m-CL	Yp m	Y-Stbd m-CL	Ys m	z m
FO P	12.639	28.739	0.000	16.100	2.150
FO S	0.000	16.100	12.639	3.461	2.150

Fuel Tank	Xa/L	P_{Ba}	Xf/L	P_{Bf}	Zp/B_B	P_{Bp}	Zs/B_B	P_{Bs}	z/Ds	P_{BZ}
FO P	0.1982	0.0286	0.2144	0.8871	0.8925	0.0366	0.5000	0.3440	0.1120	0.7932
FO S	0.1982	0.0286	0.2144	0.8871	0.5000	0.3440	0.1075	0.0366	0.1120	0.7932

Fuel Tank	P_{BL}	P_{BV}	P_{BT}	P_B
FO P	0.0843	0.6194	0.2068	0.0108
FO S	0.0843	0.6194	0.2068	0.0108

Tidal Change t_C = 0.000 m

Fuel Tank	h_C m	Ht ABL m	Volume m^3	$O_{B(i)}$ m^3	P_B	Outflow m^3	
FO P	6.387	8.537	172	363.0	0.0108	363.0	
FO S	6.387	8.537	172	363.0	0.0108	363.0	
					$O_{MB(0)}$ =	7.8	m^3

Tidal Change t_C = -2.500 m

Fuel Tank	h_C m	Ht ABL m	Volume m^3	$O_{B(i)}$ m^3	P_B	Outflow m^3	
FO P	3.824	5.974	95	440.0	0.0108	440.0	
FO S	3.824	5.974	95	440.0	0.0108	440.0	
					$O_{MB(2.5)}$ =	9.5	m^3

Bottom Damage

		Mean Outflow m^3	Factor
Bottom Damage	$O_{MB(0)}$ =	7.8	0.7
	$O_{MB(2.5)}$ =	9.5	0.3
	O_{MB} =	8.3	m^3

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SSC Report Number	Report Bibliography
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SSC 414	**Probability Based Design (Phase 4) Synthesis of the Reliability Thrust Area** P.A. Frieze 2000
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