A Probabilistic Evaluation of Tank Ship Damage in Grounding Events

by

Charles E. Rawson

B.S. Marine Engineering (1988)
United States Coast Guard Academy

Submitted to the Department of Ocean Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Naval Architecture and Marine Engineering and the Degree of Master of Engineering in Ocean Engineering Joint Program in Marine Environmental Systems

at the
Massachusetts Institute of Technology
and the
Woods Hole Oceanographic Institute

June 1998

Signature of Author.....
Department of Ocean Engineering
May 22, 1998

Certified by.....
Alan J. Brown
Senior Lecturer in Naval Architecture and Marine Engineering
Thesis Supervisor

Accepted by.....
Professor J. Kim Vandiver
Chairman, Committee for Graduate Studies
Department of Ocean Engineering

Accepted by.....
Professor Michael S. Triantafyllou
Chairman, Joint Committee for Applied
Ocean Science and Engineering

A Probabilistic Evaluation of Tank Ship Damage in Grounding Events

by

Charles E. Rawson

Submitted to the Department of Ocean Engineering
on May 22, 1998 in Partial Fulfillment of the
Requirements for the Degree of Master of Science
in Naval Architecture and Marine Engineering
and the Degree of Master of Engineering in Ocean Engineering

ABSTRACT

Recent international and domestic regulatory actions have resulted in significant changes to oil tanker designs and intensified attention on predicting tanker environmental performance following groundings or collisions. The current analytical method defined by the International Maritime Organization (IMO) applies probabilistic damage extents to proposed designs to determine expected oil outflows, which are compared to reference double hull vessels. The IMO method considers the effect of subdivision on oil outflow, but does not account for the ability of a specific structure to resist rupture and minimize cargo loss. Further, IMO damage extents are based on a limited set of tanker casualty data, and do not reflect current trends in materials or construction.

This thesis proposes a probabilistic method for evaluating the crashworthiness of new tankers using a theoretical model for predicting grounding damage extents rather than historical data. The procedure proposes developing and calibrating a probabilistic grounding scenario, then applying the scenario in a Monte Carlo simulation to alternative tanker designs for evaluation of pollution prevention effectiveness. The simulation uses the structural damage model DAMAGE to predict bottom damage extents following a grounding for a series of notional single hull, double hull and intermediate oil-tight deck tankers of comparable size designed for this research. The effect of structural enhancements such as increasing plate thickness, densely packing longitudinal stiffeners or the adding more transverse framing is examined by comparing the oil outflow characteristics of a family of modified double hull tankers. This research is done in conjunction with simultaneous research into a similar method for tanker collisions.

Thesis Supervisor: Alan J. Brown
Title: Senior Lecturer in Naval Architecture and Marine Engineering

List of Figures

List of Tables

Table of Contents

Chapter 1. Thesis Summary

1.1 Motivation

The environmental performance of tankers following accidents is an area of increasing public awareness and regulatory attention. Numerous well-publicized events of oil spilling into the oceans have focused attention on reducing the oil outflow from ships following an accident, as well as reducing pollution from other, more routine sources. Traditionally, ships are designed only to endure their own loading forces and wave actions. Recent regulatory attention has shifted to more physical or mechanical controls and rationally-based methods for the design and acceptance of tankers.

Current regulations calculate hypothetical oil outflow, and base probable damage estimates upon historical casualty data. This method does not maintain pace with the technological, material and operational changes that occur in the world's tanker fleet. Damage extent estimates are based on accidents that occurred to single hull tankers twenty years ago, and do not reflect the current materials used or vessel arrangements made necessary by newer regulations. Current regulations are primarily prescriptive, addressing deficiencies noted in earlier designs, rather than performance based. The effort now is to develop rational procedures for evaluating grounded tankers' environmental performance that takes into account structural enhancements and encourages innovative designs for pollution prevention.

1.2 Tanker Legislative History

The requirements for the safe navigation of bulk tankers have evolved dramatically from their roots in the late 19th century. Over this period, the emphasis placed by rulemakers has shifted from encouraging "good practices of safe seamanship" to mandating strict technical requirements.

The prevention of pollution from ships, like the safety of the crew and cargo, was originally the responsibility of the vessel's master and owner. As technology increased toward the end of the mid 19th century, ship owners met this responsibility through their

own or insurance companies' standards for the proper operation and design of their vessels. Following several spectacular maritime disasters, most notably the loss of over 1700 persons on the passenger liner *Titanic* in April 1912, the international community met to formulate a method to prevent further disasters. In 1914, the Convention[1] on the Safety of Life at Sea (SOLAS) was formulated and formed a basis for ensuring appropriate standards were met for all ocean-going ships. The main requirements of the SOLAS Convention were simply for adequate navigation and communication equipment and watertight, fire-resistant bulkheads.

The original SOLAS Convention was modified numerous times, and later replaced with a new Convention in 1948. The SOLAS Convention of 1948 created standards for general structure, machinery and electrical installations, fire protection, life-saving appliances, communications and safe navigation. The prevention of pollution was not specifically addressed, however certain safety standards contained in SOLAS applied strictly to vessels dedicated to carrying oil and therefore indirectly prevented oil spills by reducing the complete loss of tankers. One of the root problems with the early SOLAS Conventions was the sluggishness of an adoption procedure that enforced amendments only when ratified by two-thirds of all contracting parties [1]. This practice made modifying the regulations difficult to achieve and did not help to eliminate substandard ships in the world fleet. In fact, what occurred was the creation of numerous other Conventions, formulated by both governmental and non-governmental bodies, promulgating rules that applied to vessels of specific types or on certain routes or trades. The number of new regulations increased so substantially that ship owners found it difficult to meet their requirements.

Some of these Conventions dealt solely with the introduction of oil into the seas by ships. After World War I, numerous governments noted the problem of oil in the

[1] "Conventions" are international treaties designed as an obligation-creating instrument when ratified. "Resolutions" lay down standards of policy, and are not binding or have the same measure of authority as Conventions. "Recommendations" are not designed for creating legal obligations, but are exclusively standard-defining instruments, considered as guides for national action. "Codes" are collections of Recommendations. Codes stand somewhere between Conventions and Resolutions in their level of obligation. In practice however, Resolutions carry more weight, and some of the codes are incorporated into national law. Mankabady, Samir. 1986.

oceans. A collection of shipowners, oil companies and harbor officials met in London in 1921 to consider the problems from oil pollution. In 1922, Great Britain passed the Oil in Navigable Waters Act, which prohibited the discharge of oil or oily water into the territorial seas of Great Britain and Northern Ireland and imposed a fine of £100 for any violations [2]. Such unilateral action by the British government sparked world attention, and in 1926 an international conference on maritime oil pollution was held in Washington, DC. Although this conference failed to produce a Convention, it did result in a voluntary adoption by shipowners of a British 50 mile prohibited zone. Later, shipowners followed with similar actions for Holland, Belgium, Norway and Sweden. For United States waters, shipowners accepted a zone of 100 miles.

The question of a single standard applicable to all ships was raised to the League of Nations, who set up a special committee to examine the issue and prepare a draft Convention. However the work of this committee was interrupted by World War II and not resumed until in 1952 when the British government set up the Faulkner Committee. This Committee published a comprehensive report on the effects of oil pollution, the causes of the pollution and proposed some long and short term solutions. In 1954, a conference sponsored by the British government produced the International Convention for the Prevention of Pollution of the Sea by Oil[2] which was formally adopted in July, 1956.

OILPOL 1954 differed from the previous efforts in that it included operational controls of pollution from routine tanker operations[3] and the discharge of oily wastes from all ships' machinery spaces. It prohibited discharge of any amount of oil in certain zones[4], restricted discharge of oil mixtures to those with no more than 100 parts of oil per million parts or water, and required ports to provide adequate reception facilities to receive machinery space wastes and residues from ballasted fuel and cargo oil tanks.

---

[2] Commonly referred to as OILPOL 1954.

[3] Oil tankers normally carry cargo only during one half of their voyages. For the return trip to the oil fields, seawater is routinely taken on as ballast to ensure vessel stability. When this ballast water is pumped off prior to cargo loading, oil residues in the tanks are discharged also.

[4] These certain zones included all sea areas within 50 miles of the nearest land; certain specially defined areas; and any area within 100 miles from the nearest land along the coasts of a State which has declared such a zone. OILPOL 1954.

Following World War II and the creation of the United Nations, several countries proposed that a single permanent international body be established to combine many of the unilateral and diverse treaties and promote all aspects of maritime safety more effectively. In 1948 the United Nations Maritime Conference met in Geneva, and adopted the Convention which established the Inter-Governmental Maritime Consultative Organization[5], the first permanent international body devoted exclusively to shipping matters. Since its first meeting in London in January, 1959 the IMO has adopted more than 40 Conventions and Protocols, and adopted well over 700 codes and recommendations concerning maritime safety, the prevention of pollution and related matters[6]. Membership has grown from 28 Member States in January 1959 to the current 155 Member States and two Associate Members. Following acceptance of the Convention creating IMO, the Organization assumed responsibility for maintaining and enforcing OILPOL 1954. This was done through the Marine Environmental Protection Committee (MEPC), one of five separate standing Committees that do the work of IMO. The MEPC is responsible for all matters relating to the prevention and control of maritime pollution.

For the first years after the creation of the MEPC, the regulations pertaining to maritime pollution were almost solely related to routine operational procedures and the safety of the tanker's crew. No laws existed relating to the safe design of tank vessels, or to the development of equipment for the purpose of preventing or minimizing oil spills. This situation changed with the adoption of the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 (otherwise known as MARPOL 73/78) following the *Torrey Canyon*[7] disaster. For the first time,

---

[5] In 1982, the Inter-Governmental Maritime Consultative Organization removed the "Consultative" from its title to become the International Maritime Organization. In this thesis, the abbreviation IMO will refer to either organization.

[6] Numbers provided by IMO at their website.

[7] On March 18, 1967, the 122,000 dwt supertanker *Torrey Canyon* ran aground off England's Cornish coast near the Scilly Isles, dumping 124,000 metric tons of oil. Later testimony would reveal a number of human errors contributed to the incident, including pressure from the owners to make a port call on time, misunderstandings amongst the officers and missing publications that would have alerted the crew about their passage through dangerous shoal waters. The accident raised the world's awareness of the potential dangers of supertanker spills and showed how unprepared the world was to deal with their aftermath. [3]

laws were put into place that required vessels to be built or outfitted to minimize the accidental spillage of pollutants following an accident.

MARPOL 73/78 is organized into five Annexes, and its rules are divided into three general categories. The five Annexes include oil, noxious liquid substances (hazardous materials) carried in bulk, harmful substances in packaged form, sewage, and garbage[8]. The regulations are either designed to contain operational pollution, contain accidental pollution, or enforce the previous two categories.

In general, the operational pollution requirements were maintained from OILPOL 1954, but some new operational design requirements were added in MARPOL 73/78. An example is the requirement for all tankers to be capable of retaining all oily wastes on board using the "load on top" system[9]. This regulation required the addition of many additional pieces of equipment to the vessel, including an oil discharge monitoring and control system, oily-water separating equipment, additional piping and pumps, and slop and sludge tanks. MARPOL 73/78 also defined requirements for ballast spaces, such as the use of segregated ballast tanks and dedicated clean ballast tanks to ensure that vessels could safely operate without the need to place ballast water in cargo tanks, and ensure that vessels would have adequate stability to survive after damage by collision or grounding.

Regulations specifically designed to protect the cargo following an accident were a new addition for MARPOL 73/78. Chapter 3 of Annex I deals exclusively with "requirements for minimizing oil pollution from oil tankers due to side and bottom damages". These requirements were derived from historical data to provide a hypothetical outflow of oil. Based on hypothetical outflows, tankers were limited in size and arrangement of cargo tanks [6]. Regulations requiring the compulsory fitting of

---

[8] Only Annex I is discussed in this thesis.

[9] "Load on top" is a procedure developed by the industry where the cargo tanks are washed, and the oily wash-water is transferred to a slop tank where the water is allowed to separate from the oil and be discharged directly into the sea. This has proven to be very effective and cost efficient, however due to the time required for the slops to settle, it is not useful for vessels in coastwise (short route) trade. Additionally, corrosion problems arise when incompatible oils are stored as slops. The regulation was later modified so that only tankers of 20,000 gross tons and above were included. [4,5]

segregated ballast tanks also required they be "protectively located" in order to "provide a measure of protection against oil outflow in the event of grounding or collision" [7].

The next major event in the history of tanker legislation was the grounding of the *Exxon Valdez* in Prince William Sound in March 1989, which spilled 36,000 metric tons of crude oil and caused measureless damage to the Alaskan environment. This was the final in a series of incidents of oil spillage that had plagued U.S. coastlines for the previous three years and resulted in the passage of the Oil Pollution Act of 1990 (OPA 90), the most radical response yet by a single nation to tackle the problem of marine pollution of its shores. Although internationally regarded by ship owners and industry groups as a knee-jerk response designed to appease public pressure, there is little doubt among experts that the Act, which attempts to deal with all issues from prevention to compensation, will affect the future of the tanker market more than any other single piece of legislation [8].

The key points of OPA 90 include: a) making ship owners and operators jointly and severally liable for meeting all spilled oil removal costs; b) removing the limit of liability to pay damages if negligence or violation of regulation can be proved; c) granting individual states the right to override federal law and impose their own (unlimited) liability; d) requiring all tank vessels entering U.S. waters to possess a certificate of financial responsibility[10]; e) requiring all new tankships to have a double hull and phasing out single hull tankships by 2015.

Although the most contentious issue concerning OPA 90 is the liability section, the double hull requirement is a significant step in the change in emphasis from the control of routine operational discharges to the physical control of accidental spills. This requirement also has a substantial impact on ship owners, mostly due to the phasing out of existing tankers over time[11]. OPA 90 provides a phase-out schedule based on tonnage and the age of the vessel such that larger vessels are excluded from entry to U.S. waters

[10] A certificate of financial responsibility is issued to a vessel by the Coast Guard which guarantees that maximum liability limits can be met should an incident occur. Without such documentation, entry to U.S. waters is strictly denied.

[11] Because of the denial of single hulled vessels into U.S. ports, ship owners may have to scrap certain vessels earlier than intended. Owners would lose money based on an earlier loss of their vessel, and an increased amount of capital spending required to build a new fleet.

earlier. Double hull requirements may also increase the market prices of oil, as the cargo carrying capacity for tankers allowed into the U.S. falls below demand sometime around the turn of the century. [9]

Following the passage of OPA 90, several other key coastal States passed regulations in addition to the IMO requirements[12]. IMO reacted by adopting the International Convention on Oil Pollution Preparedness, Response and Co-operation, and the 1992 Amendments to MARPOL 73/78. The 1992 amendments[13] to MARPOL 73/78 include the new regulation 13F to Annex I that requires all new tankers be fitted with double hulls. This regulation differs from OPA 90 in that "other methods of design and construction of oil tankers may also be accepted ... provided that such methods ensure at least the same level of protection against oil pollution..."[10]. OPA 90 allows no alternative to double hulls.

In September 1995, MEPC adopted the "Interim Guidelines for Approval of Alternative Methods of Design and Construction of Oil Tankers Under Regulation 13F(5) of Annex I of MARPOL 73/78". The Guidelines provide a probabilistic-based procedure for assessing the oil outflow performance of alternative tanker designs. These Guidelines provide a rigorous method to compute oil outflow in accidental groundings and collisions and provide for the calculation of a "pollution prevention index" for comparison with a series of acceptable "reference" double hull designs. This process integrates a probabilistic methodology first used for promoting passenger vessel safety into a model predicting tanker damage from collisions and grounding, and produces a quantifiable index for the comparison of the environmental performance of various tanker configurations and designs.

[12] States such as the European Community, Australia, Canada, Japan, and the Middle East Gulf passed legislation requiring such things as increased port state inspection duties, guidelines for implementing IMO regulations for more efficiently, limiting certain tanker movements, and introducing levies on vessels bound for that States' ports.

[13] Resolution MEPC.52(32) was adopted on 6 March 1992 and provided two new regulations 13F and 13G to Annex I of MARPOL 73/78.

1.3 IMO Guidelines - Probabilistic Oil Outflow Method

A fully probabilistic evaluation of a specific vessel on a specific route would require development of the following probabilities [11]:

- The probability that the ship will have a grounding or collision;
- The conditional probability density functions for damage location and extent given a grounding or collision;
- The conditional probability density function for oil outflow given damage extent.

The IMO Guidelines do not specifically deal with the probability of whether the ship is involved in a grounding or collision. Rather, it is acknowledged the probability exists, and the vessel is assumed to have been involved in an event significant enough to breach the outer hull. The Guidelines begin with assumed probability density functions for damage extent and from these calculate a probability density function for oil outflow. This process is completed in four steps:

Step 1: Assemble Damage Cases

The Guidelines specify probability density functions (pdf's) describing the location, extent and penetration of side and bottom damage. This is done for groundings by providing 5 independent functions: longitudinal location of the center of damage; longitudinal extent of damage; vertical penetration into the hull; transverse extent (breadth) of damage; and the transverse location of the center of the damage. For applicability to any vessel, the density scales are normalized by the ship length for longitudinal location and extent, ship depth for the vertical penetration, and the ship breadth for the transverse functions.

These density functions are based on a statistical analysis conducted by Lloyd's Register in support of the IMO Comparative Study on Tanker Design [12]. Figure 1-1 contains the IMO probability density function for the longitudinal extent of damage from grounding. The histogram represents statistical data collected by the classification

societies and the linear plot represents IMO's piece-wise linear fit of 63 grounding incidents used as their data. The other density functions are constructed in a similar manner from the same incidents.

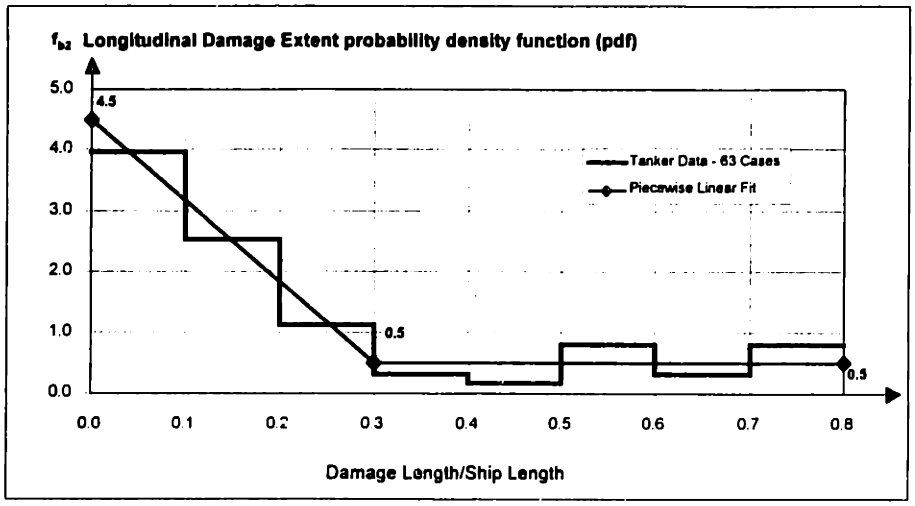


Figure 1-1 Damage Extent Probability Density Function

The entire set of damage cases represent all the possible combinations of specific cargo tank damage which may be encountered. Application of the probability density functions to the vessel's subdivision provides the probability of occurrence for each unique damage case. This is done either through a stepwise evaluation at a sufficiently fine increment, or a Monte Carlo approach utilizing a large number of simulated damage cases. The cumulative probability for all the damage cases is computed, as the running sum of probabilities beginning at the minimum outflow damage case through the maximum outflow damage case. The cumulative probability for all damage cases is 1.0.

Step 2: Calculate Oil Outflow

The next step is to compute the oil outflow associated with each unique side and bottom damage case. For side damage, total (100%) outflow is assumed for each damaged tank. For bottom damage, oil loss is calculated based on pressure balance principles, and takes into account the adverse effect on oil outflow due to falling tides by determining the outflow for each damage case at three different tide conditions. These conditions are an initial (0 meter) tide, 2 meter tidal drop, and 6 meter tidal drop, but in

no case a tidal drop greater than 50% of the ship's maximum draft. The outflows at each tide condition are combined together using a weighted average. In the instances where a double bottom or void lies below a damaged cargo tank, the Guidelines provide assumptions to calculate the amount of oil captured within these spaces and not released into the sea.

Step 3: Calculate Oil Outflow Parameters

Once an outflow value is assigned to each damage case, sufficient data exists to construct an outflow density function from which global outflow parameters may be calculated. The IMO Guidelines define three outflow parameters: probability of zero outflow, mean outflow, and extreme outflow. Once these parameters are determined for both grounding and collision cases, they are combined in a ratio of 0.6:0.4 respectively, providing overall parameter values.

Step 4: Compute the Pollution Prevention Index "E"

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

$$E = k_1 \frac{P_0}{P_{0R}} + k_2 \frac{0.01 + O_{MR}}{0.01 + O_M} + k_3 \frac{0.025 + O_{ER}}{0.025 + O_E} \qquad (1)$$

where: k_1, k_2, k_3 are weighting factors having the values 0.5, 0.4 and 0.1,

P_0 is the probability of zero oil outflow for the alternative design,

O_M is the mean oil outflow parameter for the alternative design, and

O_E is the extreme oil outflow parameter for the alternative design.

P_{OR}, O_{MR} and O_{ER} are the corresponding parameters for the reference double hull design of the same cargo oil capacity. Values for these parameters are provided in the Guidelines.

Development of the formula for the pollution prevention index "E" was an item of considerable discussion at IMO. It was recognized that the weighting factors for the outflow parameters should have a rational basis associated with the benefits of avoiding spills and the relative financial and environmental impacts of smaller spills as compared to larger spills. However, IMO was unable to obtain such information, and it was necessary to develop "E" in a more arbitrary manner. Specifically, outflow calculations were carried out for a number of double hull tanker and intermediate oil-tight deck (mid-deck) concept designs, all of which were intended to satisfy the new MARPOL 13F requirements. The weighting factors were then selected to assure that both the double hull and mid-deck concepts would be in conformance with the Guidelines.

1.4 Deficiencies with Current Guidelines

Although the Guidelines provide a much needed probabilistic methodology for evaluating environmental performance, deficiencies still exist in the current version. These include:

- the damage extent probability density functions are based on limited historical data and applied universally for all designs independent of structure;
- damage extents are normalized with ship dimensions;
- current damage extents are based on data for cases where hull was ruptured;
- damage extent probability density functions are assumed to be independent.

The damage extent probability density functions were derived from a relatively small number of incidents occurring on a narrow range of ships. All these ships were single hull vessels, and do not reflect the current use of high strength steels or current tank arrangements. No credit is given for innovative designs that may reduce damage extents. Since the probability density functions were normalized with respect to ship length, breadth and depth, the effect of local structure features and specific scantlings is not captured.

The current damage extent probability density functions are conditional upon a grounding event severe enough that the outer hull is breached. This requirement

necessarily comes from the use of historical data, as less severe incidents are much less widely reported and their facts recorded with less accuracy. For this and other reasons, the Guidelines state that "designs for tankers intended to be constructed of other materials or incorporating novel features, or designs which use impact absorbing devices should be specially considered" [13]. Rupture-resistant prevention measures cannot be evaluated using the current procedure, but instances where the hull is not penetrated contribute directly to the probability of zero outflow.

The five IMO probability density functions are assumed to be independent. This assumption is imposed because no correlation between the length, width and vertical penetration was established using strictly historical data.

1.5 Proposal

This thesis proposes a method based on fundamental principles to evaluate the crashworthiness of tankers in a grounding. It addresses deficiencies in the current IMO Guidelines. The method determines grounding damage cases by using a probabilistic structural damage evaluation model rather than extrapolated historical data. The damage cases are used to calculate oil outflow parameters as in the present Guidelines. The method is used to compare oil outflow for double hull, single hull and intermediate oil-tight deck tanker configurations of similar capacities. The effect of structural modifications on pollution prevention is also examined by applying the method to a family of double hull tank ships. This work is being done in conjunction with the work of Kurtis W. Crake, who is examining a similar method with respect to collision events [14].

The proposed method uses a Monte Carlo simulation to determine expected damage extents from Damage, a PC-based computational model. Chapter 2 describes the reasons for selecting Damage and the steps needed to use it in a probabilistic manner. Chapter 3 presents the tanker designs developed for this project, which include single hull, intermediate oil-tight deck and double hull configurations. Chapter 4 describes the sensitivity analysis phase where the parameters describing the simulation scenario are analyzed and assigned characteristic probability density functions. Chapter 5 is a

description of the Monte Carlo simulation routine. Chapter 6 describes the process for calibrating the scenario probability density functions to match existing data. Chapter 7 describes the calculation of the oil outflow parameters. Chapter 8 compares the derived simulation oil outflow parameters and damage extent probability density functions to those in the IMO Guidelines. Conclusions and recommendations for further work are discussed in Chapter 9. Figure 1-2 describes the flow of the research, from the sensitivity analysis and design of tanker models to the generation of calculated probability density functions and oil outflow parameters.

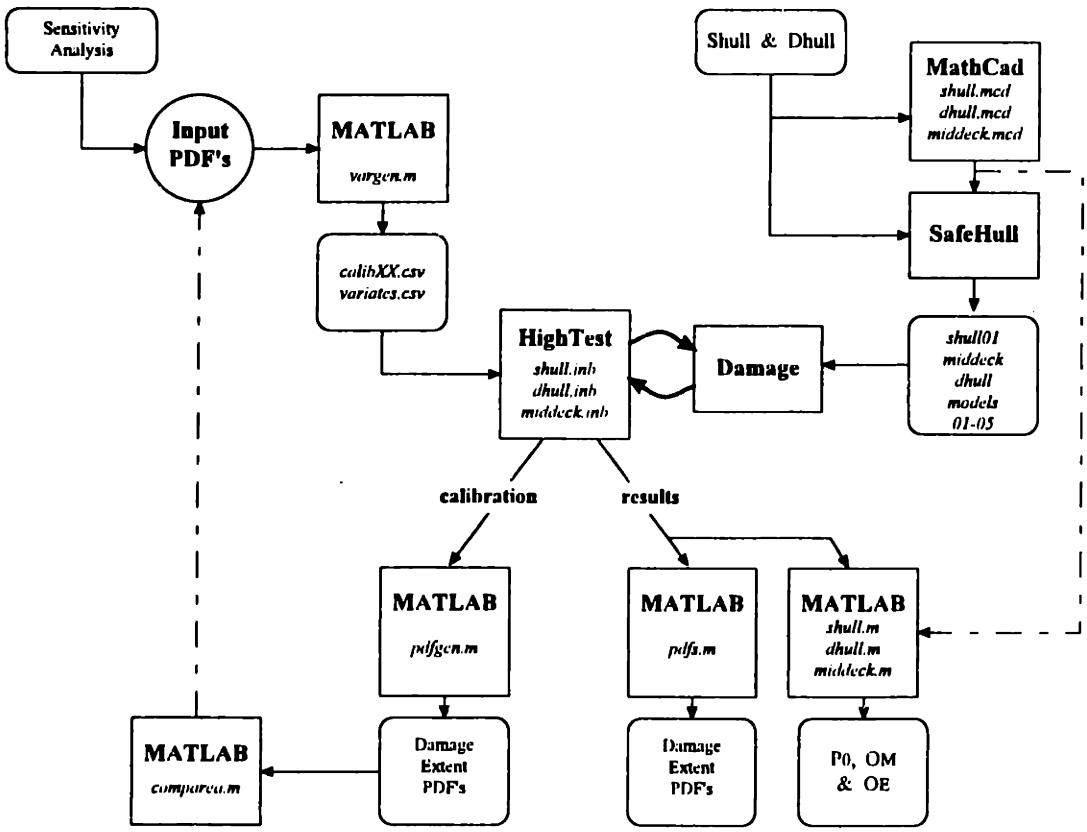


Figure 1-2 Tank Ship Probabilistic Grounding Evaluation Diagram

Chapter 2. Software Overview

2.1 Problem Statement

The goal of this research is to suggest a rational method for examining the environmental performance of tankers using a fundamentally-based model for determining damage extents. The IMO Guidelines determine damage extents following groundings or collisions from a small amount of statistical data gathered from actual tanker accidents between 1980 and 1990. Since this data represents the technology and practices of that time period, it is logical to conclude that damage extents for current technology tankers are different.

The deficiencies identified in Section 1.4 cannot be addressed using limited historical data as a basis for estimating damage extents. A theoretical model to predict damage is required. Optimally, a grounded ship damage model would use a closed form solution. Computational efficiency is a priority in a Monte Carlo simulation where thousands of data runs are required.

For a comparison of single hull, double hull and mid-deck tankers, as well as an investigation into the impact of scantling modifications on oil outflow, numerous configurations require modeling. Each ship analysis requires thousands of individual damage cases to be generated and evaluated. Finite element methods are not a good choice for this model. Finite element methods (FEM) are very time intensive, both in model definition and output generation. In later work FEM may be used to verify certain aspects of results acquired from less labor-intensive routines.

2.2 DAMAGE

In order to consider the effect of structural design or crashworthiness on damage extents, the mechanics of the grounding process and the interaction between local structural damage and global ship motion must be understood and modeled. Examining these processes in a probabilistic manner, with the variety of structural details and potential accident scenarios makes this task difficult. However the Joint MIT-Industry

Project on Tanker Safety, under the supervision of Professor Tomasz Wierzbicki, has developed a computational model to predict grounding damage to an oil tanker that provides an efficient solution to this problem.

This model is encoded in the computer program Damage (**DA**Mage Assessment of Grounding Events) that computes the damage extent of a tanker in a grounding accident [15]. Damage is based on the basic laws of mechanics and the theories of plasticity and fracture without strong dependence on empirical relations. For this reason, there is no limitation to the type of structures that can be analyzed with it, and it becomes a powerful tool for evaluating innovative ship designs.

Damage's computational model calculates the three primary mechanisms for energy dissipation in a grounding event: a change in potential energy of the ship and surrounding water; friction between the ground and the hull; and deformation and fracture of the hull. The length of the damage is determined by the principle of conservation of energy, where the kinetic energy at any point aft of the original contact location is equal to the initial kinetic energy minus the energy absorbed by the structure up to that point, minus the remaining potential energy. The energy absorbed by the structure is dissipated through two primary mechanisms, friction and plastic energy (plastic deformation and fracture).

Typically, friction accounts for 30-50% of the total energy absorption between the rock and the hull. In Damage, the rate of energy dissipation by frictional forces is calculated by applying a factor, g, to the previously calculated plastic resistance of the structure. This factor g is a function of a coefficient of friction, the geometry of the rock and the relative motion between the rock and the hull.

Plastic energy dissipation is determined by examining three separate models of the ship's structure: a plate model, a longitudinal members model, and a transverse members model. Three important restrictions are applied to these models:

- Only the flat bottom structure and primary structural members typical of a large oil tanker are considered explicitly. Secondary structural members are considered by an equivalent thickness method;
- Weld strength is not considered; and

- Inertia forces of the deforming parts of the hull are neglected.

At the conclusion of the calculations, Damage provides the user with detailed information about the heave, pitch, rock penetration, structural reaction force and plating status (rupture/no rupture) at each time step. Outputs can be either graphical or tabular in format.

It is important to note that Damage is not a finite element program. The structural models were developed using a superelement approach, which limits the potential grounding scenarios to a certain range of rock geometries. It is extremely efficient however, determining damage extents with just 300-500 intermediate steps along the damage path typically in less than 20 seconds.

Oil outflow from a grounded tanker is assumed to be the result of a prismatic (i.e., long and slender) breach of the cargo shell. The primary factors that affect oil outflow are therefore the rupture length and penetration into the hull. Current efforts to validate the program Damage indicate satisfactory accuracy with small and large scale model tests in these areas [16].

In four 1:5 scale tests conducted by the Naval Surface Warfare Center Carderock Division, Damage demonstrated less than 10% error in energy absorption and comparable error in predicting penetration to fracture of an inner shell. In three large scale tests conducted by the Association for Structural Improvement of Shipbuilding Institute in the Netherlands, Damage demonstrated similar degrees of accuracy in predicting horizontal forces. These tests also showed that the model for the external dynamics used by Damage to capture global ship motions is not yet satisfactory and the vertical penetration forces were not well predicted. However, since the energy absorption was calculated with a very good accuracy, the overall damage length was predicted accurately.

Damage is a Window-based program that extensively uses the graphical user interface capabilities of the personal computer. All the ship's structure and the grounding scenario including obstacle geometry is entered through menus such as those depicted in Figures 2-1 and 2-2. This configuration allows quick and simple input of model and

scenario data, but makes repeated (batch) Damage runs difficult as multiple dialog boxes must be accessed to alter the desired input parameters.

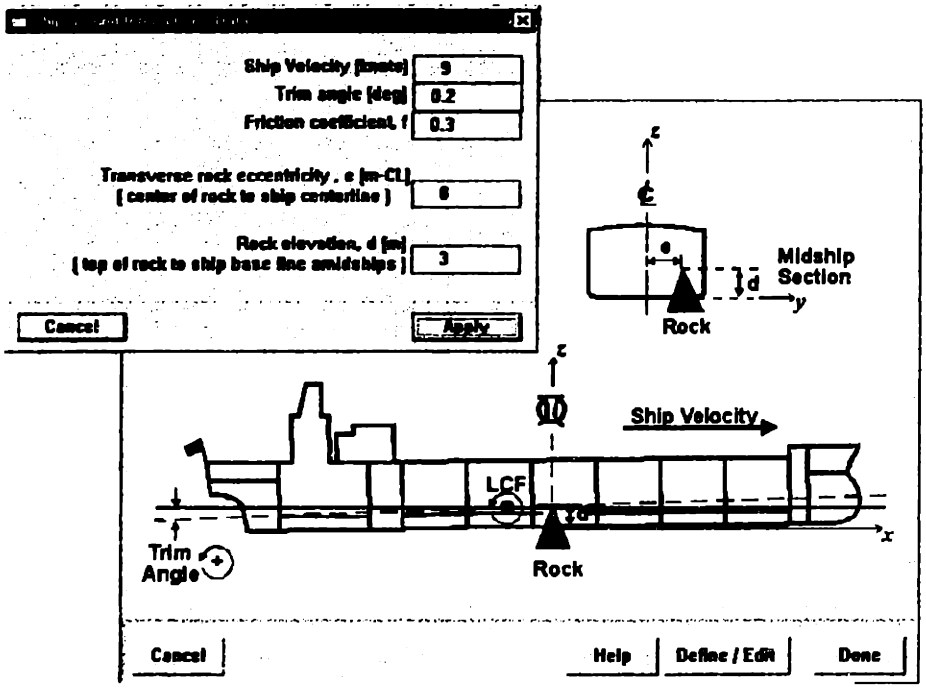


Figure 2-1 Damage "Ship-Ground Interaction" Screen Shot

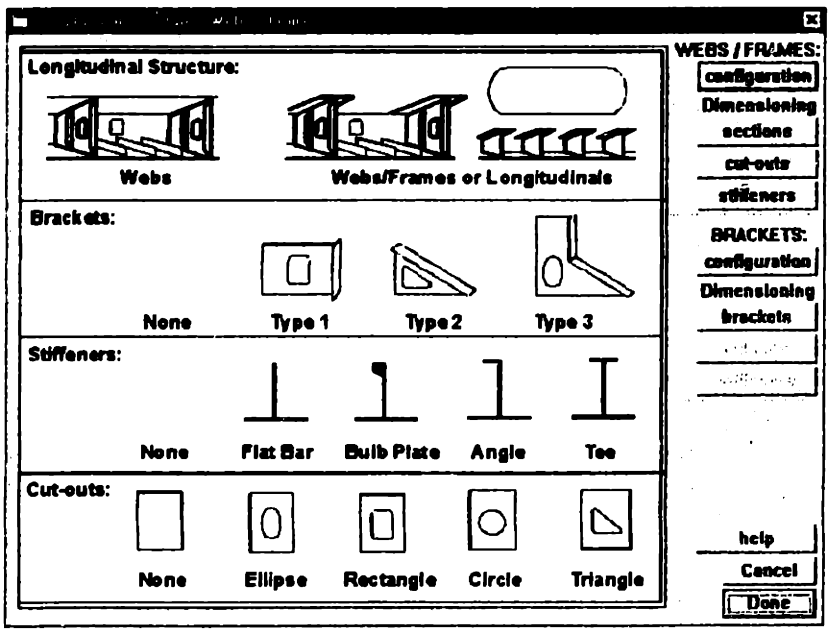


Figure 2-2 Typical Damage Structure Input Screen Shot

Another difficulty encountered when attempting to run Damage in a batch mode is the recovery of results. The program is currently configured to give detailed graphical information concerning a single completed data run. Tabular information is available, but not generated by the program until specifically requested by a user.

2.3 Vermont HighTest

These difficulties in automating the existing Damage code to run in a batch mode were examined in order to make the tool usable for determining probabilistic damage extents. One possibility was to have the original programmer of Damage, Dr. Wlodek Abramowicz of Impact Design, Europe modify the code to allow the input from a separately generated text file. Although this was the simplest and most efficient method, it was not used because the goal of this thesis was to develop an exportable method that could be used by different agencies or entities for assessing tanker environmental performance. By modifying the current version of Damage, this critical evaluation step would become static, as later modifications to Damage, such as the inclusion of hull sides for collision damage, might not possibly be supported. This was already seen during the term of this thesis, as Damage was upgraded from version 1.2 to version 2.0 in June of 1997. Therefore another manner for generating batch runs was sought.

Vermont HighTest is a package designed for the automated testing of Microsoft Windows applications. It is designed to be a flexible programming software that simplifies repetitive tasks and performs automatic actions within a programming shell. Some of the functions that HighTest performs that are useful for this purpose are:

- object-oriented recording and playing of specified Windows events;
- capturing screen images and internal details of windows or file contents; and
- constructing and customizing test scripts using its own scripting language.

For the detailed sensitivity analysis, calibration phase and the final Monte Carlo simulation phase Vermont HighTest is used to enter data from text files containing the distributed scenario inputs and automatically extract the desired outputs from Damage. A total of three HighTest program scripts are used, one for each of the major configurations of

tanker, single hull, double hull and intermediate oil-tight deck. These scripts are described in Chapter 5 of this thesis, and included in Appendix A. During the calibration phase, data runs were completed at the rate of approximately 250 per hour. In the final simulation phase after the scripts were revised for more efficiency, data runs were completed at better than 400 per hour. More than 80,000 separate Damage scenarios were recorded using this methodology.

Chapter 3. Generation of Tanker Models

3.1 Representative Tanker Model Overview

A family of representative tankers was designed for calibrating the input scenario pdf's and estimating the effect of structural enhancements on crashworthiness. The tankers are configured as either a MARPOL single hull tanker, double hull tanker or intermediate oil-tight deck (mid-deck) tanker of Suezmax (150,000 dwt) dimensions. The single hull tanker is designed consistent in material and configuration with vessels in service between 1980 and 1990, the period included in the data compiled by the classification societies to generate the current IMO damage pdf's. This design is used to calibrate the scenario probability density functions by matching the calculated damage extent density functions to the density functions provided in the Guidelines. The double hull and mid-deck configurations are designed using current shipbuilding practices and used to compare design alternatives.

All designs have the same principal dimensions listed in Table 3-1, with bulkheads located to maintain equal cargo capacity and compliance with MARPOL Regulations for protective location of segregated ballast tanks, maximum tank volume and double hull spacing. Scantlings are the minimum allowed by current classification society standards, as determined by the American Bureau of Shipping's SafeHull system. The effect of structural enhancements on crashworthiness is studied by application of the damage extent and oil outflow analysis to five separate double hull

Table 3-1 Tank Ship Principal Characteristics

LBP:	264 m
Beam:	48 m
Depth (at Deck Edge)	24 m
Draft (Full Load)	16.8 m
Waterplane Area	11,277 m^2
Displacement	178,000 mton
Deadweight	150,000 mton
Cargo Volume	167,000 m^3
Block Coefficient	0.82

design variants. Each variant is a derivative of the original baseline double hull model, with either the plating thickness, stiffener sizes, stiffener spacing or frame spacing modified. For each new variant design, the remaining structural parameters are re-examined using SafeHull to ensure minimum compliance with classification scantling requirements.

3.2 Tanker Synthesis Model

To design the tankers, a ship synthesis model was developed to generate a hull form, calculate tank volumes and check MARPOL compliance. This model uses principal dimensions as entering arguments, calculates basic naval architecture relationships, and then fits a hull shape that best approximates the block and waterplane coefficients and the longitudinal center of flotation [17]. The model is included in Appendix B.

Tank volumes and bulkhead locations are determined by balancing the applicable pollution prevention requirements of Annex I of MARPOL while maintaining the desired deadweight tonnage. The specific sections of MARPOL that apply to bulkhead location are the protective location of segregated ballast spaces (Regulation 13E), the retention of oil on board (Regulation 15) and the limitation of size and arrangement of cargo tanks (Regulation 24).

The requirement for protective location of segregated ballast spaces for the double hull and mid-deck tankers is met by the use of double sides along the entire cargo block. For the single hull design, the primary design criteria is to ensure adequate protected ballast areas while maintaining the same cargo capacity as the other models. This requires checking all combinations of wing or center ballast tanks, and locating the longitudinal bulkheads to meet the design constraints.

To do this, an assumption is made for the entire cargo area that the internal tank dimensions do not vary with depth, i.e., flat bottoms and sides. Once the hull form is determined, the tank boundaries are set and tank volumes calculated. Deadweight tonnage is determined by assigning sets of tanks as segregated ballast tanks, and removing

their volumes from the total. Protected areas are determined using the formula given in Regulation 13E:

$$\sum PA_c + \sum PA_s \geq J\left[L_c(B + 2D)\right] \qquad (2)$$

where:

PA_c	is the side shell area for each segregated ballast tank;
PA_s	is the bottom shell area for each segregated ballast tank;
J	equals 0.45 for oil tankers of 20,000 dwt; 0.30 for tankers of 200,000 dwt and is determined by linear interpolation for intermediate tonnage;
L_C	is the length of the cargo area;
B	is the breadth; and
D	is the depth.

The final location of the longitudinal tank boundary is determined by examining the combinations of tanks that provide a 150k dwt capacity while maintaining adequate protected shell area. The relationship between capacity and protected area is described in Figure 3-1.

On the left graph, the deadweight tonnage is seen to increase as the longitudinal bulkhead moves away from the centerline. This is due to the decreasing size of the wing tanks and consequent lower ballast capacity. Picking a specific tonnage, 150k in this case, leads to a specific location for a longitudinal bulkhead. In Figure 3-1, this is done with two and three sets of wing ballast tank pairs. Other combinations of ballast tank locations, including center ballast tanks were examined, but failed to provide realistic arrangements and are not shown in this figure. The area protected by wing ballast tanks decreases as the location of the longitudinal bulkhead is moved farther from the centerline. This is because the area protected on the vessel's bottom is decreased while the side area remains constant. In the right side of Figure 3-1, the required protected area is plotted against the longitudinal bulkhead location for two- and three-pair wing ballast tanks. For a two pair

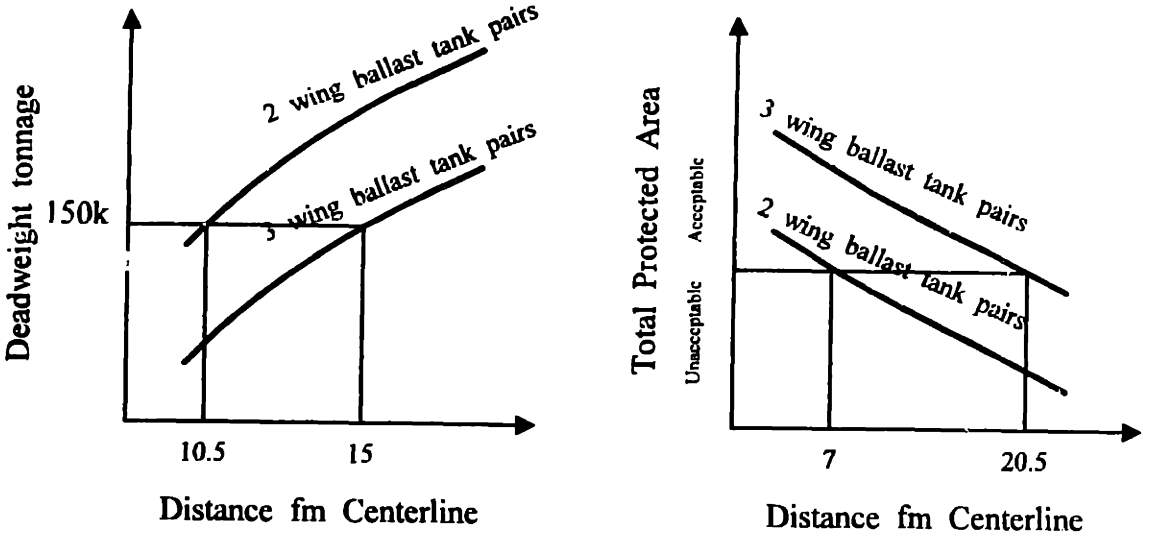


Figure 3-1 Deadweight Tonnage and Protected Area vs. Longitudinal Bulkhead Location

wing ballast tank configuration, the longitudinal bulkhead must be located no more than seven meters from the centerline to meet the protected area requirement, but to meet the tonnage constraint, the bulkhead must be located 10.5 meters from the centerline. The only realistic combination found to meet both constraints is the three pair wing ballast tank arrangement. This arrangement must have the longitudinal bulkhead located 15 meters from center to meet the tonnage requirement, and less than 20.5 meters to meet the protected area requirement. Under the constraints to:

- use the same hull form for all designs;
- maintain equal tonnage with the double hull and mid-deck designs, and;
- meet the MARPOL requirements for protective location of segregated ballast tanks

the arrangement shown in Figure 3-2 is required.

Calculations for the hypothetical outflow of oil according to Chapter III of Annex I of MARPOL were conducted for the single hull configuration. The results are used to ensure the tank volumes do not exceed the requirements of Regulation 24(2)-(4). Slop tank volumes are determined using Regulation 15(2)(c)(i). For the double hull configurations, the capacity of the slop tanks is reduced for smooth walls in accordance

with (2)(c)(iii). This assumption is considered necessary to maintain comparable cargo volumes with the mid-deck design.

3.3 American Bureau of Shipping (ABS) SafeHull

All the scantlings for the tanker family are obtained using the American Bureau of Shipping (ABS) SafeHull system. This two-part system consists of the *ABS Rules for Building and Classing Steel Vessels*, and a hull design and analysis software package [18]. The software package is contained in the program SafeHull, and is composed of two phases. Phase A is used to establish initial minimum required scantlings for a vessel according to the *Rules*. It includes consideration of hull-girder longitudinal bending and shear strength, local strength of shell and bulkhead plating and associated stiffeners, and the strength of main supporting members. Phase B consists of a finite element analysis that is used to assess the strength of major portions of the hull and to confirm the minimum scantlings established in Phase A. Only Phase A, Version 3.10 was used in the design of these tankers.

Some of the assumptions and limitations of the SafeHull Phase A tanker module are:

- vessel length must be greater than 190 m and less than 500 m (*264 m*)
- vessel length to breadth ratio is greater than 5.0 (*5.5*)
- vessel breadth to depth ratio is less than 2.5 (*2.0*)
- block coefficient is greater than 0.6 (*0.82*)
- no required value is offered for stiffeners present within the bilge.
- single hull tankers can be evaluated only if arranged with three tanks across.

Italicized values are the actual values for the tanker family used in this research.

SafeHull is a system of integrated program modules connected by a central control module. Modules used in this research include: the midship section geometric model generation; integration of tank definition and stiffener properties into the midship section; calculation of the midship section modulus and comparison to minimum required panel values for longitudinal strength; calculation of the required minimum scantlings of the

main supporting and transverse members; and the minimum required scantlings for double bottom floors and girders.

3.4 Single Hull and Mid-deck Design

The single hull tanker is designed as a "new oil tanker" [19] similar to a vessel of its size built after 1980 and required to have segregated and protectively located ballast tanks. Figure 3-2 shows the plan view tank arrangements and midship section. Consistent with the shipbuilding practice of the early 1980's, this vessel is designed with ordinary low carbon steel[14] (mild steel) plating, and high-tensile steel for its strength members. Principal scantling details are shown in Table 3-2. This design is designated "SHull01".

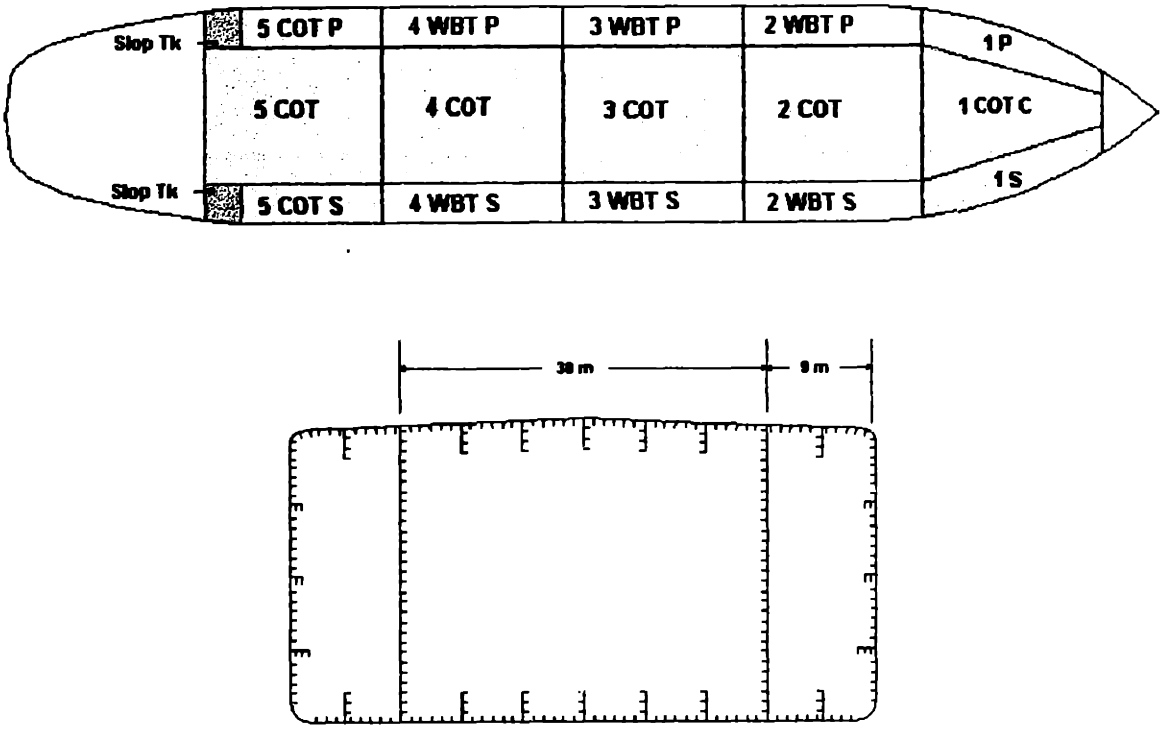


Figure 3-2 SHull01 Plan View and Midship Section

[14] In this thesis, "low carbon steel" refers to mild steel specified by ABS to be "MS24". This designation indicates a yield stress of 2400 kgf/cm^2 (~34 kpsi) and an ultimate stress of 4100 kgf/cm^2 (~58 kpsi). "High-tensile steel" refers to ABS specified steel as either "HT32" [3200 kgf/cm^2 (~45.5 kpsi) yield stress and 4500 kgf/cm^2 (~64 kpsi)] or "HT36" [3600 kgf/cm^2 (~51 kpsi) yield stress and 5000 kgf/cm^2 (~71 kpsi)].

The volume for each tank within its cargo block is shown in Table 3-3. Italicized numbers indicate ballast tanks.

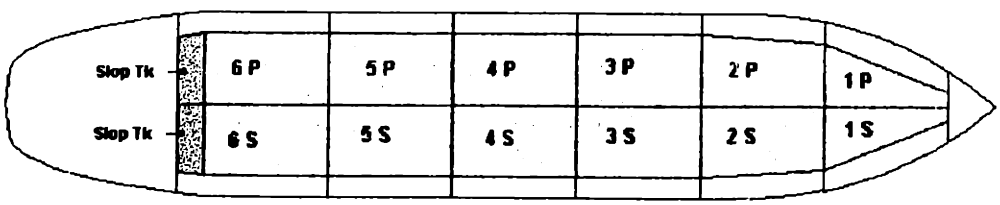
Table 3-2 Primary Scantlings of SHull01

Plating Material:	MS24
Bottom Plating Thickness:	22 mm
Average Side Shell Thickness:	25.75 mm
Average Transverse Bhd Thickness:	19.5 mm
Average Longitudinal Bhd Thickness:	19.5 mm
Deck Plating Thickness	22 mm
Stiffener Spacing	810 mm
Frame Spacing	4.65 m

Table 3-3 SHull01 Tank Volumes (m^3)

	Slop	#5 Cargo	#4 Cargo/ Ballast	#3 Cargo/ Ballast	#2 Cargo/ Ballast	#1 Cargo
Wing	2,195	6,520	*8,878*	*8,878*	*8,712*	5,975
Center		29,052	29,592	29,592	29,041	19,918

The mid-deck variant is designed with a centerline bulkhead, wing tanks above the oil-tight deck and a single center tank below. See Figure 3-3 for the vessel's midship section and upper level tank arrangement. The upper centerline bulkhead is included to allow flexibility of loading without large free surface effects. The outer tank longitudinal bulkhead is located to maintain the same cargo capacity as the double hull design. A conservative value of 0.5D is selected to ensure the mid-deck is above the possible range of any vertical penetration of damage due to grounding. This assumption has the adverse



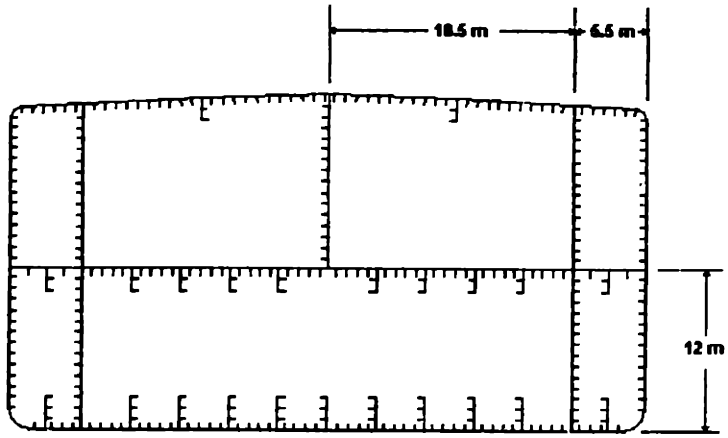


Figure 3-3 Mid-deck Plan View and Midship Section

impact that the mid-deck is high enough to allow oil outflow from the lower cargo tank in bottom damage cases with a 6 meter tidal drop. Further discussion of oil outflow calculations is found in Chapter 7.

The mid-deck design uses high-tensile steel (HT32) throughout. See Table 3-4 for scantling details. SafeHull does not adequately model the differences between mid-deck designs and double or single hull vessels. Most significantly, the oil-tight deck is not considered due to the lack of applicable guidance in the *Rules*. This shortcoming has little effect for this research, as this deck is not involved in any damage scenarios, but should be noted when comparing the structure of the different configurations. Table 3-5 shows the cargo tank volumes for the mid-deck model.

Table 3-4 Primary Scantlings of Mid-deck Design

Plating Material:	HT32
Bottom Plating Thickness:	18 mm
Average Side Shell Thickness:	18 mm
Average Transverse Bhd Thickness:	15.5 mm
Deck Plating Thickness	23.25 mm
Mid-deck Plating Thickness	18.5
Stiffener Spacing	810 mm
Frame Spacing	4.7 m

Table 3-5 Tank Volumes for Mid-deck Design (m^3)

	Slop	#6 Cargo	#5 Cargo	#4 Cargo	#3 Cargo	#2 Cargo	#1 Cargo
Upper Wings	1,626	7,326	7,326	7,326	7,326	6,909	3,979
Lower Center		17,903	14,652	14,652	14,652	13,819	7,959

3.5 Double Hull Models

The double hull design has a double bottom depth of 0.1D. Two-meter double sides are used to comply with MARPOL protective location requirements. A three tank across configuration is used to match the single hull layout and to reduce lolling. Void

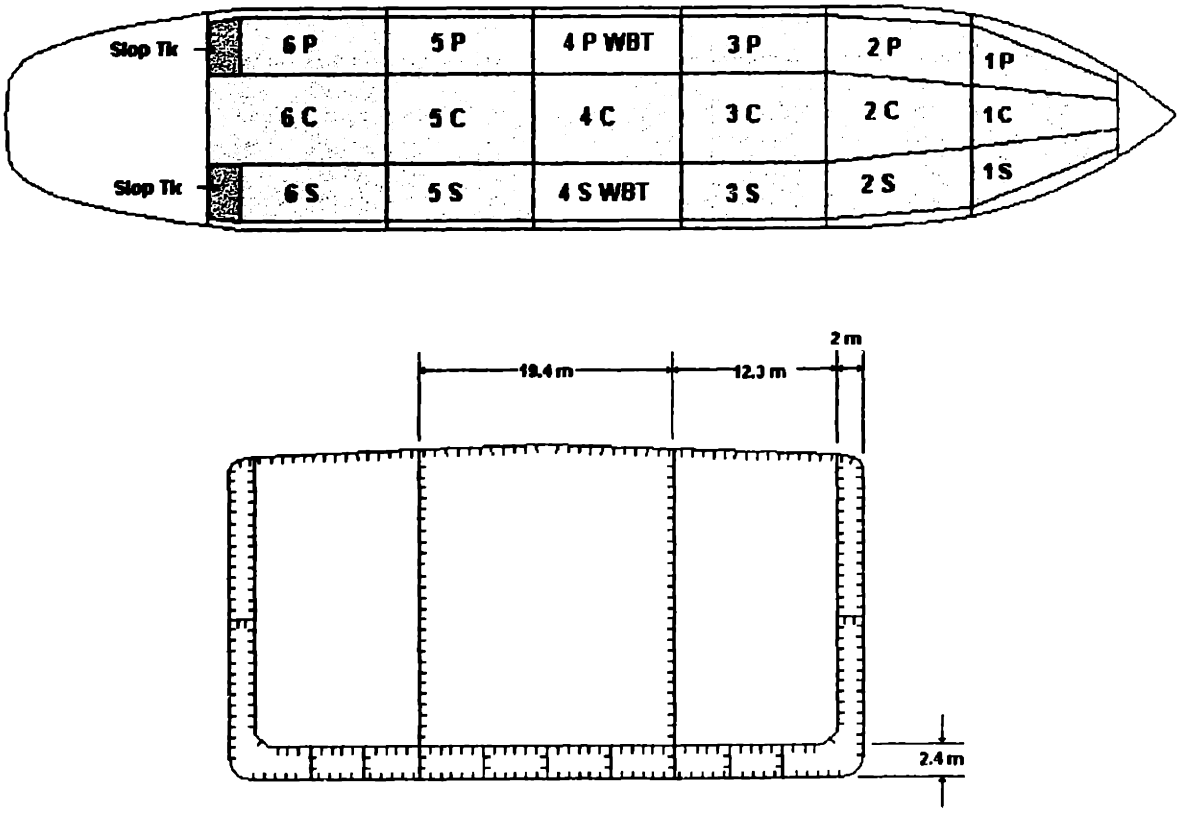


Figure 3-4 Double Hull Plan View and Midship Section

spaces in way of the cargo block are separated into four compartments: two double bottom tanks straddling the centerline, and J-shaped tanks in the bilge area extending up to the main deck.

Table 3-6 Tank Volumes for Double Hull Designs (m^3)

	Slop	#6	#5	#4	#3	#2	#1
Wing COT	1,953	8,767	8,767	*8,767*	8,767	8,348	5,399
Center COT		16,908	13,828	13,828	13,828	13,167	8,516
J- shape WBT	*498*	*2,208*	*2,208*	*2,208*	*2,208*	*2,173*	*1,932*
DB WBT	*244*	*1,093*	*1,093*	*1,093*	*1,093*	*1,045*	*708*

A baseline and four separate double hull variants are developed for subsequent analysis of the impact of structural enhancements on crashworthiness. Table 3-7 shows representative scantlings for the baseline double hull design. Each variant is a derivative of the baseline double hull design, with either the plating thickness, stiffener sizes, stiffener spacing or frame spacing modified as described in Table 3-8. For each variant design, the remaining structural parameters are re-examined and modified using SafeHull to ensure minimum compliance with classification scantling requirements. In most cases, the variation of one parameter had no impact on the others, as modifying a parameter such as frame spacing has no regulatory effect on the required values for plate thicknesses. However, decreasing the stiffener spacing impacts the required plating thickness and stiffener sizes; therefore in DHull04 plating and stiffener scantlings are adjusted downward to the minimum required.

Table 3-7 Primary Scantlings of Baseline Double Hull Design

Plating Material:	HT32
Bottom Plating Thickness:	18.75 mm
Inner Bottom Plating Thickness	18 mm
Average Side Shell Thickness:	18 mm
Average Inner Skin Thickness	18.5 mm
Average Transverse Bhd Thickness:	18 mm
Average Longitudinal Bhd Thickness:	17.25 mm
Deck Plating Thickness	21 mm
Stiffener Spacing	810 mm
Frame Spacing	4.7 m

Table 3-8 Variant Design Structural Parameters

Model ID	Varied Parameter	Scantling
DHull01	Baseline Design	See Table 3-5
DHull02	150% Plate Thickness	e.g. Bottom Plating Thickness: 28.1 mm
DHull03	150% Stiffener Size	varies
DHull04	75% Stiffener Spacing	600 mm
DHull05	75% Frame Spacing	3.7 m

Table 3-9 gives several measures of the hull scantlings for comparison. The sectional area is the total cross sectional area of the midship section.

Table 3-9 Primary Measures of Model Hull Scantlings

Model	Deck SM_O/SM_R*	Bottom SM_O/SM_R*	Height of N.A. above B.L.	Moment of Inertia about N.A	Moment of Inertia about C.L.	Sectional Area
SHull01	102.20%	128.64%	10.597 m	657 m^4	2123 m^4	74,726 cm^2
DHull01	100.13%	139.64%	10.101 m	663 m^4	2039 m^4	76,335 cm^2
DHull02	133.29%	178.17%	10.348 m	885 m^4	2738 m^4	100,994 cm^2
DHull03	102.33%	153.61%	9.645 m	698 m^4	2241 m^4	82,785 cm^2
DHull04	100.26%	142.94%	9.984 m	660 m^4	2027 m^4	75,853 cm^2
DHull05	100.13%	139.64%	10.101 m	663 m^4	2039 m^4	76,335 cm^2
Middeck	100.11%	114.16%	11.193 m	615 m^4	2032 m^4	75,105 cm^2

* SM_O/SM_R relates the Offered Section Modulus to the ABS Required Section Modulus.

Chapter 4. Input Parameter Sensitivity Analysis and Generation

4.1 Analysis of Critical Scenario Parameters

The inputs required for Damage include vessel definitions and scenario definitions. Parameters that define the tanker model, including length, tonnage, scantlings and the number and configuration of the cargo tanks are all vessel specific. Scenario parameters include the velocity and trim of the vessel at grounding, and those that describe the type of bottom and relative location of the obstruction. To examine the effect of structural variations on the crashworthiness of a tanker, probability density functions are developed for the scenario parameters and applied to a discrete set of tanker designs using Damage. The scenario parameters are calibrated by comparing the Damage-calculated damage extent probability density functions for the MARPOL single hull tanker design (SHull01) to the damage extent functions defined in the IMO Guidelines.

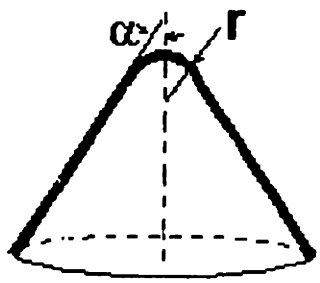


Figure 4-1 Damage Obstruction Geometry

Scenario defining parameters required in Damage include the ship velocity, the ship trim angle, a friction coefficient, the transverse rock eccentricity, the rock elevation, the rock cone angle and the rock tip radius. Figure 2-1 shows the input screen for five of these parameters, and the remaining two, rock tip radius r and rock cone angle α, are described in Figure 4-1. The friction coefficient is assumed to be 0.3 for all cases, leaving six values to be evaluated in a sensitivity analysis determining their effect on ship damage. To complete the sensitivity analysis, a standard scenario is defined using the scenario parameters and evaluated using Damage. Each parameter is individually varied through a specified range with the other parameters remaining at their standard condition values.

Three standard conditions are defined, differing only in the rock elevation. The standard conditions are shown in Table 4-1. The parameter ranges are determined by examining the boundaries of the Damage routines and the values expected in actual vessel situations. Parameter ranges used in the sensitivity phase are listed in Table 4-2.

Table 4-1 Sensitivity Analysis Standard Conditions

	Condition 1	Condition 2	Condition 3
Velocity	9 knots	9 knots	9 knots
Trim Angle:	0.2 degrees	0.2 degrees	0.2 degrees
Eccentricity:	8 meters	8 meters	8 meters
Rock Elevation:	3 meters	1 meter	5 meters
Pinnacle Radius	1 meter	1 meter	1 meter
Cone Angle:	45 degrees	45 degrees	45 degrees

Table 4-2 Sensitivity Analysis Parameter Ranges

Velocity	3 - 15 knots
Trim Angle:	-1.0 - 1.0 degrees
Eccentricity:	0 - Ship's beam
Rock Elevation:	0 - 5 meters
Pinnacle Radius	0 - 2 meters
Cone Angle:	0 - 60 degrees

At each variation of the standard conditions, the rupture length calculated by Damage is recorded as the metric of comparison. Rupture length is used based on the assumption that oil outflow depends on how many cargo tanks are ruptured, not those simply structurally damaged. The rupture lengths are then plotted as a function of the input parameter. Damage also provides details on transverse extent and penetration of the cone as the ship traverses the obstruction. These results are plotted as either maximum penetration above the baseline or maximum damage width versus the range of the input parameter. Figure 4-2 shows both sets of plots for Condition 1, and describes how the parameters affect the overall rupture length and size over their expected ranges. The plots resulting from the other standard conditions show different values for the rupture lengths, but the same trends. These plots are in Appendix C.

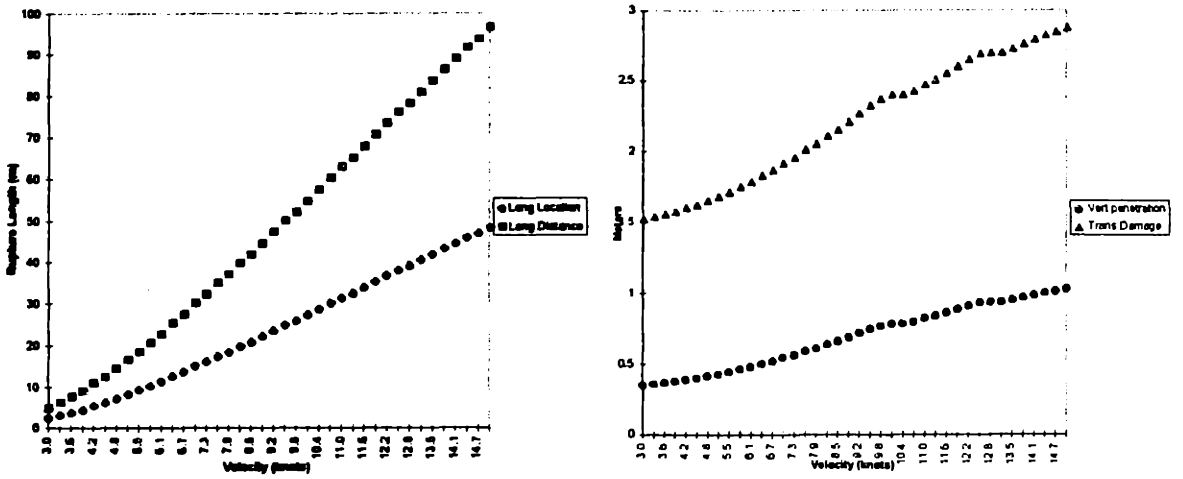


Figure 4-2 (a) Sensitivity Analysis Condition 1, Velocity Plots

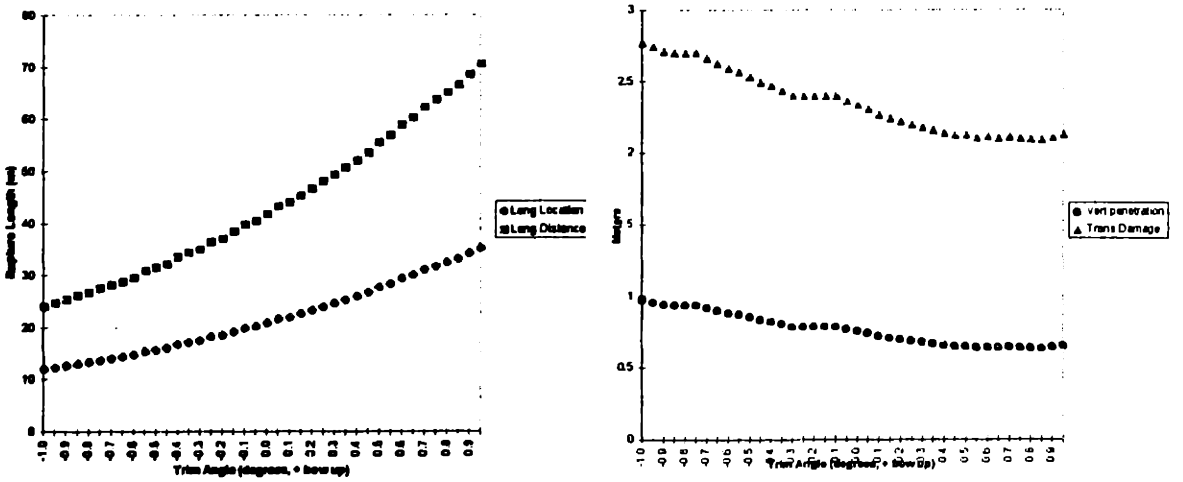


Figure 4-2 (b) Sensitivity Analysis Condition 1, Ship's Trim Plots

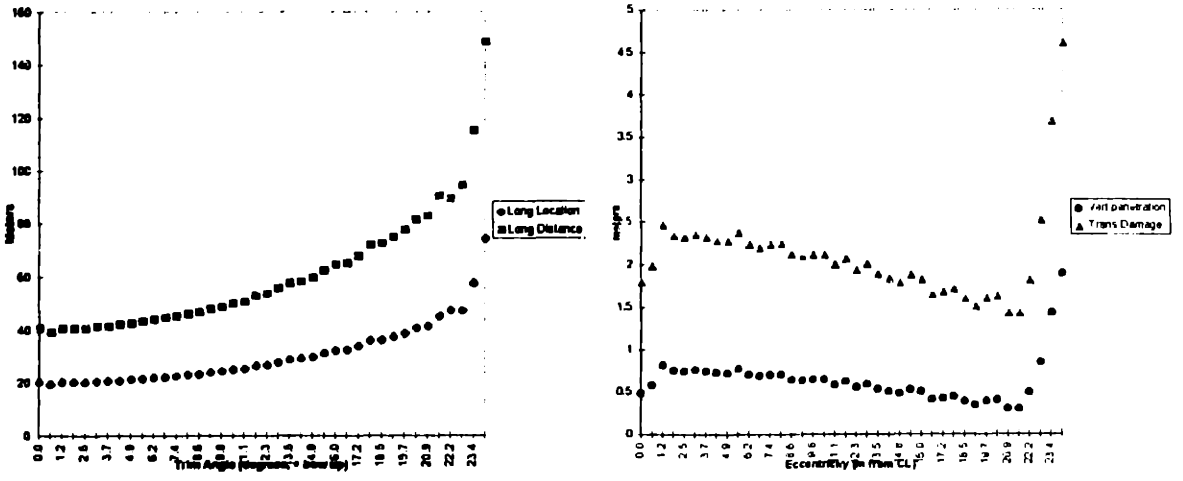


Figure 4-2 (c) Sensitivity Analysis Condition 1, Eccentricity Plots

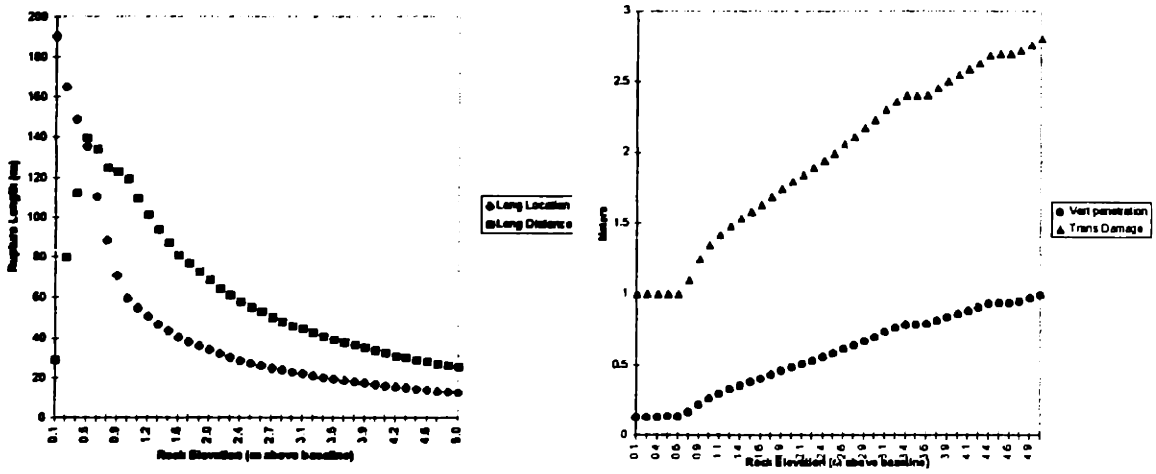


Figure 4-2 (d) Sensitivity Analysis Condition 1, Cone Elevation Plots

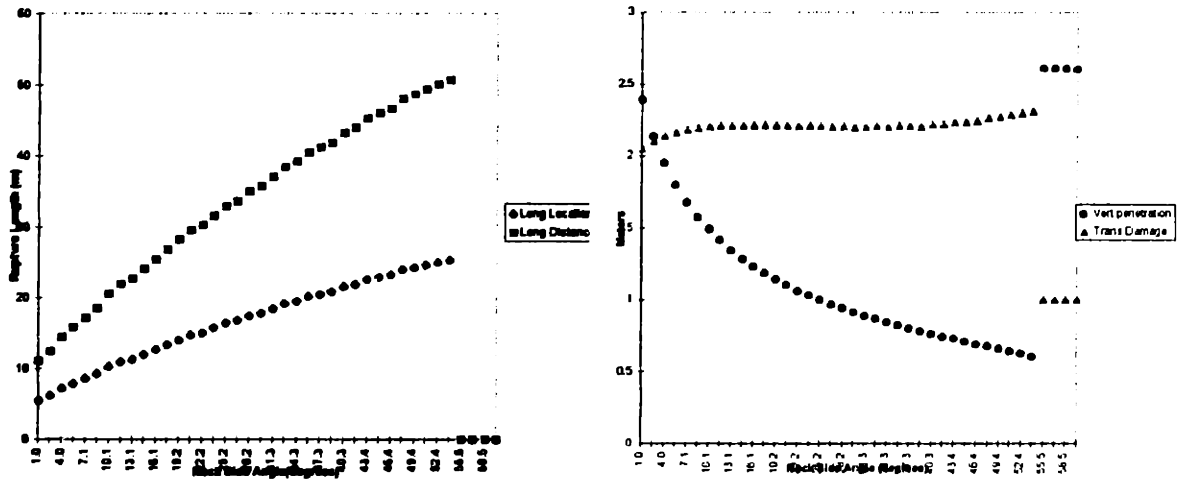


Figure 4-2 (e) Sensitivity Analysis Condition 1, Cone Side Angle Plots

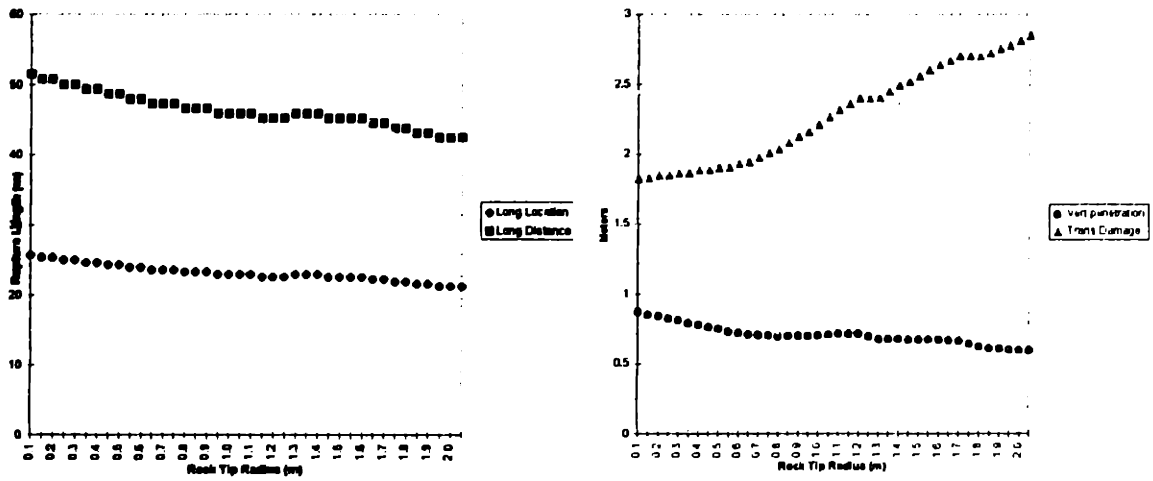


Figure 4-2 (f) Sensitivity Analysis Standard Condition 1, Cone Tip Radius Plots

The plots in Figure 4-2 show some anomalies that are accounted for in later steps of the simulation. For example, the vertical penetration and transverse extent plots in Figure 4-2(e) plateau at values of the cone side angle greater than about 55.5 degrees. Based upon this observation, the cone side angle was limited to values less than 55 degrees. In Figure 4-2(c), the rupture length appears to increase exponentially at eccentricity values greater than about 20 meters (0.83B). The explanation for this is the proximity to the vessels' turn of the bilge. The sensitivity analysis was completed using Damage version 1.2, which does not model the vessel's bilge area. Other than these irregularities, the trends shown in Figure 4-2 and Appendix C correlate very well to intuitive reasoning for expected damage magnitudes.

The parameters in the sensitivity analysis are ranked according to their effect on rupture length. This effect is determined by comparing the slope of the plots (change in rupture length divided by nominal change in input parameter) in Figure 4-2. By increasing the input parameter range, the slope of the induced rupture line is affected, but the intent of this analysis is not to quantify specific changes in rupture length as an input parameter is varied, but to examine the trends the parameters induce and the relative strength of their impacts. The resultant damage is most sensitive to the elevation of the cone above the ship's baseline and the ship's velocity at the time of the grounding. The results of the sensitivity analysis are shown in Table 4-3.

Table 4-3 Sensitivity Analysis Qualitative Results

Parameter	Sensitivity	Ranking
Elevation	High	1
Velocity	High	2
Eccentricity	Medium	3
Trim	Medium	4
Alpha	Medium	5
Radius	Low	6

4.2 Selection of PDF shapes

With the sensitivity analysis complete, the next step is to estimate realistic descriptions of the six input parameter probability density functions. Locating prior data on these parameters was difficult. No studies were found that contained route specific information on tanker transits such as trim conditions or velocity at a particular location. There was also no data or basis to define a generic cone shaped obstruction. Since the only significant data available was the existing IMO damage probability density functions, this data was used to calibrate scenario probability density functions initially postulated based on rational argument and expert opinion.

The velocity is assumed to have a bi-modal normal distribution, centered around a maneuvering speed and a cruising speed. See Figure 4-4 (a) on page 41 for an illustration of this function. For the calibration phase, the maneuvering speed is assumed to be five knots, the transit speed is 10 knots, the maximum speed is 20 knots and the minimum speed is two knots. The standard deviations for each curve are assumed to be 1.0 knots. The area under the two bell curves is assumed to be equal, which implies that groundings are equally likely to occur in a maneuvering scenario or a transit scenario.

The probability density functions for eccentricity of the obstruction and the ship's trim are assumed to be uniform, meaning any particular location or trim value has equal probability of occurrence across the entire range. See Figures 4-4 (b) and (c). For eccentricity, this is rational as the grounding can occur at any transverse location. For trim, an attempt was made define a trend over a typical route, but informal feedback from tanker operators indicated there was no such trend. Therefore the trim angle probability density function is assumed to be constant, with a range from -1 degree to 1 degree. For the tanker models used here, this translates to a maximum difference of about 4.6 meters between the forward and aft draft readings.

The obstruction elevation probability density function is assumed to be linearly decreasing, with elevations at the baseline occurring more often than higher elevated rocks as depicted in Figure 4-4 (d). This shape is defined by only one variable, the maximum

possible obstruction elevation above the baseline. Elevations below the baseline do not cause grounding. Elevations above the waterline are visible obstructions. The linear distribution between these two extremes is rational.

Cone tip radius and cone side angle model naturally occurring underwater rocks, so uniform probability density functions are not realistic. Because of their step-function shape, flat density functions have a discontinuity at the parameter range extremities, which is not naturally occurring. For this reason, the obstruction shape parameters are assumed to be normally distributed about a mean value which is determined in the calibration phase. See Figures 4-4 (e) and (f).

4.3 Random Parameter Generation

The random parameter values used in the Monte Carlo simulations are generated using a MATLAB script file entitled *vargen.m*. The script file generates any desired number of sets of the input parameters described above into a text file that is later read into the simulation script. The output file consists of columns of parameter values that are distributed according to their individual probability density functions. The script is designed for the flexibility needed in the calibration phase which requires the simple addition or modification of any of the parameters or their pdf's. On a Pentium 133 Mhz PC, the routine generates 10,000 parameter sets in less than one minute. The script flowchart is shown in Figure 4-3.

The random parameters for the uniform and linear probability density functions are generated by inverting the cumulative distribution functions. Cumulative distribution functions are found by integrating the probability density functions over the range of allowable values. Normally distributed parameters are generated by a modified Box-Müller algorithm. Both of these methods are described by Dagpunar[20].

The inversion method generates random parameters with a probability density

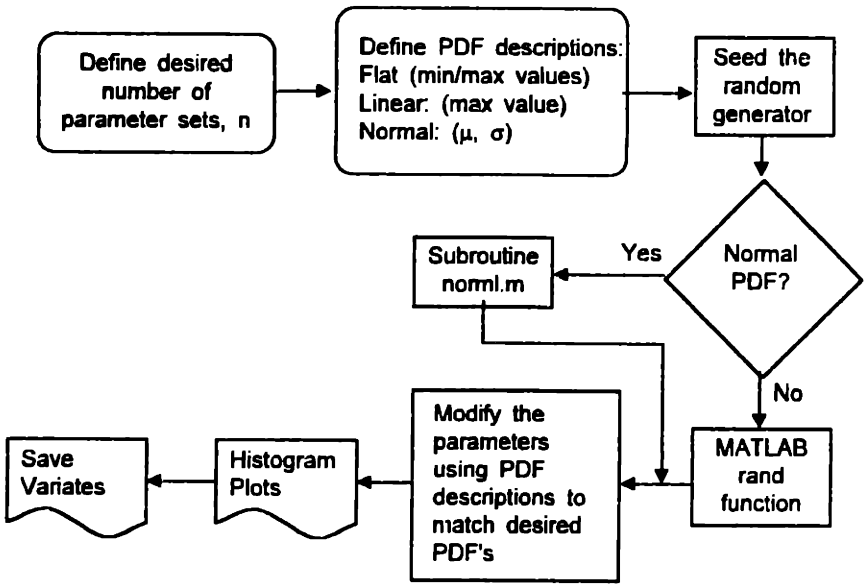


Figure 4-3 Flowchart for Generating Random Scenario Parameters

function f(x) given the distribution function, F(x). Using the transformation

$$X = F^{-1}(R) \tag{3}$$

any number of random parameters, X, can be generated that have the density function f(x) using a uniformly distributed random number R on the interval [0,1].

Uniform distributions display flat or constant probability density functions. For the case of parameters that vary from *a* to *b*, the probability density function is:

$$f(x) = \begin{cases} \dfrac{1}{b-a} & \text{for} \quad a \le x \le b \\ 0 & \text{elsewhere} \end{cases} \tag{4}$$

and the cumulative density function is:

$$F(x) = \int_{-\infty}^{x} f(s)ds = \begin{cases} \dfrac{x-a}{b-a} & \text{for} \quad a \le x \le b \\ 0 & \text{elsewhere} \end{cases} \tag{5}$$

When the cdf is inverted and evaluated on R, a uniform random variable on the interval [0,1], the transformation equation for a uniform distribution on [a,b] is determined:

$$X = a + R \cdot (b - a) \tag{6}$$

Random parameters of any distribution shape can be found using these steps, as long as the cdf can be inverted. The probability density function for the rock elevation parameter is described as linearly decreasing from a maximum value at the ship's baseline to zero at the maximum rock height. This line is expressed as:

$$f(x) = -\frac{2}{L^2}x + \frac{2}{L} \qquad \text{for } 0 \le x \le L \tag{7}$$

where L is the maximum penetration in meters above the baseline.

Again the cumulative density function, F(x), is found by integrating f(x) from $-\infty$ to x, so that :

$$F(x) = \int_{-\infty}^{x} f(s)ds = -\frac{x^2}{L^2} + \frac{2x}{L} \tag{8}$$

Inverting the cdf yields a quadratic equation for a random parameter X as a function of a

single random number R that possesses a linear pdf with the maximum value of L:

$$X = L - L\sqrt{1-R^2} = L(1-\sqrt{1-R^2}) \tag{9}$$

Random parameters for the normal distributions are generated using a modified Box-Müller algorithm. In the original proof of this method, the standard normal deviates are generated from two independent uniformly distributed random numbers:

$$Z = \sqrt{-2\ln R_1}\cdot\cos(2\pi R_2) \tag{10}$$

where R_1 and R_2 are uniformly distributed numbers on [0,1]. Subsequent empirical evaluations of the parameters from this routine found deficiencies due to the fact the small values of R_1 always produce small values of Z. A later modification to this routine eliminated this trend by avoiding the trigonometric functions. In 1964 Marsaglia and Bray proposed:

$$Z = \sqrt{-2\ln(U_1^2+U_2^2)}\cdot\frac{U_1}{\sqrt{(U_1^2+U_2^2)}} \tag{11}$$

The deviate Z is then be transformed into the desired normally distributed parameter using the mean and standard deviation:

$$X = \mu + Z\sigma \tag{12}$$

where μ is the mean, and

σ is the standard deviation.

In the script *vargen.m*, the bi-modal nature of the velocity parameter is generated by comparing a separate random indicator on the interval [0,1] to a certain percentage, then directing the routine to use the corresponding high or low mean and variance. For this

phase, 50% of the parameters are expected to be around the cruising speed. For random numbers greater than 0.5, a mean of 10 knots is used.

This routine is used to generate scenarios for the Monte Carlo simulation in both the calibration phase and final data collection phases. Figure 4-4 shows the final calibrated target scenario density functions, plotted with the calculated values for the density functions described by the actual 10,000 parameter sets used. As expected, these figures show close correlation between the proposed target probability density functions and the actual parameters used for the simulation. The differences between the target and calculated values in the cone tip angle and cone side angle are due to the application of limiting boundaries to a prescribed parameter range.

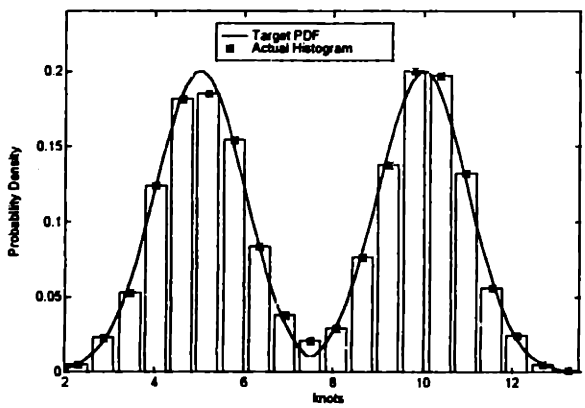


Figure 4-4 (a) Input Scenario PDF - Velocity

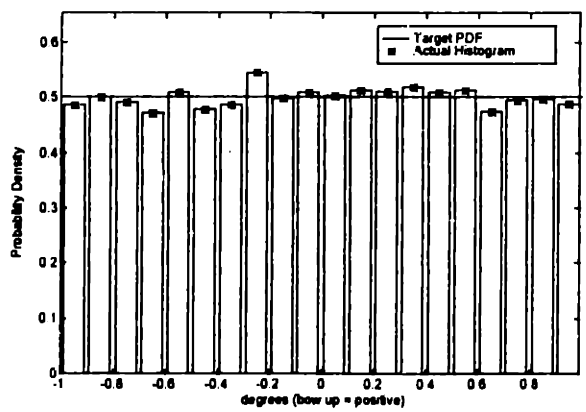


Figure 4-4 (b) Input Scenario PDF - Trim

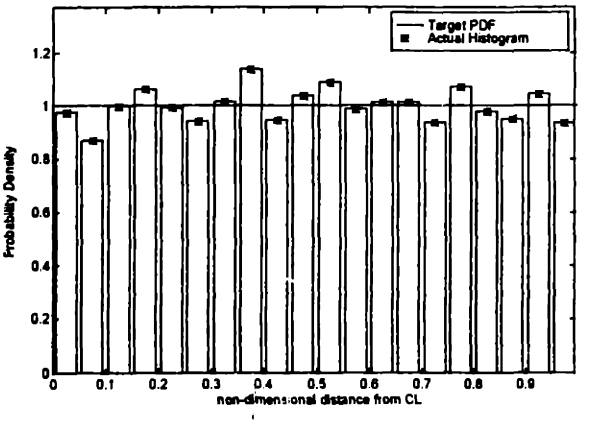


Figure 4-4 (c) Input Scenario PDF - Eccentricity

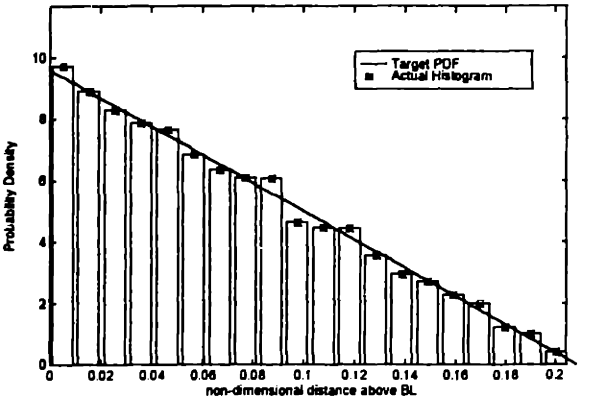


Figure 4-4 (d) Input Scenario PDF - Obstruction Elevation

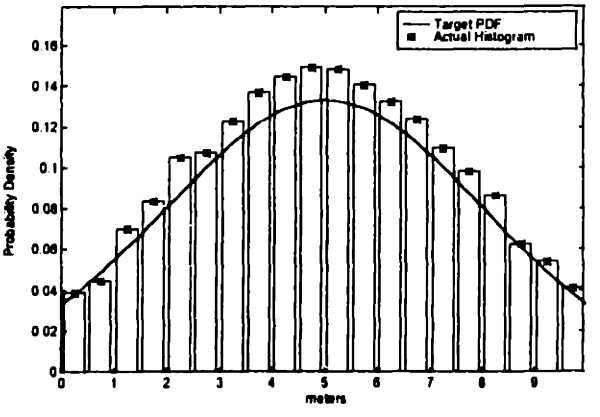


Figure 4-4 (e) Input Scenario PDF - Cone Tip Radius

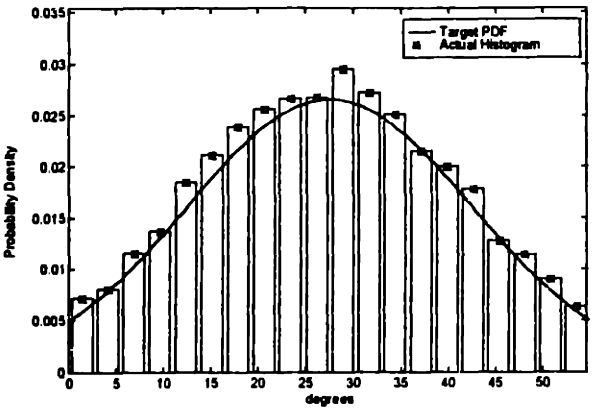


Figure 4-4 (f) Input Scenario PDF - Cone Side Angle

Chapter 5. A Monte Carlo Simulation Using Damage

5.1 Simulation Script

Because the goal of this research is to define an exportable method of evaluating tanker environmental performance, the Monte Carlo simulation must be done in a manner that can be reproduced and modified to include the use of new damage evaluation tools. For this reason, the decision was made to not modify the existing Damage program, but create an overlay such that any current version of a similar comparison tool can be used. This allows the methodology to be applied using any ship damage prediction model.

As shown in Chapter 2, Damage relies on the graphical user interface for its inputs. Additionally, the program's outputs default to graphs as shown in Figure 5-1. These graphs provide the vertical penetration of damage, transverse extent of damage, energy dissipation and kinetic energy all as a function of the longitudinal location of the vessel

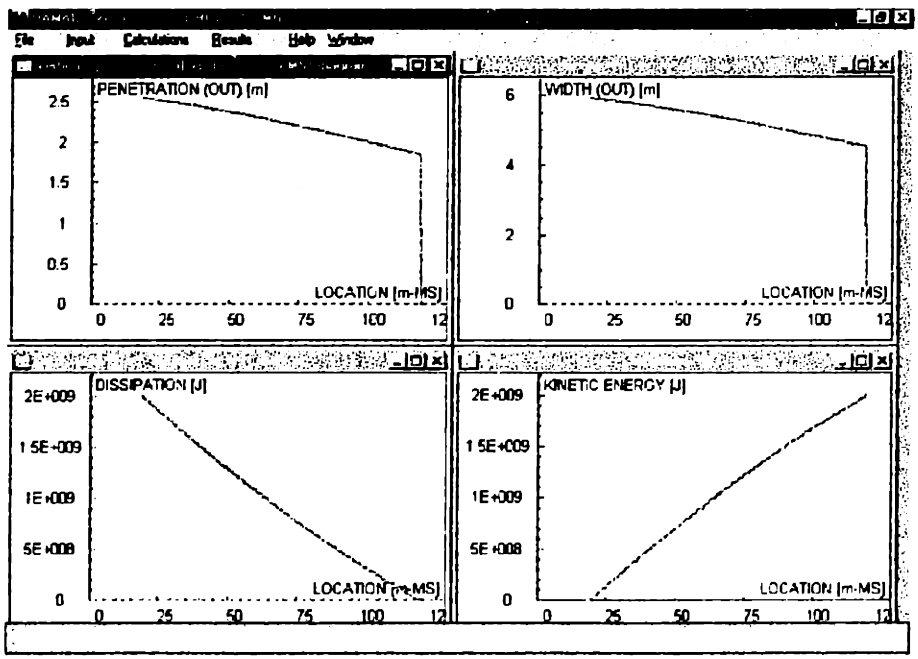


Figure 5-1 Damage Output Screen Shot

relative to the vessel's midship. Default results such as vertical penetration and damage width provide details of outer hull damage. These default graphs cannot be changed, but an option is available for the user to create custom graphs to display results such as inner

hull damage in double hull ships, horizontal or vertical force components, or pitch and heel angles.

Damage also can produce tabular results, as either a summary sheet or in columns displaying the data points used to generate the graphs. The summary sheet contains information such as the elapsed time of the grounding, total energy dissipated and the location of the rupture initiation and completion for the inner and outer hulls. Any of these tabular results are generated upon completion of the calculations as a separate request.

In order to create damage extent probability density functions similar to those provided by IMO in the Guidelines, the specific longitudinal and transverse boundaries of the rupture and the vertical extent to which the obstruction damaged the hull must be recorded. As seen in Figure 5-1, these damage extents vary depending on the longitudinal location. This is due to the effect of the global ship dynamics as the vessel rides over the obstruction. The damage extents are not all monotonically increasing. Pitch or roll may decrease the penetration or width. It is assumed the damage is wholly described by a rectangular box, with length equal to the rupture length, width equal to the maximum transverse extent and height equal to the maximum vertical penetration. This assumption reduces the amount of information required to be exported from Damage, as the entire damage extent for a given scenario is completely described by four values, maximum vertical penetration, maximum transverse damage and the location of the rupture initiation and completion. All of these values are obtained from Damage.

Exact longitudinal rupture locations are available in the results summary; vertical penetrations and transverse extents are available in the default graphs or tabulated as a function of another parameter, such as time or location. Since the functions are not monotonically increasing, a method for finding the maximum value is required. Searching the tabular outputs for maximum value is inefficient, as a separate text file has to be created and then 300 to 500 values in that file searched for every scenario examined. Instead, Damage can provide background information about each of its output graphs that includes the maximum Y-axis value. This value, although only a screen image and not actual text that can be assigned to a variable, is retrieved by HighTest and exported to any

Windows application, in this case a text editor, Notepad. The "Max Y" value displayed by Damage is not the maximum Y data point, but the upper bound of the graph's y-axis. Conveniently, this value is a scaled value of the actual maximum Y data point, and is later converted to the data maximum. The scaling factor was determined by comparing several hundred "Max Y" values to the maximum data value in the tabular results. Therefore:

$$y \cong \frac{Y}{f} \tag{13}$$

where: y is the desired Damage result; and

Y is the "Max Y" value obtained from the graph configuration; and

f equals 1.103

In this manner, maximum values for transverse extent and vertical penetration are extracted from Damage and saved for later reduction into damage extent probability density functions or oil outflow distributions.

Figure 5-2 describes the control flow of the simulation conducted in Vermont HighTest for a single hull or mid-deck model. The decision box for determining if the rupture initiation location matched the rupture completion location is used to increase the efficiency of the simulation, as less dialog boxes require access.

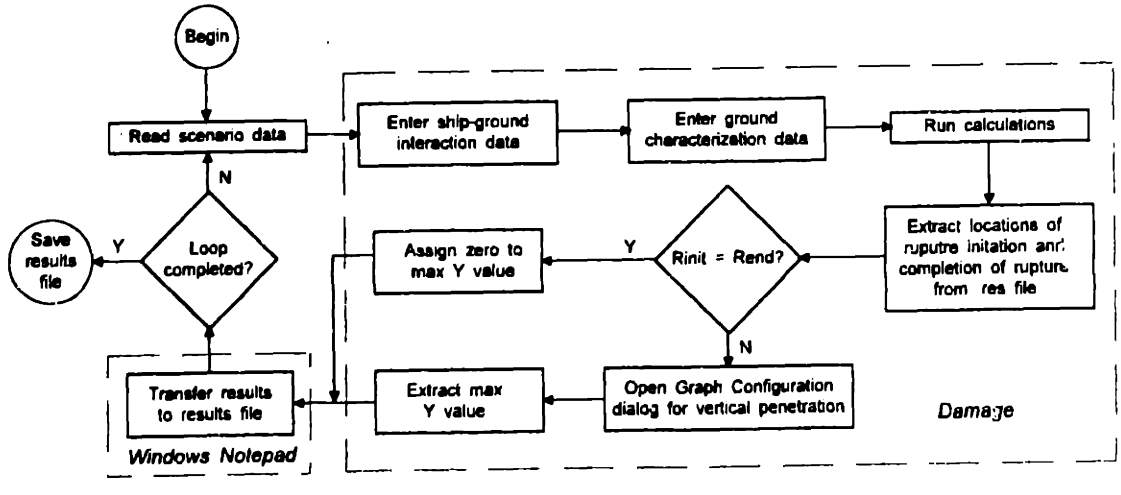


Figure 5-2 SHull Simulation Script Diagram

The double hull simulation script is similar, except that each of the four pieces of information are recorded for both the inner and outer hulls. Since HighTest cannot maintain more than one screen image ("Max Y" value) at a time, the program shifts control from Damage to the result file, then returns to Damage and repeats itself to retrieve the inner hull "Max Y" image.

5.2 Transverse Extent of Damage

Figure 5-2 shows the Monte Carlo script as it was used in the final phase of data gathering. After the calibration phase, irregularities were noted in the inner hull transverse extent of damage graph. In particular, the transverse extent of damage of the inner hull is sometimes displayed with a discontinuity where Damage shifts internal mechanics models due to the inner hull no longer being ruptured at that point. The result is that the "Max Y" value no longer maintains a consistent, scaled relationship with the desired extent of damage after a rupture and the method described above is no longer valid. This irregularity did not affect earlier data gathering, as all the previous models had been single hull tankers, and the trend wasn't noted on the outer hull.

Further examination of the gathered results indicates that the desired transverse extent of damage following a rupture is very closely linked with the rock geometry. The width of the rock can be found as a function of two of the scenario input parameters, cone side angle and cone tip radius, and the Damage vertical penetration result. Figure 5-3 describes the relationship of these parameters. This distance, multiplied by a factor to account for plate damage, is used to approximate the transverse extent of damage.

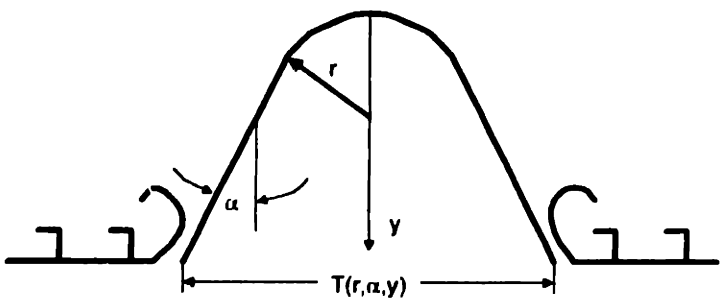


Figure 5-3 Obstruction Geometry for Determining Transverse Extent

The width of the obstruction at the plate surface is determined as:

$$T(r,\alpha,y) = \begin{cases} 2\sqrt{2ry - y^2} & \text{if} \quad y \le r\left[1 - \sin(\alpha)\right] \\ 2\left\{r\cos(\alpha) + \left[y - r + r\sin(\alpha)\right] \cdot \tan(\alpha)\right\} & \text{elsewhere} \end{cases} \quad (14)$$

where:

	$T(r,\alpha,y)$	is the width of the obstruction at the plate
	r	is the input cone tip radius
	α	is the input cone side angle, and
	y	is the output vertical penetration.

This relationship was tested on the data gathered from over 1000 previously conducted rupture scenarios with the calculated extent averaging approximately 6% less than the Damage determined extent of damage. The standard deviation for the difference was approximately 5%, with an average percent deviation of less than three percent. Based on these results, the calculated extent of transverse damage for the remaining simulations is assumed to be 110% of T.

Chapter 6. Scenario Calibration

6.1 Methodology

The scenario probability density functions for the Monte Carlo simulation are derived from expert opinion, the results of the sensitivity analysis and a calibration phase of simulations. Density functions for velocity, ship's trim and rock eccentricity are estimated from available tanker operation statistics and expert opinion. The parameters for the obstruction shape density functions are more difficult to define due to the infinite number of possible rock shapes and reef formations. The method used in this thesis is to calibrate assumed rock density functions by completing simulations with various obstruction properties, prepare damage extent probability density functions from these results, and compare the calculated functions to those derived from statistical data and defined in the IMO Guidelines.

The reader should note that the obstruction defined by this thesis is not intended to be representative of the type and shape of obstruction a tanker is likely to strike, rather a notional obstruction that produces damage similar to that observed in actual grounding events and recorded by IMO.

Chapter 1 describes the bottom damage due to stranding probability density functions contained in the Guidelines. This chapter describes the matrix of scenario parameter probability density functions used in the calibration phase, how the resulting calculated damage information is reduced to probability density functions, and the method used to compare the IMO density functions to the calculated functions for selection of the best input scenario.

6.2 Generation of Damage Extent Probability Density Functions

The Damage simulation generates cases where the shell plating is not ruptured when the ship grounds, and specific rupture location and extents when rupture occurs. In order to compare the results to the Guidelines, which considers only cases where rupture occurs, these no-rupture cases are extracted from the data.

The remaining damage cases are non-dimensionalized by the ship's length, breadth or depth, and the longitudinal location of damage determined as the midpoint between the rupture initiation and rupture termination point. Additionally, the x-axis origin is moved from midship, as Damage displays, to the aft perpendicular to better match the IMO functions. From its definition, a probability density function can be written as:

$$f(x^*) = \frac{n}{N \cdot \Delta x} \tag{15}$$

where:

	$f(x^*)$	is the probability density function at x^*
	n	is the number of occurrences in a bin centered on x^*
	N	is the total number of grounding cases, and
	Δx	is the width of the bin.

For the purposes of the calibration phase, N is the total number of grounding cases where a plating rupture occurs. The values of the density function at x^* are plotted together with the IMO functions, as shown in Figure 6-1. Comparisons are made directly between the discrete calculated probability densities and the IMO functions.

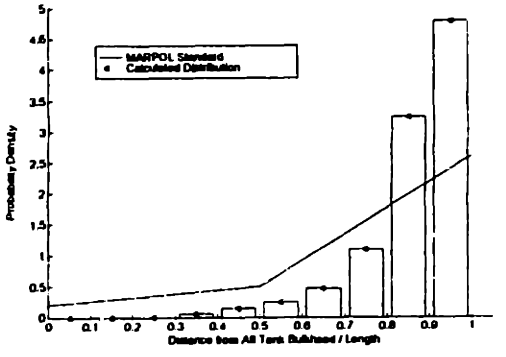


Figure 6-1(a) Longitudinal Location

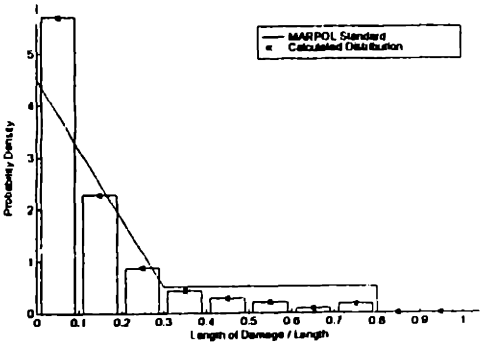


Figure 6-1(b) Longitudinal Extent

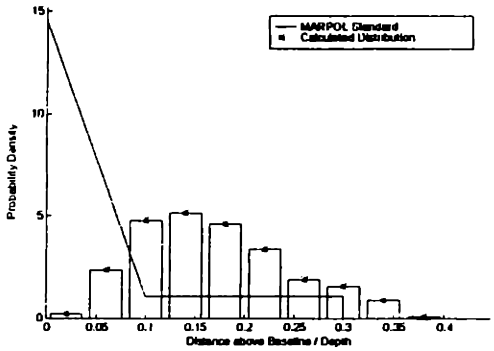


Figure 6-1(c) Vertical Penetration

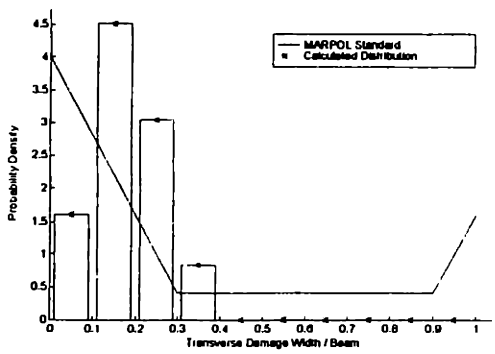


Figure 6-1(d) Transverse Extent

6.3 Calibration Matrix

In order to measure the best fit of the calculated density functions to the IMO density functions, a matrix of input scenario probability density functions is developed. Density functions for velocity, trim and eccentricity are based on rational argument, observation and expert opinion, so these are not altered in the calibration. The sensitivity analysis indicates that rock elevation has a large effect on rupture length; cone side angle and cone tip radius have less effect. To reduce the number of possible permutations, cone side angle is assumed to be normally distributed between 0 and 55°, with a mean at 27.5°. Obstruction elevation and tip radius are varied in the matrix.

Table 6-1 lists the density functions used for each parameter that are not altered in the calibration. Table 6-2 describes the tip radius and obstruction elevation density functions as they are varied in a particular run. For each of these calibration runs, random variates for all six parameters are generated using the routine described in Chapter 4, and applied in Damage to determine rupture extents. Figure 6-1 displays the calculated damage extent probability density functions using the input scenario file *calib09*. Appendix C contains the calculated damage extent probability density functions for all calibration sets.

Table 6-1 Scenario Density Functions Not Varied in Calibration Phase

Parameter	PDF description
Velocity	Bi-modal normal distribution centered on 5 and 10 knots, σ=1 knot
Trim	Uniform distribution between -1° and 1°
Eccentricity	Uniform distribution between 0 and half-beam
Cone Side Angle	Normal distribution bounded by [0,55], μ=27.5°, σ=3

Table 6-2 Scenario Density Functions Varied in Calibration Phase

scenario input file name	Obstruction Elevation			
Tip Radius	1	2	3	4
A	*calib16*	*calib15*	*calib14*	*calib20*
B	*calib13*	*calib11*	*calib10*	*calib21*
C	*calib12*	*calib09*	*calib08*	*calib22*
D	*calib19*	*calib18*	*calib17*	*calib23*

PDF descriptions:

A: Normal distribution bounded by [0,2], μ=1.0, σ=0.5 meters
B: Normal distribution bounded by [0,5], μ=2.5, σ=1.2 meters
C: Normal distribution bounded by [0,10], μ=5.0, σ=3.0 meters
D: Normal distribution bounded by [0,15], μ=7.5, σ=4.0 meters
1: Linearly decreasing with maximum value at 16.8 meters above baseline
2: Linearly decreasing with maximum value at 10 meters above baseline
3: Linearly decreasing with maximum value at 5 meters above baseline
4: Linearly decreasing with maximum value at 2 meters above baseline

6.4 Density Function Comparison Results

To compare the calculated density functions to the IMO Guideline density functions, a Matlab function entitled *compare.m* is used. This function uses the previously calculated probability density function values, and examines the difference in area between these calculated values and the IMO defined functions. Smaller area differences indicate a

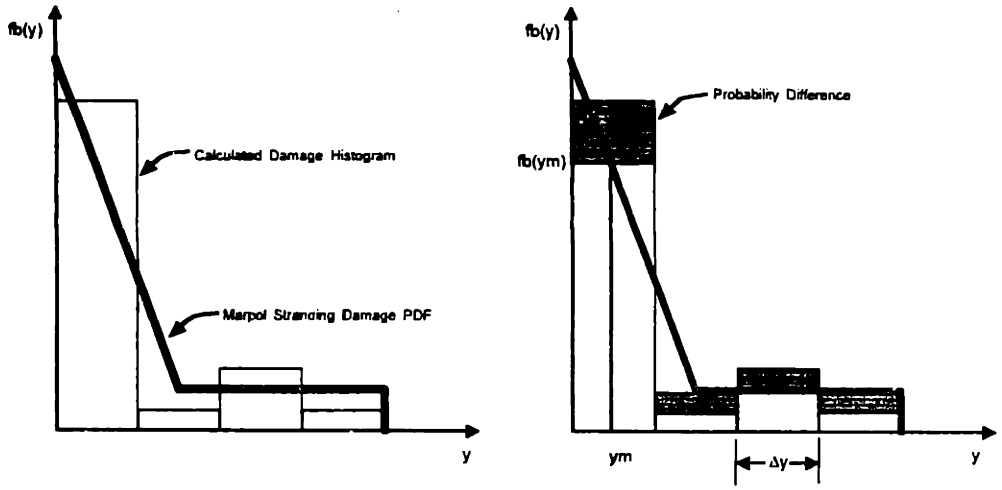


Figure 6-2 Area Between Calculated and IMO Guidelines Density Functions

better fit of the calculated densities to the IMO functions. Graphically, this process is shown in Figure 6-2.

The total area between the functions is expressed as:

$$A_T = \sum_{i=1}^{bins} \left| f_b(y_{m_i}) - f(y_{m_i}) \right| \cdot \Delta y \qquad (16)$$

where:

	A_T	is the total area between the density functions
	$f_b(y_m)$	is the IMO stranding damage density function evaluated at y_m
	$f(y_m)$	is the calculated density function at y_m
	y_m	is the midpoint of the bin, and
	Δy	is the width of each bin.

Because probability density functions are by definition normalized to have an area of one, the difference in area between any two pdfs must be zero. The absolute value function is therefore necessary to determine the difference between the two.

The function as written provides the area between the density functions for all four of the graphs that are calculated from the simulation: longitudinal location, longitudinal

extent, vertical penetration and transverse extent. The final comparisons between calibration sets are made based on an average of these four area differences.

As these sets were being analyzed, it was noted that the area difference changed depending upon the number of input bins used. Figure 6-3 shows the area difference plotted as a function of the number of bins for a single calibration set. This is a result of the fact that for smaller bins, the likelihood of being within that bin is smaller and therefore the random nature of the simulation becomes more dominant. Although this fact is offset by the smaller Δy values, the bin size does have an effect on the final result, with the optimal calibration set depending upon the number of bins selected. When the number of bins is increased above 30, the calculated density function values become increasingly scattered until the comparison methodology brakes down. Ten bins are used for the selection process. This bin size is picked based on the IMO statistical report that uses ten bins for its historical data and because the area difference stabilizes with 10 more bins.

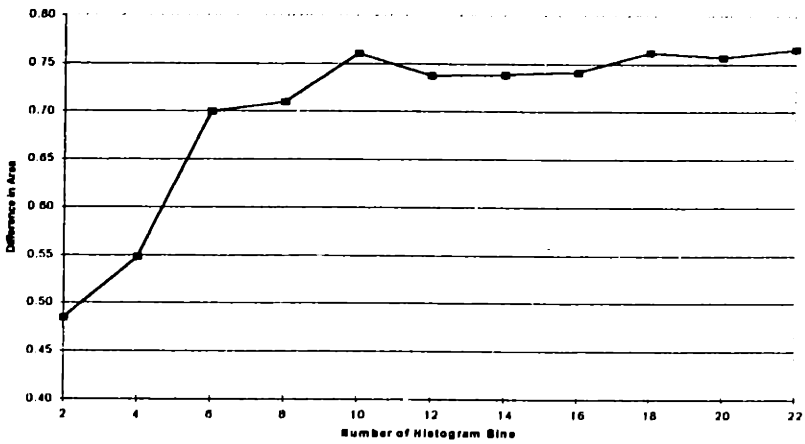


Figure 6-3 Average Probability Difference vs. Number of Histogram Bins

Table 6-3 shows the average probability differences calculated using 10 histogram bins for each of the calibration data sets after 600 scenarios are completed. Table 6-4 shows the probabilities of plate rupture for each calibration set. The IMO damage extent density functions define damage given a grounding that ruptures the tanker outer hull, so the IMO probability of rupture is one. In this analysis, rupture probabilities are significant because they are integrated into the final mean outflow parameter. Extreme values, either

high or low, for rupture probability would not be desirable. Based on these results, the input scenario *calib08* is selected as the scenario definition that best re-creates the tanker grounding damage described by the IMO probability density functions. In summary, this scenario is defined as:

- bi-modal normal velocity distribution centered on 5 and 10 knots;
- uniform trim distribution between -1° and 1°;
- uniform eccentricity distribution between 0 and half-beam;
- normal cone side angle distribution centered on 27.5°;
- normal cone tip radius distribution centered on 5 meters;
- linearly decreasing rock elevation distribution with a maximum elevation of 5 meters.

Table 6-3 Calibration Phase Average Probability Differences

Average Probability Difference		**Obstruction Elevation** 16.8	10	5	2
Max	2	0.607	0.590	0.699	0.872
Tip	5	0.859	0.693	0.595	0.675
Radius	10	1.010	0.841	**0.579**	0.769
	15	1.028	0.947	0.626	0.798

Table 6-4 Calibration Phase Rupture Probabilities

Rupture Probability		**Obstruction Elevation** 16.8	10	5	2
Max	2	0.90	0.85	0.80	0.62
Tip	5	0.76	0.65	0.54	0.25
Radius	10	0.58	0.37	**0.21**	0.10
	15	0.48	0.25	0.13	0.06

6.5 Alternate Method to Compare Scenario Results

As described earlier, the area between density functions method for determining the optimum input scenario parameters is dependent on the number of histogram bins used to generate the density function. An alternate method of comparison was also used to

evaluate the same calibration matrix results. This method uses the cumulative distribution functions generated from the Damage results and the IMO density functions. Figure 6-4 shows the distribution function for longitudinal iocation for the calibration data set *calib08*, with the number of histograms bins varied. The figure shows how the distribution function converges a smoother curve as the number of bins is increased.

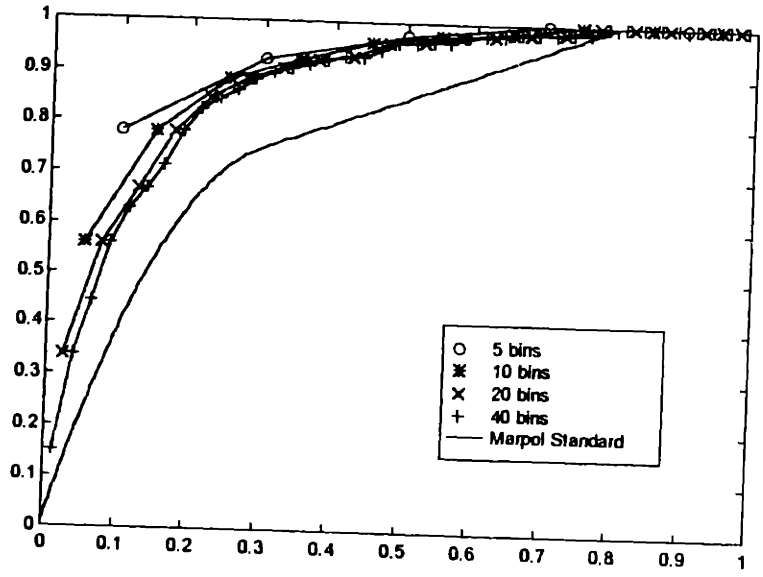


Figure 6-4 Longitudinal Location Calculated Distribution Function

In the alternate method, 40 bins are used to define the calculated cumulative density functions, and these cdf's are compared to the corresponding MARPOL cdf using the area between the distribution functions as the measure of comparison. This process is shown in Figure 6-5. The calculated distribution functions are determined by incrementally summing the areas underneath the corresponding density functions as:

$$F(x_n) = \sum_{i=1}^{n} f(x_i)\Delta x \qquad (17)$$

where:

- $F(x_n)$ is the cumulative distribution at x_n
- $f(x_i)$ is the calculated density function at x_i, and
- Δx equals $x_i - x_{i-1}$.

The area under the calculated cumulative distribution function from x=0 to x=1 is determined by summing the values of F at each x_n and multiplying the sum by Δx. The area under the IMO distribution functions was is determined from the bottom damage

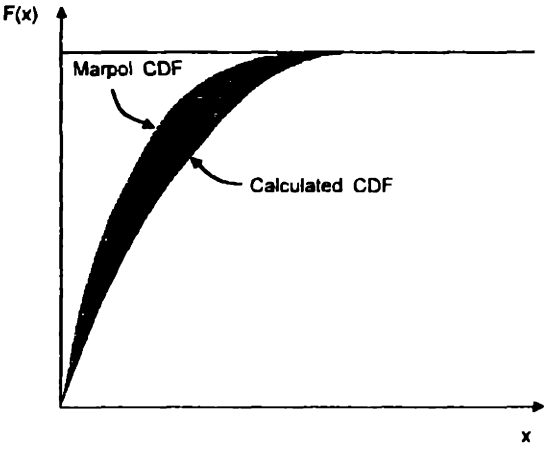


Figure 6-5 Area Between Calculated and IMO Guidelines Distribution Functions

density functions defined in the Guidelines. Here, the area is:

$$A = \int_0^d \int_0^{\infty} f_b(s)dsdx \qquad (18)$$

where: A is the area under a cumulative distribution, and

$f_b(s)$ is a IMO bottom damage density function.

The IMO area is subtracted from the calculated area, and the area difference from each of the four damage extent functions is averaged. This averaged area difference is used to determine which input scenario set best fits the original data. The results using this method with 40 histogram bins are shown in Table 6-5. The same scenario set, *calib08*, best fits the IMO functions.

Table 6-5 Calibration Phase Average Distribution Differences

Average Distribution Difference		**Obstruction Elevation**			
		16.8	10	5	2
Max	2	0.109	0.105	0.101	0.131
Tip	5	0.135	0.107	0.079	0.093
Radius	10	0.138	0.115	**0.075**	0.097
	15	0.139	0.125	0.079	0.113

Chapter 7. Calculation of Oil Outflow

7.1 IMO Calculation of Oil Outflow and Oil Outflow Parameters

In the IMO probabilistic oil outflow method described earlier, the third step of the process is to calculate the oil outflow associated with each unique bottom damage case. This outflow is calculated using a pressure balance calculation. In order to generate the balance of forces, the following assumptions are made:

- The vessel is assumed to remain stranded on a shelf at its original intact draft;
- An inert gas pressure of 0.05 bar;
- The flooded volume of double bottom ballast tanks or voids located below breached cargo tanks retain up to 50% oil by volume;
- Breached cargo tanks which bound the outer sheli have a minimum outflow of 1% of the cargo tank volume. This is intended to account for the expected oil loss of initial impact and through dynamic effects such as currents and waves.

The calculations are carried out for three tidal conditions: 0.0 meters tide, then a 2.0 meter tidal drop and a 6.0 meter tidal drop. In each case, the oil volume lost from a cargo tank is calculated from:

$$z_c = \frac{z_s \rho_s g}{\rho_c g + 100 \cdot \Delta p} \qquad (19)$$

where:

	z_c	is the height of remaining oil in the damage tank
	ρ_c	is the cargo oil density
	g	is gravitational acceleration
	Δp	is the inert gas overpressure
	z_s	is the external sea water head above the tank bottom, and
	ρ_s	is sea water density.

The oil captured in the double bottoms/voids is 50% of the flooded volume of the void after grounding. The height of oil/water mix in the void, z_{wo}, is assumed to be midway

between the final draft and the height of remaining oil in the damage tank, or one-half of z_s plus z_c. Figure 7-1 illustrates these and other pertinent heights.

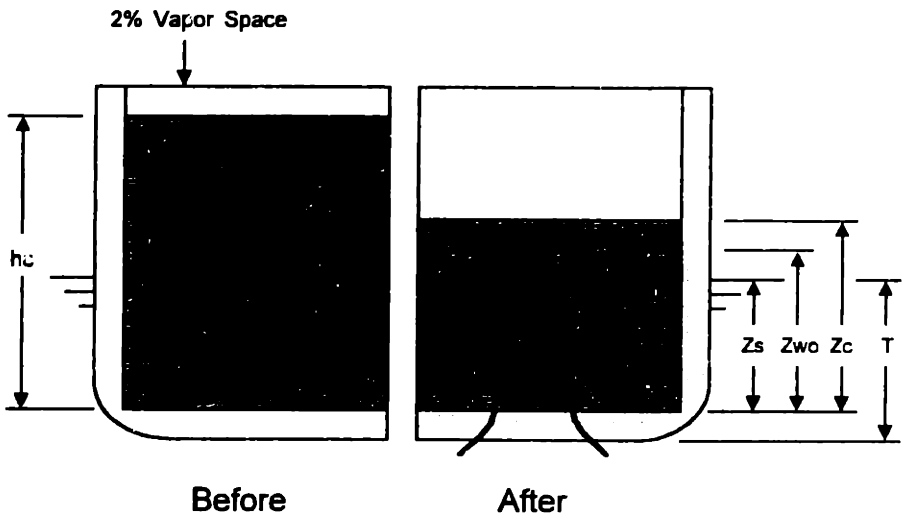


Figure 7-1 Oil Outflow Scheme for Bottom Damage

Once the oil outflow is determined for each tidal condition, a combined outflow is computed by a weighted average of the stranded conditions. The weighting is as follows:

0.4 for	0 m tide condition
0.5 for minus	2 m tide condition
0.1 for minus	6 m tide condition.

This combined outflow is then calculated for the remaining damage cases. Once the outflows have been determined, the next step of computing the oil outflow parameters is completed.

The *probability of zero outflow*, P_0, represents the likelihood that no oil will be released into the environment, given a grounding event which breaches the outer hull. P_0 equals the cumulative probability of all such damage cases with no outflow.

The *mean outflow parameter*, O_M, is the non-dimensionalized mean or expected outflow, and provides an indication of a design's overall effectiveness in limiting oil

outflow. The mean outflow parameter is defined as:

$$O_M = \sum_{i=1}^{n} \frac{P_i O_i}{C} \tag{20}$$

where: n is the total number of damage cases examined

P_i is the probability of damage case *i*

O_i is the outflow associated with damage case *i*, and

C is the total cargo oil capacity.

The *extreme outflow parameter*, O_E, is the non-dimensionalized extreme outflow, and provides an indication of the expected oil outflow from particularly severe casualties. O_E is a weighted average of the outflow from the largest 10% of all the damage cases ranked by outflow. The extreme outflow parameter is defined as:

$$O_E = 10\left(\frac{\sum P_{ie} O_{ie}}{C}\right) \tag{21}$$

where: the index "ie" represents the 10% most extreme outflow cases.

7.2 Determination of Calculated Outflow and Outflow Parameters

Using the optimal scenario probability density functions from the previous chapter, data runs are completed using Damage and HighTest on all design variants. This provides a set of probabilistic damage cases for each variant including extents, locations and probabilities.

To convert this data into the oil outflow parameters, Matlab scripts were written for the single hull, double hull and mid-deck configurations to reduce the damage cases into non-dimensional outflow distributions and parameters in three steps. The first step is to determine the tanks that are breached in each damage case. This includes the double bottom and J-ballast tanks for the double hull configurations. Next the oil outflow for

each case is determined using the hydrostatic balance principles described by IMO in the Guidelines and presented above. Finally, the outflow and probability for each case are used to calculate the oil outflow parameters for each variant.

Since the Damage-generated data files all refer to locations as distances from midships, the centerline and the baseline, step one first resets the origin to the forward perpendicular, centerline and the baseline. Breaching of tanks is determined longitudinally first, then transversely. Breaches are defined as the intersection of the cases where the rupture begins forward of the aft bulkhead and is completed aft of the forward bulkhead, or:

$$X_{init} \leq X_A \cap X_{end} \geq X_F \qquad (22)$$

where:
- X_{init} is the X location of the rupture initiation point measured from the forward perpendicular
- X_A is the X location of the aft tank bulkhead
- X_{end} is the X location of the rupture completion point, and
- X_F is the X location of the forward tank bulkhead.

This algorithm works for the transverse tank breaches by replacing the X location with Y locations relative to the centerline. Since the inboard and outboard extents of the rupture are not explicitly a result of Damage, these locations are determined as the eccentricity (distance from the centerline to the center of the obstruction) plus or minus one-half the calculated transverse damage extent. Tank rupture information is saved in a binary indicator array with values of one for ruptured tanks, and zero for undamaged tanks. This array is then multiplied by an array containing the tank volumes and summed to provide the oil outflow for each damage case.

Hydrostatic balance and the varying tide conditions are accounted for by applying percentage losses to the total possible oil outflow. In this method, the percent of oil

volume lost from a tank, V_{lost}, is:

$$V_{lost} = 1 - \frac{z_c}{h_c} \qquad (23)$$

where: z_c is the height of remaining oil in the damaged tank, and

h_c is the maximum height of cargo, or 0.98 times Depth.

The oil captured by the double bottoms and J-ballast tanks is computed in a similar manner. The void rupture data is stored in an indicator array, this time with values of zero and one-half, to account for the voids capturing only 50% of their volume. Each double bottom fills completely with seawater/oil mix, while the J-ballast tanks only fill to the level z_{wo}. A correction similar to V_{lost} is applied to the volumes captured in the J-ballast tanks to account for tidal changes.

In Matlab, z_c and z_{wo} are defined as 3-by-1 vectors using the three tide conditions. In this way V_{lost} and the product of the total possible outflow and V_{lost} become vectors containing tide information. The three tidal outflows are combined using the weighting described in the Guidelines to produce the particular outflow for that set. This process is conducted for each data set, and the outflows stored in a single vector variable. The oil outflow parameters are then determined from this outflow vector.

The mean and extreme outflow parameters are calculated using Equations (20) and (21). Since the probability P_i is the same for each damage case in the simulation, Equation 20 becomes:

$$O_M = \frac{\sum_{i=1}^{N} O_i}{N \cdot C} \qquad (24)$$

where N is the total number of damage cases in the simulation. Equation 21 becomes:

$$O_E = \frac{10 \cdot \sum_{j=1}^{N/10} O_j}{N \cdot C} \qquad (25)$$

For the calculated probability of zero outflow, the value determined is interpreted as the likelihood that no oil is released into the environment given a grounding event. This differs from the IMO definition, where P_0 is the likelihood that no oil is released given a grounding event in which the outer hull of the vessel is breached. The IMO definition of P_0 does not allow any credit for the resistance of a vessel to rupture; P_0 calculated here reflects the differing ability of bottom plating to avoid rupture and rewards designs that can achieve this.

Likewise, the mean outflow calculated here is the mean outflow given that the vessel has grounded. The IMO measure, mean outflow given outer hull rupture can be determined from the model data by either using only cases which rupture the outer hull in equation 20, or by dividing the model mean outflow given grounding by the probability of outflow, $1-P_0$.

Two key assumptions are made in determining whether tanks are breached. Damage only defines a vessel's cargo block and assumes the entire block is parallel middle-body, with no structural or shape changes. This is not the case for the models used in this study. Therefore, for the forward tanks, where the actual vessel breadth is less then the maximum breadth defined in Damage, the transverse damage location and extents are linearly scaled with breadth. It is also assumed that the longitudinal tank bulkheads remain parallel to the centerline.

7.3 Required Number of Observations for Simulation

The quality of the Monte Carlo simulation depends on the number of observations conducted. When evaluating simple or known integrals using a Monte Carlo simulation, variance is inversely proportional to sample size, or the accuracy of the estimate is proportional to the square root of the amount of computational effort expended.
An analytical estimate of the required sample size is difficult to calculate in complex models. A simpler more intuitive approach is to test for convergence. A primary result of the simulation, the mean outflow, O_M, is monitored as a function of the number of cases conducted. When this parameter ceases to change convergence is assumed and no more

cases are required. Figures 7-2 through 7-4 show these relationships for the single hull, mid-deck and a double hull configuration. The remaining double hull results are in Appendix D. O_M for the single hull and mid-deck designs is determined with fewer observations than the double hull models. This is a result of the differences in P_0, as more total observations are required to generate the same number of data sets containing ruptured tanks. For the single hull and mid-deck models, convergence is achieved above 2,000 cases and for the double hull variants, convergence is achieved above 7,000 cases. For calculation of the oil outflow parameters: 4,000 cases are used for the single hull variant; 5,000 cases for the mid-deck variant; and 8,000 for the double hull variants.

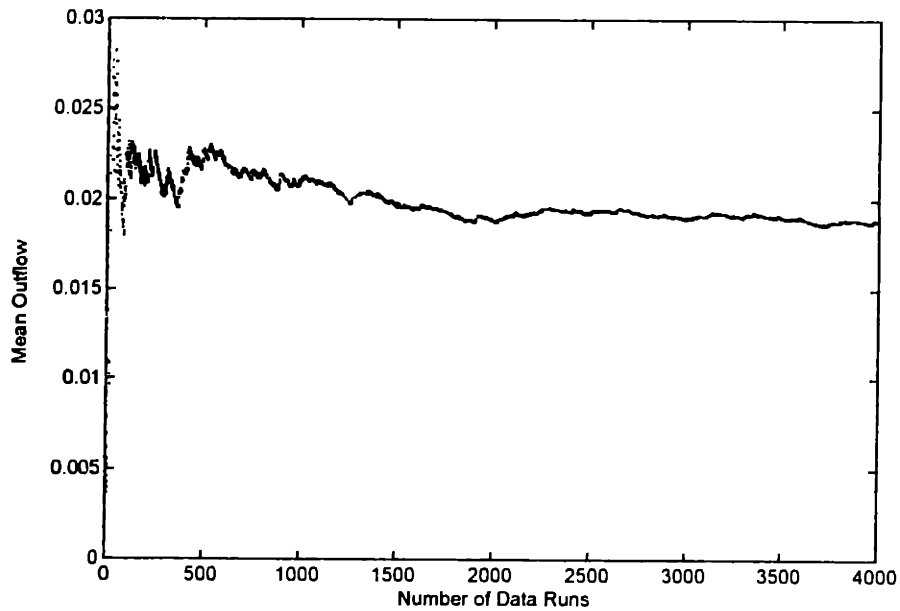


Figure 7-2 Mean Outflow vs. Number of Single Hull Damage Cases

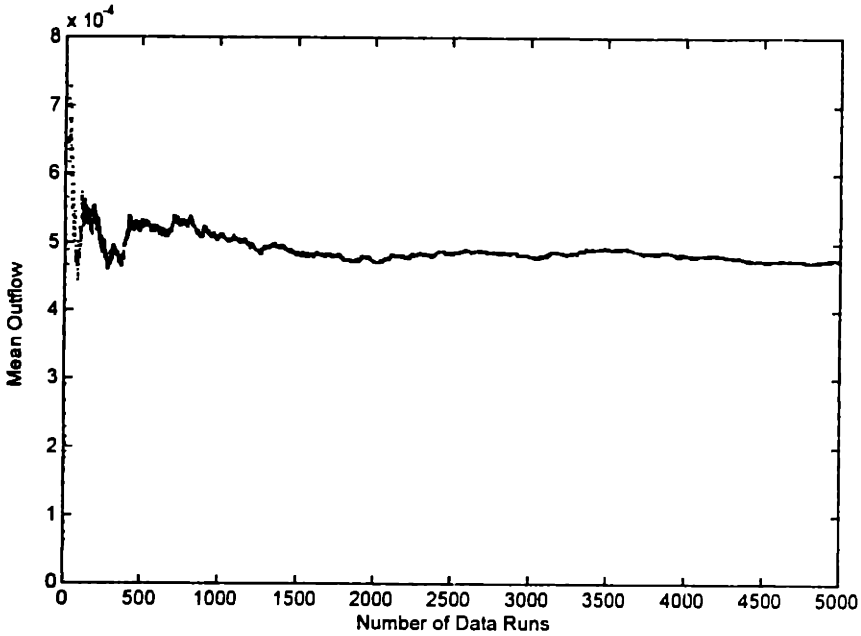


Figure 7-3 Mean Outflow vs. Number of Mid-deck Damage Cases

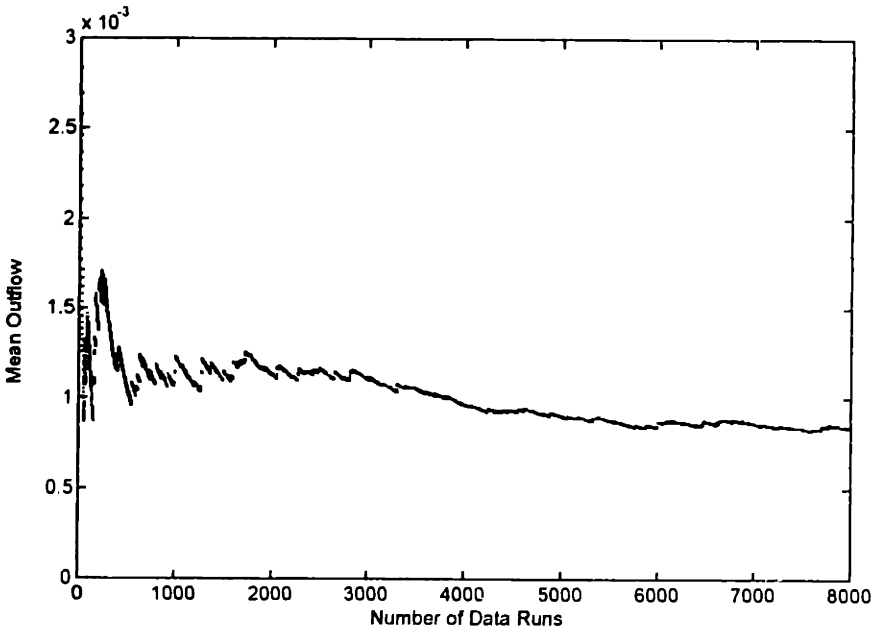


Figure 7-4 Mean Outflow vs. Number of Double Hull Damage Cases

Chapter 8. Results

8.1 Outflow Results and Analysis

As described in Chapter 1, the IMO Guidelines use Equation (1) to compare a tanker's oil outflow performance to a reference double hull design. The weighting factors used in this equation are based on a political rather than rational basis. To address this issue, the SNAME T&R Ad Hoc Panel on Environmental Performance of Tankers [21] proposed using spill cost (as a function of spill size) as the spill consequence metric. This metric is then used as a comparison tool when evaluating alternative designs. They present a probability weighted or mean accident cost as:

$$\textit{Mean Accident Cost} = \int_0^{Cap} p(Q) \cdot \text{Cost}(Q) dQ \qquad (26)$$

where Cap is the total ship capacity (in m^3)

Q is the oil outflow (in m^3)

p(Q) is the outflow probability density function for the specific ship

Cost(Q) is the outflow cost (in $M)

The Panel concluded the lack of adequate cost information presents a fundamental problem in any effort to assemble an outflow cost function, and recommended further research into this issue. There is insufficient data to define or select a particular cost function at this time; however, for a wide range of reasonable cost functions, mean outflow dominates the resulting risk. Based on this result, until data becomes available to define a single cost curve, the mean outflow parameter, O_M, is a more rational single metric for tanker risk. A particular design is considered satisfactory when O_M is less than or equal to O_{MR} for its applicable reference tanker. Probability of zero outflow is not considered explicitly. A rational alternative to using reference tankers is to specify a maximum value for O_M applicable to all tankers, or provide a required O_M curve with O_{MR}

as a function of cargo capacity. In either case the resulting pollution prevention risk index is:

$$E_{risk} = \frac{O_{MR}}{O_M} \tag{27}$$

In this index, mean outflow includes both grounding and collision outflow.

Table 8-1 shows the grounding-only oil outflow parameters calculated for each model using a Monte Carlo simulation to determine the damage extents. These parameters are conditional upon the vessel grounding: the probability of the tanker grounding is assumed to be one. The probability of zero outflow given a grounding, grounding mean outflow parameter, and grounding extreme outflow parameter are presented for each model. To determine the complete mean outflow for a design alternative, the O_M parameter presented below is combined with O_M calculated for collision events. P_0 and O_E are not required for Equation 27, but are provided for comparison of the models.

Table 8-1 Calculated Grounding Oil Outflow Parameters

	P_0	O_M ($\times 10^{-2}$)	O_E
Baseline Double Hull (DHull)	0.978	0.073	0. 0022
DHull02 increased plating	0.983	0.048	0.0015
DHull03 increased stiffener size	0.979	0.067	0.0020
DHull04 decreased stiff. spacing	0.977	0.077	0.0023
DHull05 decreased frame spacing	0.979	0.067	0.0022
Intermediate oil-tight deck	0.722	0.047	0.0012
Single Hull	0.774	1.897	0.0515

Increasing the plate thicknesses by 50% decreases the tanker environmental risk by about 35% from the baseline variant using O_M as the metric for tanker risk from grounding. With the exception of decreasing the stiffener spacing, the other structural alternatives have a smaller but still positive impact on reducing risk. By decreasing the stiffener spacing, the risk is increased because the *Rules for Building and Classing Steel Vessels* allow for a decrease in plating thickness. Based on these results, plate thickness

dominates the structural alternatives in determining oil outflow risk following a grounding. This is significant because it is contrary to the minimum weight design optimization paradigm.

The mid-deck tanker reduces grounding outflow risk by over 35% from the baseline variant. This is comparable to the best double hull variant alternative, the increased plating model. The reduction in risk in primarily the result of the significantly smaller mean outflow given outflow than in double hull designs. In most cases, the outflow from a ruptured mid-deck tank is assumed to be 1% of the capacity, where the double hull releases more oil following rupture. Offsetting this result is the outcome is the lower probability of zero outflow compared a double hull.

It was also demonstrated by the Ad Hoc Panel that a standard Rayleigh distribution provides an excellent fit to the outflow probability density functions calculated using the IMO Guidelines method for a double hull tanker. For mid-deck tankers, the fit was not as close, but still good. Using the IMO probability of zero outflow given rupture of the outer skin, P_0, and the mean outflow given outflow, the non-dimensional outflow is:

$$p(x, P_0, \mu) = (1 - P_0) \cdot \frac{x}{A\mu^2} \cdot e^{\frac{-x}{2A\mu^2}} \qquad (28)$$

where: A equals $2/\pi$

x is the non-dimensional outflow (Q/Cap)

μ is the non-dimensional mean outflow given outflow.

Figures 8-1 through 8-3 depict the oil outflow probability densities calculated from the Monte Carlo simulation data with the Rayleigh distribution outflow calculated using Equation (28). Also in these figures are the same data plotted as a cumulative density function to better illustrate the correlation. As with the Ad Hoc Panel results, the double hull outflow densities show very a very good fit to the Rayleigh distribution, with the mid-deck model not quite as good.

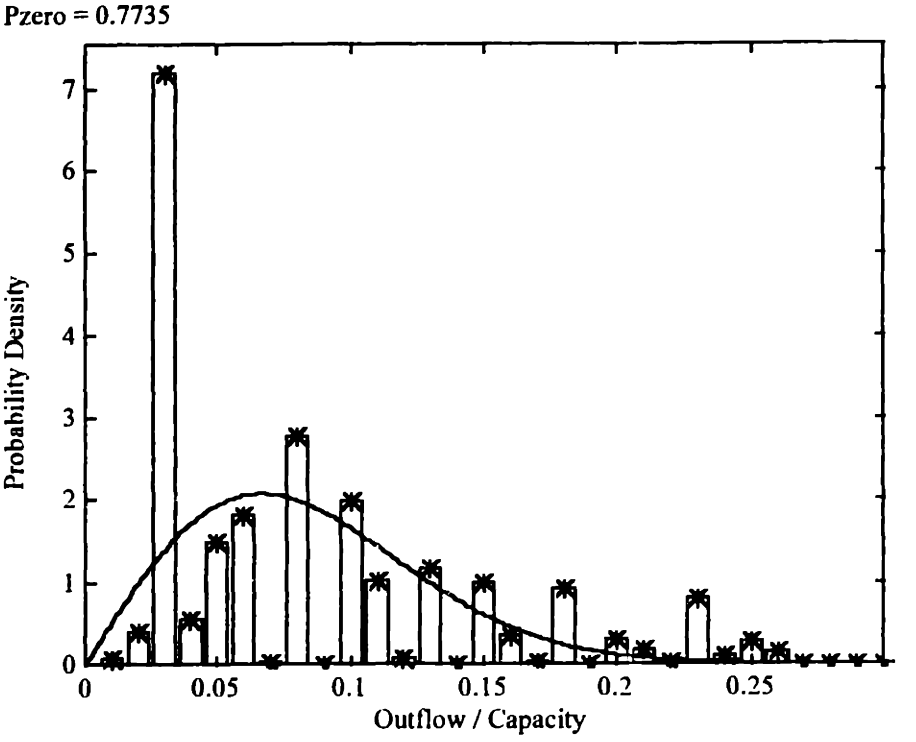


Figure 8-1(a) Single Hull Oil Outflow Probability Density Function

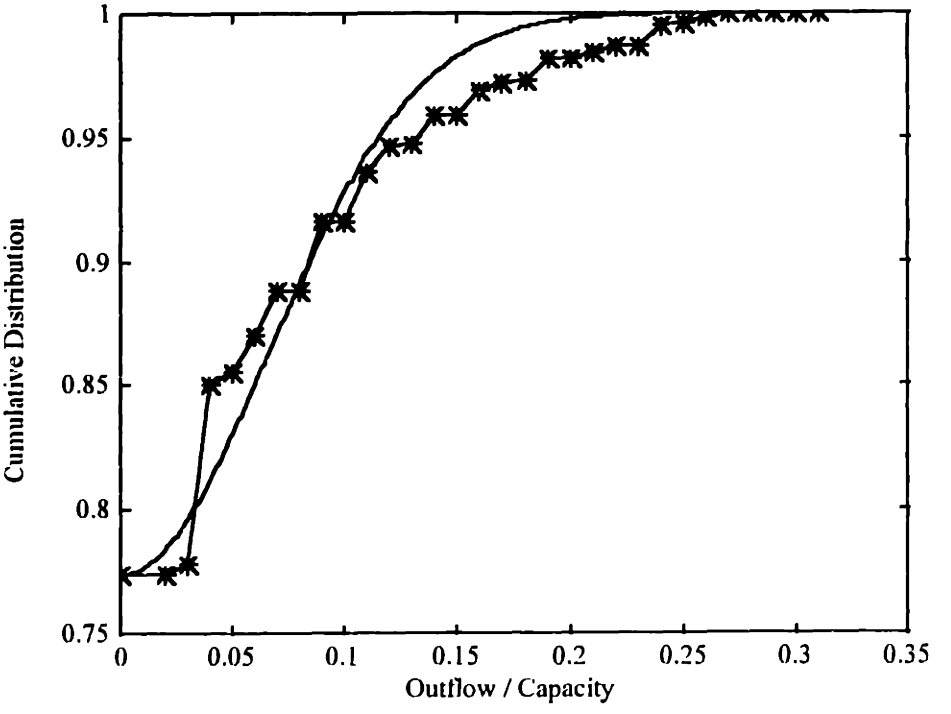


Figure 8-1(b) Single Hull Oil Outflow Cumulative Distribution Function

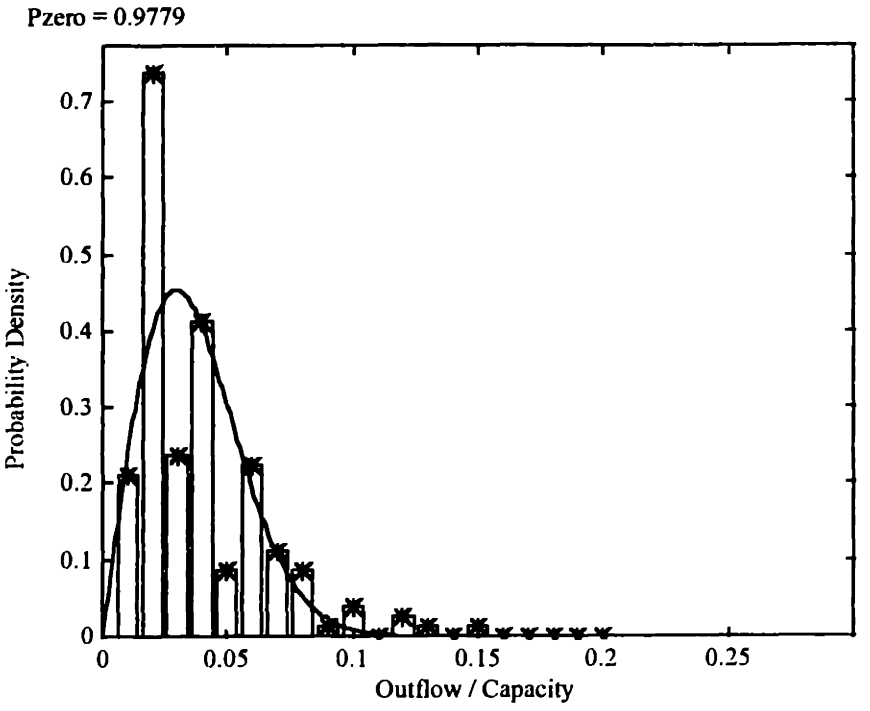


Figure 8-2(a) Baseline Double Hull Oil Outflow Probability Density Function

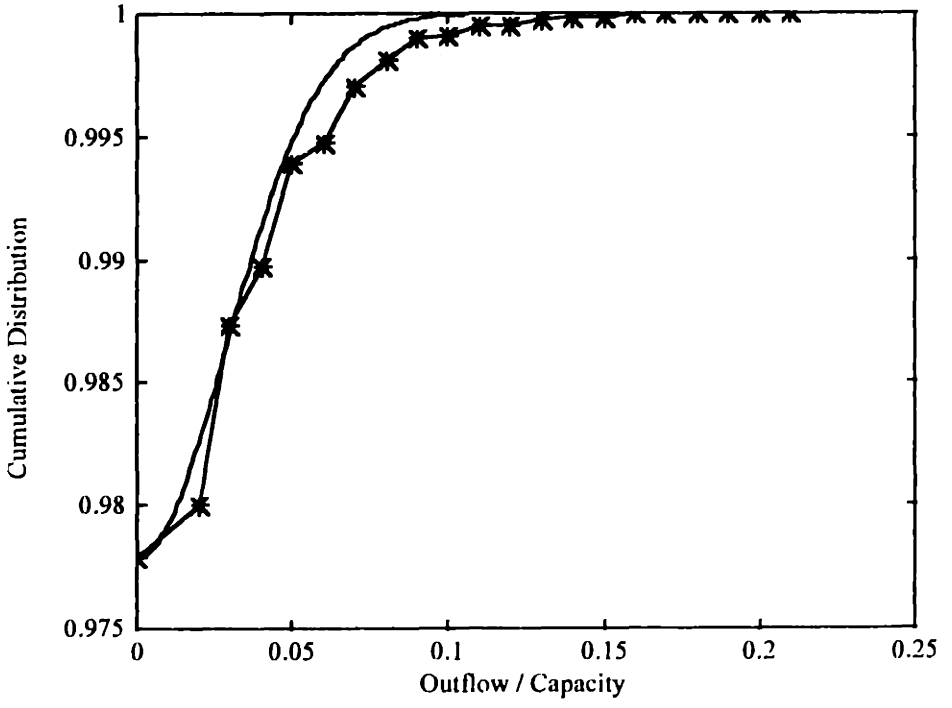


Figure 8-2(b) Baseline Double Hull Oil Outflow Cumulative Distribution Function

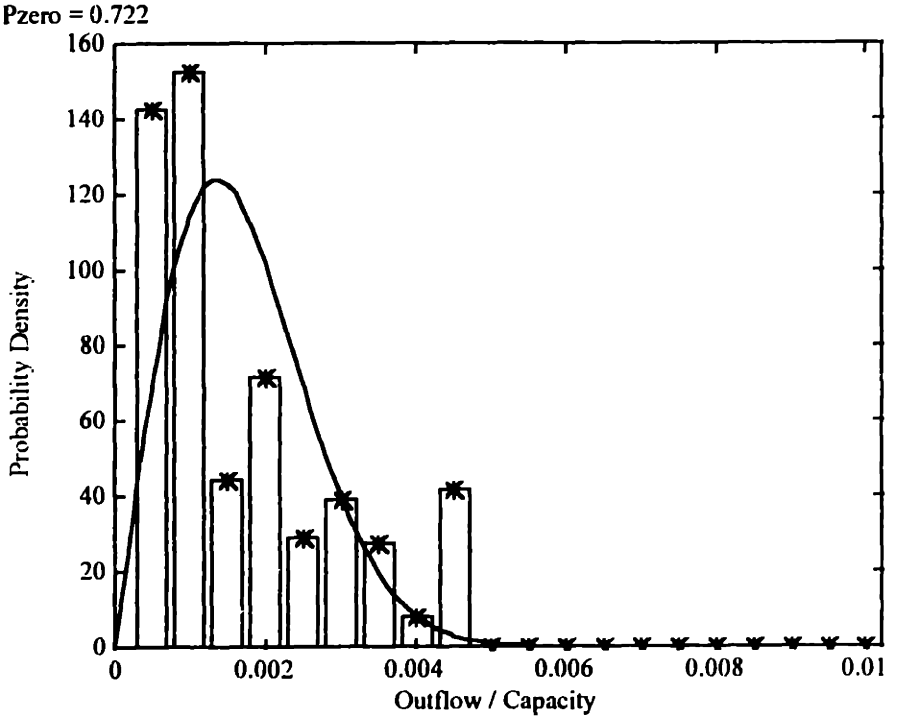


Figure 8-3(a) Mid-deck Oil Outflow Probability Density Function

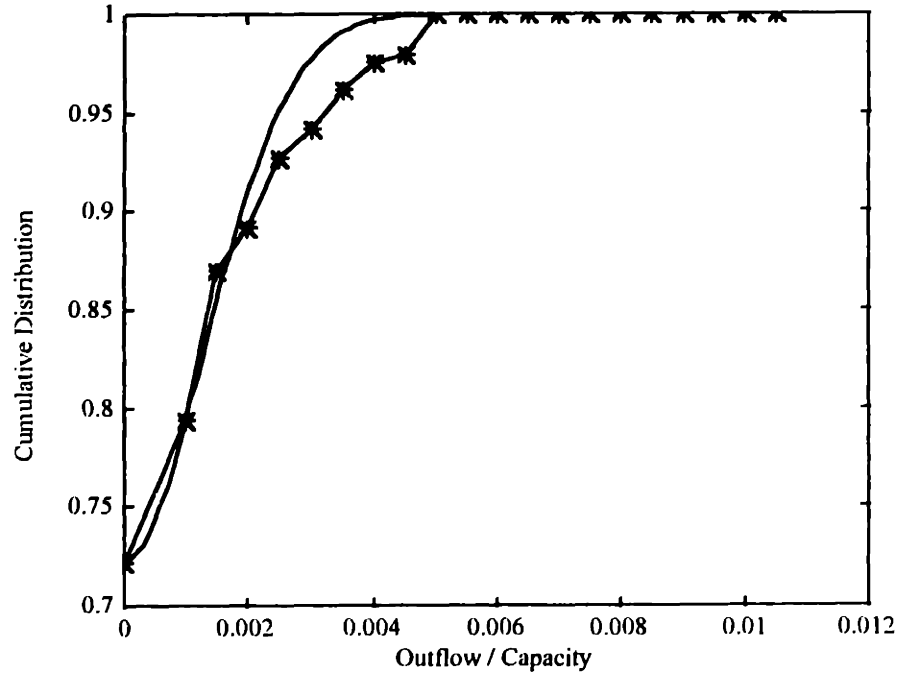


Figure 8-3(b) Mid-deck Oil Outflow Probability Density Function

To evaluate the cost effectiveness of structural modifications relative to oil outflow risk in groundings, the benefit of reduced oil outflows is compared to a cost parameter. The major variation in cost between the designs used in this study is the construction, or steel weight. Cost is modeled as proportional to the volume of steel used per length, which is given for each model in Table 3-6. To compare the cost factor to the pollution prevention factor, all parameters are normalized by the Baseline Double Hull design value and the factors multiplied. The result is a quantitative ranking of the designs, where lower values represent better cost effectiveness. Compared to the single hull tankers' performance, the table shows the double hull and mid-deck configurations are fairly consistent with each other. The mid-deck tanker appears superior in this analysis based on its reduced oil outflow without an increase in material costs. This analysis does not consider the relative cost of the mid-deck and double hull designs. Increasing scantlings from a minimum-scantling double hull tanker reduces this margin, but does not eliminate it.

Table 8-2 Tanker Models' Cost Effectiveness Rating

	Cost Factor (CF)	$O_M / (O_M)_{\text{Baseline DH}}$ (PF)	CF x PF
Intermediate oil-tight deck	0.93	0.64	0.60
DHull, increased plating	1.23	0.66	0.81
DHull, decreased frame spacing	1.02	0.92	0.94
DHull, increased stiffener size	1.03	0.92	0.95
Baseline Double Hull (DHull)	1.00	1.00	1.00
DHull, decreased stiff. spacing	0.96	1.05	1.01
Single Hull	0.76	25.99	19.75
	lower better	lower better	lower better

8.2 Calculated Damage Extent Probability Density Functions

Because the damage extents, probability and outflow for each damage case is calculated, there is no need for the intermediate step of using damage extent probability

density functions in determining the oil outflow parameters. However, these functions are useful in comparing the expected damage extents of the single hull, double hull and mid-deck configurations. Figures 8-4 through 8-7 depict the extent of damage to the cargo block for the three configurations. It should be noted that a comparison between these functions and those in the Guidelines are not appropriate due to the use of different conditional probabilities. The density functions defined in the IMO Guidelines show damage given a grounding such that the cargo block is ruptured. Figures 8-4 through 8-7 depict the damage extents given only that the vessel grounded and therefore include all groundings whether or not the cargo block is ruptured. The left graph includes the entire probability density range, and in the right side, the same data is presented with the y-axis limited to better illustrate the differences between the configurations.

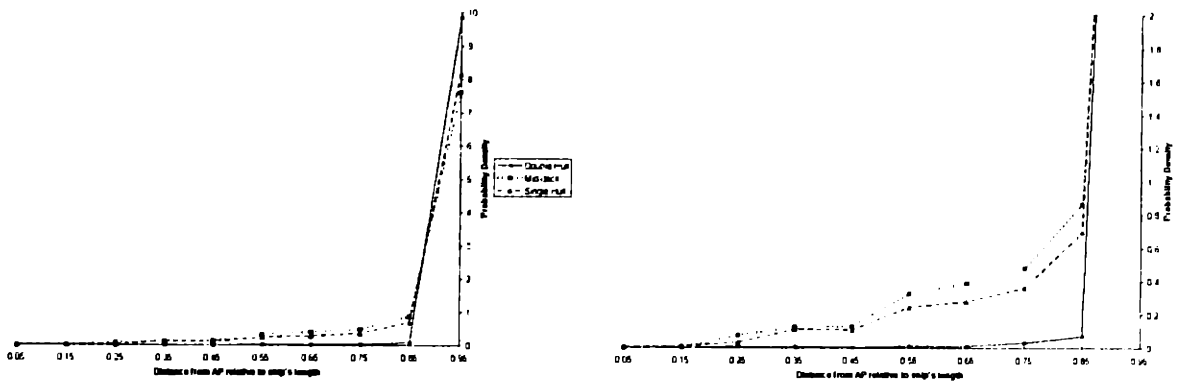


Figure 8-4 Calculated Longitudinal Location of Damage

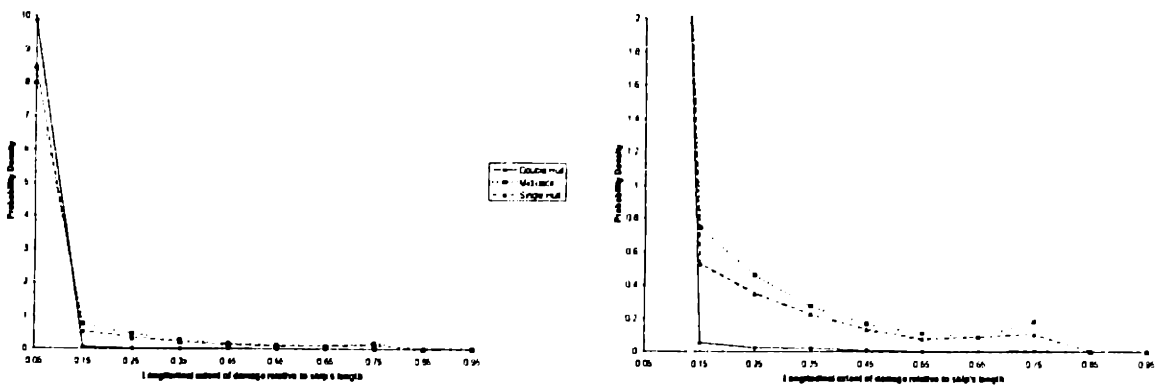


Figure 8-5 Calculated Longitudinal Extent of Damage

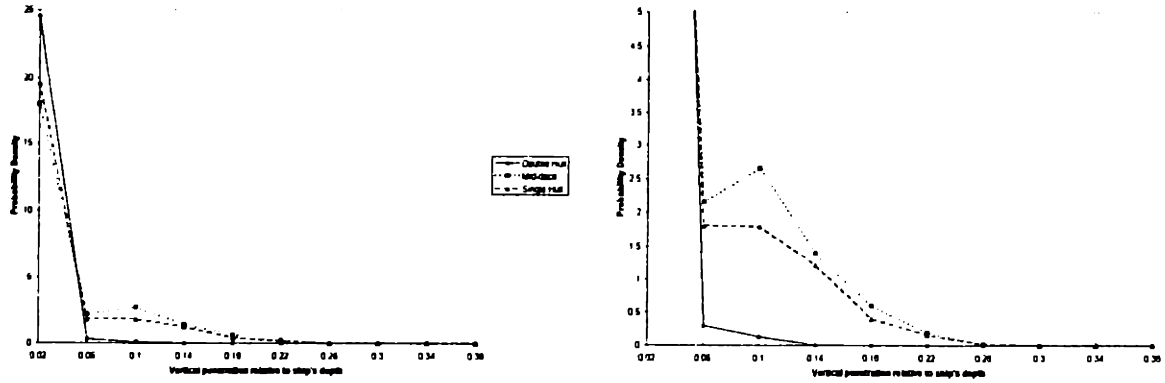


Figure 8-6 Calculated Vertical Penetration Extent

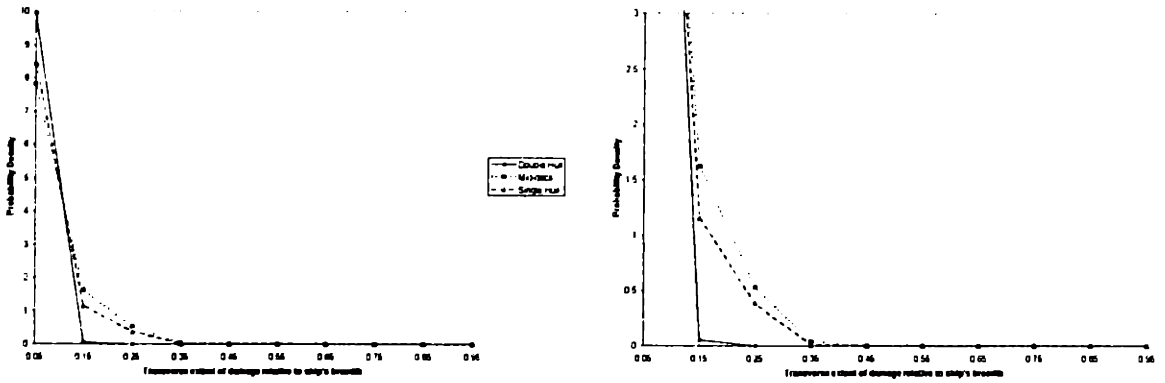


Figure 8-7 Calculated Transverse Extent of Damage

The damage extents for the single hull and mid-deck configurations are similar. In each case, the single hull configuration exhibits smaller damage extents due to the thicker bottom plate used in the model. The thicker bottom plate is required to ensure compliance with the section modulus requirements of ABS Rules. The mid-deck configuration meets this requirement with reduced bottom plating thickness because the mid-deck contributes to the overall section modulus. The extents for the double hull configuration show larger values of probability density for very small damage values. This is a result of the fewer instances of inner bottom rupture.

Chapter 9 Conclusions and Recommendations

9.1 Conclusions

The procedure for evaluating the crashworthiness of tankers following a grounding described in this thesis uses a probabilistic method to produce damage extent probability functions from a structural damage model. The damage extents are applied to a specific tanker design and the non-dimensional mean oil outflow is determined and used for comparisons to a reference design. The ratio of the mean oil outflow of the reference design to the design in question provides a pollution prevention index. This process differs from the process defined by IMO in that:

- Damage extents are determined using a damage prediction model that is based on ship structural design characteristics.
- A Monte Carlo simulation using calibrated accident scenario probability density functions is used to generate probable damage extents.
- The mean outflow parameter, O_M, is used as the accident risk index.
- O_M is conditional on the tanker grounding vice outer skin rupture.

In Chapter 1, deficiencies in the current IMO methodology are presented. These include:

- the damage extent probability density functions are based on limited historical data and applied universally for all designs independent of structure;
- damage extents are normalized with ship dimensions;
- damage extent probability density functions are assumed to be independent;
- current damage extents are based on data for cases where hull was ruptured.

Because the proposed procedure determines damage cases directly from the scenario distributions, the deficiencies in the current IMO methodology that deal with damage extent probability density functions are avoided. A design that resists hull rupture is rewarded using the new procedure since the probability of zero outflow and mean

outflow is conditional only on a vessel grounding, rather than the IMO condition requiring a grounding and rupture.

Application of the evaluation process outlined by the IMO Guidelines assumes independent longitudinal extents and vertical/transverse penetrations. Because the IMO probability density functions are developed from a limited set of data, it was impossible for IMO to include any kind of coupling between the longitudinal and transverse extents and still have enough cases to provide a valid statistical basis. One of the benefits of the method outlined in this thesis is that the coupling is captured in the damage prediction, and therefore included in the oil outflow parameters.

The procedure quantifies the hypothesis that both double hull and mid-deck designs are superior to conventional single hull tankers in environmental performance. It also has the ability to compare structural and arrangement modifications and provide a basis for rational decision-making.

9.2 Recommendations

The choice of Damage as a damage prediction model is not exclusive. Using the calibration techniques described here, other models may be used to generate damage cases. Later versions of Damage that include side definitions may be used to examine oil outflow following collisions. Damage validation efforts indicate good correlation of predicted forces to model tests, but the global ship model is not yet a good predictor of vertical rock penetrations. The impact of vertical penetration is critical to the evaluation of double hull oil outflow, and further work is necessary to ensure better predictions.

In this thesis, calculated damage extent probability density functions for a MARPOL "new oil tanker" are compared to the density functions for bottom damage defined by MARPOL in the Guidelines. This proposed method of calibrating the scenario probability density functions can be applied to other damage models that do not use the same scenario defining parameters. For example, a modified Minorsky approach to collision damage is used by Crake to examine oil outflow in collision incidents. The same calibration method is used to determine the collision scenario.

The tanker models used here are based upon the initial scantling requirements determined by the American Bureau of Shipping SafeHull system. Further refinements and finite element analysis of the designs would ensure the acceptability of the structural components for intended service and give new insights into the impact of local structures on crashworthiness. Further refinements and definition of ship structures must then be modeled in the damage predicting model, and Damage is currently not capable of more precise structural definitions. Research and improvements to the Damage code is continuing. The latest version, v3.0, includes a batch mode capable of completing sensitivity analyses similar to those conducted for this research. Incorporating a batch mode capable of simultaneously varying several scenario parameters probabilistically would greatly reduce the computational effort used in conducting Monte Carlo simulations. The calibration accomplished here is intended to verify the proposed method. A more comprehensive sensitivity analysis and calibration matrix would likely lead to an increase in the quality of the fit of the calculated density functions to the IMO statistics.

The cost -effectiveness of a specific design should be addressed in more detail than presented here. Actual vessel cost includes maintenance and operation costs and a better cost metric than volume of steel used in construction. With better cost models for both vessel operation and pollution effectiveness, a true cost-effectiveness analysis can be conducted.

References

(1) Drewry Shipping Consultants. 1991. Tanker Regulations - Implications for the Market. Report in the Seaborne Trade and Transport Series. London, U.K.

(2) Mankabady, Samir. 1986. The International Maritime Organization. Croom Helm Ltd. Kent, U.K.

(3) Professional Mariner. 1997. Maritime Milestones, the Torrey Canyon's Enduring Legacy. Issue #27.

(4) Tankerman Handbook. 1972. U.S. Coast Guard Publication.

(5) Mankabady, Samir. 1986.

(6) MARPOL 73/78. Annex I, Chapter 3, Regulations 22 through 25.

(7) MARPOL 73/78. Annex I, Chapter 2, Regulation 13E.

(8) Drewry Shipping Consultants. 1991.

(9) Ibid.

(10) MARPOL 73/78. Annex I, Regulation 13F(5).

(11) Brown, Alan and Amrozowicz, Michael. 1996. Tanker Environmental Risk - Putting the Pieces Together. SNAME/SNAJ International Conference on Designs and Methodologies for Collision and Grounding Protection of Ships.

(12) International Maritime Organization. 199?. IMO Comparitive Study on Oil Tanker Design. IMO Paper MEPC 32/7/15, Distribution of Actual Penetrations and Damage Locations Along Ship's Length for Collisions and Groundings.

(13) International Maritime Organization. 1995. Interim Guidelines for Approval of Alternative Methods of Design and Construction of Oil Tankers under Regulation 13F(5) of Annex I of MARPOL 73/78. Resolution MEPC.66(37).

(14) Crake, K.W. A Probabilistic Evaluation of Tank Ship Damage in a Collision Event. M.S. Thesis. Massachusetts Institute of Technology. 1998.

(15) Simonsen, B.C. DAMAGE Code Verification. Presented at the 10th Steering Committee Meeting of the Joint MIT/Industry Consortium on Tanker Safety. 1998

(16) Little, P., Pippenger, D., Simonsen, B.C. 1996. Development of a Computational Model for Predicting Damage to Tankers. SNAME/SNAJ International Conference on Designs and Methodologies for Collision and Grounding Protection of Ships.

(17) Rawson, C. 1998. Suezmax Tanker Designs for Evaluating Damage. Projects in New Construction Naval Ship Design Report.

(18) American Bureau of Shipping. 1995. The ABS SafeHull System for TANKER, Version 3.0.

(19) MARPOL 73/78. Annex I, Regulation 1(27).

(20) Dagpunar, J. 1988. Principles of Random Variate Generation. Oxford University Press. Oxford, U.K.

(21) Sirkar, J., et. al., A Framework for Assessing the Environmental Performance of Tankers in Accidental Groundings and Collisions. Presented at the SNAME Annual Meeting, October 1997.

Appendix A Program Scripts

vargen.m

```
% vargen.m

% Routine to generate random variates for use in the Hightest "DAMAGE"
% script routine.

% Required items:
% sub-script "norml.m"
% Select n, the number of variates to produce.
% Check the variable limit constants against desired.
% Verify output file name. ([variates.asc])

% Open output file in Excel, to remove the "e"s, and save as
% a comma-delimited text file ([variates.csv]).

% Output file contains:
% Velocity Trim          Elevation          Eccentricity          Radius      Alfa

% Date created:  03/23/97
% Last Updated:  02/18/98

% Variable definitions
% n         = total number of desired variates sets
% R         = MATLAB generated random numbers for flat and linear variates
% V         = desired variates
% i         = loop counter
% s         = random number generator seed
% N         = number of bins for visual test of variates

clear
n = 1000;

% Normally distributed variates Section
velocity = [10,5,1,1];          % Hi mean, lo mean, hi sigma, lo sigma
tip = [5.0, 3];                 % Tip Radius:  mean, sigma
side = [27.5, 15];              % Alpha:   mean, sigma

% Flat pdf constant section
trim = [-1, 1];                 % Trim Range: Min value, Max value
eccen = [0, 24];                % Eccentricity Range:  Min, Max

% Linear pdf constants section
L = 5;                          % Upper limit for Rock Elevation.

% Start the routine
s=clock;                        % Seeds the random number generator with time.
s=(s(2)+s(3)+s(4)+s(5)+s(6))*1e6;
rand('seed',s);

R = rand(n,4);                  % Random numbers for velocity mode, trim, eccentricity, elevation
V(:,1) = norml(n,1);            % Normal variates for velocity
V(:,5) = norml(n,1);            % Normal variates for alpha
V(:,6) = norml(n,1);            % Normal variates for tip radius
```

vargen.m

```
for i = 1:n

% Velocity
        if R(i,1) > .5
                V(i,1) = velocity(1) + V(i,1) * velocity(3);
        else
                V(i,1) = velocity(2) + V(i,1) * velocity(4);
        end
        if V(i,1) > 20
                V(i,1) = 20;
        end
        if V(i,1) < 2
                V(i,1) = 2;
        end

% Tip Radius
        while abs(V(i,5) * tip(2)) > tip(1),
                V(i,5) = norml;
        end
        V(i,5) = tip(1) + V(i,5) * tip(2);

% Alpha (Side Angle)
        while abs(V(i,6) * side(2)) > side(1),
                V(i,6) = norml;
        end
        V(i,6) = side(1) + V(i,6) * side(2);

% Flat pdf section
        V(i,2) = trim(2) + (trim(1) - trim(2)) * R(i,2);
        V(i,4) = eccen(2) + (eccen(1) - eccen(2)) * R(i,4);

% Linear pdf section
        V(i,3) = L * (1 - sqrt(1-R(i,3)));

end
% Quick Test
N = 30;
for i = 1:6
        figure(1)
        subplot(3,2,i)
        hist(V(:,i),N)
end
%save c:\thesis\matlab\calib16.asc V -ascii
```

norml.m

```
function y = norml(n,x)
% NORML  Normally distributed number generator.
%   NORML(N,X) returns N sets of X random numbers that are normally distributed.
%   NORML(N) returns N normally distributed random numbers.

if nargin == 0
   n = 1;
   x = 1;
end

if nargin == 1
   x = 1;
end

%s=clock;                        % Seeds the random number generator.
%s=(s(2)+s(3)+s(4)+s(5)+s(6))*1e6;
%rand('seed',s);

R = rand(n,2*x);

for i = 1:n
   for j = 1:2:2*x
            U(1) = 2*R(i,j)-1;
            U(2) = 2*R(i,j+1)-1;
            S = U(1)^2 + U(2)^2;
            while S>=1
                              U = 2*rand(2)-1;
                              S = U(1)^2 + U(2)^2;
            end
            y(i,j/2+0.5) = U(1) * sqrt(-2*log(S)/S);
   end
end
```

pdfgen.m

```
% pdfgen.m

% Routine to generate the damage extent pdf's calibration phase.
% Size of histogram bin, number of data sets used can be
% adjusted in constants section.

% Requires:
% compare.m (PDF method) or compare2.m (CDF method)
% oddeven.m (for plotting options)

% Variable definitions
% fid, file, id:                Result file identifiers
% i, j:                         Loop counters
% a:                            raw data matrix
% b:                            Intermediate (temporary) data matrix
% data:                         non-dimensionalized data matrix
% N:                            length of data matrices
% Offset, Breadth, Length, Depth:           Ship data, for non-dimensionalizing
% init, num:                   Used to select certain, rather than all, data sets
% Mx, M:                       X and Y coordinates of Marpol pdf graphs
% prob_rupture:                1 - Pzero
% p:                           Number of histogram bins for pdfs
% n:                           histogram output
% x, dx:                       X axis points and differential for pdfs
% pdf:                         histogram output converted to probability densities
% xb, pdfb:                    X and Y points for pdf bar charts
% area:                        Areas between calculated and Marpol prob. densities
% maxy:                        Limits the plot extents

clear                          %Comment out for autopdf

% Result file selection
file = 'mstelxx.res';                                   %Comment out these
id = input('Enter the result file ID number:','s');     %six lines prior
if isempty(id)                                          %to running
        file = 'baseline.res';                          %autopdf
else file(6:7) = id;
end

fid = fopen(file);
a = fscanf(fid, '%g %g %g %g %g', [5 inf]);
a = a';
fclose(fid);

% Non-dimensionalizing factors
Length = 264;           % Length of cargo area
Breadth = 48;           % Ship's breadth
Depth = 24;             % Ship's depth (not draft)
Offset = 132;           % Distance from bulkhead T1 to midships

%p=input('Enter the number of histogram bins:');
%if isempty(p)
        p=10;           % Number of increments for histogram
%end
```

pdfgen.m

```
% Limiting size of input data file
init = 1;                    % Position of first data point
num = length(a);             % Number of desired data points to be considered
num = num + init - 1;        % Don't change.
a = a(init:num,:);
N = length(a);

% Generating MARPOL pdf's
Mx = [0,0.5,1,1;0,0.3,0.8,0.8;0,0.1,0.3,0.3;0,0.3,0.9,1]';
M = [0.2,0.5,2.6,2.6;4.5,0.5,0.5,0;14.5,1.1,1.1,0;4,0.4,0.4,1.6]';

% Section to eliminate non-rupture cases
% Comment out to retain all cases
j = 1;
for i = 1:N
        if a(i,2) > 0
                b(j,:) = a(i,:);
                j = j + 1;
        end;
end;
a = b;
prob_rupture = j / N
N = length(a);               % End of non-rupture section

% Generating PDF's
data(:,1) = (Offset - (a(:,2) + a(:,3))/2) ./ Length;   % Location
data(:,2) = (a(:,2)-a(:,3)) ./ Length;                  % Extent
data(:,3) = a(:,4) ./ (1.103 * Depth);                  % Penetration
data(:,4) = a(:,5) ./ (1.103 * Breadth);                % Transverse

x(:,1) = [1/(2*p): 1/p: 1-1/(2*p)]';
x(:,2) = x(:,1);
x(:,3) = 0.4 * x(:,1);
x(:,4) = x(:,1);

dx = [1/p, 1/p, 0.4/p, 1/p];

for i = 1:4,
        [n(i,:),x(:,i)] = hist(data(:,i),x(:,i));    % Generates histograms
end
n=n';

for i = 1:4
        pdf(:,i)=(n(:,i)/N) ./ dx(i);
        [xb(:,i),pdfb(:,i)] = bar(x(:,i), pdf(:,i));
end
x(:,1) = 1 - x(:,1);
xb(:,1) = 1 - xb(:,1);                  % Reverses the plot for long location
%[area] = compare(pdf,x)                % Subroutine for finding probability difference
```

pdfgen.m

```
figure                                          %Use this for 1x4 plots
for i = 1:4,
        %if oddeven(i) == 1, figure             %These three lines for 2x2 plots
        %end
        %subplot(2,1,oddeven(i))
        %figure                                 %Use this for 4x1 plots
        subplot(2,2,i)                          %Use this also for 1x4 plot
        hold on
        plot(xb(:,i),pdfb(:,i),'w',x(:,i),pdf(:,i),'w*', Mx(:,i),M(:,i),'w')
        if max(M(:,i)) > max(pdfb(:,i))
                        maxy(i) = 1.05 * max(M(:,i));
        else maxy(i) = 1.05 * max(pdfb(:,i));
        end
        axis([0,max(xb(:,i))+(0.5/p),0,maxy(i)])
        ylabel('Probability Density')
        %legend('MARPOL Standard', 'Calculated Distribution')
        if i == 1
                        xlabel('Distance from Aft Tank Bulkhead / Length')
                        title('Longitudinal Location')
        elseif i == 2
                        xlabel('Length of Damage / Length')
                        title('Longitudinal Extent')
        elseif i == 3
                        xlabel('Distance above Baseline / Depth')
                        title('Vertical Penetration')
        else
                        xlabel('Transverse Damage Width / Beam')
                        title('Transverse Extent')
        end
end
```

compare.m

```
function [area] = compare(pdf,x)
%       Minimum difference in area method of comparing theoretical and simulation pdf's.
%       compare(pdf,x) is called from pdfgen.m and uses the output pdf's, and
%       the x matrix containing x-axis points.
%       Returns a plot of the difference between the two pdf's.
%
%       Also returns a 1 by c+1 "Area" matrix which contains the area of the space between
%       the actual and theoretical values.  The first c values correspond to the
%       extent Marpol graphs, and the final value is the overall average.

[r,c] = size(x);                % Number of data pieces in histogram output file

% Generating MARPOL pdf's
for i = 1:r
        M(i,1) = 4 * x(i,1) - 1.4;
        M(i,2) = 0.0;
        M(i,3) = 0;
        M(i,4) = 12 * x(i,4) - 10.4;
        if x(i,4) <=.9
                        M(i,4) = .4;
        end
        if x(i,2)  <= .8
                        M(i,2) = 0.5;
        end
        if x(i,1) <= .5
                        M(i,1) = 0.2 + 0.8 * x(i,1);
        end
        if x(i,2) <= .3
                        M(i,2) = 4.5 - 13.33 * x(i,2);
                        M(i,4) = 4 - 12 * x(i,4);
        end
        if x(i,3) <= .3
                        M(i,3) = 1.1;
        end
        if x(i,3) <= .1
                        M(i,3) = 14.5 - 134 * x(i,3);
        end
end

diff = abs((pdf - M));
dx = x(2,:) - x(1,:);
dx(1) = -dx(1);                 %LongLoc graph had been reversed

area(1) = sum(diff(:,1)) * dx(1);
area(2) = sum(diff(:,2)) * dx(2);
area(3) = sum(diff(:,3)) * dx(3);
area(4) = sum(diff(:,4)) * dx(4);
area(c+1) = mean (area(1,1:c));
```

shull.m

```
% shull.m

% Routine for finding outflows for shull model.
% Required items:  transext.m

clear

% Open results file
file = 'shull01.res';
fid = fopen(file);
a = fscanf(fid, '%g %g %g %g %g %g %g', [7 inf]);
a = a';
fclose(fid);

[row,col] = size(a);
n = row                         % Total number of data sets

% Non-dimensionalizing factors
Draft = 16.8;                   % Ship's original draft
Depth = 24;                     % Tank depth
Offset = 132;                   % Distance to midships

% Exclude non-rupture cases, determine transverse rupture extents
% Rupture Init, Rupture End, VertPen, Eccentricity, Transext
j = 0;
for i = 1:row
        if a(i,col-2) - a(i,col-1) > 0
                j = j + 1;
                b(j,1) = Offset - a(i,col-2);
                b(j,2) = Offset - a(i,col-1);
                b(j,3) = a(i,col);
                b(j,4) = a(i,2);
                b(j,5) = 1.1 * transext(a(i,col), a(i,3), a(i,4));
        end;
end;
a = b;

% Hydrostatic balance
tide = [0;2;6];
rho_c = 0.9;
rho_s = 1.025;
delta_p = 0.05;
g = 9.807;
Zs = Draft - tide;
Zc = (Zs*rho_s*g - 100*delta_p) / (rho_c*g);
Zwo = (Zc + Zs) / 2;
Hc = 0.98*Depth;
Vol_lost = (Hc - Zc) / Hc;      % Percent loss of cargo

% Define TankBoundaries, volumes, and indicator variable
t_bnd =     [24.0,24.0,24.0,24.0,24.0,24.0,24.0;...          % L0
              15, 15, 15, 15, 15, 15, 0;...                  % L1
             -15,-15,-15,-15,-15,-15, 0;...                  % L2
             218.5, 204.7, 177.4, 136.3, 95.2, 54.1, 13];    % Bhds
```

shull.m

```
t_vol = [ 2195, 6520,    0,    0,    0,  5975;...                    % Wing Cargo
              0,29052, 29595, 29592, 29041, 19918;...                % Center Cargo
           2195, 6520,    0,    0,    0,  5975];                     % Opposite Wing


C = sum(sum(t_vol));                                                  % Max Cargo Volume

% Assign indicator variables based upon damage
for i = 1:length(a)
   t_spill = zeros(size(t_vol));
   for j = 1:size(t_bnd,2)-1
      inside = a(i,4) - a(i,5)/2;                                     % Inner edge of rupture
      outside = a(i,4) + a(i,5)/2;                                    % Outer edge of rupture
      if inside < t_bnd(1,j)                                          % Tests for rupture beyond hull
         if a(i,2) > t_bnd(4,j+1)                                     % Tests for rupture within
            if a(i,1) < t_bnd(4,j)                                    %  longitudinal tank extents
               if outside > t_bnd(2,j)
                  t_spill(1,j) = 1;
               end
               if outside > t_bnd(3,j)
                  if inside < t_bnd(2,j)
                     t_spill(2,j) = 1;
                  end
               end
               if inside< t_bnd(3,j)
                  t_spill(3,j) = 1;
               end
            end
         end
      end
   end
   if t_spill(2,1) == 1                                               % Ensures area between slop tanks is included
      t_spill(2,2) == 1;                                              %  in #5 Center COT
   end
   if t_spill(2,2) == 1
      t_spill(2,1) ==1;
   end
   Vout = Vol_lost * sum(sum(t_vol .* t_spill));
   outflow(i,1) = 0.4*Vout(1) + 0.5*Vout(2) + 0.1*Vout(3);
end
outflow = nonzeros(outflow);                                          % Removes PL/SBT-only damages
Pzero = 1 - length(outflow)/n
Mean_outflow = sum(outflow) / (n * C)
Mean_outflow_given_outflow = Mean_outflow / (1-Pzero)
outflow = sort(outflow);                                              % For extreme outflow
l = length(outflow);
Extreme_outflow = 10 * sum(outflow(floor(0.9*l):l)) / (n * C)

% Plot outflow pdf
P=num2str(Pzero);                                                     % Plot Pzero on graph
P0=['Pzero = '];
P0=[P0,P];
outflow = outflow / C;                                                % Non-dimensionalize outflow
```

shull.m

```
bins = [0.01:0.01:0.3];
[pdf,x] = hist(outflow,bins);
dx = x(2) - x(1);
pdf = pdf / (n * dx);
[xb,pdfb]=bar(x,pdf);                          % For bar plots

% Rayliegh distribution
X=[0:.001:0.3];
mu_square = Mean_outflow_given_outflow^2;
A = 2/pi;
Rpdf = (1-Pzero) * X ./(A*mu_square) .* exp(-X.^2./(2*A*mu_square));

plot(x,pdf,'w*',xb,pdfb,'w',X,Rpdf,'w')
%title([file])
axis([0,0.3,0,max(pdf)*1.05])
text(-3*dx,1.1*max(pdf),[P0])
ylabel('Probability Density')
xlabel('Outflow / Capacity')

figure
cdf=cumsum(pdf)*dx + Pzero;
cdf=[Pzero,cdf];
x=[0,x+dx];
Rcdf = cumsum(Rpdf)*0.001 + Pzero;
plot(x,cdf,'w*',x,cdf,'w',X,Rcdf,'w')
ylabel('Cumulative Distribution')
xlabel('Outflow / Capacity')
```

dhull.m

```
% dhull.m

% Routine for finding outflows for dhull models.
% Required items:  transext.m

clear

% Open result file
file = 'dhullxx.res';
id = input('Enter the results file ID:','s');
file(6:7) = id;
fid = fopen(file);
a = fscanf(fid, '%g %g %g %g %g %g %g %g %g %g', [10 inf]);
a = a';
fclose(fid);

% Non-dimensionalizing factors
Draft = 16.8;                   % Ship's original draft
Depth = 24;                     % Tank depth
Ddb = 2.4;                      % Double bottom depth
Bds = 2.0;                      % Double side breadth
Offset = 132;                   % Distance to midships

% Define TankBoundaries, volumes, and spill multiplier
t_bnd =     [22.0,22.0,22.0,22.0,22.0,22.0,22.0,22.0;...        % L0
              9.7, 9.7, 9.7, 9.7, 9.7, 9.7,  9.7, 0;...         % L1
             -9.7,-9.7,-9.7,-9.7,-9.7,-9.7, -9.7, 0;...         % L2
             13.8, 13.8, 13.8, 13.8, 13.8, 13.8, 13.8, 0;...    % L3
              0,   0,   0,   0,   0,   0,   0,   0;...          % L4
             -13.8,-13.8,-13.8,-13.8,-13.8,-13.8,-13.8, 0;...   % L5
             218.5, 211, 178, 145, 112, 79, 46, 13];            % Bhds

t_vol =     [1953 ,8767, 8767,    0, 8767, 8348,5399;...        % Wing Cargo
               0,16908,13828,13828,13828,13167,8516;...         % Center Cargo
             1953, 8767, 8767,    0, 8767, 8348,5399;...        % Opposite Wing
             498,2208,2208.2208,2208,2173,1932;...              % J ballast
             244,1093,1093,1093,1093,1045,708;...               % DB ballast
             244,1093,1093,1093,1093,1045,708;...               % Opposite DB
             498,2208,2208,2208,2208,2173,1932];                % Opposite J

C = sum(sum(t_vol(1:3,:)));             % Max Cargo Volume

% Hydrostatic balance
tide = [0;2;6];
rho_c = 0.9;
rho_s = 1.025;
delta_p = 0.05;
g = 9.807;
Zs = Draft - Ddb - tide;
Zc = (Zs*rho_s*g - 100*delta_p) / (rho_c*g);
Zwo = (Zc + Zs) / 2;
Hc = 0.98 * (Depth - Ddb);
Vol_lost(1:3) = (Hc - Zc) / Hc;         % Cargo Lost
Tlength = t_bnd(7,3) - t_bnd(7,4);      % J-tank capture
```

```
Jtank = t_vol(4,3);
Vol_lost(4:6) = 1 - Bds * Tlength * (Depth - Ddb - Zwo) / Jtank;
Vol_lost(7:9) = ones(3,1);

[row,col] = size(a);
n = row                                          % Number of original input cases

% Exclude non-rupture cases, determine transverse extents
% Rupture Init, Rupture End, VertPen, Eccentricity, Transext
j = 0;
for i = 1:row
        if a(i,col-2) - a(i,col-1) > 0
                j = j + 1;
                b(j,1) = Offset - a(i,col-2);
                b(j,2) = Offset - a(i,col-1);
                b(j,3) = a(i,col);
                b(j,4) = a(i,2);
                b(j,5) = 1.1 * transext(a(i,col), a(i,3), a(i,4));
        end;
end;
a = b;

% Assign spill multipliers based upon damage
for i = 1:length(a)
   t_spill = zeros(size(t_vol));
   for j = 1:size(t_bnd,2)-1
      inside = a(i,4) - a(i,5)/2;                % Inner edge of rupture
      outside = a(i,4) + a(i,5)/2;               % Outer edge of rupture
      if inside < t_bnd(1,j)                     % Tests for rupture beyond hull
         if a(i,2) > t_bnd(7,j+1)                % Tests for rupture within
            if a(i,1) < t_bnd(7,j)               % longitudinal tank extents
               if outside > t_bnd(2,j)
                  t_spill(1,j) = 1;
               end
               if outside > t_bnd(3,j)
                  if inside < t_bnd(2,j)
                     t_spill(2,j) = 1;
                  end
               end
               if inside< t_bnd(3,j)
                  t_spill(3,j) = 1;
               end
               if outside > t_bnd(4,j)
                  t_spill(4,j) = -0.5;
               end
               if outside > t_bnd(5,j)
                  if inside< t_bnd(4,j)
                     t_spill(5,j) = -0.5;
                  end
               end
               if outside > t_bnd(6,j)
                  if inside < t_bnd(5,j)
                     t_spill(6,j) = -0.5;
                  end
```

```
            end
            if inside < t_bnd(6,j)
               t_spill(7,j) = -0.5;
            end
          end
        end
      end
    end
    if t_spill(2,1) == 1                          % Ensures area between slop tanks is included
      t_spill(2,2) == 1;                          %   in #6 Center COT
    end
    if t_spill(2,2) == 1
      t_spill(2,1) == 1;
    end
            % Vout          = volume of ruptured tanks
            % Vjtanks       = volume of ruptured J-tanks
            % Vdb           = volume of ruptured double bottoms
            % Vout          = Cargo volume lost after correction for tide
    Vout = sum(sum(t_vol(1:3,:) .* t_spill(1:3,:)));
    Vjtanks = sum(t_vol(4,:) .* t_spill(4,:)) + sum(t_vol(7,:) .* t_spill(7,:));
    Vdb = sum(sum(t_vol(5:6,:) .* t_spill(5:6,:)));
    Vout = Vol_lost(1:3) * Vout + Vol_lost(4:6) * Vjtanks + Vol_lost(7:9) * Vdb;
    outflow(i,1) = (0.4*Vout(1) + 0.5*Vout(2) + 0.1*Vout(3));
end
outflow = nonzeros(outflow);                      % Excludes ballast tank hits
Pzero = 1 - length(outflow)/n
Mean_outflow = sum(outflow) / (n * C)
Mean_outflow_given_outflow = Mean_outflow / (1-Pzero)
outflow = sort(outflow);                          % For extreme outflow
l = length(outflow);
Extreme_outflow = 10 * sum(outflow(floor(0.9*l):l)) / (n * C)

% Plot outflow pdf and cdf
P=num2str(Pzero);
P0=['Pzero = '];
P0=[P0,P];
outflow = outflow / C;
bins = [0.01:0.01:0.2];
[pdf,x] = hist(outflow,bins);
dx = x(2) - x(1);
pdf = pdf / (n * dx);
[xb,pdfb]=bar(x,pdf);

% Rayleigh distribution
X=[0:.001:0.2];
mu_square = Mean_outflow_given_outflow^2;
A = 2/pi;
Rpdf = (1-Pzero) * X ./(A*mu_square) .* exp(-X.^2./(2*A*mu_square));

plot(x,pdf,'w*',xb,pdfb,'w',X,Rpdf,'w')
%title([file])
axis([0,0.3,0,max(pdf)*1.05])
text(-3*dx,1.1*max(pdf),[P0])
```

```
ylabel('Probability Density')
xlabel('Outflow / Capacity')

figure
cdf=cumsum(pdf)*dx + Pzero;
cdf=[Pzero,cdf];
x=[0,x+dx];
Rcdf = cumsum(Rpdf)*0.001 + Pzero;
plot(x,cdf,'w*',x,cdf,'w',X,Rcdf,'w')
ylabel('Cumulative Distribution')
xlabel('Outflow / Capacity')
```

middeck.m

```
% middeck.m

% Routine for finding outflows for middeck model.
% Required items:  transext.m

clear

% Open results file
file = 'middeck.res';
fid = fopen(file);
a = fscanf(fid, '%g %g %g %g %g %g %g', [7 inf]);
a = a';
fclose(fid);
%a = a(1:1000,:);

% Non-dimensionalizing factors
Draft = 16.8;                   % Ship's original draft
Depth = 12;                     % Tank depth
Offset = 132;                   % Distance to midships

[row,col] = size(a);
n = row

% Exclude non-rupture cases, determine transverse extents
% Rupture Init, Rupture End, VertPen, Eccentricity, Transext
j = 0;
for i = 1:row
        if a(i,col-2) - a(i,col-1) > 0
                j = j + 1;
                b(j,1) = Offset - a(i,col-2);
                b(j,2) = Offset - a(i,col-1);
                b(j,3) = a(i,col);
                b(j,4) = a(i,2);
                b(j,5) = 1.1 * transext(a(i,col), a(i,3), a(i,4));
        end;
end;
a = b;

% Hydrostatic balance
tide = [0;2;6];
rho_c = 0.9;
rho_s = 1.025;
delta_p = 0.05;
g = 9.807;
Zs = Draft - tide;
Zc = (Zs*rho_s*g - 100*delta_p) / (rho_c*g);
Hc = 0.98*Depth;
Vol_lost = (Hc - Zc) / Hc;
for i = 1:3
   if Zc(i) > Depth
     Vol_lost(i) = 0.01;
   end
end
```

middeck.m

```
% Define TankBoundaries, volumes, and spill multiplier
t_bnd =     [18.5,18.5,18.5,18.5,18.5,18.5,18.5;...          % L0
            218.5,178, 145, 112, 79, 46, 13];                % Bhds

t_vol = [17903,14652,14652,14652,13819,7959];                % Lower Cargo

C = sum(sum(t_vol)) * 2;                                     % Max Cargo Volume

% Assign spill multipliers for damage cases
for i = 1:length(a)
   t_spill = zeros(size(t_vol));
   for j = 1:size(t_bnd,2)-1
      inside = a(i,4) - a(i,5)/2;                  % Inner edge of rupture
      if inside < t_bnd(1,j)                       % Tests for rupture beyond hull
         if a(i,2) > t_bnd(2,j+1)                  % Tests for rupture within
            if a(i,1) < t_bnd(2,j)                 %  longitudinal tank extents
               t_spill(1,j) = 1;
            end
         end
      end
   end
   Vout = Vol_lost * sum(sum(t_vol .* t_spill));
   outflow(i,1) = 0.4*Vout(1) + 0.5*Vout(2) + 0.1*Vout(3);
end
outflow = nonzeros(outflow);                         % Excludes WBT-only ruptures
Pzero = 1 - length(outflow)/n
Mean_outflow = sum(outflow) / (n * C)
Mean_outflow_given_outflow = Mean_outflow / (1-Pzero)
outflow = sort(outflow);
l = length(outflow);
Extreme_outflow = 10 * sum(outflow(floor(0.9*l):l)) / (n * C)

% Plot outflow pdf and cdf
P=num2str(Pzero);
P0=['Pzero = '];
P0=[P0,P];
outflow = outflow / C;
bins = [0.0005:0.0005:0.01];
[pdf,x] = hist(outflow,bins);
dx = x(2) - x(1);
pdf = pdf / (n * dx);
[xb,pdfb]=bar(x,pdf);

% Rayliegh distribution
X=[0:.0001:0.01];
mu_square = Mean_outflow_given_outflow^2;
A = 2/pi;
Rpdf = (1-Pzero) * X ./(A*mu_square) .* exp(-X.^2./(2*A*mu_square));

plot(x,pdf,'w*',xb,pdfb,'w',X,Rpdf,'w')
%title([file])
axis([0,max(xb),0,max(pdf)*1.05])
text(-3*dx,1.1*max(pdf),[P0])
```

```
ylabel('Probability Density')
xlabel('Outflow / Capacity')

figure
cdf=cumsum(pdf)*dx + Pzero;
cdf=[Pzero,cdf];
x=[0,x+dx];
Rcdf = cumsum(Rpdf)*0.0001 + Pzero;
plot(x,cdf,'w*',x,cdf,'w',X,Rcdf,'w')
ylabel('Cumulative Distribution')
xlabel('Outflow / Capacity')
```

shull95.inb

```
;FileName: \\hightest\suites\shull95.inb
;
;Author:  C. E. Rawson
;
;Product:    DAMAGE Version 2.0
;Abstract:  Run a Monte Carlo simulation using the DAMAGE program on Win95 for model SHULL01.
;       * * *  Prior to running this macro ensure the following:
;              Random Variates in located in the file c:\thesis\simulation\variates.csv
;              The For  .. Loop needs to have the number of lines in the variates file.
;              Output will be to a file called c:\thesis\simul\shull01.csv.
;              This output file, and the DAMAGE program (running "Shull01") must also be open.

Declare("i", INTEGER, LOCAL)
Declare("j", INTEGER, LOCAL)

Declare("Velocity", FLOAT, LOCAL)
Declare("Trim", FLOAT, LOCAL)
Declare("Eccentricity", FLOAT, LOCAL)
Declare("Elevation", FLOAT, LOCAL)
Declare("Radius", FLOAT, LOCAL)
Declare("Alpha", FLOAT, LOCAL)

Declare("Buffer", STRING, LOCAL)
Declare("Location1", FLOAT, LOCAL)
Declare("Location2", FLOAT, LOCAL)

;Start Loop.

For i = 1 To 600 By 1          ;This is the line that has the number of input records
ReadRecord("C:\\thesis\\simulation\\variates.csv", ",", i, Velocity, Trim, Elevation, Eccentricity, Radius,
Alpha)
Set j = j + 1              ;Counter for the file saving routine

;Read in Variates.
WaitWindow("_mg.cpp", "DAMAGE Version 2.0  - SHULL01.DMG", NULL, 4, 5.00)
ActivateWindow("_mg.cpp", "DAMAGE Version 2.0  - SHULL01.DMG", NULL)
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("ii")
Keys("[Tab][Tab][Enter][Tab][Tab]")
Set Buffer = Velocity
Keys(Buffer)
Keys("[Tab]")
Set Buffer = Trim
Keys(Buffer)
Keys("[Tab][Tab]")
Set Buffer = Eccentricity
Keys(Buffer)
Keys("[Tab]")
Set Buffer = Elevation
Keys(Buffer)
Keys("[Tab][Tab][Enter][Tab][Tab][Enter]")
```

```
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("ig")
Keys("[Tab][Enter][Tab][Tab]")
Set Buffer = Radius
Keys(Buffer)
Keys("[Tab]")
Set Buffer = Alpha
Keys(Buffer)
Keys("[Enter][Tab][Tab][Tab][Tab][Enter]")

;Start the calculations

KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("c1")

;Generate the Results summary for collection of Rupture Locations

KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("rr")
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("fx")

ReadRecord("c:\\damage\\results\\Shull01.res", ":", 18, Buffer, Location1)
ReadRecord("c:\\damage\\results\\Shull01.res", ":", 19, Buffer, Location2)

If Location1 > Location2 Then
   WaitWindow("ChartIcon", "Vertical penetration [m] vs. location [m-MS] diagram", NULL, 4, 5.00)
   ActivateWindow("ChartIcon", "Vertical penetration [m] vs. location [m-MS] diagram", NULL)
   MouseDoubleClick(282, 78, "I", "[Left]")
   Keys("[Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab]")
   KeyMod("Ctrl")
   Keys("c")
   KeyMod("")
   Keys("[Enter]")
EndIf
WaitWindow("Notepad", "shull01.csv - Notepad", NULL, 4, 5.00)
ActivateWindow("Notepad", "shull01.csv - Notepad", NULL)
KeyMod("Ctrl")
Keys("[End]")
KeyMod("")

 Set Buffer = i
Keys(Buffer)
Keys(", ")
Set Buffer = Eccentricity
Keys(Buffer)
```

```
Keys(", ")
Set Buffer = Alpha
Keys(Buffer)
Keys(", ")
Set Buffer = Radius
Keys(Buffer)
Keys(", ")
Set Buffer = Location1
Keys(Buffer)
Keys(", ")
Set Buffer = Location2
Keys(Buffer)
Keys(", ")
If Location1 > Location2 Then
   KeyMod("Ctrl")
   Keys("v")
   KeyMod("")
Else
   Set Buffer = "0.0"
   Keys(Buffer)
EndIf
Keys("[Enter]")

;Routine to save the output file every 10 runs.
If j =  10 Then
   KeyMod("Alt")
   Keys("[Alt]")
   KeyMod("")
   Keys("fs")
   Set j = 0
EndIf

Next i

;Routine to save the output file at the end of the simulation.
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("fs")
```

```
FileName: \\hightest\suites\dhull95.inb
;
;Author:  C. E. Rawson
;
;Product:    DAMAGE Version 2.0
;Abstract:  Run a Monte Carlo simulation using the DAMAGE program on Win95 for double hull
;           models.
;      * * *  Prior to running this macro ensure the following:
;           All the xx's have been replaced with desired model id.
;           Random Variates in located in the file c:\thesis\simulation\variates.csv
;           The For  .. Loop needs to have the number of lines in the variates file.
;           Output will be to a file called c:\thesis\simul\dhullxx.txt.
;           This output file, and the DAMAGE program (running "DHULL") must also be open.

Declare("i", INTEGER, LOCAL)
Declare("j", INTEGER, LOCAL)

Declare("Velocity", FLOAT, LOCAL)
Declare("Trim", FLOAT, LOCAL)
Declare("Eccentricity", FLOAT, LOCAL)
Declare("Elevation", FLOAT, LOCAL)
Declare("Radius", FLOAT, LOCAL)
Declare("Alpha", FLOAT, LOCAL)

Declare("Buffer", STRING, LOCAL)
Declare("Location1", FLOAT, LOCAL)
Declare("Location2", FLOAT, LOCAL)
Declare("Location3", FLOAT, LOCAL)
Declare("Location4", FLOAT, LOCAL)

;Start Loop.

For i = 1 To 600 By 1          ;This is the line that has the number of input records
ReadRecord("C:\\thesis\\simulation\\variates.csv", ",", i, Velocity, Trim, Elevation, Eccentricity, Radius,
Alpha)
Set j = j + 1              ;Counter for the file saving routine .

;Read in Variates.
WaitWindow("_mg.cpp", "DAMAGE Version 2.0  - DHULL03.DMG", NULL, 4, 5.00)
ActivateWindow("_mg.cpp", "DAMAGE Version 2.0  - DHULL03.DMG", NULL)
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("ii")
Keys("[Tab][Tab][Enter][Tab][Tab]")
Set Buffer = Velocity
Keys(Buffer)
Keys("[Tab]")
Set Buffer = Trim
Keys(Buffer)
Keys("[Tab][Tab]")
Set Buffer = Eccentricity
Keys(Buffer)
Keys("[Tab]")
```

dhull95.inb

```
Set Buffer = Elevation
Keys(Buffer)
Keys("[Tab][Tab][Enter][Tab][Tab][Enter]")

KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("ig")
Keys("[Tab][Enter][Tab][Tab]")
Set Buffer = Radius
Keys(Buffer)
Keys("[Tab]")
Set Buffer = Alpha
Keys(Buffer)
Keys("[Enter][Tab][Tab][Tab][Tab][Enter]")

;Start the calculations

KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("c1")

;Generate the Results summary for collection of Rupture Locations

KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("rr")
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("fx")

ReadRecord("c:\\damage\\results\\Dhull03.res", ":", 18, Buffer, Location1)
ReadRecord("c:\\damage\\results\\Dhull03.res", ":", 19, Buffer, Location2)
ReadRecord("c:\\damage\\results\\Dhull03.res", ":", 27, Buffer, Location3)
ReadRecord("c:\\damage\\results\\Dhull03.res", ":", 28, Buffer, Location4)

If Location1 > Location2 Then
   WaitWindow("ChartIcon", "Vertical penetration [m] vs. location [m-MS] diagram", NULL, 4, 5.00)
   ActivateWindow("ChartIcon", "Vertical penetration [m] vs. location [m-MS] diagram", NULL)
   MouseDoubleClick(282, 78, "I", "[Left]")
   Keys("[Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab]")
   KeyMod("Ctrl")
   Keys("c")
   KeyMod("")
   Keys("[Enter]")
EndIf
   WaitWindow("Notepad", "dhull03.csv - Notepad", NULL, 4, 5.00)
   ActivateWindow("Notepad", "dhull03.csv - Notepad", NULL)
   KeyMod("Ctrl")
   Keys("[End]")
   KeyMod("")
```

```
    Set Buffer = i
    Keys(Buffer)
    Keys(", ")
    Set Buffer = Eccentricity
    Keys(Buffer)
    Keys(", ")
    Set Buffer = Alpha
    Keys(Buffer)
    Keys(", ")
    Set Buffer = Radius
    Keys(Buffer)
    Keys(", ")
    Set Buffer = Location1
    Keys(Buffer)
    Keys(", ")
    Set Buffer = Location2
    Keys(Buffer)
    Keys(", ")
 If Location1 = Location2 Then
    Set Buffer = "0.0"
    Keys(Buffer)
 Else
    KeyMod("Ctrl")
    Keys("v")
    KeyMod("")
 EndIf
 Keys(", ")

 Set Buffer = Location3
 Keys(Buffer)
 Keys(", ")
 Set Buffer = Location4
 Keys(Buffer)
 Keys(", ")

 ; IF statement to ensure no extra work if no rupture of inner hull.
 If Location3 = Location4 Then
    Set Buffer = "0.0"
    Keys(Buffer)
 Else
    ActivateWindow("_mg.cpp", "DAMAGE Version 2.0  - DHULL03.DMG", NULL, 10.0)
    KeyMod("Alt")
    Keys("[Alt]")
    KeyMod("")
    Keys("rg")
    ActivateWindow(".mg.cpp", "Graph Configuration", NULL, 10.0)
    Keys("[Down][Down][Tab][Tab][Tab][Down][Down][Enter]")
    ActivateWindow("_mg.cpp", "DAMAGE Version 2.0  - DHULL03.DMG", NULL, 10.0)
    Keys("[Enter]")
    ActivateWindow("_mg.cpp", "DAMAGE Version 2.0  - DHULL03.DMG", NULL, 10.0)
    ActivateWindow("ChartIcon", "GRAPH UTILITY - create your own graph", NULL, 10.0)
    MouseDoubleClick(241, 98, "I", "[Left]")
    ActivateWindow(".mg.cpp", "Graph Configuration", NULL, 10.0)
```

```
    Keys("[Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab]")
    KeyMod("Ctrl")
    Keys("c")
    KeyMod("")
    Keys("[Enter]")
    ActivateWindow("_mg.cpp", "DAMAGE Version 2.0  - DHULL03.DMG", NULL, 10.0)
    KeyMod("Ctrl")
    Keys("[F4]")
    CloseWindow("GRAPH UTILITY - create your own graph")
    KeyMod("")

    WaitWindow("Notepad", "dhull03.csv - Notepad", NULL, 4, 5.00)
    ActivateWindow("Notepad", "dhull03.csv - Notepad", NULL)
    KeyMod("Ctrl")
    Keys("[End]v")
    KeyMod("")
EndIf
Keys("[Enter]")

;Routine to save the output file every 10 runs.
If j =  10 Then
    KeyMod("Alt")
    Keys("[Alt]")
    KeyMod("")
    Keys("fs")
    Set j = 0
EndIf

Next i

;Routine to save the output file at the end of the simulation.
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("fs")
```

middeck.inb

```
;FileName: \\hightest\suites\middeck.inb
;
;Author:  C. E. Rawson
;
;Product:    DAMAGE Version 2.0
;Abstract:  Run a Monte Carlo simulation using the DAMAGE program on Win95 for model MIDDECK.
;       * * *  Prior to running this macro ensure the following:
;              Random Variates in located in the file c:\thesis\simulation\variates.csv
;              The For  .. Loop needs to have the number of lines in the variates file.
;              Output will be to a file called c:\thesis\simul\middeck.csv.
;              This output file, and the DAMAGE program (running "Middeck") must also be open.

Declare("i", INTEGER, LOCAL)
Declare("j", INTEGER, LOCAL)

Declare("Velocity", FLOAT, LOCAL)
Declare("Trim", FLOAT, LOCAL)
Declare("Eccentricity", FLOAT, LOCAL)
Declare("Elevation", FLOAT, LOCAL)
Declare("Radius", FLOAT, LOCAL)
Declare("Alpha", FLOAT, LOCAL)

Declare("Buffer", STRING, LOCAL)
Declare("Location1", FLOAT, LOCAL)
Declare("Location2", FLOAT, LOCAL)

;Start Loop.

For i = 1 To 600 By 1          ;This is the line that has the number of input records
ReadRecord("C:\\thesis\\simulation\\variates.csv", ",", i, Velocity, Trim, Elevation, Eccentricity, Radius,
Alpha)
Set j = j + 1              ;Counter for the file saving routine

;Read in Variates.
WaitWindow("_mg.cpp", "DAMAGE Version 2.0  - MIDDECK.DMG", NULL, 4, 5.00)
ActivateWindow("_mg.cpp", "DAMAGE Version 2.0  - MIDDECK.DMG", NULL)
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("ii")
Keys("[Tab][Tab][Enter][Tab][Tab]")
Set Buffer = Velocity
Keys(Buffer)
Keys("[Tab]")
Set Buffer = Trim
Keys(Buffer)
Keys("[Tab][Tab]")
Set Buffer = Eccentricity
Keys(Buffer)
Keys("[Tab]")
Set Buffer = Elevation
Keys(Buffer)
Keys("[Tab][Tab][Enter][Tab][Tab][Enter]")
```

middeck.inb

```
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("ig")
Keys("[Tab][Enter][Tab][Tab]")
Set Buffer = Radius
Keys(Buffer)
Keys("[Tab]")
Set Buffer = Alpha
Keys(Buffer)
Keys("[Enter][Tab][Tab][Tab][Tab][Enter]")

;Start the calculations

KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("cl")

;Generate the Results summary for collection of Rupture Locations

KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("rr")
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("fx")

ReadRecord("c:\\damage\\results\\Middeck.res", ":", 18, Buffer, Location1)
ReadRecord("c:\\damage\\results\\Middeck.res", ":", 19, Buffer, Location2)

If Location1 > Location2 Then
   WaitWindow("ChartIcon", "Vertical penetration [m] vs. location [m-MS] diagram", NULL, 4, 5.00)
   ActivateWindow("ChartIcon", "Vertical penetration [m] vs. location [m-MS] diagram", NULL)
   MouseDoubleClick(282, 78, "I", "[Left]")
   Keys("[Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab][Tab]")
   KeyMod("Ctrl")
   Keys("c")
   KeyMod("")
   Keys("[Enter]")
EndIf
WaitWindow("Notepad", "middeck.csv - Notepad", NULL, 4, 5.00)
ActivateWindow("Notepad", "middeck.csv - Notepad", NULL)
KeyMod("Ctrl")
Keys("[End]")
KeyMod("")

Set Buffer = i
Keys(Buffer)
Keys(", ")
Set Buffer = Eccentricity
Keys(Buffer)
```

```
Keys(", ")
Set Buffer = Alpha
Keys(Buffer)
Keys(", ")
Set Buffer = Radius
Keys(Buffer)
Keys(", ")
Set Buffer = Location1
Keys(Buffer)
Keys(", ")
Set Buffer = Location2
Keys(Buffer)
Keys(", ")
If Location1 > Location2 Then
   KeyMod("Ctrl")
   Keys("v")
   KeyMod("")
Else
   Set Buffer = "0.0"
   Keys(Buffer)
EndIf
Keys("[Enter]")

;Routine to save the output file every 10 runs.
If j =  10 Then
   KeyMod("Alt")
   Keys("[Alt]")
   KeyMod("")
   Keys("fs")
   Set j = 0
EndIf

Next i

;Routine to save the output file at the end of the simulation.
KeyMod("Alt")
Keys("[Alt]")
KeyMod("")
Keys("fs")
```

Conversions & Constants:

$ton := 2240 \cdot lbf \qquad MN := 10^6 \cdot newton \qquad \delta := 99.5 \cdot \frac{m^3}{MN} \qquad \rho_c := 0.9 \cdot \frac{tonne}{m^3}$

Given values:

$L := 264 \cdot m \qquad B := 48 \cdot m \qquad D := 24 \cdot m \qquad T := 16.8 \cdot m$

$r := 1600 \cdot mm \qquad \Delta := 178411 \cdot tonne \qquad D_{db} := 0 \cdot m \qquad A_{wp} := 11277 \cdot m^2$

$GM := 5.94 \cdot m \qquad LCF := \frac{L}{2} - 231 \cdot m \qquad B_{ds} := 0 \cdot m \qquad B_{bhd} := 15 \cdot m$

Elemental Relationships: $V := \Delta \cdot \delta \cdot g$

$$C_m := \frac{B \cdot T - \frac{3 \cdot r^2}{7}}{B \cdot T} \qquad C_m = 0.999 \qquad L_{PMB} := L \cdot (PMB_2 - PMB_1)$$

$$C_P := \frac{V}{L \cdot B \cdot T \cdot C_m} \qquad C_P = 0.819$$

$$C_B := C_m \cdot C_P \qquad C_B = 0.818$$

$$C_{wp} := \frac{A_{wp}}{L \cdot B} \qquad C_{wp} = 0.89$$

$$KB := T \cdot \left(\frac{C_{wp}}{C_{wp} + C_B}\right) \qquad KB = 8.755 \cdot m$$

Half-Breadth Curve: $x := 0 .. L$

$$y_{wl}(x) := \begin{cases} \frac{B}{2} \cdot \left(\frac{x}{PMB_1 \cdot L}\right)^{\frac{1}{N_1}} & \text{if } x < PMB_1 \cdot L \\ \frac{B}{2} & \text{if } PMB_1 \cdot L < x < PMB_2 \cdot L \\ \frac{B}{2} \cdot \left(1 - \left(\frac{x - L}{1 - PMB_2}\right)^{N_2}\right) & \text{if } x > PMB_2 \cdot L \end{cases}$$

$$C_{wpcalc} := \frac{2}{L \cdot B} \cdot \int_0^L y_{wl}(x)\, dx$$

$$M_y = 2\cdot\int_0^{L}\int_0^{y_{wl}(x)} x\,dy\,dx \qquad LCF_{calc} = \frac{M_y}{C_{wpcalc}\cdot L\cdot B}$$

$$I_T = \int_0^{L}\frac{y_{wl}(x)^3}{3}\,dx \qquad C_{IT} = \frac{12\cdot I_T}{B^3\cdot L}$$

$$BM = \frac{I_T}{V}$$

Section Area Curve:

$$Ar(x) = \begin{cases} B\cdot T\cdot C_m\cdot\left(\frac{x}{PMB_1\cdot L}\right)^{\frac{1}{n_1}} & \text{if } x < PMB_1\cdot L \\ B\cdot T\cdot C_m & \text{if } PMB_1\cdot L < x < PMB_2\cdot L \\ B\cdot T\cdot C_m\cdot\left(\frac{1-\frac{x}{L}}{1-PMB_2}\right)^{n_2} & \text{if } x > PMB_2\cdot L \end{cases}$$

$$C_{Bcalc} = \frac{1}{L\cdot B\cdot T}\int_0^{L} Ar(x)\,dx \qquad V_{calc} = C_{Bcalc}\cdot L\cdot B\cdot T$$

Bouyancy Curve:

$$b(x) = \frac{Ar(x)}{\delta\cdot g} \qquad \Delta_{calc} = \int_0^{L} b(x)\,dx$$

Determine hull shape:

$$PMB = \begin{pmatrix} .20 \\ .72 \end{pmatrix} \qquad L_{PMB} = 137.28\cdot m \qquad N = \begin{matrix} 4.0 \\ 2.5 \end{matrix} \qquad n = \begin{matrix} 1.6 \\ 1.6 \end{matrix}$$

breadth area

$C_{wp} = 0.89$ $LCF = 131.8\cdot m$ $C_B = 0.818$

$C_{wpcalc} = 0.88$ $LCF_{calc} = 126.9\cdot m$ $C_{Bcalc} = 0.814$

$\frac{C_{wp} - C_{wpcalc}}{C_{wp}} = 0.011$ $\frac{LCF - LCF_{calc}}{LCF} = 0.037$ $\frac{C_B - C_{Bcalc}}{C_B} = 4.324\cdot 10^{-3}$

Define Tanks & Examine Cargo Loading:

$B_{bhd} = 15 \cdot m$

# of Tanks: num := 5

Frame counter: i := 1..num

Tank counter: j := 1..num

$B_{ds} = 0 \cdot m$

$D_{db} = 0 \cdot m$

Frame location: X_i

Breadth at each Frame: $Y_i := 2 \cdot y_{wl}(X_i)$ $Y_{tank_i} := Y_i - 2 \cdot B_{ds}$

Y_{tank_i}
45.5·m
86.6·m
127.7·m
168.8·m
209.9·m
251·m

Tank Volumes: $VTank_j := (D - D_{db}) \cdot (X_{j+1} - X_j) \cdot \frac{Y_{tank_{j+1}} + Y_{tank_j}}{2}$

Tank Weights: $WTank_j := \alpha_j \cdot VTank_j \cdot \rho_c$ $W_c := \sum WTank$

Define Tank Capacities: For uniform loading: $\beta := 1$ $W_c = 149919 \cdot tonne$

Ratio of Center tank to total: $f := \frac{2 \cdot B_{bhd}}{B}$

Ratio of Wing Tank to total: $F := 1 - f$

Tank fillage:

α_j Tank ID: num := 1..j

α_j	Tank ID
β	5
f·β	4
f·β	3
f·β	2
β	1

$VTank = \begin{pmatrix} 46483 \\ 47347 \\ 47347 \\ 46466 \\ 31869 \end{pmatrix} \cdot m^3$ $WTank = \begin{pmatrix} 41834 \\ 26633 \\ 26633 \\ 26137 \\ 28682 \end{pmatrix} \cdot tonne$ $Y = \begin{pmatrix} 46.247 \\ 48 \\ 48 \\ 48 \\ 46.213 \\ 18.404 \end{pmatrix} \cdot m$

$Wing\_Tank\_Volumes_j := \frac{F \cdot VTank_j}{2}$ $Center\_Tank\_Volumes_j := f \cdot VTank_j$

$Slop\_Tank\_Reqd := 0.02 \cdot \sum VTank$ $Slop\_Tank\_Reqd = 4390 \cdot m^3$

$Wing\_Tank\_Volumes_1 := Wing\_Tank\_Volumes_1 - \frac{Slop\_Tank\_Reqd}{2}$

$Slop\_Bhd := \frac{Slop\_Tank\_Reqd}{(2 \cdot Wing\_Tank\_Volumes)_1} \cdot X_2 - X_1 + X_1$ $Slop\_Bhd = 59.337 \cdot m$

$Wing\_Tank\_Volumes = \begin{pmatrix} 6520 \\ 8878 \\ 8878 \\ 8712 \\ 5975 \end{pmatrix} \cdot m^3$ $Center\_Tank\_Volumes = \begin{pmatrix} 29052 \\ 29592 \\ 29592 \\ 29041 \\ 19918 \end{pmatrix} \cdot m^3$

Appendix C Sensitivity Analysis Results

The following plots are similar to those found in Chapter 4, displaying the rupture length and damage extents as a function of some varied parameter. Figure C-1 was done from the Condition 2 (See Table 4-1) and Figure C-2 was completed using Condition 3.

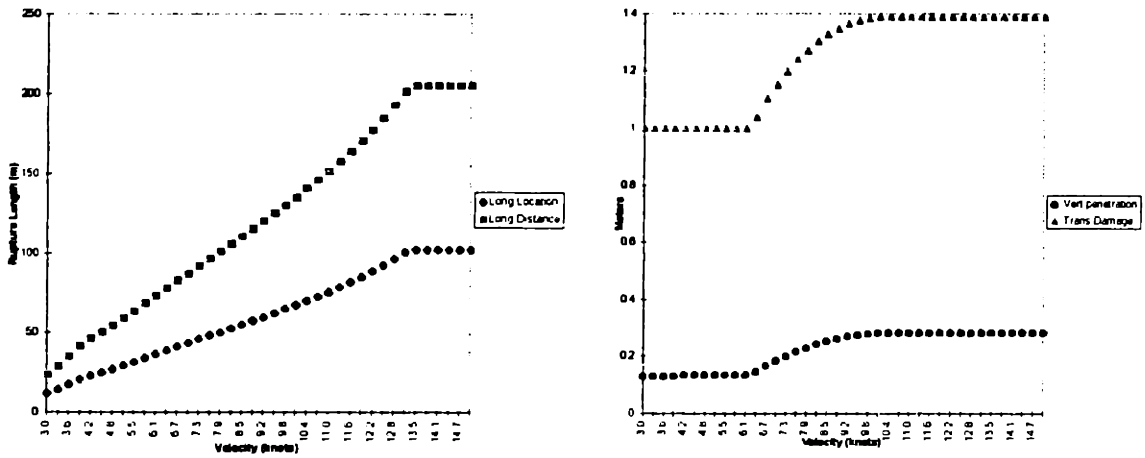


Figure C-1 (a) Sensitivity Analysis Condition 2, Velocity Plots

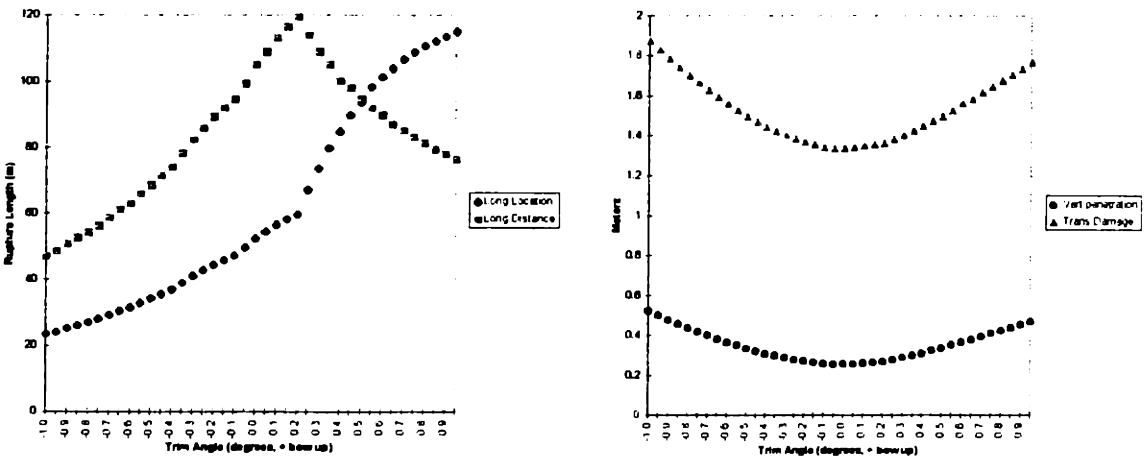


Figure C-1 (b) Sensitivity Analysis Condition 2, Ship's Trim Plots

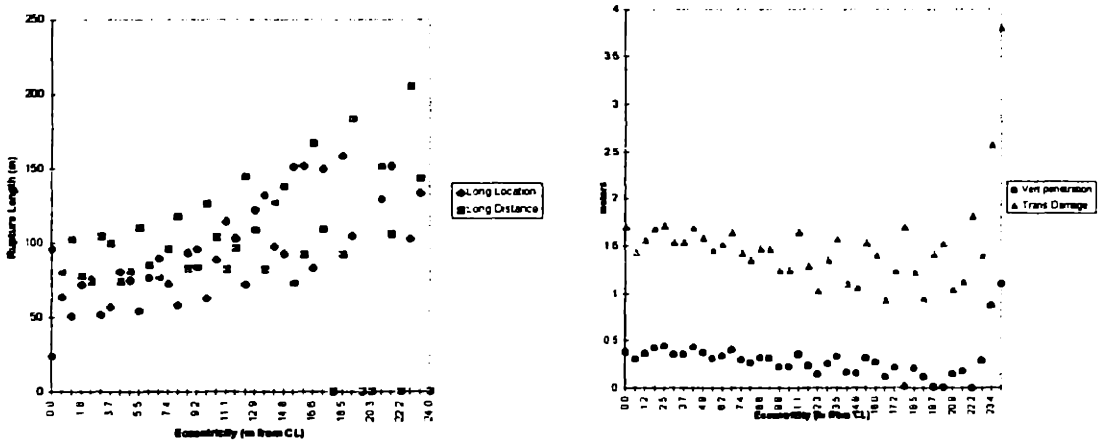


Figure C-1 (c) Sensitivity Analysis Condition 2, Eccentricity Plots

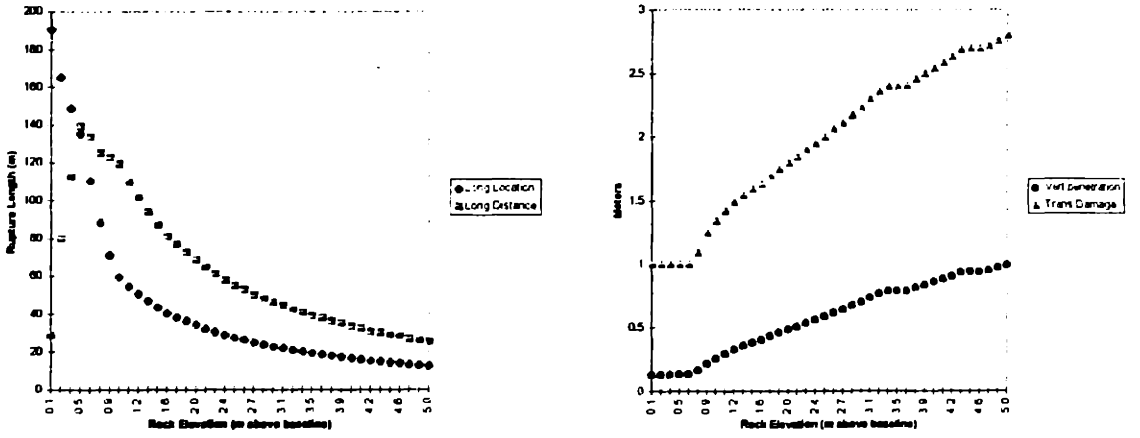


Figure C-1 (d) Sensitivity Analysis Condition 2, Cone Elevation Plots

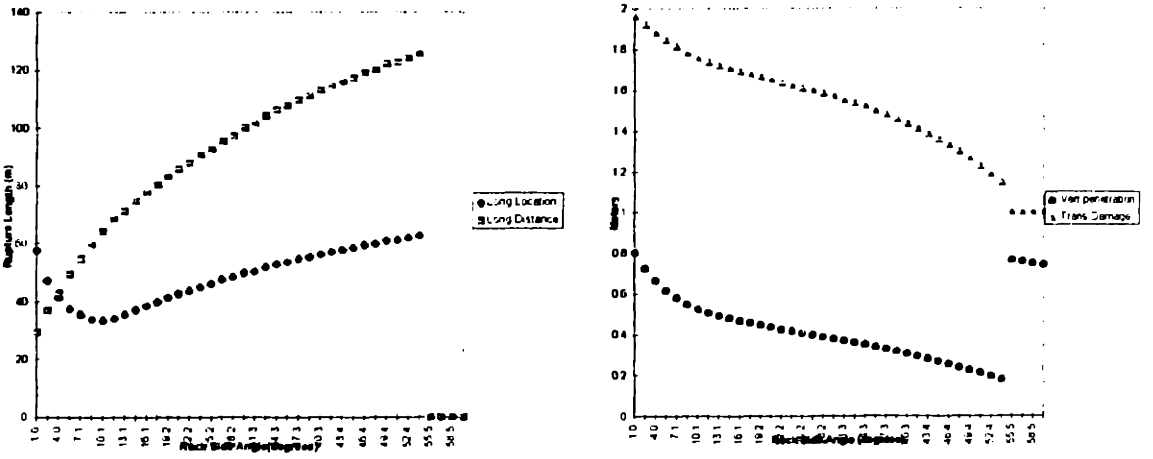


Figure C-1 (e) Sensitivity Analysis Condition 2, Cone Side Angle Plots

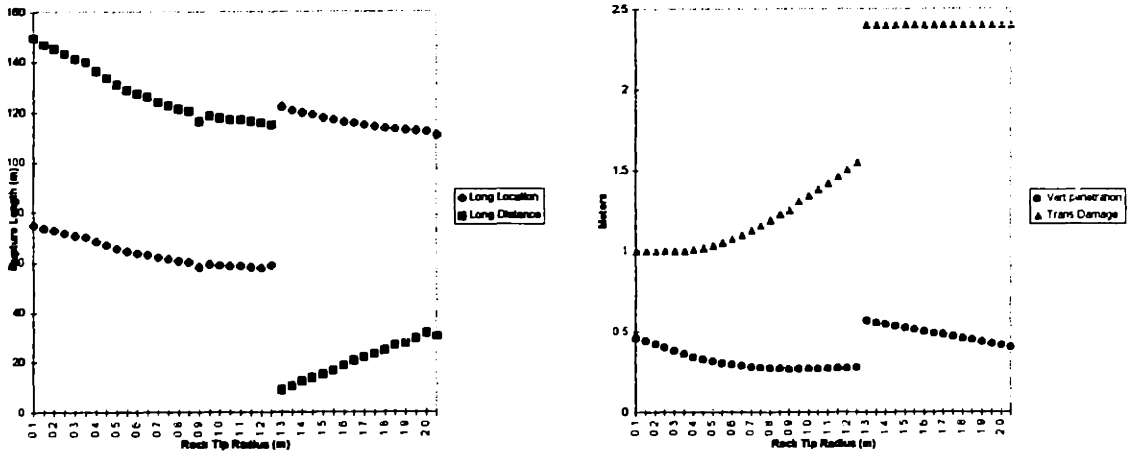


Figure C-1 (f) Sensitivity Analysis Condition 2, Cone Tip Radius Plots

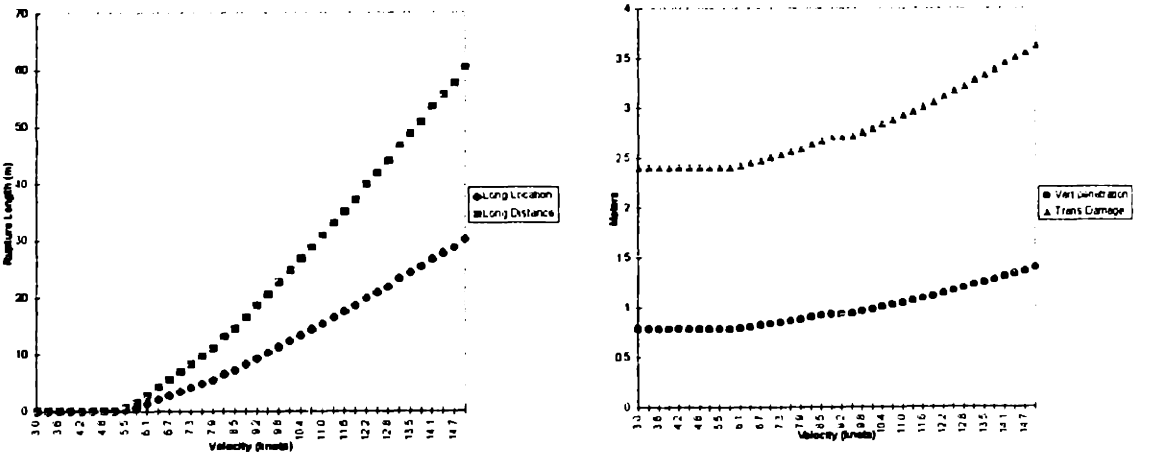


Figure C-2 (a) Sensitivity Analysis Condition 3, Velocity Plots

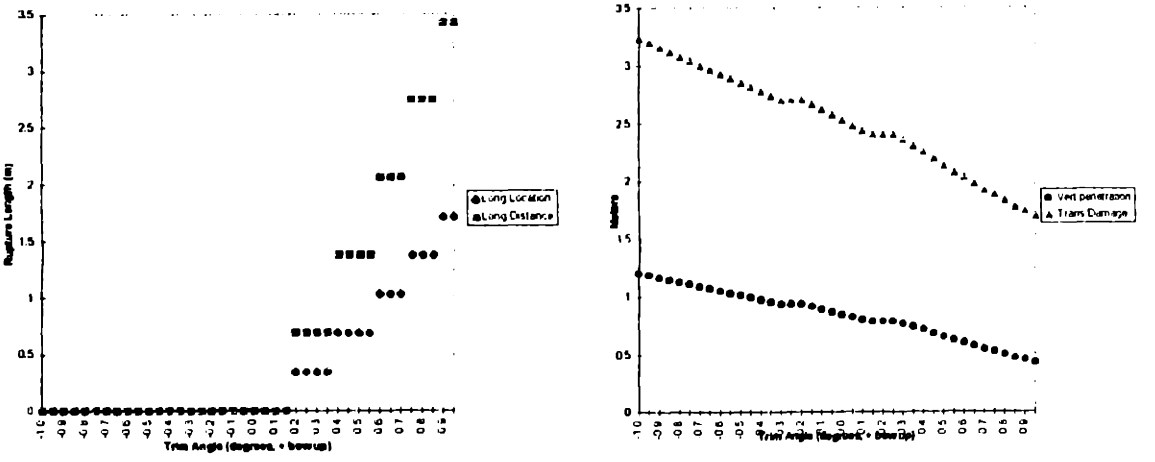


Figure C-2 (b) Sensitivity Analysis Condition 3, Ship's Trim Plots

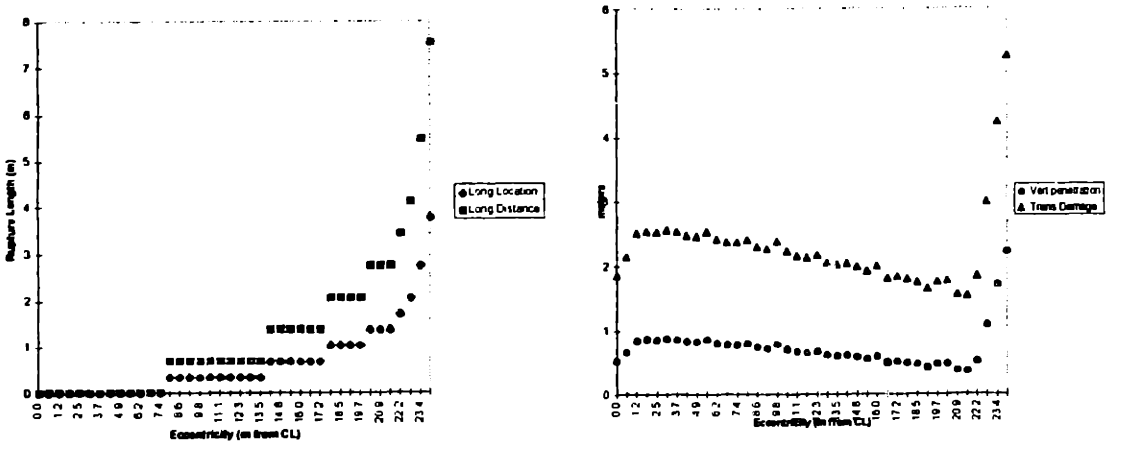


Figure C-3 (c) Sensitivity Analysis Condition 3, Eccentricity Plots

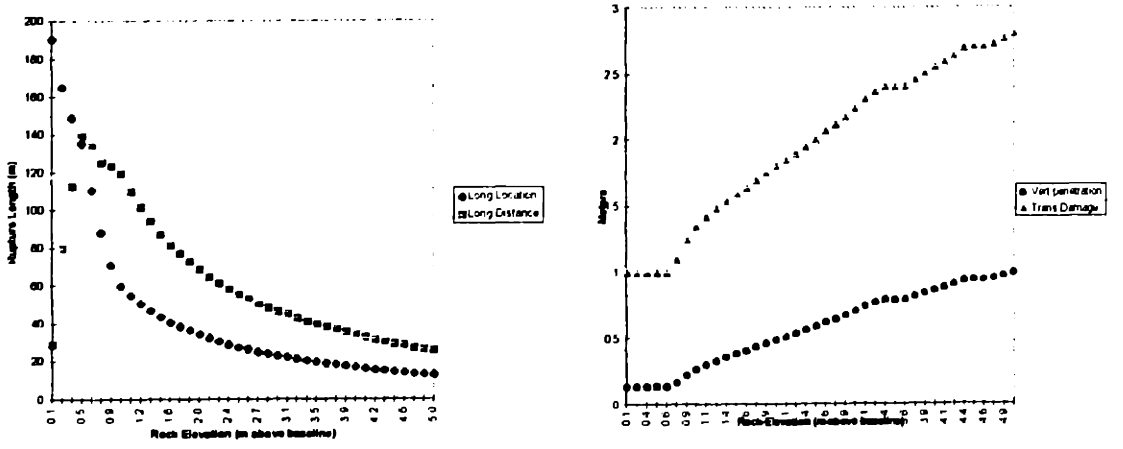


Figure C-4 (d) Sensitivity Analysis Condition 3, Cone Elevation Plots

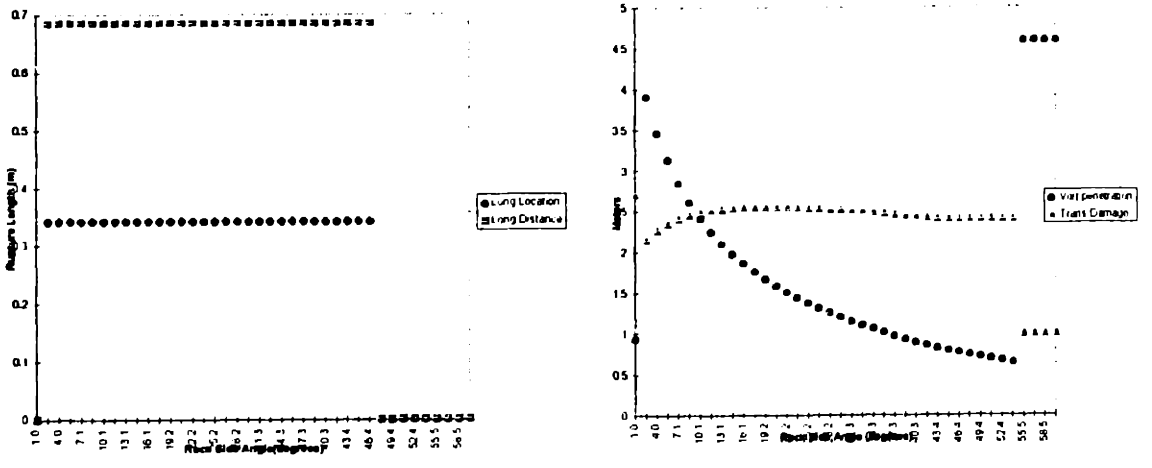


Figure C-5 (e) Sensitivity Analysis Condition 3, Cone Side Angle Plots

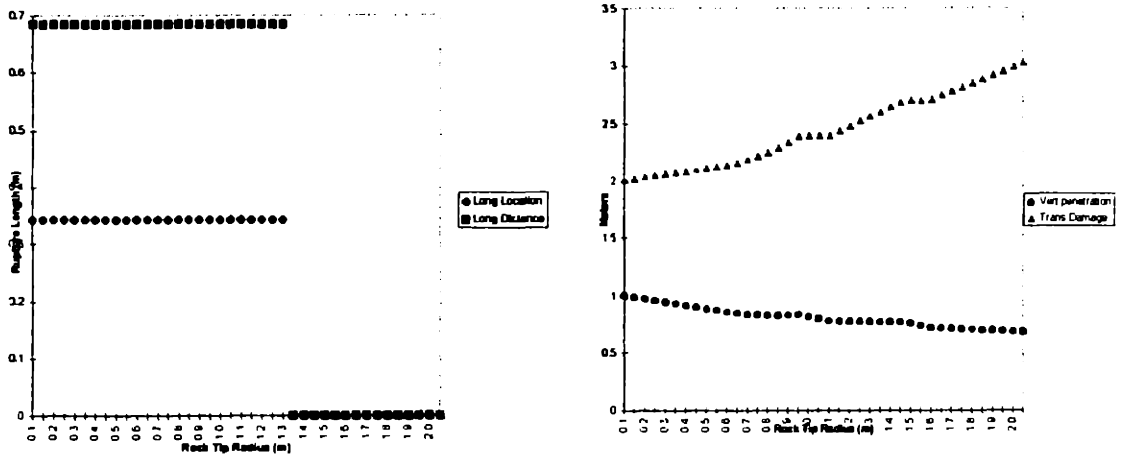


Figure C-6 (f) Sensitivity Analysis Condition 3, Cone Tip Radius Plots

Appendix D Calibration Phase Damage Extent Probability Density Functions

The following plots are damage extent probability density functions determined for each of the scenario variations described in Chapter 6. The histogram plots represent the distributions calculated from the results from Damage, and the lines represent the IMO defined density functions.

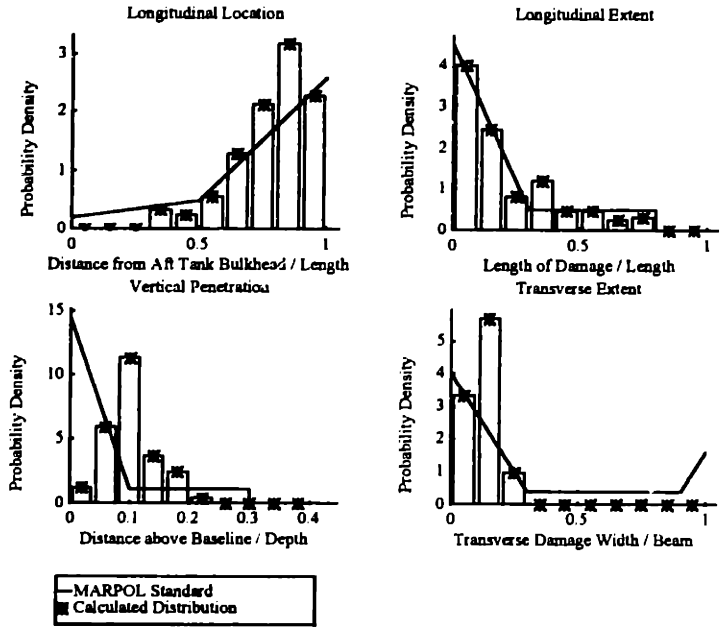


Figure D-1 Calibration file 08: 5 m. max obstruction elevation, 10 m. max tip radius

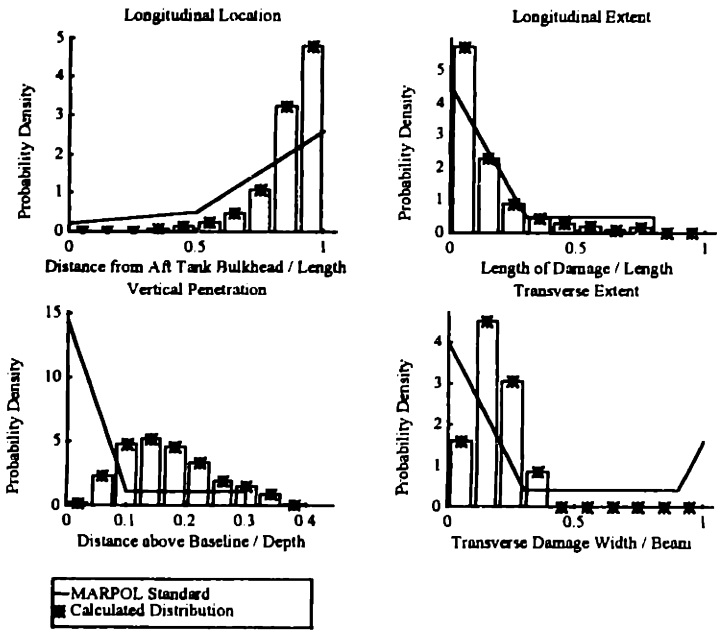


Figure D-2 Calibration file 09: 10 m. max obstruction elevation, 10 m. max tip radius

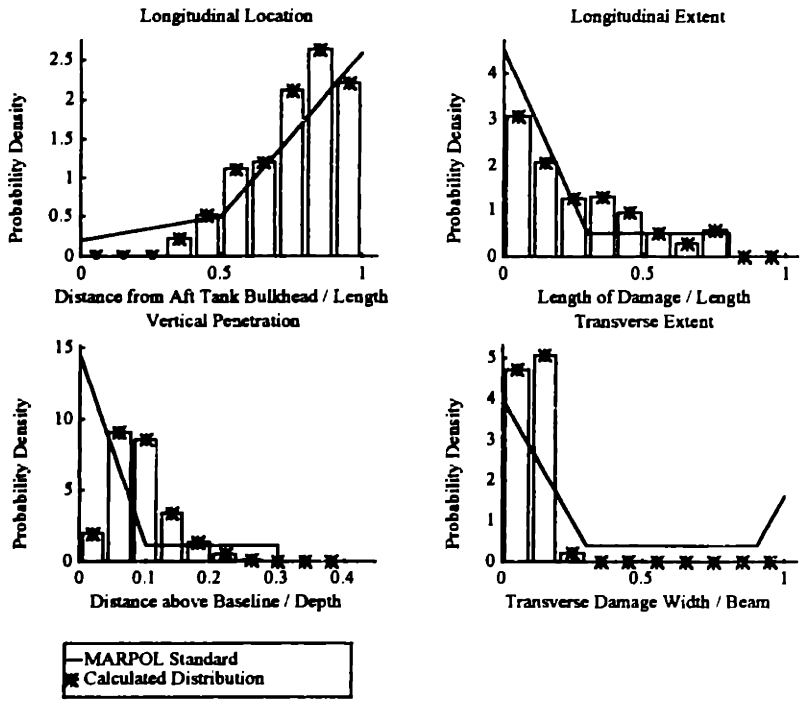


Figure D-3 Calibration file 10: 5 m. max obstruction elevation, 5 m. max tip radius

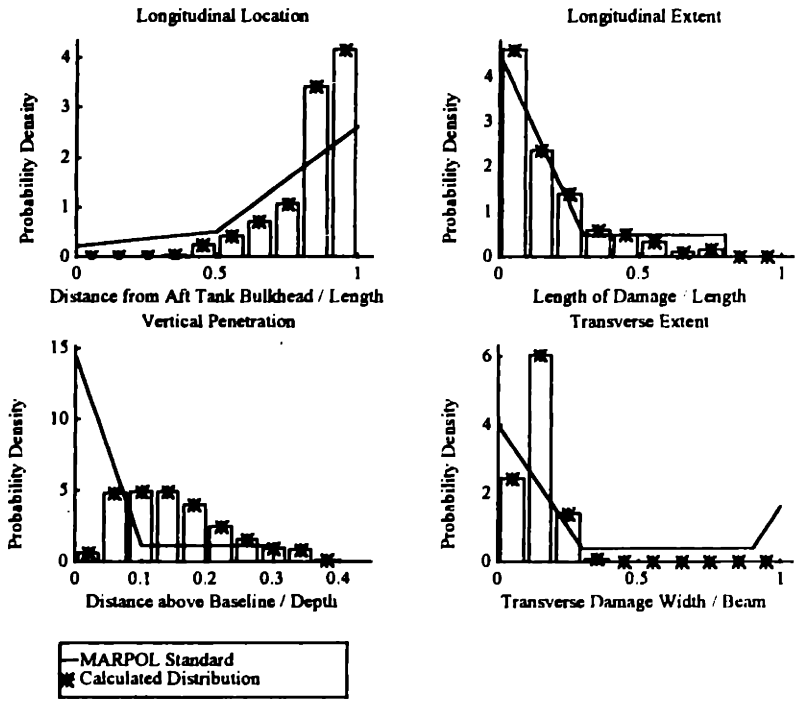


Figure D-4 Calibration file 11: 10 m. max obstruction elevation, 5 m. max tip radius

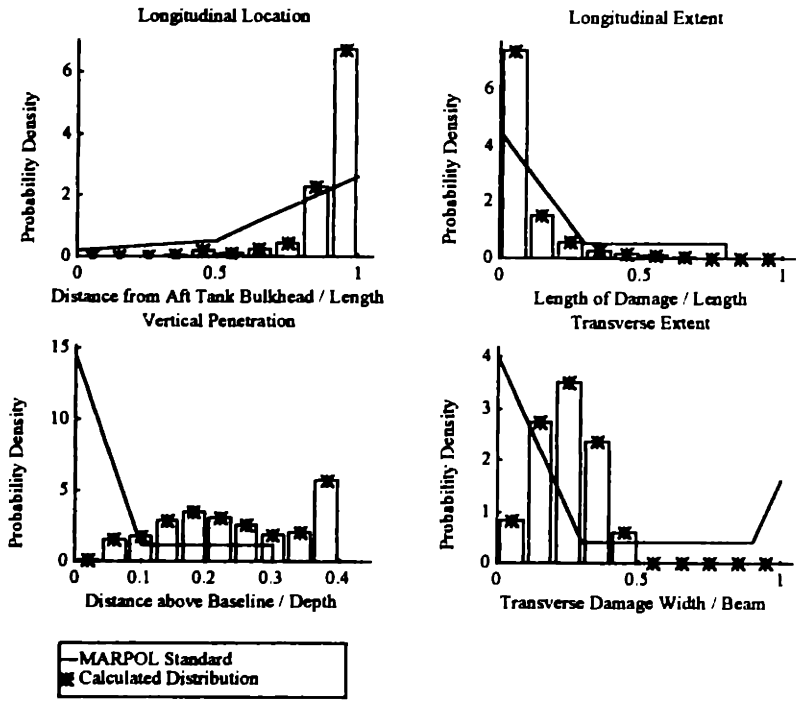


Figure D-5 Calibration file 12: 16.8 m. max obstruction elevation, 10 m. max tip radius

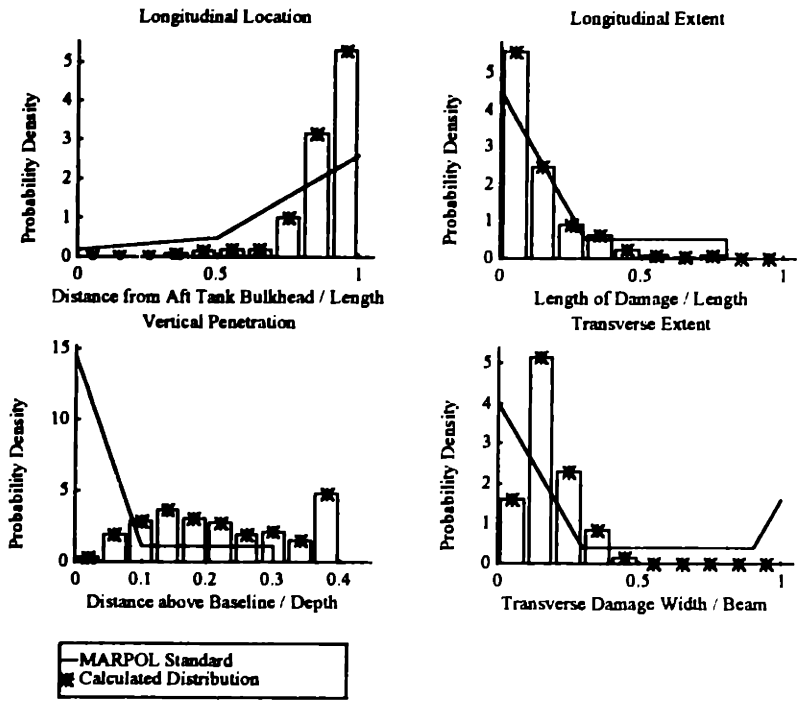


Figure D-6 Calibration file 13: 16.8 m. max obstruction elevation, 5 m. max tip radius

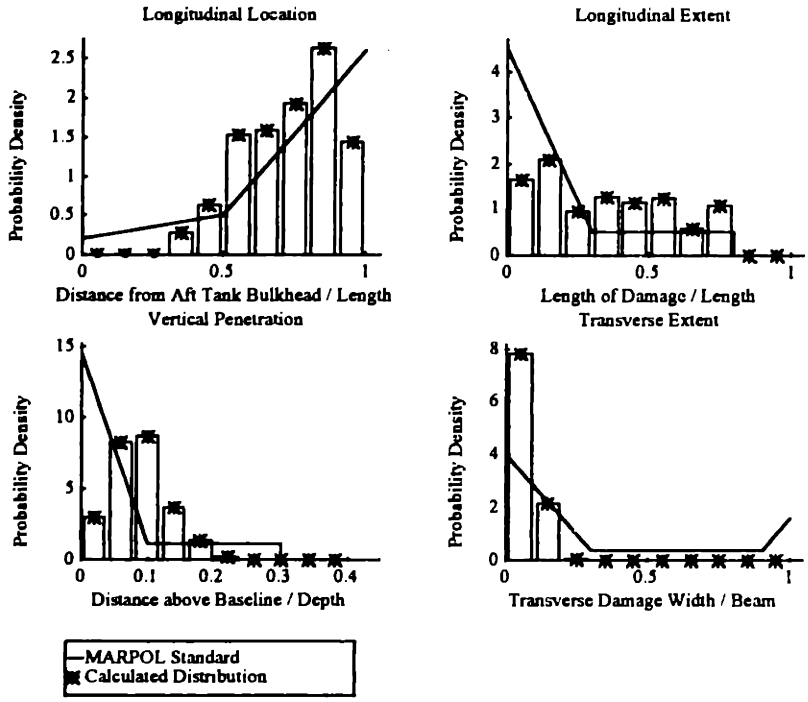


Figure D-7 Calibration file 14: 5 m. max obstruction elevation, 2 m. max tip radius

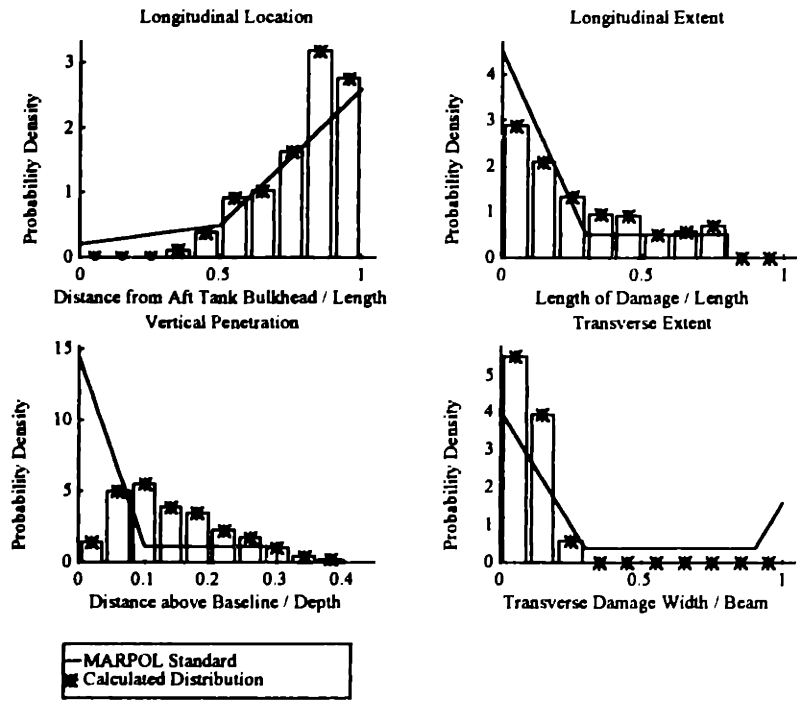


Figure D-8 Calibration file 15: 10 m. max obstruction elevation, 2 m. max tip radius

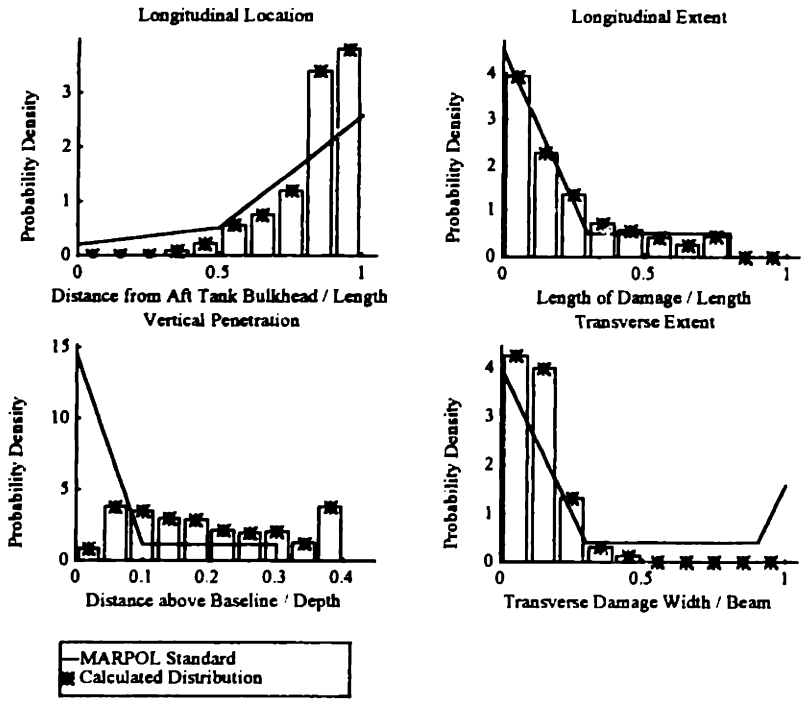


Figure D-9 Calibration file 16: 16.8 m. max obstruction elevation, 2 m. max tip radius

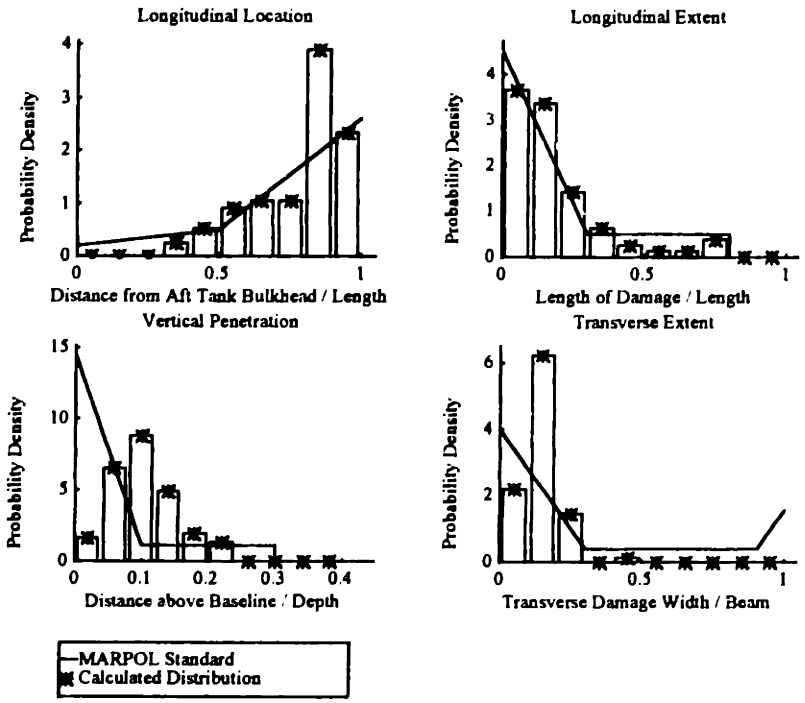


Figure D-10 Calibration file 17: 5 m. max obstruction elevation, 15 m. max tip radius

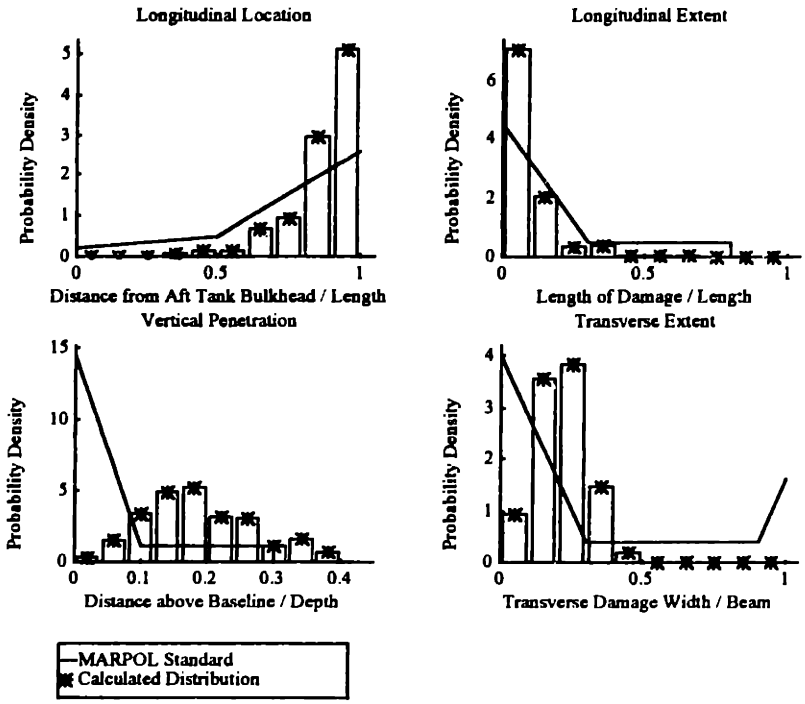


Figure D-11 Calibration file 18: 10 m. max obstruction elevation, 15 m. max tip radius

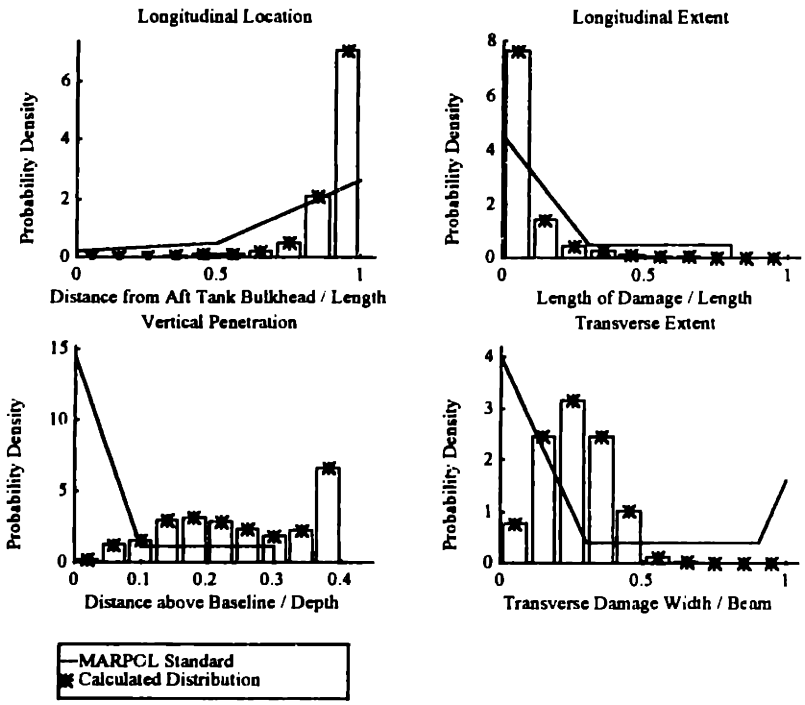


Figure D-12 Calibration file 19: 16.8 m. max obstruction elevation, 15 m. max tip radius

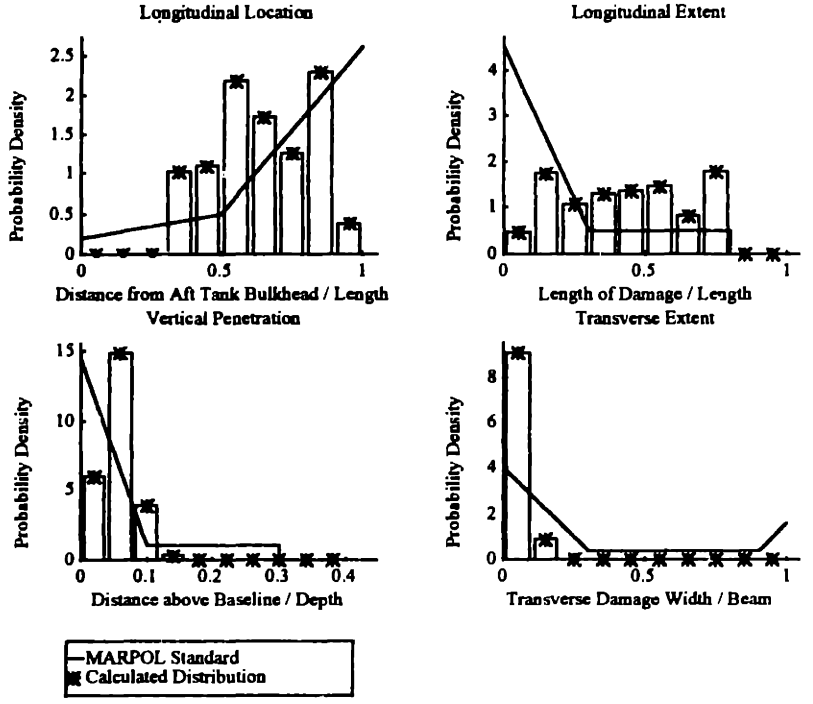


Figure D-13 Calibration file 20: 2 m. max obstruction elevation, 2 m. max tip radius

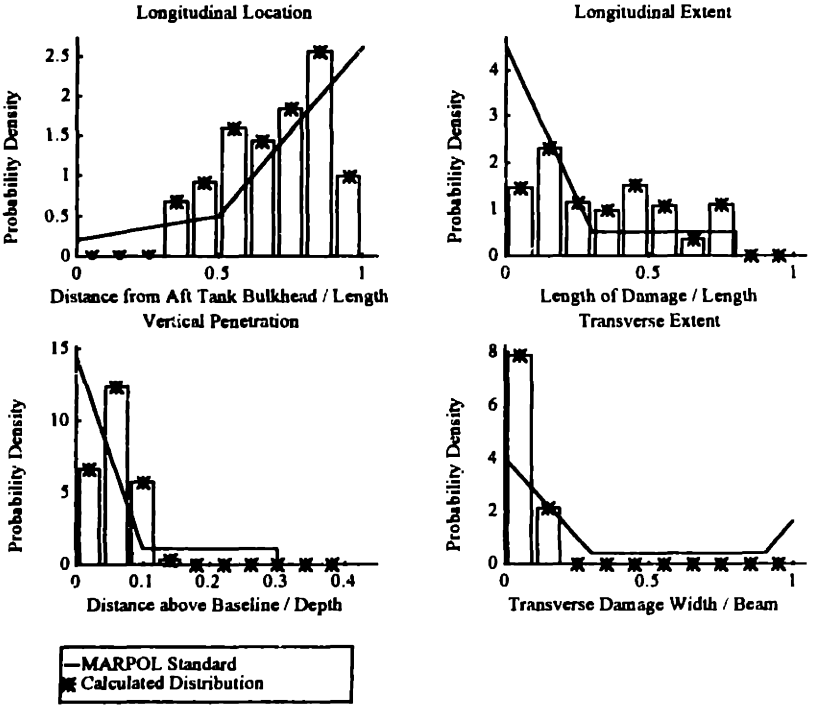


Figure D-14 Calibration file 21: 2 m. max obstruction elevation, 5 m. max tip radius

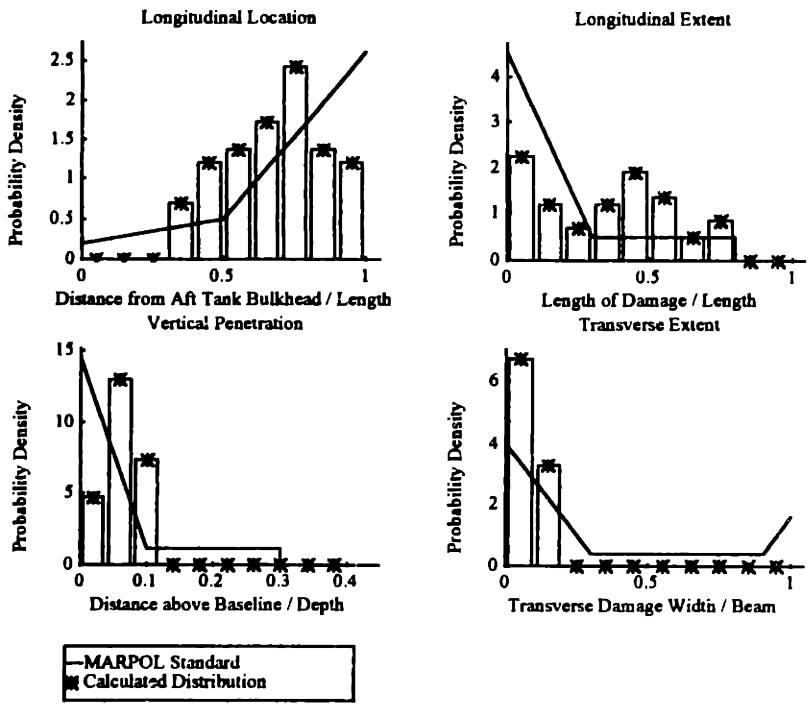


Figure D-15 Calibration file 22: 2 m. max obstruction elevation, 10 m. max tip radius

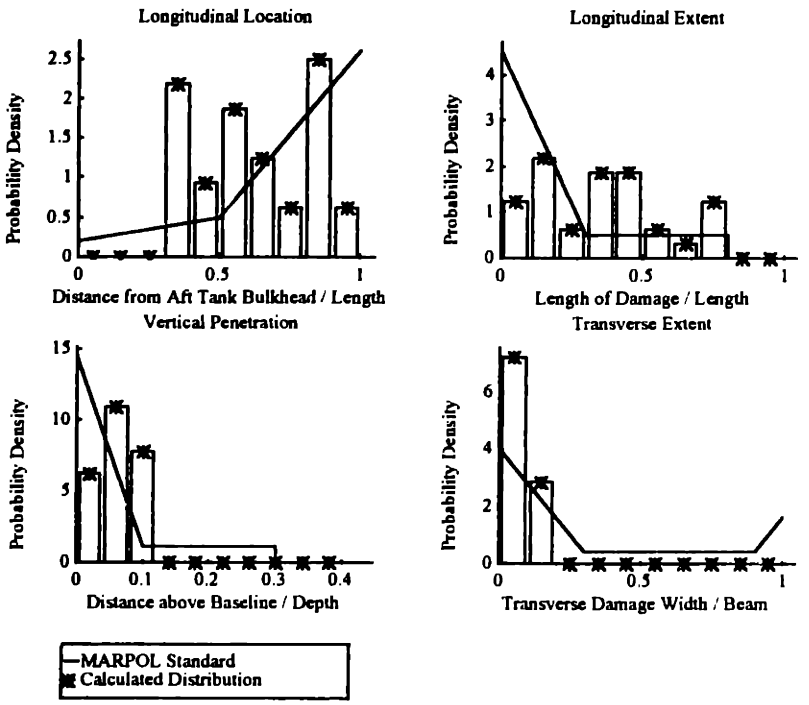


Figure D-16 Calibration file 23: 2 m. max obstruction elevation, 15 m. max tip radius

Appendix E Mean Outflow vs. Number of Double Hull Data Sets

This appendix contains the Mean Outflow vs. Number of Data Sets for the double hull models not pictured in Chapter 7.

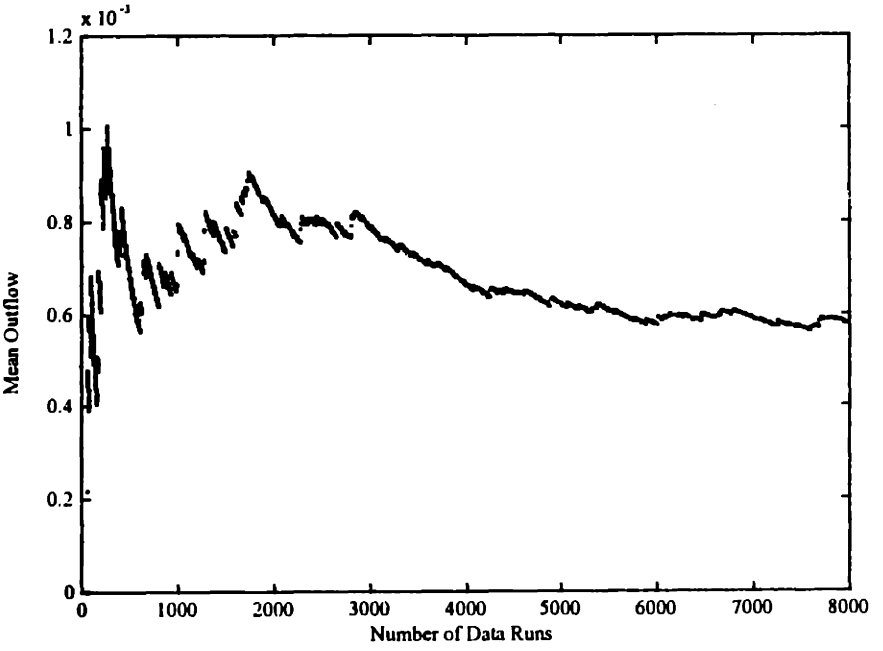


Figure E-1 Mean Outflow vs. Data Sets for DHull02

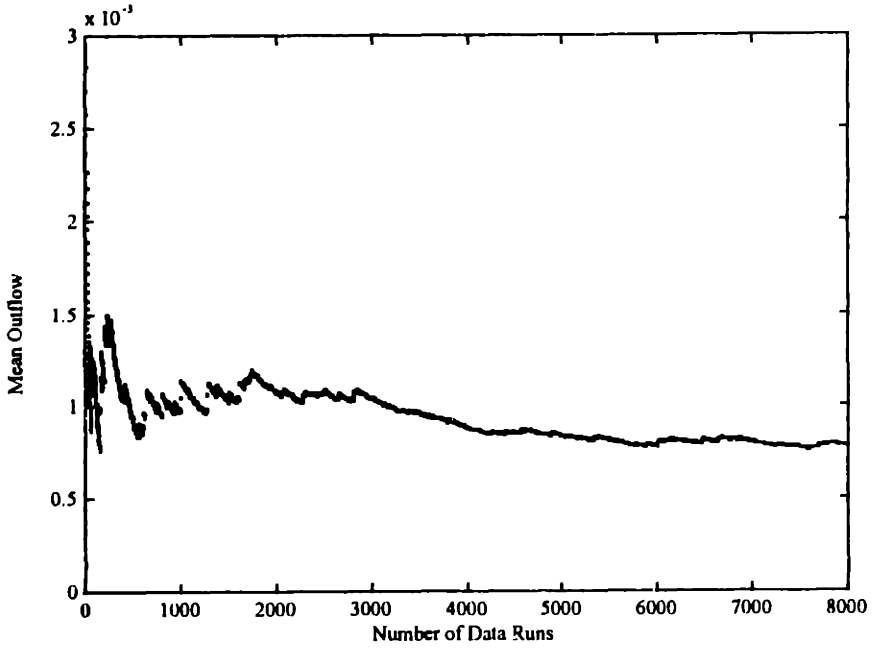


Figure E-2 Mean Outflow vs. Data Sets for DHull03

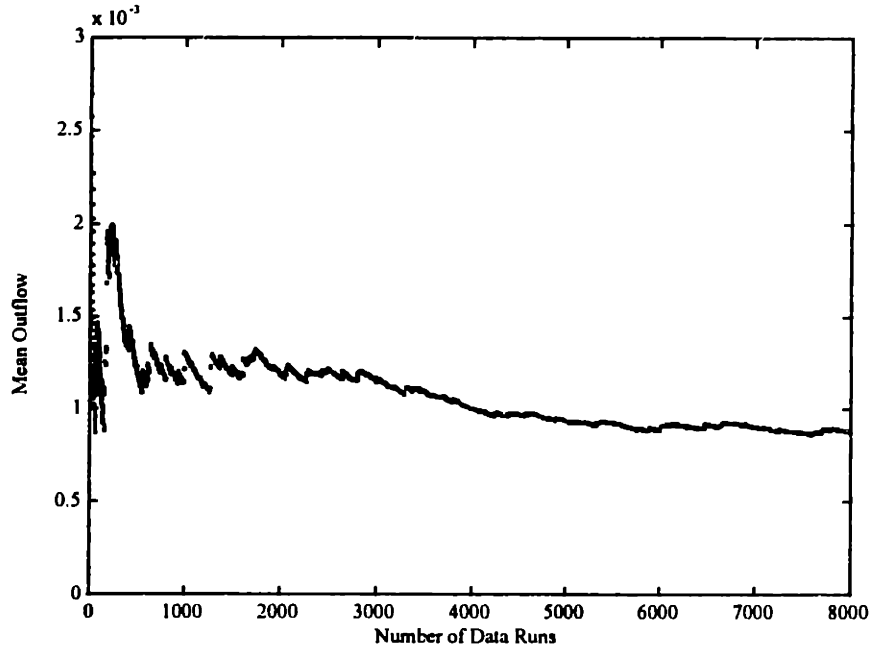


Figure E-3 Mean Outflow vs. Data Sets for DHull04

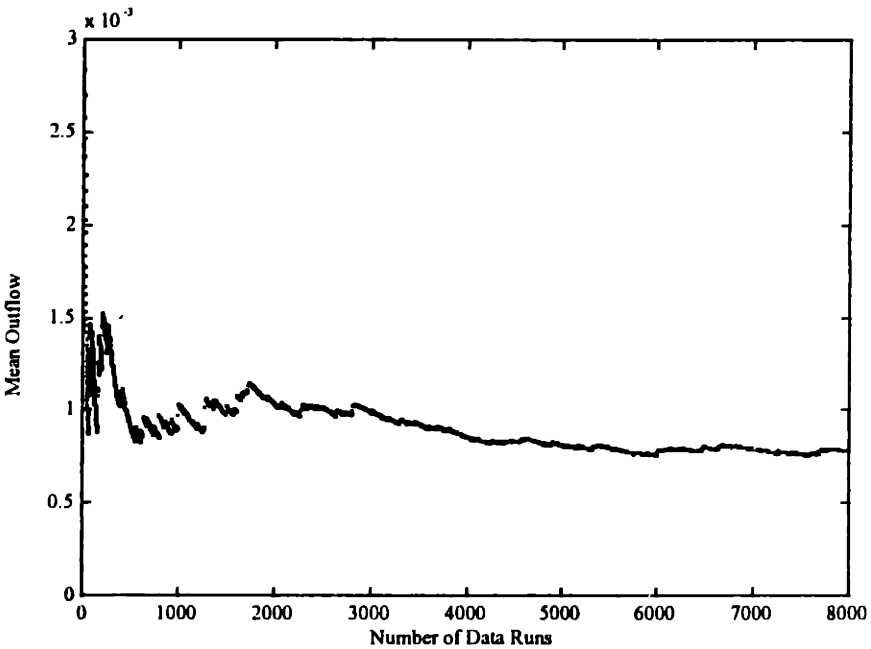


Figure E-4 Mean Outflow vs. Data Sets for DHull05

Appendix F Oil Outflow Distribution Functions

This appendix contains the oil outflow probability density and cumulative distribution functions for the double hull models not shown in Chapter 8.

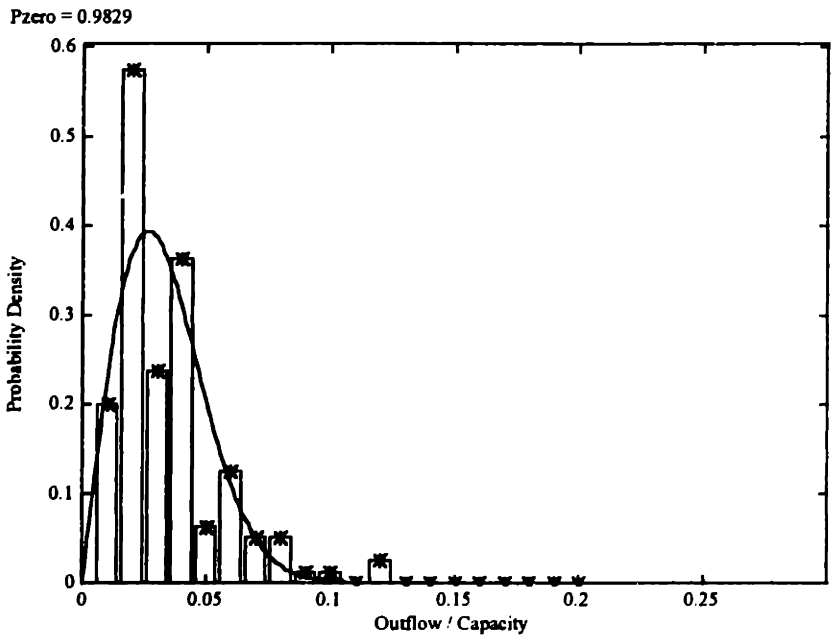


Figure F-1(a) DHull02 Oil Outflow Probability Density Function

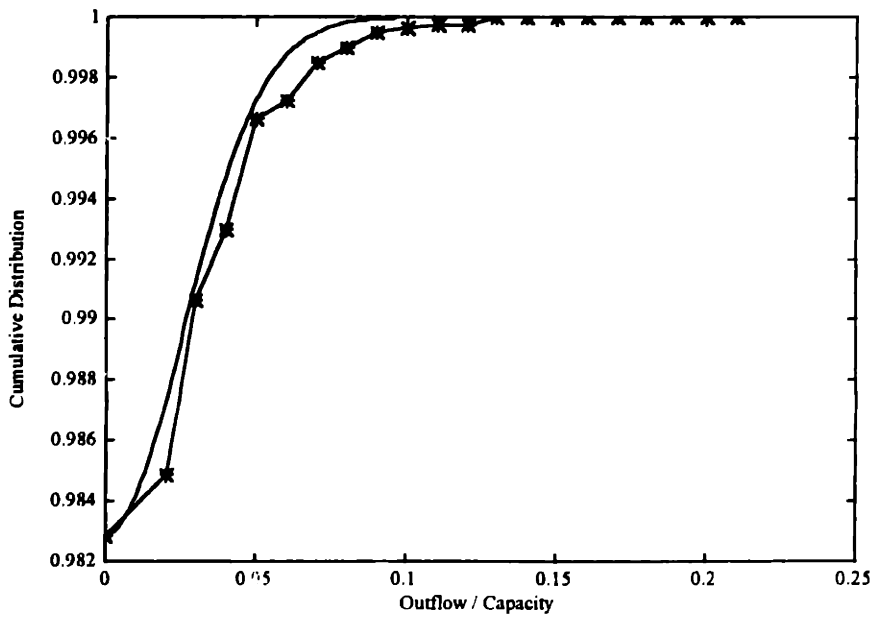


Figure F-1(b) DHull02 Oil Outflow Cumulative Distribution Function

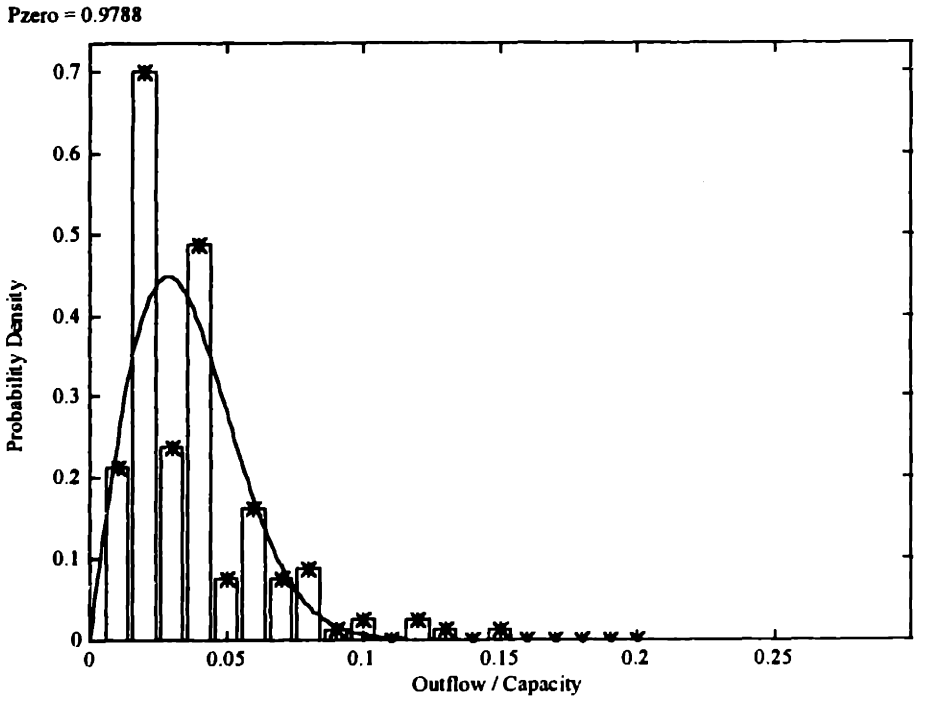


Figure F-2(a) DHull03 Oil Outflow Probability Density Function

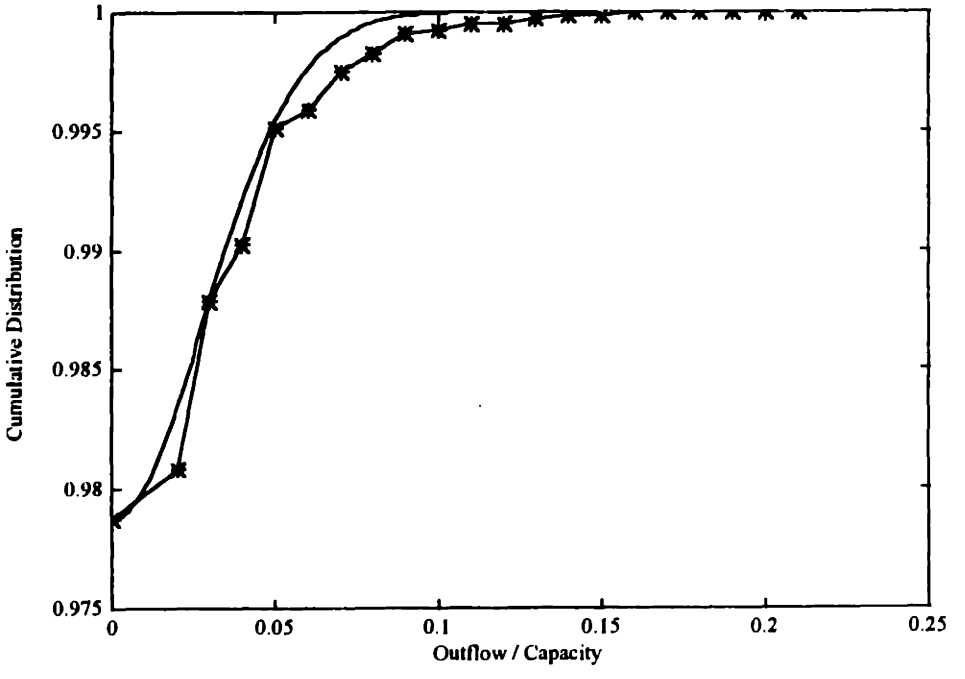


Figure F-2(b) DHull03 Oil Outflow Cumulative Distribution Function

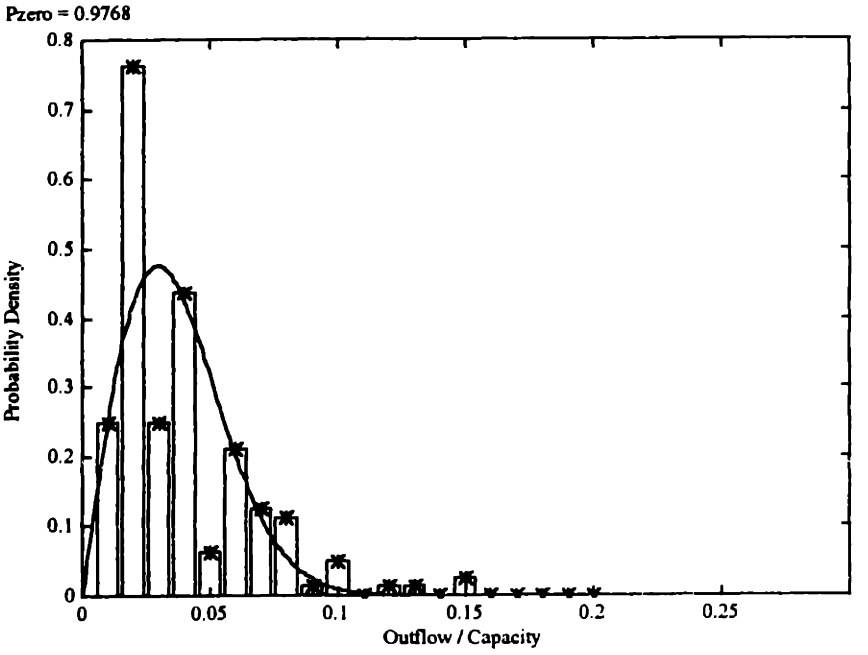


Figure F-3(a) DHull04 Oil Outflow Probability Density Function

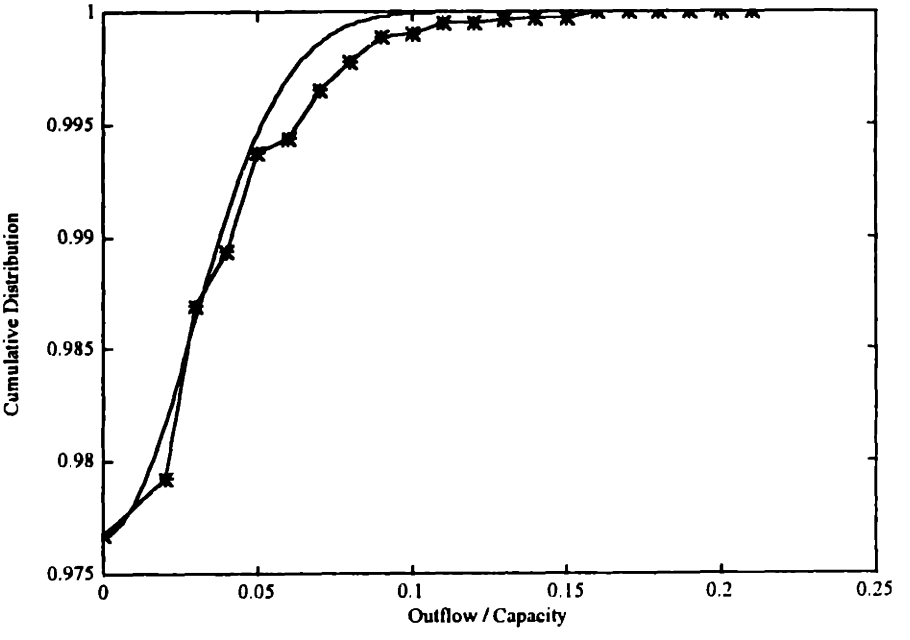


Figure F-3(b) DHull04 Oil Outflow Cumulative Distribution Function

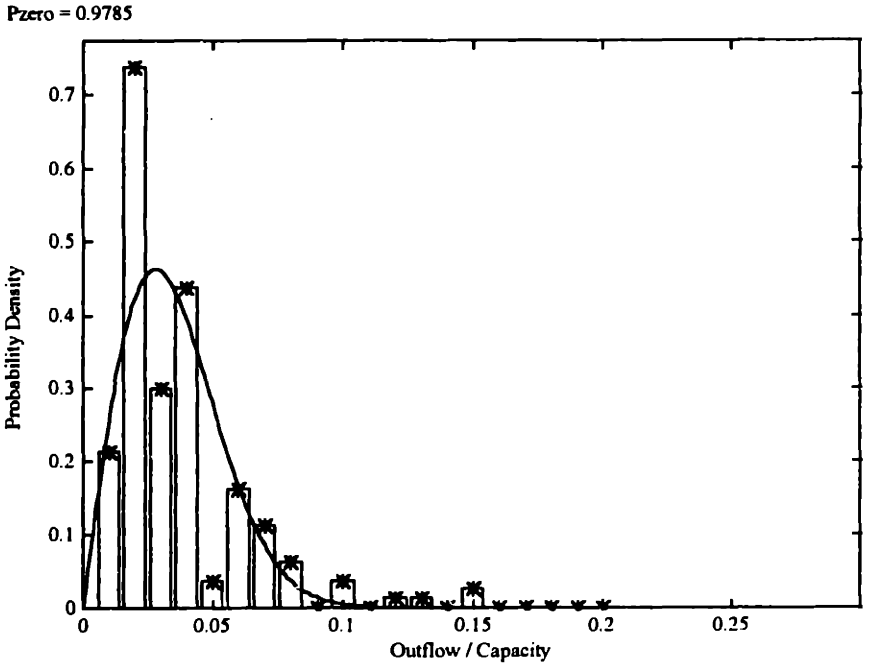


Figure F-4(a) DHull05 Oil Outflow Probability Density Function

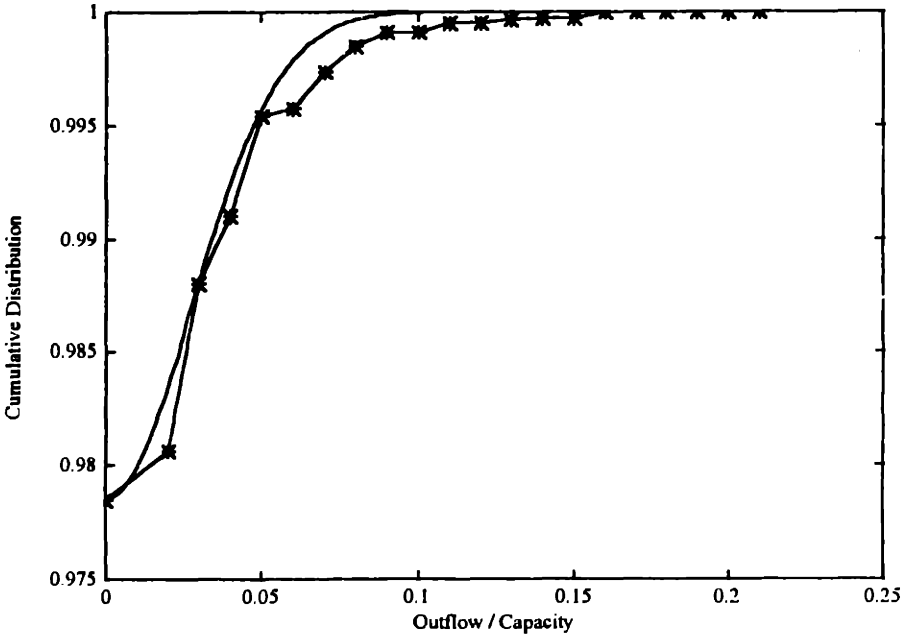


Figure F-4(b) DHull05 Oil Outflow Cumulative Distribution Function