SPECIAL REPORT 259

ENVIRONMENTAL PERFORMANCE of TANKER DESIGNS in COLLISION and GROUNDING

Method for Comparison

MARINE BOARD
TRANSPORTATION RESEARCH BOARD
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Committee for
EVALUATING DOUBLE-HULL
TANKER DESIGN ALTERNATIVES

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National Academy Press
Washington, D.C.
2001

Transportation Research Board Special Report 259

Subscriber Categories
IB energy and environment
IV operations and safety
IX marine transportation

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This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This study was sponsored by the U.S. Coast Guard.

Cover photo courtesy of Miles Kulukundis and Frontline Ltd.

Library of Congress Cataloging-in-Publication Data

Environmental performance of tanker designs in collision and grounding : method for comparison / Committee for Evaluating Double Hull Tanker Design Alternatives.

p. cm.—(Special report / Marine Board, Transportation Research Board, National Research Council ; 259)

ISBN 0-309-07240-9

1. Tankers—Design and construction—Evaluation—Methodology. 2. Tankers—Accidents—Environmental aspects. 3. Petroleum—Transportation—Safety measures. 4. Oil spills—Data processing. I. National Research Council (U.S.). Committee for Evaluating Double Hull Tanker Design Alternatives. II. National Research Council (U.S.). Marine Board. III. Special report (National Research Council (U.S.). Transportation Research Board) ; 259.

VM455 .E58 2001
623.8′245—dc21

2001057451

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PREFACE

Following the grounding of the *Exxon Valdez* in Prince William Sound in March 1989, which resulted in the loss of more than 11 million gallons of crude oil into Alaskan waters, the U.S. Congress promulgated P.L. 101-380, the Oil Pollution Act of 1990 (OPA 90). The intent of this law was to minimize oil spills through a variety of mechanisms, including improved tanker design, changes in operations, and other actions aimed at improving the capability to manage the cleanup of oil spills should they occur. Section 4115 of OPA 90 mandated changes in ship design and construction to prevent or minimize spillage in accidents, establishing the double-hull standard for tankers that transport oil in U.S. waters and call on U.S. ports. Following the passage of OPA 90, changes in the international regulatory regime in the form of two additions to MARPOL 73/78 mandated a worldwide transition to double-hull vessels or their equivalent.[1]

Since 1990, then, the world tanker fleet has been changing to double-hull construction. During the same time, however, a number of alternative tanker designs have been proposed with the intent of providing performance equivalent to or better than double hulls. While both OPA 90 and MARPOL regulations allow for the possibility of accepting alternative designs, provided they are equivalent to or better than double hulls in limiting oil outflow in case of a contact accident, the United States Coast Guard (USCG) has not accepted any other design as equivalent. IMO, on the other hand, has adopted two alternative designs as

[1] MARPOL 73/78 is the International Convention for the Prevention of Pollution from Ships, developed by the International Maritime Organization (IMO) in 1973 and modified by the Protocol of 1978. MARPOL 73/78, Regulation I/13F, specifies hull configuration requirements for new tankers of 600 deadweight tons (DWT) capacity or greater contracted after July 1, 1993; oil tankers of more than 5,000 DWT are required to have double hulls or the equivalent. MARPOL 73/78, Regulation I/13G, addresses operational requirements to reduce oil outflow from single-hull vessels in the world tanker fleet and specifies a schedule for retrofitting or retiring such vessels.

equivalent to the double hull. To date, no alternative designs have actually been built.

The Coast Guard Authorization Act of 1998 mandated the Secretary of Transportation to commission the Marine Board of the National Research Council's (NRC) Transportation Research Board (TRB) to develop a rationally based approach and method for assessing the environmental performance of alternative tanker designs relative to the double-hull standard. (A copy of the relevant legislation is found in Appendix B.) Under the auspices of the Marine Board, NRC convened an 11-member Committee for Evaluating Double-Hull Tanker Design Alternatives with appropriate scientific and technical expertise in risk assessment, tanker design, tanker operations, crashworthiness of ships, and costs and damages (including environmental damages) related to oil spills. Committee members had extensive experience in the day-to-day operations of all relevant technologies, as well as in the overall analysis of operations and risks and in systems management (see Study Committee Biographical Information at the end of this report).

The committee as a whole met five times between June 1999 and January 2001, and subgroups met periodically throughout that period. The early meetings included extensive presentations in sessions open to the public, during which experts from government, academia, and industry described a variety of issues and views for the committee. (See Appendix A for a listing of the presentations provided.) This final report represents a synthesis of the information gathered by the committee, which encompassed the data, analytical tools, and simulation methods currently available for the development of a rationally based approach for assessing the environmental performance of alternative tanker designs relative to the double-hull standard.

ACKNOWLEDGMENTS

During the course of this study, the committee and staff received numerous briefings and presentations, consulted with experts, and subcontracted modeling work. The committee wishes to thank the many individuals who thus contributed their time and effort to the project. In particular, the committee would like to thank Deborah French and her colleagues at Applied Science Associates, Inc., who conducted the spill consequence modeling; Dagmar Etkin of Environmental Research Consulting, who modeled the mechanical containment and recovery costs and shoreline cleanup costs, and provided data on worldwide tanker oil

spills for 1973 through 2000; Alan Brown, who performed the modeling of the structural damage and resulting outflow for different collision scenarios; and Kirsi Tikka, who carried out the modeling of the structural damage and resulting outflow for different grounding scenarios. Appreciation is also expressed to the many individuals and organizational representatives who provided information, including B. John Garrick, Garrick Consulting; William O. Gray, Gray Maritime Company; Ron Heintz, Auke Bay Laboratory, National Marine Fisheries Service/National Oceanic and Atmospheric Administration (NMFS/NOAA); Keith Michel, Herbert Engineering; Frank Nicastro, Exxon Company, International (retired); RADM Robert C. North, USCG; Jim Sartucci, Legislative Assistant, Office of Senator Trent Lott; Professor Preben Pedersen, Technical University of Denmark; Stan Rice, Auke Bay Laboratory, NMFS/NOAA; CAPT Edward K. Roe (USCG, retired), Marine Safety Systems, Inc.; RADM Joel D. Sipes (USCG, retired), Marine Safety Systems, Inc.; Jaideep Sirkar, USCG; and Wayne Willis, ICF Kaiser International. Representatives of federal and state agencies, as well as private companies, also provided invaluable assistance to the committee and the staff. Thanks are due especially to the liaison representatives from USCG, H. Paul Cojeen and David A. DuPont, who responded promptly and with a generous spirit to the committee's many requests for information.

The study was performed under the overall supervision of Stephen R. Godwin, Director of Studies and Information Services. Susan Garbini served as project director through January 1999, and Beverly M. Huey served as project director from February 1999 through the completion of the report. The committee also wishes to thank Pete Johnson for his efforts in acquiring and organizing data and in drafting sections of the report; and Suzanne Schneider, Associate Executive Director of TRB, who managed the report review process. The report was edited by Rona Briere and prepared for publication under the supervision of Nancy A. Ackerman, Director of Reports and Editorial Services. Special thanks go to Donna Henry-Rahamtalla for assistance with meeting arrangements and correspondence with the committee and to Alisa Decatur for assistance with word processing and production of the final manuscript.

The report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee thanks the following individuals for their participation in the review of this report: Don V. Aurand, Ecosystem Management and Associates, Purcellville, Virginia; Lars Carlsson, Concordia Maritime AB, Gothenburg, Sweden; B. John Garrick, Garrick Consulting, Laguna Beach, California; Bruce Hutchinson, Glosten Associates, Seattle, Washington; Henry S. Marcus, Massachusetts Institute of Technology, Cambridge; R. Keith Michel, Herbert Engineering Corporation, Alameda, California; Ann Rothe, Trustees for Alaska, Anchorage; and Theodore Tomasi, ENTRIX, Inc., New Castle, Delaware. Although these reviewers provided many constructive comments and suggestions, they were not asked to endorse the report's findings and conclusions, nor did they see the final draft before its release.

The review of this report was overseen by Robert A. Frosch, Harvard University, Cambridge, and Lester A. Hoel, University of Virginia, Charlottesville. Appointed by NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests solely with the authoring committee and the institution.

ACRONYMS AND GLOSSARY

ACRONYMS

ABS	American Bureau of Shipping
ASA	Applied Science Associates
CWA	Clean Water Act
DH	double hull
DNV	Det Norske Veritas
DWT	deadweight ton
IACS	International Association of Classification Societies
IMO	International Maritime Organization
INTERTANKO	International Association of Independent Tanker Owners
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee of the International Maritime Organization
MIT	Massachusetts Institute of Technology
MLW	mean low water
NOAA	U.S. National Oceanic and Atmospheric Administration
NRC	National Research Council
NRDA	Natural Resources Damage Assessment
NRDAM/CME	Natural Resources Damage Assessment Model for Coastal and Marine Environments
OCIMF	Oil Companies International Marine Forum
OPA 90	Oil Pollution Act of 1990 (P.L. 101-380)
P&I	protection and indemnity
PAH	polycyclic aromatic hydrocarbons
QRA	quantitative risk assessment
SH	single hull
SNAME	Society of Naval Architects and Marine Engineers
SSC	Ship Structures Committee
TRB	Transportation Research Board
USCG	United States Coast Guard
VTS	vessel traffic service

GLOSSARY

Ballast. Water (usually seawater) carried in designated tanks of a vessel to increase the vessel's draft to a safe and efficient operating level when not carrying cargo.

Central ballast tank. A tank (or tanks) designed to carry ballast and located in the center of the vessel.

Collision. An event in which one vessel strikes another, usually causing some damage to the vessel(s) and sometimes an oil spill. In this study, collisions are also defined to include allisions, events in which a vessel strikes a fixed object such as a pier, bridge, or other fixed structure.

Crashworthiness. A measure of the ability of a vessel to withstand damage following a collision or grounding incident.

Crude carrier. A tank vessel designed to carry crude oil.

Deadweight tonnage. A measure of the weight of cargo (plus fuel, water, and supplies) a vessel can carry.

Domestic trade. Transportation of goods from one port or location in the United States to another.

Draft. The vertical distance between a vessel's waterline and baseline.

Grounding. An event in which a vessel strikes a fixed object, such as a rock or wreck, on the bottom of the sea or waterway, or the seafloor itself.

Mid-deck. A tank vessel design with a watertight deck located about midway between the vessel's upper deck and bottom so that if the vessel is holed below this deck, hydrostatic pressure will prevent (or minimize) oil spills.

Natural resource damage. A measure of harm done to resources in the natural environment following an oil spill.

Oil slick. The layer of oil floating on a body of water following an oil spill, which usually spreads in area and diminishes in thickness with time.

Oil transport and fate. The migration of a quantity of oil spilled from the initial spill location (transport) and its ultimate effect on the environment or ecosystem.

Outflow. The amount of oil that escapes into the surrounding environment from a tank vessel after a collision or grounding.

Plastic deformation. The phenomenon of metal stretching without breaking when subjected to a force such as that resulting from a vessel collision or grounding. The metal will break (or fracture) when the force becomes great enough.

Product carrier. A tank vessel designed to carry refined petroleum products, such as fuel oil or gasoline.

Response cost. The cost associated with responding to an oil spill, usually including the cost of mobilizing people and equipment, conducting cleanup operations, and disposing of spilled oil and waste.

Sheen. A very thin oil slick characterized by being just thick enough to have a visible "sheen" when observed by the naked eye.

Stability. The measure of a vessel's ability to float in an upright orientation.

Structural damage. The physical damage sustained by a metal structure after being struck during an event such as a collision or grounding.

Subdivision. Division of the overall tank space on a vessel into a number of individual watertight and/or oiltight tanks or compartments.

Third-party damage. The monetary damage from an oil spill to parties not involved in the spill, such as users of beaches, recreational boaters, fishermen, and nearby property owners.

Underpressure system. A tank vessel design that utilizes a vacuum system in cargo tanks to prevent or minimize oil spills if the tanks are ruptured in a collision or grounding.

U.S. flag vessels. Vessels registered under the jurisdiction of the United States and thus subject to U.S. laws and regulations and entitled to fly the U.S. flag.

U.S. waters. As defined in OPA 90, waters subject to the jurisdiction of the United States, including the Exclusive Economic Zone.

CONTENTS

EXECUTIVE SUMMARY

To reduce the risk of oil spills from accidents, the United States requires that all tankers calling on U.S. ports in the future be fitted with a double hull. The world tanker fleet is changing to double hulls in accordance with both U.S. law and a similar provision in an international agreement. Even as this change has been occurring, however, some organizations have proposed alternative designs as equivalent or superior to a double hull in preventing the outflow of oil in an accident. U.S. law allows for the evaluation and approval of alternative designs that can be determined to have performance equivalent to or better than the double hull in protecting the environment. To date, however, the United States Coast Guard (USCG) has not made that determination for any alternative design. The International Maritime Organization (IMO) has approved two designs as equivalent to the double hull; because most tankers might trade with the United States at some time, however, the U.S. double-hull regulation has thus far set the standard for the world.

Proponents of alternative tanker designs have approached USCG and the U.S. Congress with proposals they believe will offer performance equivalent to or better than the double hull and have asked whether these designs would be accepted under U.S. law. Moreover, some have proposed that regulations be based on performance criteria for designs instead of prescriptive criteria. They believe that if a method of evaluating equivalence to double hulls can be developed, a better design can be invented, whereas technological innovation will be discouraged if only a single prescriptive design, such as the double hull, remains a fixed requirement. Some proponents also believe that U.S. regulations should be more consistent with international law, especially in an area that has so close a connection to international trade.

STUDY PURPOSE

In the above context, Congress requested that the present study be undertaken by a committee under the auspices of the Marine Board of the National Research Council's (NRC) Transportation Research Board to determine whether a methodology could be established for measuring the equivalency of alternatives to double-hull designs with regard to environmental performance. Congress made this request through the USCG Authorization Act of 1998 but specified that the investigation be conducted independently of past USCG policy on double-hull equivalency. The committee was charged to develop a rationally based approach for assessing the environmental performance of alternative tanker designs relative to the double-hull standard. The proposed methodology was then to be applied to double-hull tankers and alternative designs to demonstrate that it could be used for an assessment. The committee was asked to ensure that the proposed methodology would be applicable to conditions prevailing in U.S. waters. The committee's charge also included refining and adjusting existing tanker damage extent functions used for measuring the crashworthiness of tank vessel structures. In addition, the committee was to develop a generalized spill cost database and use this database in formulating a rationally based approach for the calculation of an environmental index.

BACKGROUND

Status of Design Proposals

A number of organizations have submitted proposed alternatives to double-hull designs to either USCG (for the United States) or IMO (representing the international community), both of which have developed regulations addressing minimum tanker design standards. Under the IMO guidelines, the double hull and two other designs—the mid-deck design and a special variation on that concept proposed by the Swedish government and approved in 1997—are permitted. In addition to the alternatives submitted to IMO, several other concepts have been developed in the United States.

Status of Existing Methodologies

While considerable effort has gone into schemes for measuring the environmental performance of tankers following accidents, none of these approaches carries the analysis through to a conclusion based on relative damage to the environment from an oil spill. The IMO method of comparing designs is based on a formula that assigns relative weighting factors to three outflow parameters related to spill size (zero, mean, and extreme outflow). Use of these weighting factors was based on IMO's decision to select a formula that would ensure the equivalency of the double-hull and mid-deck designs. However, these factors provide no measure of the possible environmental damage itself. Moreover, the IMO methodology uses historical distributions of ship structural damage that are not applicable to new designs, in particular to designs based on innovative structural concepts.

In its recent decisions on whether to accept double-hull alternatives, USCG applied a method that employs estimates of the same three outflow parameters used by IMO (zero, mean, and extreme). Judgment is then applied regarding the importance of the zero outflow factor. USCG puts the greatest emphasis on avoiding all spills because it interprets the Clean Water Act as prohibiting any such discharges. However, the environmental consequence judgment involved in this method has not been expressed quantitatively.

Other researchers have investigated methods of applying past work on the probabilities of zero, mean, and extreme outflows to some surrogate for environmental consequences, such as cost (see below). However, none have assembled the cost data needed to yield conclusive results.

Limitations of Cost Data for Measuring Environmental Damage

As noted, the committee's charge included development of a generalized spill cost database that could assist in formulating a rationally based approach for calculation of an environmental index. The goal behind this charge was to apply the historical record of oil spill costs as a basis for comparing alternative tanker designs.

The committee identified and obtained many data sets that describe the costs associated with oil spills. However, the existing cost data for past oil spills have been gathered irregularly and are difficult or impossible to obtain. Moreover, because of extreme variability in the cost data associated with environmental damage assessment, as well as in third-party cost data, past data are neither reliable nor comparable.

The committee also considered whether it would be possible and appropriate to develop its own database that would reflect a high degree of quality control and include a large number of events. For example, in some cases a cost estimate reported in a data set will reflect the costs as of a certain date, when additional costs were incurred after the initial report. The committee concluded that the difficulties involved in obtaining data and in estimating environmental consequences would make the resultant data set of limited use. In addition, considering the fact that very few large-scale spills actually occur, it would be difficult to generalize from these limited events to generate a consequence model. As a result, the committee decided to develop a response function relating spill consequences to spill characteristics (e.g., volume of spill, location of spill, type of oil) using a modeling approach. Combining the expertise of committee members with a review of risk analysis in other fields, the committee decided to develop a risk-based methodology that uses environmental consequences following a spill as a means of comparing the performance of proposed alternatives against that of a standardized double-hull vessel for each of the comparable sizes.

DEVELOPMENT OF A NEW METHODOLOGY

Given the status of previous efforts to establish a methodology for comparing the environmental performance of alternative tanker designs, the committee concluded that the development of a new approach was warranted. The methodology developed by the committee is divided into three main components: (*a*) structural damage and oil outflow calculation, (*b*) consequence assessment, and (*c*) design comparison.

For the first component, the committee selected scenarios (collision and grounding events) that represented conditions in U.S. waters, specifically in those areas with a high density of tanker traffic. Once the collision and grounding events had been identified, the committee used damage models to determine the structural damage and resulting outflow in each accident.

The second component of the methodology involves the assessment of consequences from an accidental spill. The committee used an environmental impact model that predicts oil fate and transport and allows for random sampling of weather conditions on the basis of historical weather data. This model provides a number of physical consequence measures, such as the area of the sheen, the toxicity in the water column, and the length and area of oiled shoreline. The committee decided to limit the assessment of consequences to these physical measures instead of extending it to impacts on biological resources. Doing so would keep the analysis as systematic and well specified as possible without necessitating difficult decisions as to what threshold levels would damage biological resources and how those resources are valued.

In addition to the physical consequence measures, the committee considered several nonenvironmental measures of consequence, including spill cleanup and response costs, the value of lost product, and third-party damages. These measures were eliminated from the final analysis for several reasons. The value of lost product, measured on a per gallon basis, is not expected to vary significantly with spill size. More important, the collective best judgment of the committee was that the physical consequence metrics used in the analysis are reasonable proxy measures for likely third-party losses and cleanup and response costs.

The final component of the methodology involves the comparison of two designs. By subjecting each design to the same set of accident scenarios, one can directly compare the resulting performance of the designs for each scenario. Since the relative impact on the environment can be assessed for each design, the better-performing design is evident for each accident scenario.

APPLICATION OF THE NEW METHODOLOGY

The committee prepared two examples to demonstrate the application of the methodology and perform an initial test of its validity. Both examples involved comparing the performance of a double-hull design with that of a single-hull design. One example used vessels with a 150,000-deadweight ton (DWT) capacity and the other vessels with a 40,000-DWT capacity design. None of the alternative designs proposed to USCG was available to the committee in sufficient detail to be used in the examples.

The committee selected four case study locations in U.S. waters: Big Stone Anchorage (Delaware Bay), Galveston lightering area (Gulf of Mexico), Carquinez Strait Bridge (San Francisco Bay), and Farallon Islands (offshore San Francisco). These locations have large volumes of tanker traffic, and adequate oil spill modeling data are available for each. These four locations also demonstrate sufficient variation in site characteristics and conditions to provide an adequate test of the components of the methodology. The committee ran a total of 80,000 accident scenarios: 10,000 collision and 10,000 grounding events for each of two designs (single-hull and double-hull) of the two different sizes (150,000 and 40,000 DWT).

To determine environmental consequences for these events, the committee conducted a separate analysis and generated a set of consequence functions for the necessary range of oil outflows, also considering such factors as weather, oil types, and geography for the selected locations. With four sites, 200 weather events, two oil types (crude and product), and seven spill volumes, a total of 11,200 spills was simulated in the models used. The seven spill volumes were chosen to represent the full range of possibilities.

The consequence functions selected by the committee represent ratios of the environmental consequence for a spill of a certain size to that for a 500,000-gallon reference spill. The consequence function is not linear. That is, for spills smaller than the reference spill size, the consequence for each gallon spilled is relatively greater than for the reference size, and that difference continues to increase as the spill size decreases. The opposite is true for larger spills. For example, for a spill of 100 times the reference size (a spill of 50 million gallons) the environmental consequence function would be only about 8 times greater. To test the validity of this result, the committee also conducted several sensitivity analyses—for different oil types, different case study sites, and different consequence metrics. These analyses provide upper and lower bounds for the consequence function graph and can be used to make the final design comparisons more accurate and complete.

Each of the 80,000 outflows was converted to a consequence measure, relative to the 500,000-gallon spill equivalent. By calculating and analyzing the differences in this measure across the scenarios, one can determine the relative performance of two designs. However, this result is not meant to be predictive of environmental consequences for any specific spill.

Since the committee did not attempt to determine the likelihood of any of the scenarios actually occurring, the analysis cannot be used to determine the real savings that might accrue through use of a particular design in a given time period. The latter is a very different and more difficult problem that would require a detailed risk analysis of a specific port area with defined operations and traffic patterns. This is the type of analysis that would be required, for example, if one wanted to determine whether the additional costs of an alternative design were justified.

CONCLUSIONS AND RECOMMENDATIONS

The committee developed a rationally based approach for assessing the performance of alternative tanker designs on the basis of their relative ability to prevent environmental damage from oil spills following collision and grounding accidents. This methodology can be used as a tool by regulatory authorities in determining whether to approve an alternative to the double-hull tanker design. First, however, a few other things need to be accomplished: (*a*) peer review of the methodology; (*b*) testing of the methodology; and (*c*) a comprehensive review of the methodology by stakeholders, including the tanker industry and environmental groups, as well as regulatory, oversight, and review organizations. The methodology is a significant improvement over existing methods; however, it needs further refinement to enhance its accuracy and reliability. On the basis of its work, the committee makes the following recommendations.

Overall Methodology

***Recommendation 1:* USCG should use the proposed methodology for evaluating alternative tanker designs and at the same time undertake a program to refine the methodology to address the issues discussed in this report.**

***Recommendation 2:* USCG should institute a standard procedure for evaluating specific designs submitted as equivalent to a double-hull design. This procedure should include the methodology proposed by the committee for assessing equivalency on the basis of environmental consequences from oil spills following collision and grounding accidents. Other appropriate factors, such as those associated with the safety and operation of the vessel, will have to be evaluated in conjunction with the use of this methodology.**

***Recommendation 3:* To continue and validate the work of the committee, USCG should apply the committee's methodology to compare other alternative designs with the double hull. The committee suggests that one alternative assessed be the middeck design, which is available in a detailed form and has already been evaluated by IMO.**

Double-Hull Reference Ships

Although the committee's charge referred to comparing alternative designs with the double-hull standard, the committee did not select a standard double-hull design. To test its methodology, the committee selected one available double-hull design without regard to whether it represented an accepted standard. Since each design may have qualities and characteristics that differ from a minimum standard in a significant way, selection of one standard by which all alternatives would be measured in the future would represent a policy decision. In using the methodology, however, a critical first step is to define such standard double-hull reference ships in a number of size ranges, thus enabling all proposed new designs to be measured on the same basis.

Recommendation 4: **USCG should define in sufficient detail and make available the standard reference ships needed for the methodology. This concept is similar in nature to the reference ships currently used by IMO. In developing the standard reference ships, USCG should refer to the discussion of design of double-hull tank vessels in the 1998 NRC report entitled *Double-Hull Tanker Legislation: An Assessment of the Oil Pollution Act of 1990.***

Need for Vessel Design Details

The committee's approach to developing this methodology entailed rigorous computational methods that included analyzing the crashworthiness of ship structures, calculating oil outflows in specific accident scenarios, and modeling spills and their complex behaviors while reducing the results to numerical values. The methodology is necessarily complex and requires substantial detail in all input values, including complete design details for any vessel to be evaluated. Given these complexities, it would be unreasonable to expect that the methodology could be used to evaluate a concept in the absence of a complete ship design. The committee concludes that if an alternative design is to be evaluated by USCG, sufficient design and analysis detail must be available.

Recommendation 5: **Anyone proposing an alternative design should be required to submit to USCG not only a complete description, including design plans, but also an analysis of the design and its performance within the framework of the models used in the proposed methodology, including such aspects as outflow under different accident scenarios. Sufficient information should also be provided to allow USCG to perform an independent review of the proposed design. In addition, USCG should prepare specific instructions for those who wish to submit alternative designs, including a list of required design plans, structural and mechanical details, and relevant calculations. The format and organization of a submission should also be specified.**

Consideration of Active Systems

Several designs for oil tankers, including the double hull, protect against oil spills by creating an arrangement of the ship's structure that will prevent or mitigate oil outflow. These "passive" approaches may create a void space between cargo oil tanks and the sea, or locate tanks where they are less likely to leak or be punctured, or use hydrostatic pressure balance to prevent leaks after a puncture. In contrast to passive systems, some alternative designs incorporate "active" systems with the use of valves, sensors, piping, pumps, or other mechanical devices that would be activated after an accident to mitigate oil outflow. Active systems present additional factors to be considered when evaluating alternatives. Their unique characteristics pose multiple types of risks that need to be considered in conjunction with relevant operational protocols. These complexities add an overlay to the proposed methodology that the committee could not test within this study because of a lack of sufficient detail on any active system.

> ***Recommendation 6:* Any submittal to USCG of an alternative design that includes an active system should contain a quantitative life-cycle risk analysis, along with supporting information, so that independent verification can be accomplished by either USCG or others. In addition, USCG should develop the capability to review and evaluate all of the risk assessment factors that might be presented in such a submittal.**

Components of the Methodology

In its outflow analysis, the committee concluded that use of historical data, and therefore the IMO methodology and other methods based on such data, is not appropriate for evaluating new tanker designs. Accordingly, the methodology proposed in this report uses direct computational tools instead of historical data to determine the crashworthiness of either double-hull or alternative designs. The structural damage databases currently available, including the one updated by the committee, include only single-hull tankers and combination carriers. Collecting new data would not provide a usable database for the purposes of this methodology since data on innovative designs simply do not exist.

In addition, in developing the methodology, the committee concluded that existing computational tools for determining damage extent and outflow are not fully validated, and methods are based on simplifying assumptions whose effects on the results are not yet entirely understood. The committee believes that the computational tools used for this study provide a better comparative method than the current approach based on the use of historical damage data, although further work is needed to validate and improve these tools.

Recommendation 7: **USCG should undertake a program to collect collision and grounding data in sufficient detail for use in validating both collision and grounding analyses. The USCG accident investigation report should routinely include data of the detail and extent necessary for this purpose. The data should be stored in a format that is easily accessible and conveniently usable by researchers. USCG should encourage others, through IMO, to collect detailed accident investigation data in a uniform manner. In addition, USCG should initiate a program for the continued development of grounding and collision analyses. The following areas need the most development:**

- **Addition of other than powered grounding on a single pinnacle,**
- **Addition of collision with solid objects,**
- **Addition of a deformable bow in the collision model, and**
- **Further development of the collision model at the structural member level.**

As more data become available, USCG should maintain a continuing program of testing and validation of the collision and grounding analysis tools.

As discussed earlier, the consequence analysis performed by the committee indicated that the relationship between spill size and environmental consequence is not linear. In other words, the impact of spills increases with volume, but the marginal impact of each gallon spilled decreases. Thus the evaluation of an alternative design based on outflow alone would not be valid and could yield a misleading result. This conclusion led the committee to select an approach that could relate measures of environmental damage to each oil spill scenario. Moreover, as explained above, the committee chose to use physical consequences, instead of historical spill costs, as the most consistently measurable and comparable method of evaluating environmental consequences.

Recommendation 8: **The committee recommends that USCG take the committee's findings on evaluating environmental consequences of spills into account in its regulatory initiatives relative to environmental impacts of oil spills, including cost–benefit analyses.**

In its design comparison, the committee concluded that a complete distribution of the differences in environmental impact (impact differences) is necessary for such comparisons because it provides information on the regions where one design performs better than another. The use of simple descriptive statistics, such as the mean, is not sufficient and can be misleading. Furthermore, it is important to compare the impact differences between alternative designs event by event, instead of comparing the cumulative impacts of designs for all events. The impact difference is a function of the difference in the consequences of the outflows from each design, and since this relationship is not linear, it is not a function of the outflow difference. For example, the impact difference for an event in which one design spills 200,000 gallons and the other spills no oil can be larger than that for an event in which one design spills 60 million gallons and the other 70 million gallons, even though the actual outflow difference is much larger in the latter case. The methodology proposed by the committee yields a distribution of impact differences for each event, which in turn provides information on the magnitude of the impact differences as well as their frequency.

> ***Recommendation 9:* The committee recommends that USCG propose to IMO that it replace its current guidelines with a rational methodology for evaluating alternative tanker designs based on the principles presented in this report.**

The committee understands that to implement all of its recommendations will require substantial time and effort on the part of USCG but has neither estimated the cost involved nor determined whether USCG has the necessary resources available. Therefore, the committee cannot propose an appropriate schedule for the recommended tasks, nor can it set priorities for this work relative to USCG's other responsibilities. The committee does, however, believe that the work presented to illustrate the proposed methodology provides a foundation that can be used by USCG in its implementation efforts.

1
INTRODUCTION

Current law [P.L. 101-380, the Oil Pollution Act of 1990 (OPA 90)] requires that all tankers calling on U.S. ports in the future be fitted with a double hull to reduce the risk of oil spills from accidents. The law also specifies a schedule for phasing out single-hull ships.[1] A similar provision is contained in an international agreement under Regulation I/13F of the International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78[2] (IMO 1996) of the International Maritime Organization (IMO), a specialized agency of the United Nations. In response to OPA 90 and MARPOL provisions, the world tanker fleet is changing to double-hull designs. However, international standards authorize, and in fact have allowed approval of, some alternative designs that are considered at least the equivalent of a double-hull design in preventing the outflow of oil in an accident. OPA 90 also allows for the evaluation of alternative designs that the United States Coast Guard (USCG) can determine to be at least equivalent to double-hull designs with regard to effectiveness in preventing the spillage of oil following a contact accident.[3] However, in a report required by Congress, USCG (1992) set forth its determination that only the double-hull design meets the requirements of U.S. law. The basis for this conclusion is USCG's interpretation of the Clean Water Act, according to which USCG looks primarily at the probability of zero outflow in the event of an accident.

Since the passage of OPA 90, several ship designers and other proponents of alternative tanker designs have approached the U.S. Congress with proposed designs they believe offer performance that is equivalent to or better than the double hull. Moreover, some members of the

[1] See NRC (1998) for a discussion of the schedule for phasing out single-hull tankers.

[2] So called because it was developed in 1973 and modified by the Protocol of 1978.

[3] OPA 90 also directed the Secretary of Transportation to prepare a study on other possible structural or operational requirements that might be at least as effective as double hulls in protecting the marine environment and to report back to Congress with any recommendations for legislative action. That report was completed in 1992 (USCG 1992).

design community favor regulations that would call for performance criteria for designs instead of prescriptive criteria. These proponents believe that if a method of evaluating equivalence to double hulls can be developed, a better design can be invented, whereas such inventiveness may be constrained if only a single prescriptive design, such as the double hull, remains a fixed requirement. There are also those who believe U.S. regulations should be more consistent with international law, especially in an area so closely connected to international trade.

STUDY PURPOSE

In the above context, Congress requested that the present study be undertaken by a committee under the auspices of the Marine Board of the National Research Council's (NRC) Transportation Research Board (TRB) to determine whether a methodology could be established for measuring the equivalency of alternatives to double-hull designs with regard to environmental performance. Congress made this request through the USCG Authorization Act of 1998 but specified that the investigation be conducted independently of past USCG policy on double-hull equivalency (see Appendix B). Specifically, the committee was charged to accomplish the following:

- *Develop a rationally based approach for assessing the environmental performance of alternative tanker designs relative to the double-hull standard.* This element of the committee's charge is the primary focus of the study and this report. The committee began its work by considering the limitations of existing methodologies, as well as investigating the state of the art of assessment techniques to identify those most appropriate for this application. The committee then developed a methodology, prepared the analyses necessary for its application, and performed testing to demonstrate its use.
- *Refine the IMO tanker damage extent functions and propose a method for adjusting the probability density functions to reflect the crashworthiness of tank vessel structures.* The committee investigated the available data and methods for using those data to determine vessel crashworthiness. However, the available data could not be used for this purpose, and the committee's methodology employs a different technique that does not require historical data.
- *Develop a generalized spill cost database and use this database in formulating a rationally based approach for the calculation of an environmental index.* The committee collected and analyzed available spill

cost data. However, the data were inadequate for the purpose, and the committee therefore carried out this portion of its charge using a modeling approach.

- *Apply the proposed methodology to double-hull tankers and alternative designs.* The committee performed a test application of the proposed methodology.
- *Ensure that the methodology proposed is applicable to conditions prevailing in U.S. waters.* The committee selected characteristics and locations for developing and testing its methodology that reflect conditions in U.S. waters.

BACKGROUND

During the past two decades, significant efforts to improve safety and protect the environment have resulted in a downward trend in the total amounts of oil spilled as a result of tanker accidents worldwide. Since the early 1990s, these reductions have been especially significant in U.S. waters. Even so, the threat of tanker spills continues to evoke public concern, and the occasional large spill can result in major environmental damage.

Measures to improve the environmental performance of tankers are many and varied. The first line of defense against pollution is prevention of accidents through such safe ship operational measures as crew training, competence assurance, navigational aids, and traffic management. Because such measures include human factors as well as elements susceptible to mechanical failure, a second line of defense comprises design and construction approaches that can prevent or minimize oil spills in the event of a contact accident (e.g., collision or grounding). Accordingly, since the early 1970s, researchers and engineers have developed tanker designs aimed at preventing or limiting oil outflow after a collision or grounding accident. Double bottoms, double sides, double hulls, and a myriad of other structural arrangements have been proposed and used, and studies have provided evidence to show their effectiveness. By the 1990s, however, a consensus had emerged among regulators—especially in the United States—that a double-hull standard would offer the best protection against oil spills following collision and grounding accidents. Since then, the U.S. regulations requiring double hulls for tankers operating in U.S. waters (discussed below) have resulted in a gradual change in the world tanker fleet, about 39 percent of which now comprises tankers with double hulls (see Table 1-1). That percentage is expected to continue to grow as new ships under construction enter the fleet and old ones are scrapped.

TABLE 1-1 Distribution of World Tanker Fleet by Size and Proportion Double-Hull

Size of Fleet (thousands of DWT)	Number of Ships in Fleet	DWT of Fleet (millions)	Number of Double-Hull Ships	DWT of Double-Hull Ships (millions)	Proportion of Double-Hull Ships in Fleet[a] (%)
10–60	1,901	57.8	658	20.0	35
60–80	257	17.4	90	6.3	36
80–120	592	56.4	268	26.4	47
120–200	324	46.7	143	20.7	44
200+	450	131.1	155	45.6	35
Total	**3,524**	**309.2**	**1,314**	**119.0**	**39**

NOTE: Figures shown are as of early 2001. DWT = deadweight tons.
[a] Share is based on DWT percentage.
SOURCE: Personal communication, D. Rauta, INTERTANKO, March 8, 2001.

As noted, despite this trend toward double-hull tankers, many researchers and organizations have continued to propose alternative design approaches for achieving similar or better performance in preventing oil outflow following tanker accidents. It has been difficult to evaluate these alternative designs, however, because there has been no rigorous and generally accepted method for comparing them against the double-hull standard, and USCG has not recognized the IMO guidelines, which provide a methodology for assessing equivalency. When NRC (1991) issued a report comparing alternative designs with double hulls, it noted that there were no accepted criteria for measuring equivalency but concluded nonetheless that no alternative proposed to date was superior to the double hull for all accident scenarios. USCG has issued regulations to implement the double-hull approach but has been criticized for not having a method of evaluating whether new approaches might offer equal or better protection.

As context for the discussion in the following chapters, the remainder of this section presents a review of relevant trends in oil tanker transportation in U.S. waters, the U.S. flag tanker fleet, tanker accidents and oil spills, and new tanker design and construction. A brief summary of the salient regulatory changes and the industry response to those changes is also provided.

Relevant Trends

Oil Tanker Transportation in U.S. Waters

Total world trade of oil by tanker is near its highest level since the early 1980s. Within this overall trend, tanker trade to the United States is growing, while that to some other regions of the world is declining. U.S. oil consumption has been increasing at the same time that domestic oil production has been decreasing; imports have thus been growing at a steady rate. Oil imports were at about 5 million barrels per day in the mid-1980s and are now above 10 million barrels per day. In 2000, the United States imported about 8.8 million barrels of crude oil and about 2.1 million barrels of product each day. These trends point to continuing growth in tanker traffic in U.S. waters (EIA 2000).

The world tanker fleet is near record high levels and consists of more than 3,500 ships totaling about 300 million deadweight tons (DWT). It is not possible to isolate the portion of the world fleet that only carries petroleum to the United States, but looking at the fleet as a whole (Table 1-1) provides a reasonable picture of the proportion engaged in U.S. trade. Another illustration of the growing oil tanker trade in U.S. waters can be found in data on the number of U.S. port calls for tankers, which show a steady growth throughout the 1990s from about 3,300 annual port calls in 1990 to about 4,400 in 1998 (NRC 1998).

The above data illustrate the growing importance of imported oil to the United States and the continuing increase in tanker traffic in U.S. waters. This trend will probably continue in the short term as U.S. oil production drops further and most sources of imports continue to be predominantly in locations served by tankers.[4] At the same time, the conversion of the world fleet to double-hull ships is continuing at a fairly steady rate, and these ships will make up a majority of tankers operating in U.S. waters within a few years.[5]

U.S. Flag Tanker Fleet

The U.S. flag tanker fleet is not engaged in transporting oil imported to the United States, but rather consists of a small number of vessels either carrying refined products from one U.S. port to another or transporting crude oil from Alaska to refineries in the lower 48 states. U.S. law (Title 46, USC 388) requires that all vessels engaged in U.S. coastwise trade be built in this country and operated under U.S. flag. A few new tankers have been built for registry in the United States since the passage of OPA 90, but the fleet still consists mainly of older double-hull and single-hull vessels. The phase-out requirements of OPA 90 are in full force, but because of time-frame allowances, the demise of the U.S. flag single-hull tanker fleet is

[4] According to the U.S. Department of Energy (2000, p. 5), "U.S. crude oil production is projected to decline at an average rate of 0.7% from 1999 to 2020 to 5.1 million barrels per day. Advances in exploration and production technologies do not offset declining resources. . . . Percent net imports are projected to increase from 51% in 1999 to 64% in 2020."

[5] Proposed IMO amendments to MARPOL Regulation 13G would accelerate the replacement of the existing single-hull world tanker fleet by double-hull or equivalent designs as approved by IMO.

TABLE 1-2 U.S. Flag Tanker Fleet, Numbers and Deadweight

Size (thousands of DWT)	Numbers in Fleet	Fleet (millions of DWT)	Number of Double-Hull Ships	Double Hulls (millions of DWT)	Double Hull Share[a] (%)
10–60	59	2.3	18	0.7	31
60–80	6	0.4	0	0	0
80–120	8	0.7	0	0	0
120–200	18	2.7	3	0.4	14
200+	4	1.0	0	0	0
Total	**95**	**7.1**	**21**	**1.1**	**15**

NOTE: Figures shown are as of mid-2000. They do not include four tankers that were converted from single-hull to double-hull and three double-hull fleet oilers that were operated by the Military Sealift Command.
[a] Based on DWT.
SOURCE: Personal communication, A. Landsburg, U.S. Maritime Administration, Dec. 15, 2000.

yet to come. The future demand for U.S. flag tankers is less clear because other options are available for transportation of domestic oil.

Table 1-2 shows the status of tankers in the U.S. flag fleet as of mid-2000, according to data supplied to the committee by the U.S. Maritime Administration. About 15 percent of the fleet is now double-hull, but it includes only six vessels (about 0.2 million DWT) that were built recently (in the 1990s) and four existing single-hull tankers converted to double-hull through the addition of new forebodies. Not shown in the table are 12 new double-hull tankers for the domestic trade that were under construction or contracted in U.S. shipyards as of the end of 2000.[6] There has also been some recent construction of new double-hull tank barges, as well as modification of single-hull tank barges to double-hull. Thus, while there is little prospect for much future growth in the U.S. flag tanker fleet, new double-hull vessels are gradually replacing the older vessels in this small, specialized fleet.

Tanker Accidents and Oil Spills

The most recent data on oil spills in U.S. waters show a reduction in both the number of spills and the amount of oil spilled during the past decade at the same time that oil shipments and tanker traffic have been increasing. The worldwide trend also appears to be characterized by reductions in spill amounts, but complete data are not available, and the evidence here is less compelling. The committee commissioned a brief analysis of existing worldwide data on annual amounts spilled as a result

[6] These include contracts for three Alaska Class oil tankers, with options for three more, with National Steel and Shipbuilding Co., San Diego, California, for BP Oil Shipping Co.; and contracts for four tankers, with options for two more, with Avondale Shipyard, New Orleans, Louisiana, for Phillips Petroleum Co.

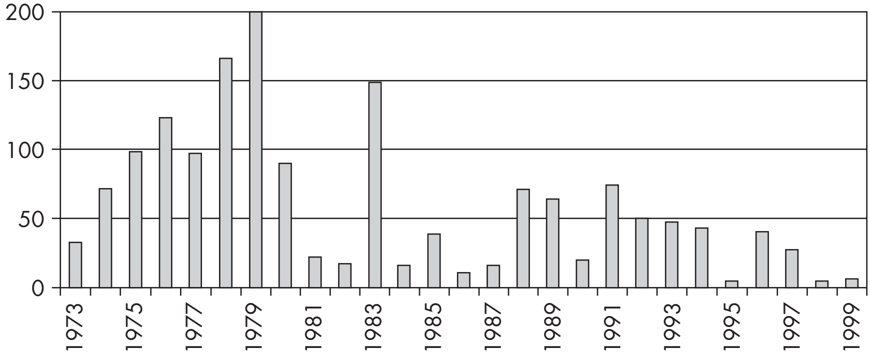

FIGURE 1-1 Oil spills of more than 2,000 gallons resulting from tanker accidents worldwide (in millions of gallons), 1973–1999 (Etkin 2000).

of tanker accidents for each year from 1973 through 1999; the results of this analysis are shown in Figure 1-1.[7]

For trends in spills in U.S. waters, the committee received data collected and published by USCG in October 2000, which are illustrated in Figures 1-2 and 1-3. Figure 1-2 shows a dramatic decrease in oil spills from tanker accidents in U.S. waters during the period 1973–1999. Figure 1-3 depicts spills from tanker accidents compared with those from other sources. These data reveal that tanker accidents (excluding barges) were responsible for about 10 percent of the oil spilled in U.S. waters during the 1990s compared with about 24 percent in the 1980s. These same data show a steady reduction in the amount of oil spilled in tanker accidents in U.S. waters in the 1990s compared with the previous two decades.

Although the number of spill incidents and the amounts of oil spilled have shown a meaningful decreasing trend in recent years, significant and large spills worldwide continue to characterize the industry. In addition, history has shown that one very large accident can change the statistics in a major way. It should be noted that most of the large catastrophic tanker accidents are single rare events, and the amount of oil spilled during these events tends to overshadow all other spills. Table 1-3 gives the largest tanker accidents worldwide during the past 25 years, ranked by amount of oil spilled. The *Exxon Valdez* spill was by no means the largest (it is 26th on this list), even though its effect was most significant in terms of U.S. perception and resulting policy changes.

[7] These data were prepared by Dagmar Etkin of Environmental Research Consulting and constitute a portion of the proprietary databases from that organization. NRC's Ocean Studies Board is currently working to develop more accurate estimates of worldwide oil spills, and the results are scheduled to be published in late 2001.

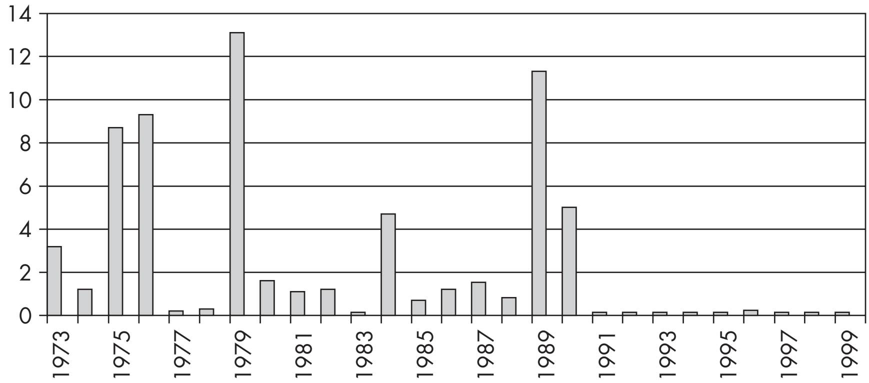

FIGURE 1-2 Oil spills resulting from tankship accidents in U.S. waters (in millions of gallons), 1973–1999 (USCG 2000).

The trend toward fewer tanker accidents and resulting spills has probably occurred because of many factors. While no attempt is made in this report to identify which causes have been most significant, a few comments are useful as context. Even though the world tanker fleet is gradually changing to double-hull construction, this change cannot as yet have contributed in a large way to a reduction in oil spills because of the difference in time frames. The available spill data, therefore, cannot be used to show the effectiveness of any specific tanker design alternative. Consequently, this committee has concluded that the only practical method available for evaluating the effectiveness of alternative tanker designs in reducing spills is to employ some form of predictive modeling.

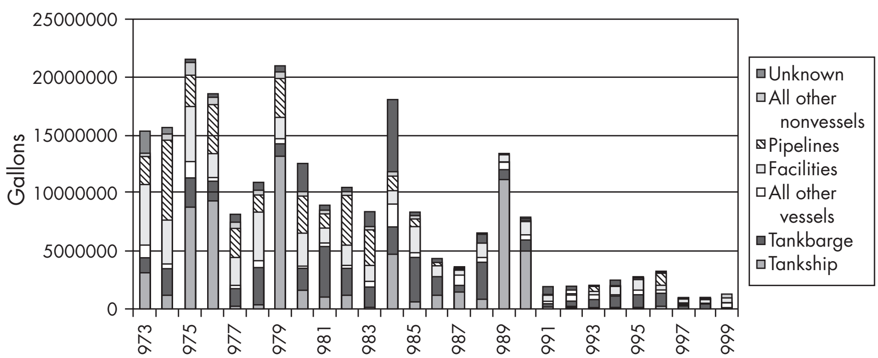

FIGURE 1-3 Trends in oil spills resulting from marine accidents in U.S. waters: total volume of spills by source (in gallons), 1973–1999 (USCG 2000).

TABLE 1-3 Thirty Largest Tanker Spills Since 1975 (*Oil Spill Intelligence Report* 1997)

Vessel	Year	Spillage (Millions of Gallons)	Location
Atlantic Empress	1979	84	Caribbean
Castillo de Bellver	1983	79	Atlantic
Amoco Cadiz	1978	68	France—Atlantic
Odyssey	1988	43	Canada—Atlantic
Haven	1991	42	Mediterranean
Irenes Serenade	1980	37	Mediterranean
Hawaiian Patriot	1977	31	Hawaii—Pacific
Independentza	1979	29	Bosporus Strait
Urquiola	1976	28	Spain
Braer	1993	25	Shetland Islands
Jacob Maersk	1975	24	Portugal
Aegean Sea	1992	22	Spain
Sea Empress	1996	21	United Kingdom
Nova	1985	21	Persian Gulf
Khark 5	1989	20	Morocco—Atlantic
Epic Coloctronis	1975	18	Caribbean
Katina P	1992	16	Mozambique
Assimi	1983	16	Gulf of Oman
ABT Summer	1991	15	Angola—Atlantic
Andros Patria	1978	15	Bay of Biscay
British Ambassador	1975	14	Pacific
Pericles GC	1983	14	Persian Gulf
Tadotsu	1978	13	Strait of Malacca
Juan A Lavalleja	1980	11	Algeria
Thanassis A	1994	11	South China Sea
Exxon Valdez	1989	11	Alaska—Prince William Sound
Burmah Agate	1979	11	Texas—Gulf of Mexico
Athenian Adventure	1988	11	Canada—Atlantic
Borag	1975	10	East China Sea
St. Peter	1975	10	Columbia—Pacific

Using its existing data, USCG compiled for the committee an analysis of 1,660 tank vessel collision[8] and grounding incidents in U.S. waters that occurred during the past 20 years. About half of these were collision and the other half grounding incidents. Most of the incidents did not result in any spillage of oil: only about 250 of the incidents involved oil spillage, and only a few resulted in large amounts of spill.

[8] For the purposes of this discussion, the term *collision* is defined as including both collisions (between two moving vessels) and allisions (between a moving vessel and a fixed object).

Indeed, the three largest spills represented about 85 percent of the total amount spilled. In about 70 of the collision and grounding incidents involving oil spills recorded during this 20-year period, more than 100 gallons was spilled. These data also illustrate the current trend toward less oil being spilled as a result of tanker accidents in U.S. waters, as well as the scarcity of available recorded incidents in a form necessary for a rigorous statistical analysis.

New Tanker Design and Construction

As noted above, the world tanker fleet has gradually been changing to double-hull construction to comply with U.S. regulations that followed passage of OPA 90. Some of the first double-hull tankers built primarily in anticipation of both OPA 90 and IMO double-hull standards were characterized by single cargo tank configurations: there were no longitudinal bulkhead divisions in the cargo tanks. These designs raised questions for both the industry and regulators about whether such configurations had the potential to result in unexpectedly large oil outflows for some incidents. The designs also posed restrictions during cargo operations to which not all tanker operators were accustomed. This issue was subsequently addressed by IMO, classification societies, and USCG, and was examined in an NRC (1998) report. The latter included a recommendation to improve the double-hull standards, along with specific recommendations relative to the reference vessels that are used as a basis for comparing alternative designs in the current IMO process. While the configuration issue has been largely resolved, it illustrates the fact that future developers of innovative designs should recognize the potential for unanticipated problems, and regulations need to have enough flexibility to address such problems adequately.

Regulatory Changes and Industry Response

In 1990, following the grounding of the *Exxon Valdez* in Prince William Sound in March 1989 and the spillage of more than 11 million gallons of crude oil into Alaskan waters, the U.S. Congress promulgated OPA 90. The intent of this law was to minimize oil pollution through improved tanker design, enhanced operational safety, and other actions designed to improve oil spill cleanup capabilities. Section 4115 of OPA 90 mandated changes in ship design and construction to prevent or minimize spillage in accidents by establishing the double-hull requirement for tankers transporting oil in U.S. waters and calling on U.S. ports. The legislation required that all new tank vessels operating in U.S. waters be equipped with a double hull, with the exception that tank vessels of less than 5,000 gross tons could be equipped with a "double containment system" determined by the Secretary of Transportation to be as effective as a double hull [OPA 90, Sec. 4115(c)(2)]. These requirements apply to all tankers operating in U.S. waters, not just to U.S. flag vessels.

OPA 90 had a worldwide impact on the international regulatory regime in the form of two additions to MARPOL 73/78. Regulation I/13F (MARPOL 13F) and Regulation I/13G (MARPOL 13G) for practical purposes mandated a worldwide transition to double-hull vessels or their equivalent. However, USCG has not accepted MARPOL Regulation I/13F for comparison of alternatives, in part because it is believed to place too little emphasis on zero outflow probability (i.e., the prevention of small spills) and in part because the IMO approach is regarded as conflicting with the intent of OPA 90 (see Box 1-1).

The international tanker industry does not generally support the imposition of regulatory requirements for prescriptive ship design features

BOX 1-1 U.S. Statement of Nonacceptance of MARPOL Regulation 13F

"In 1992, the United States Embassy in London formally deposited a declaration with IMO stating that acceptance of MARPOL Regulations 13F and 13G would require the express approval of the U.S. Government to enter into force for the United States.

The U.S. reservation against MARPOL 13F is based on conflicts with OPA 90, as follows:

1. Applicable vessel size: OPA 90 applies to all tank vessels regardless of size, whereas MARPOL 13F doesn't apply to tank vessels less than 600 GTs;
2. Applicability dates: OPA 90 applies to tank vessels contracted for construction after 30 June 1990 (or delivered after 31 December 1993) whereas MARPOL 13F applies to tank vessels contracted for construction after 5 July 1993 (or delivered after 5 July 1996);
3. Allowable designs: OPA 90 *only* allows double hull construction whereas MARPOL 13F also allows the mid-deck design, and provides for acceptance of other possible alternatives."

such as double hulls. Nonetheless, since the passage of OPA 90, most of the industry has gradually come to accept double-hull tankers as the standard with which the world fleet will comply over time. Thus the industry as a whole (shipbuilders, owners, and operators) has neither lobbied in favor of alternatives to the double-hull tanker nor rallied to support research designed to measure the effectiveness of such alternatives. The industry has no strong interest in promoting double-hull alternatives because it has already made significant investments in new double-hull tankers and gained public support in doing so. This is not to say that some in the industry would not support alternatives, but they would do so only if they (*a*) had political support and (*b*) did not incur liability for minor spills as the result of characteristics of the type proposed. Indeed, some industry members want to encourage the development of alternative designs, primarily because they consider double hulls to pose safety risks and to be more difficult to salvage when involved in major incidents. They continue to stress the need to evaluate alternatives that may offer superior effectiveness, to encourage research into new designs and advanced technology, and to press for the adoption of measurable performance standards based on desired environmental goals. Because the industry is fragmented in its response to the regulations and the politics of the issue dictates a low profile on any matter related to spilled oil, there is no consensus and no pressure on the industry to take a public position.

There are primarily two organizations that speak on behalf of tanker owners and operators: the International Association of Independent Tanker Owners (INTERTANKO) and the Oil Companies International Marine Forum (OCIMF), the former representing independent tanker owners and the latter fleets owned or controlled by oil companies. Within those two groups are many different interests and values that may reflect political needs or public image, among other things. Both organizations are facilitators for consensus, not governors of policy.

SCOPE AND APPROACH

The focus of this report is on the committee's development and application of a computational methodology for comparing the environmental performance of alternative tanker designs. A description of how the methodology was developed is given, an initial example of its application is provided, its strengths and limitations are reviewed, and ways in which it can be further developed and implemented are discussed. The methodology does not provide all of the information necessary for regulators (in this case, USCG) to approve a design, but it can serve as a tool for comparing alternative tanker designs against a specific double-hull standard. When fully implemented and used in conjunction with other tools, this methodology will allow USCG to determine whether a specific alternative design should be approved. To use this methodology appropriately, USCG will have to develop a double-hull standard for each vessel size to be compared, thus creating reference ships similar to those used in the current IMO methodology.

As a first step, the committee reviewed and updated the IMO tanker damage extent functions and their application to the crashworthiness of tank vessel structures. The committee also investigated historical data on oil spill costs and the potential for using these data to calculate an environmental index. Finding that historical data do not provide a basis for evaluating new design concepts, the committee developed its own models of tanker accidents, structural damage, oil outflow, and resulting environmental consequences. For this purpose, hypothetical spill scenarios at typical locations in U.S. coastal and harbor waters were used to represent the conditions prevailing in future situations involving tanker transport into U.S. oil ports and terminals. The results of the structural damage and outflow models were combined with those of the spill consequence models to provide a comparative index of performance that is described in this report.

Models and model results are used for a number of steps in the methodology and are discussed throughout the report. Although models are essential tools, they are only estimates, and the reader should note that uncertainty is always present. When applying the recommended methodology, it is important to understand this uncertainty by examining the upper and lower bounds of numerical results. Moreover, the methodology is limited to comparison of performance in collision and grounding accidents. It does not address such issues as safety, risk of fire and explosion, operational considerations, or structural integrity during normal operations, all of which are important when evaluating alternative designs. The committee's methodology must therefore be used in conjunction with other evaluation measures and judgment.

Consistent with its charge, the committee did not perform a complete risk assessment of a tanker design or use its methodology to determine overall risk levels for tankers; rather, the methodology was used only to measure relative effects of environmental consequences from collision or grounding accidents as compared with the double-hull design. The committee also conducted some tests to demonstrate how the methodology might be applied. These tests were not intended to evaluate any specific design, but only to illustrate the applicability of the methodology. In addition, in this report a description of how regulators might wish to apply the methodology along with other measures of overall risk is given, appropriate cautions regarding its limitations are noted, and the data required for its full development and application are identified.

ORGANIZATION OF THIS REPORT

Previous methods used to evaluate alternative tanker designs; alternatives proposed to date; and the various historical databases on spill costs, damage statistics, and collision and grounding are reviewed in Chapter 2. The methodology developed by the committee is detailed in Chapter 3. In Chapter 4, the application of the methodology is illustrated through a description of its use to compare two alternative designs with double-hull designs of comparable size. The committee's conclusions and recommendations are given in Chapter 5.

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ABBREVIATIONS

DOE	U.S. Department of Energy
EIA	Energy Information Administration
IMO	International Maritime Organization
NRC	National Research Council
USCG	United States Coast Guard

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2

ASSESSMENT OF PREVIOUS EVALUATION METHODS, PROPOSALS FOR ALTERNATIVE DESIGNS, AND HISTORICAL DATABASES

Past efforts to develop methodologies for evaluating alternative tanker designs and the proposals that have been submitted for approval to regulatory authorities for designs that might provide performance equivalent to that of double hulls are summarized in this chapter. In the comprehensive report entitled *Tanker Spills: Prevention by Design* (NRC 1991), the alternative designs that were available as of the date of that study are reviewed, and their effectiveness is evaluated. The discussion in this chapter focuses on more recent design proposals and potential approaches to measuring equivalency. Also discussed are the limitations of historical databases with regard to spill costs, damage statistics, and collision and grounding incidents. A brief review of quantitative risk-assessment techniques and their application to the present study is given in the final section.

PREVIOUS EVALUATION METHODS AND THEIR LIMITATIONS

In 1989 USCG commissioned an NRC study of tanker designs and their pollution-prevention qualities. The study report (NRC 1991) includes an assessment of whether other structural and operational tank vessel requirements would offer protection for the marine environment equal to or greater than that provided by the double-hull design (based on oil outflow following an accident). The 1991 report describes the evaluation of a number of design variations known at that time. Several were believed to have the ability to reduce oil outflow, but either sufficient detail was not provided or technical features were still evolving, so that further study was needed to assess the design concept. The NRC report identifies four oil spill control methods under which all designs can be catalogued:

- Barrier: In addition to the outer hull, provides a secondary obstacle to the loss of cargo in the event of an accident.
- Outflow management: Restricts the amount of cargo subject to outflow and is either passive (through smaller tanks) or active (by manipulation of hydrostatic balance or cargo transfer).
- Increased penetration resistance: Controls the worst case through a more absorbent hull that transfers the momentum from an impact, resulting in a hull that is crushed rather than ruptured.
- Accident response: Minimizes the loss of oil from an accident through either systems that monitor accident conditions or features that assist with salvage operations.

A major conclusion of the study was that "the committee did not identify any design as superior to the double hull for all accident scenarios" (NRC 1991, xxi). However, the committee recommended that other design alternatives proposed in the course of future research be considered.

Following passage of the OPA 90 legislation, USCG also commissioned a study (Herbert Engineering Corporation 1992) to assess the environmental performance of alternative designs on the basis of the calculation of three measures of merit:

- The likelihood that the design will not spill oil given a collision or grounding that breaches the outer hull, generally referred to as the "probability of zero outflow";
- The mean or average expected outflow from a collision or grounding; and
- The extreme outflow, which is a measure of the expected outflow in the most severe collision or grounding.

USCG subsequently submitted a report to Congress on alternatives to double-hull tank vessel design (USCG 1992), incorporating the conclusions of the NRC and other studies (e.g., Herbert Engineering Corporation 1992). USCG determined that certain alternative designs exhibit superior mean outflow and extreme outflow characteristics as compared with a double hull. However, the likelihood of a spill following a collision or grounding was found to be higher for all of the alternative designs investigated. Since double hulls were projected to have fewer spills, the conclusion of the study was that none of the alternative designs exhibited environmental performance equivalent to that of double hulls. The report notes further that tanker design is only one facet of the "total safety and pollution prevention system" and suggests that other measures affecting safe vessel operations and management should be pursued. The many shortcomings of existing evaluation methodologies are also cited, and further work in this area is recommended.

USCG and others have supported work aimed at developing methods for predicting the effects of a collision or grounding on the hull structure of a ship. This work will add to current understanding of the structural performance of tankers during accidents. It will also be needed for future analyses of accidental oil outflow for any new tanker designs proposed. It has not, however, led to the development of a comprehensive methodology for evaluating equivalency to double-hull designs.

The IMO method of comparing alternative designs (IMO 1996) uses a formula that assigns relative weighting factors to the three parameters related to spill size noted above (zero, mean, and extreme outflow).[1] The weighting factors used are based on a decision by IMO to select a formula that would ensure the equivalency of the double hull and the middeck design (discussed below), but they provide no measure of the possible environmental damage itself (Sirkar et al. 1997). However, the IMO method is probably the only one that is described fully enough for practical application to an actual design and in fact has been used for that purpose (see below).

The committee has reviewed the IMO methodology and considered the implications of its use, as well as its limitations. In the methodology, damage to a ship is described by damage extent and damage location distributions, which are based on limited historical damage data. The distributions are the same for each type of design, and there are no cases in which the outer hull is not damaged. The outflow distribution and the outflow parameters (zero, mean, and extreme outflow) are determined by analyzing all possible damage cases corresponding to the damage distributions. The outflow parameters are then combined into an environmental index using weighting factors. The fact that IMO's choice of weighting factors cannot be related to any real measures of environmental consequence in itself would appear to eliminate the method from consid-

[1] Appendix C describes the IMO methodology in detail.

eration. Moreover, the historical distributions of ship structural damage are not applicable to new designs, particularly to those incorporating structural innovations. Therefore, the committee believes IMO's work on vessel accidents, structural damage, and oil outflow probabilities is most valuable, but cannot be directly adapted to a more rigorous methodology. Both the structural resistance involved in grounding and collision and a more appropriate measure of relative environmental consequences must be incorporated into a new scheme.

As noted, USCG has used an evaluation method in its decisions concerning double-hull alternatives that incorporates estimates of the above three oil spill outflow ranges (zero, mean, and extreme). These estimates are made using the same damage distributions and the same approach used by IMO. USCG then applies its judgment concerning the primary importance of the zero outflow factor without resorting to any weighting factors for these three ranges. USCG places the greatest emphasis on avoiding all spills because it interprets the Clean Water Act as prohibiting any such discharges.[2] However, the environmental consequence judgment required by this policy cannot be expressed quantitatively in a rigorous analysis. Currently, then, USCG does not have in place a well-specified methodology for evaluating the equivalency of alternatives to double-hull tankers.

A number of researchers have investigated methods of applying the past work on probabilities of zero, mean, and extreme outflows to some appropriate surrogate for environmental damage related to spill size. The most developed and recent work on this approach was published by Sirkar et al. (1997). The authors attempt to establish an analytical means of assessing the relative importance of the different measures of merit. The authors also propose that total cost of a spill as a function of its size could be used as a surrogate for relative environmental impact from accidental tanker spills. In conducting their study, the authors found that the available data on historical spill costs were not sufficient, and they suggest that additional data be collected to carry out the proposed analysis. However, many believe that cost as a function of spill size is not a reliable measure of environmental impact because several factors other than the size of a spill (e.g., location, weather conditions) greatly influence its cost. This issue is discussed below, as well as in the description of the committee's methodology and its application in Chapters 3 and 4, respectively.

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[2] The Federal Water Pollution Control Act of 1972 states: "The Congress hereby declares that it is the policy of the United States that there should be no discharge of oil or hazardous substances into or upon the navigable water of the United States." OPA 90 is an amendment to this act.

While the present study does not include an evaluation of any of the specific concepts proposed to USCG or IMO (as presented in the next section), it is important to note that any future evaluation methodology adopted must be able to accommodate the review of such proposals. Some of the important features of an appropriate methodology are discussed below.

First, it is important that an evaluation methodology be clearly understood by all parties and consistently applied to all proposals. A specific set of requirements for proposals should be published, including detailed instructions as to what design and test data are needed and in what form. Furthermore, the double-hull standard reference ship used for comparison must be defined in a clear and unambiguous manner. The application of the methodology should also be as transparent as possible so that each person or company submitting a proposal will know all the evaluation criteria to be used.

In addition, the methodology should accommodate the variety of conceptual approaches that may be expected. From past experience, it is clear that both passive and active systems in many combinations may be submitted.[3] Also, systems with new and unique materials reflecting different performance characteristics must be considered, since they pose unique problems. Finally, it should be noted that some proposed systems have performance histories while others do not, and the methodology must provide a way to evaluate and consider the relative merits of both.

PROPOSALS FOR ALTERNATIVE DESIGNS

Even though the U.S. requirements for double-hull tankers reviewed in Chapter 1 have had the effect of setting an international standard (because most tankers may trade in U.S. ports at some time), the international community has investigated a number of alternative designs in recent years. Design proposals for alternatives to double-hull oil tankers have come from many sources and continue to be put forward with the anticipation that, if they have proven merit, they will gain needed support from both the industry and regulators. Since both USCG (for the United States) and IMO (representing the international community) have regulations addressing the design of oil tankers (see Chapter 1), those who propose

[3] A *passive* system is defined as one that is integral to the vessel's structure and requires no moving parts or action by a third party to be effective. A double-hull vessel is an example of a passive system. An *active* system is defined as one that requires, in whole or in part, an action by a third party or system to be effective. An emergency transfer system is an example of an active system.

alternatives usually submit them to either or both of these agencies. The following discussion therefore draws on reports from both USCG and IMO to describe the designs that have been proposed.

Alternative Designs Proposed to IMO

In 1992, IMO adopted both the double-hull tanker (submitted by the United States) and the mid-deck tanker (submitted by the Japanese government) as acceptable design types to replace the world's single-hull tanker fleet. Adoption of these designs led to the establishment of the IMO regulation permitting alternative designs that meet the stated requirements for equivalent weighted outflow. The mid-deck design was reviewed for the 1991 NRC report as well; the conclusion reached was that the design had potential but needed more study. The only other design IMO has approved since 1992 is the Coulombi Egg concept, proposed by the Swedish government, which was determined to meet the IMO equivalency test for design approval in 1997. One other design that received some international attention is the Polmis concept (proprietary), proposed by a German organization, but it was never formally submitted to or approved by IMO.

The mid-deck design concept utilizes hydrostatic pressure balance in lower cargo tanks (below the mid-deck) to prevent or minimize oil loss upon bottom damage and wide wing tanks to protect against oil loss upon side damage. It thus has a double side and single bottom, plus a horizontal deck placed so that internal pressure in tanks below the deck is significantly lower than the external sea pressure. The mid-deck design meets the minimum wing tank width requirements contained in IMO regulations. According to a report prepared for USCG (Herbert Engineering Corporation 1992), the mid-deck design has the most favorable extreme outflow performance and less favorable zero outflow performance following bottom damage.

The Coulombi Egg design is a special variation on the mid-deck concept with a mid-deck, cofferdams, and sloping bulkheads in the wing ballast tanks. It utilizes hydrostatic pressure balance plus overflow into wing ballast tanks to minimize oil loss upon bottom damage. When originally submitted to IMO, this design included active systems; since the submission did not provide an appropriate safety assessment of those systems, however, they were deleted from the final approved design, and other modifications were made to the passive system to ensure approval.

The process by which IMO approves an alternative design requires that a proposal be submitted by a government to the international organization. To date, only the one proposal noted above (Coulombi Egg) has been submitted to and approved by IMO. As of this writing, the committee could find no other active proposal for an alternative design within the international community.

Alternative Designs Proposed to USCG

Table 2-1 provides a list of design alternatives that were proposed and evaluated by various parties prior to USCG's 1992 report to Congress. They include all of the concepts evaluated in the 1991 NRC report plus those mentioned above that were submitted to IMO. They also include the underpressure system, a design still being actively developed by a U.S. company. This design uses an active vacuum pumping system, which is then blanketed by an inert gas system in the oil cargo tanks to limit oil outflow upon bottom damage. The Herbert Engineering (1992) study prepared for USCG before its 1992 report to Congress evaluated the mid-deck, Coulombi Egg, and Polmis concepts.

Since 1992, a number of additional proposals have been submitted to USCG for consideration; USCG provided the committee with information on 14 of these proposals for this study (see Table 2-2). In addition to these 14, the committee received information on one other active proposal for a design concept—the central ballast tank design—

TABLE 2-1 Tanker Design Alternatives Proposed to USCG Before 1992

	Where Evaluated		
Design Concept	NRC (1991)	IMO (1992)	Herbert Engineering (1992)
Protectively located segregated ballast (MARPOL tanker)	X		
Double bottom	X		
Double sides	X		
Double hull	X	X	X
Resilient membrane	X		
Hydrostatic balance	X		
Intermediate oil-tight deck (mid-deck)	X	X	X
Vacuum systems (underpressure)	X		X
Smaller tanks	X		
Penetration-resistant hulls	X		
Emergency oil transfer systems	X		
Polmis concept			X
Coulombi Egg concept		X	X

TABLE 2-2 Tanker Design Alternatives Proposed to USCG from 1992 to 1999

Date Submitted	Concept Description	Remarks
October 1992	Emergency transfer system (to center tanks)	
April 1993	Concrete hull	Proprietary
May 1993	External protective hull retrofit	For existing tankers
June 1993	Emergency transfer system to containment bag	
November 1993	Flexible membrane tank liner	
January 1994	Collision-resistant double hull	
January 1994	Fiberglass-reinforced plastic tanks	Proprietary
March 1994	Onboard oil spill recovery system	
November 1994	Takes exception to IMO weighting factors	
January 1995	Liquid cargo containment system	Proprietary
February 1995	Flexible internal tank liner	
July 1998	Self-sealing cylinder for double-hull vessel	
March 1999	Arrangement with independent tanks	
April 1999	Concrete hull	Proprietary

SOURCE: Letter from USCG to TRB, Aug. 12, 1999.

from its developer, Marine Safety Systems, Inc., of Houston, Texas (Marine Safety Systems, Inc. 1997). This design has not been submitted formally to USCG for evaluation; however, it has been under development for several years, and its developer has prepared evaluations of its performance using the IMO methodology. The central ballast tank design places ballast tanks in the center of a tanker and provides an active transfer system to move oil by gravity from damaged cargo tanks to the central ballast tank. The design also includes a double bottom to protect against outflow in the case of bottom damage. As of this writing, only the developer has prepared a detailed oil outflow performance analysis for the central ballast tank design.

The 14 concepts submitted to USCG after 1992 reflect a range of development and evaluation to date. Some include detailed schematics and test results, while others are merely short letters describing a design idea. Four of the proposals were submitted as proprietary and thus are not available for public review. Some of the proposals were submitted for the purpose of requesting USCG approval of a concept for new tankers, while others could be considered for both new and existing tankers. One was intended specifically for existing tankers. Each submittal included a request that USCG approve the concept under OPA 90.

To date, USCG has not approved any proposed alternative tanker design concepts as equivalent to the double hull. It has replied to those submitting proposals that the concepts will be evaluated according to the three measures of oil outflow noted above using the methodology set forth in USCG's 1992 report to Congress. As noted earlier, however, USCG currently has no fully developed methodology for evaluating alternative designs.[4]

LIMITATIONS OF HISTORICAL DATABASES

Cost Data

As noted in Chapter 1, the committee's charge included specific reference to environmental and spill cleanup costs:

> The committee will also develop a generalized spill cost database, which includes all relevant costs such as clean-up costs and environmental spill costs, and use this cost database to assist in developing a rationally based approach for calculation of an environmental index.

The intent of this charge was clearly to apply the historical record of oil spill consequences, as reflected in reported costs, as a basis for comparing alternative tanker designs.[5] The committee addressed this charge in two steps: the types of information that would appropriately belong in such a database were first reviewed, and available existing databases were then examined to determine whether they met the committee's predefined criteria for inclusion.

The committee considered the types of data that appropriately belong in a spill consequence database to be applied in a regulatory setting. From an economic perspective, a regulatory process should involve comparison of available alternatives on the basis of net economic effects. That is, economists look to monetize all the impacts of a set of regulatory alternatives and to select the alternative with the greatest net benefits. Impacts can be positive (benefits such as reduced environmental damage) or negative (costs such as increased investment in equipment

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[4] USCG has allowed use of the IMO methodology for evaluating the equivalency of those double-hull tankers built prior to the implementation of OPA 90 that are not in full compliance with the act's double-hull clearance requirements. In such evaluations, USCG has required that both the probability of zero outflow and the mean outflow be superior to those of the reference tanker having the minimum double-hull dimensions mandated by OPA 90.

[5] The term *costs* as used in the committee's charge encompasses the monetized value of all deleterious human health, economic, and environmental consequences of oil spills. The committee has chosen instead to use the term *consequences* to better reflect the range of monetizable and nonmonetizable effects of oil spills. The term *cost* is used more typically in the context of regulatory cost–benefit analysis to reflect the costs incurred by regulated entities (e.g., businesses), government agencies, and the public. Avoided deleterious effects in this context are generally referred to as *benefits*. In addition, the economic implications of oil spills are generally referred to as *damages* in the context of natural resource damage assessment; that term is used in this report to represent the physical change in a ship due to a grounding or collision.

needed to meet a requirement). In the present case, a regulatory standard has already been selected and implemented. At this time, the overall cost–benefit ratio for the double-hull requirement is not up for discussion. Instead, the committee was asked to consider whether alternative designs could achieve the same or a more favorable net economic effect relative to the double hull.

In a simple world, every gallon of product released to the environment would result in the same level of economic consequence. There would be no need to address consequences because alternative tanker designs could be compared solely on the basis of the expected distribution of oil released. It is the committee's assumption, however, that the consequences of oil spills, on average, are not a constant function of spill size. For example, an alternative to the double-hull design may reduce the probability of small spills but increase the probability of a catastrophic release. Which of these distributions of expected releases is preferred will depend on an understanding of the consequences of the releases for human health, the economy, and the environment.

A variety of consequences result from oil spills. However, because not all of these consequences represent true changes in social welfare (i.e., the overall well-being of all members of a society or community), they are not necessarily relevant for purposes of regulatory review. The following are examples:

- An oil company may pay a fine as a result of a release.
- An insurance company may settle out of court with a group of businesses affected by a spill.
- Liability limits may allow a firm to avoid paying some damages, while additional damages may or may not be collected from a central fund.

In the case of fines, no real economic cost is represented. Instead fines, while clearly affecting a firm's bottom line, represent transfer payments between parties and thus not a net change in social welfare.[6] In the case of a settlement amount, one would need to understand the basis of the settlement to understand whether it represented a true measure of social welfare loss. For example, a settlement with a private party affected

[6] A parallel example is automobile speeding tickets. The "price" of these tickets is not based on the economic benefits expected to result from encouraging lower driving speeds (lives saved, accidents avoided), but on a variety of political and social factors (e.g., the cost of issuing a ticket, the fine that is perceived to generate the desired reduction in speeding). Thus, the economic benefit resulting from lower speed limits is not equal to the revenues generated through additional fines.

by a spill might reflect the revenues lost by the party, but not the economic surplus losses suffered by consumers of the good or service provided by that party. Similarly, the fact that a legally defined liability limit exists does not change the underlying welfare losses that could result from a spill, only the financial exposure of the spiller.

Since much of the spill-cost data available in the United States relates to natural-resource damage claims, it is important to understand these measures of consequence. Specifically, the amount recovered by a natural-resource trustee may not be equal to the true social welfare loss due to the releases. For example, trustees can recover the full value of lost revenues and fees resulting from a release (e.g., a beach closure that results from a spill might lead to a state park being closed and thus the loss of admission fees). In addition, trustees are directed to collect damages to "restore, replace or acquire the equivalent of" injured natural resources. The courts have interpreted this clause as allowing trustees to develop a restoration plan following a spill that may cost more or less than the actual social welfare loss due to the spill (i.e., there is no strict rule that the costs of restoration not exceed the economic loss resulting from a release). In the cost–benefit framework typically applied to regulatory review, one is not interested solely in restoration costs, but also in the economic loss associated with the damaged environmental resources prior to restoration. In some cases, restoration costs may reflect social welfare losses, but in many cases they will not. Finally, Natural Resource Damage Assessment (NRDA) settlements and awards do not address the loss of human life or value of lost product resulting from a release.

Overall, the committee adopted a framework for evaluating the appropriateness of available data in which economic consequences encompass the following:[7]

- The value of lost product,
- The cost of spill cleanup and response (private and public),
- The social welfare component of third-party damages (fisheries closed, waterways closed, recreationalists displaced),
- The social welfare value of human health impacts, and
- The social welfare value of the ecological change that results from a spill.

[7] Note that economic, ecological, and human health costs can result from a single spill, and thus consideration of multiple loss categories does not necessarily imply double counting.

The following costs should not be included in such a database:

- Fines, penalties, and punitive damage awards.
- Unreviewed settlements/court awards, since
  – Not all cases are pursued (or pursued with equal effort);
  – It is not always clear what cost categories were included in the settlement;
  – Settlements reflect a variety of factors unrelated to the true magnitude of the loss (e.g., litigation risk, political pressures); and
  – In the case of NRDA, settlements/awards may be based on environmental restoration costs, not the absolute level of social welfare change.
- Liability limits.

The committee identified and obtained a number of data sets that describe the costs associated with oil spills and compared these data against the criteria described above. These data sets included the following:

- Cutter Information Corporation's database (a commercially available database of spill cleanup and other costs);
- USCG's Liability Trust Fund database, which addresses cleanup and removal costs;
- A National Oceanic and Atmospheric Administration (NOAA) database of spill consequences (Helton and Penn 1999); and
- Data gathered from protection and indemnity clubs.

In some instances, there is overlap between these data sets. Overall, however, they reflect varying purposes, time periods, admittance criteria, and so on; and none meets the criteria described above. In addition, even if these data sets met all of the committee's criteria, the total number of salient events they reflect is quite small (fewer than 100 spills). Given the very large geographic and temporal scale of these databases, as well as the wide range of spill sizes represented, the resultant information base is quite sparse.

The committee considered whether it would be possible and appropriate to commission the development of a database that would meet the criteria defined above, demonstrate a high degree of quality control,[8] and include a large number of events. The committee decided that, even if such a data set could be established at little cost, the difficulties involved

[8] The need for greater quality control is illustrated by the fact that in some cases a cost estimate reported in a data set will reflect the costs as of a certain date, when in fact additional costs were incurred after the initial report.

in obtaining data from private entities and in estimating environmental consequences for cases in which no such estimate had been developed would make the resultant data set of limited use. In addition, because very few large-scale spills actually occur, it would be difficult to generalize from these limited events to generate a consequence model. As a result, the committee decided to develop a response function of spill characteristics (e.g., volume of spill, type of oil) using a modeling approach. The committee also concluded that the cost of an oil spill does not serve as an adequate surrogate for environmental consequences. In lieu of costs, therefore, the committee chose to use physical consequence measures. Moreover, the committee rejected attempting to measure the biota usage of affected habitats because of significant variability both seasonally and in abundance of species. Details on the committee's approach to these issues are provided in Chapters 3 and 4.

Historical Damage Data

In 1992, IMO gathered data on collision and grounding incidents for the period 1980 through 1990 in the process of drafting and adopting its interim guidelines for approval of alternative tanker designs under MARPOL (IMO 1996; see also Chapter 1). These data, provided by the International Association of Classification Societies (IACS), were used in assessing the probability of oil outflow using damage statistics for tanker accidents to provide probability density functions of the location and extent of damage for a contact accident. The incidents for which data were gathered included 62 collision and 68 grounding incidents by single-hull tankers or combination carriers.

The committee was asked to update and review these data. To this end, information was requested and received from Lloyds Register, Det Norske Veritas (DNV), and the American Bureau of Shipping for the period 1992 to 1998. Some of the data were not used because they were not in the format needed for analysis and comparison. The remaining data were limited with regard to the number of contact accidents (18 collision and 10 grounding). Again, all the data appeared to be for single-hull tankers. The committee developed histograms of both the original IMO data and the new data and found that the latter do not significantly change the original histograms. This finding is not particularly surprising given the limited number of new contact accidents and the fact that both data sets were for single-hull tankers. In any case, since the committee's task required taking crashworthiness into account, historical damage data were not applicable. Thus the new data were not a factor in the committee's modeling of collision or grounding events and structural damage.

Collision and Grounding Data for U.S. Waters

At the committee's request, USCG prepared an analysis of its accident and pollution data covering all tank vessel collision[9] and grounding incidents in U.S. waters during the past 20 years (1979 to 1999). Each incident is recorded with the date of its occurrence, vessel name and ID number, primary and secondary causes of the accident, amount of oil spilled (if known), and location. A total of 1,900 incidents was recorded during this time period.

A review of these 1,900 incidents shows that 1,660 could clearly be identified as either collision or grounding events. Of these 1,660 incidents, 47 percent were collision and 53 percent were grounding incidents. Most of the incidents recorded did not result in any oil being spilled. Only 55 collision and grounding incidents in this database involved any oil being spilled; of these, 51 percent were collision and 49 percent grounding. According to these data, then, collision and grounding of tank vessels in U.S. waters appear to occur with roughly the same frequency.

A review of these same data also shows that the three largest spills represented about 91 percent of the total amount spilled (23.6 million of the total 25.8 million gallons). Table 2-3 shows a breakdown of collision and grounding incidents during the 20-year period based on these data.

Fewer than 50 of these collision and grounding incidents resulted in a spill of more than 1,000 gallons of oil. The incidents occurred along all U.S. coasts and within major harbors and waterways, including New York Harbor, Delaware Bay, Galveston Bay, coastal Pacific Ocean waters, the Gulf of Mexico, and the Mississippi River. While the data representing tanker spills are relatively sparse, they provide some indication of the frequency of these types of incidents, where they have occurred, and the amounts of oil involved. The committee used these data to inform its development of accident scenarios and to indicate the possible range of distribution of accident events.

QUANTITATIVE RISK-ASSESSMENT TECHNIQUES AND THEIR APPLICATION TO SIMILAR PROBLEMS

For the reasons stated previously, there are serious questions about the reliability of data from virtually all existing sources for creating an analytical

[9] As noted earlier, for the purposes of this discussion, the term *collision* is defined as including both collisions (between two moving vessels) and allisions (between a moving vessel and a fixed object).

TABLE 2-3 Summary of Tank Vessel Collision and Grounding Incidents in U.S. Waters, 1979–1999

Sample	Total Number	Number of Collision Incidents	Number of Grounding Incidents	Proportion of Collision Incidents (%)	Proportion of Grounding Incidents (%)
All incidents	1,660	780	880	47	53
Polluting incidents	55	28	27	51	49

SOURCE: Letter from USCG to TRB, Aug. 12, 1999.

methodology for use in comparing tanker designs. While the IMO interim guidelines are useful as a starting point in developing any methodology, the fact that they were adopted after IMO had already accepted the double-hull and mid-deck tanker designs as equivalent has led to some question concerning the analytical soundness of the conclusions thus derived. Indeed, USCG and others in the United States have raised major questions about the weighting factors used in the IMO methodology. Moreover, using this methodology, an alternative design that was only marginally worse than a double-hull design for the probability of zero outflow but dramatically better with regard to mean and extreme outflow could reasonably be considered equivalent—something USCG's emphasis on zero outflow would not permit.

These considerations led the committee to look elsewhere for a more rigorous and defensible methodology. In the process, the committee reviewed previous NRC work (e.g., Garrick 1999), as well as work in progress elsewhere in the marine field. For example, the Technical University of Denmark currently has a contract to develop a risk-assessment model for vessel traffic in Danish waters. This model will incorporate the determination of collision and grounding probabilities based on traffic patterns and physical properties of waterways, calculation of damage extent in cases of collision and grounding, and an outflow calculation based on hydrostatic and hydrodynamic principles (Pedersen 2000). Similar work has already been completed for Prince William Sound in Alaska (DNV et al. 1996). These studies used a risk-based methodology.

For the past 25 years, the engineering community has been using risk-based methods to understand the inherent safety of complex systems. Notable in this history was the release of a nuclear reactor safety study (U.S. Nuclear Regulatory Commission 1975). This report was the first to set forth the logical questions now common in all formal risk assessments: What can go wrong? What is the likelihood? and What are the consequences? The same approach has been used extensively throughout the nuclear industry (e.g., Pickard, Lowe, and Garrick, Inc., et al. 1981) and in the energy, space, building, and chemical industries (e.g., Keeney et al. 1978; NRC 1991; Pate-Cornell and Fischbeck 1994; Rasmussen 1981).

On the basis of these historical applications, the expertise of committee members, and presentations on the use of risk analysis in previous work done by NRC, the committee decided to develop a risk-based methodology that would probabilistically generate realistic accident scenarios (for both collision and grounding) and use distributions of environmental consequences following a spill to compare the performance of proposed alternatives against that of a standardized double-hull vessel for all comparable sizes. The committee also refined or adopted modifications and improvements now available in the areas of structural damage assessment for both collision and grounding. The results of those efforts are detailed in the following chapter.

REFERENCES

ABBREVIATIONS

DNV	Det Norske Veritas
IMO	International Maritime Organization
NRC	National Research Council
SNAME	Society of Naval Architects and Marine Engineers
USCG	United States Coast Guard

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3

DESCRIPTION OF THE PROPOSED METHODOLOGY

As noted in Chapter 1, the committee developed an overall methodology for use by USCG in evaluating the relative environmental performance of alternative tanker designs following a collision or grounding accident. This methodology is intended for use in conjunction with other factors to determine whether USCG should approve an alternative design to a double-hull tanker. The key components of the methodology, the data needed for its implementation, and the nature of the results to be expected are described in this chapter. The status of the methodology's development and the efforts required to enable its routine application are also reviewed.

OVERVIEW

If a tanker runs aground or collides with another vessel,[1] the severity of the damage to the ship caused by the impact and the amount of oil spilled depend on the design of the tanker, its loading condition, mitigation efforts by its crew, the location of the impact, and the type of accident. Once the oil is in the water, the environmental, economic, and financial consequences of the spill will depend on the volume of oil spilled, the type of oil, the location of the spill, resources at risk, seasonality, and the weather conditions at the time of and after the accident, as well as any recovery and cleanup efforts. A rigorous evaluation of the environmental performance of a tanker should take all these variables into account. Moreover, all possible accident scenarios and their outcomes should be considered. In developing its methodology, the committee considered all the above factors, but to accomplish its mandate had to adopt some simplifica-

[1] Collisions with fixed objects, such as piers and bridges, are not considered within the committee's illustration of the methodology. However, a more complete future evaluation should take this type of incident into account.

tions. The simplifications were necessary because of the limitations of existing technology for modeling physical phenomena and the redundancy of factors that did not introduce new information into the analysis. Throughout the study, the committee took care to ensure that the simplifications were not introducing bias into the methodology.

The methodology has three main components or steps:

1. Structural damage and oil outflow calculation,
2. Consequence assessment, and
3. Design comparison.

The results of the first two steps feed into the design comparison. The division of each step into tasks is shown in Figure 3-1. Each task involves both theoretical and methodological challenges, which are discussed later. An overview of each step is provided in the remainder of this section; each step is then reviewed in detail in the sections that follow.

Structural Damage and Oil Outflow Calculation

The first step in evaluating the environmental performance of a tanker design is calculation of the structural damage and oil outflow in pos-

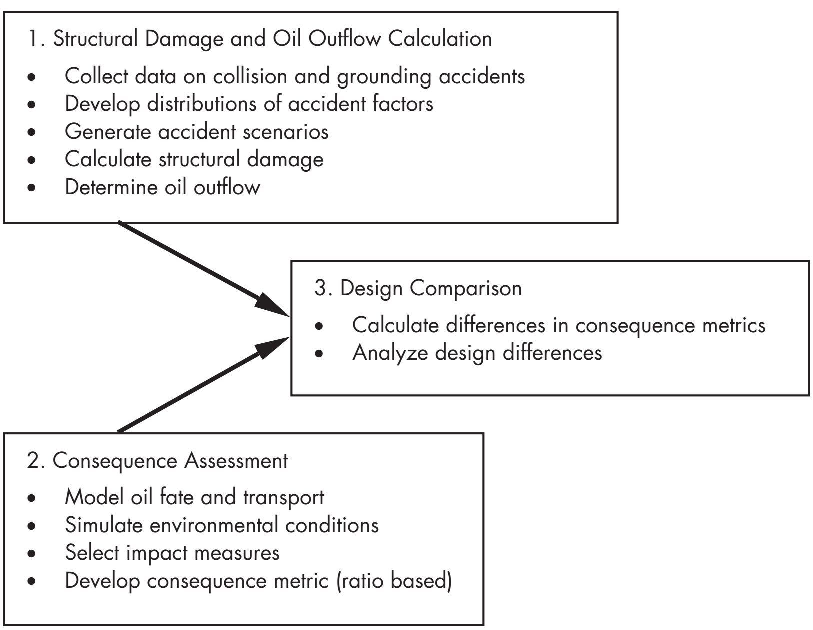

FIGURE 3-1 Components of the methodology.

sible accident scenarios. To this end, the accident scenarios, or collision and grounding events, must be selected. The parameters (accident factors) that define the collision and grounding events include the speed of the vessel, its loading condition, and the type of obstacle or colliding vessel. The accident factors used by the committee were selected to represent conditions in U.S. waters, specifically in areas with a high density of tanker traffic. The factors are defined with distributions that represent the range of their possible values, as well as the frequencies at which these values occur and their correlation structure. By sampling from these distributions, a large number of collision and grounding events were generated that model possible accidents and their relative frequencies in the selected areas of tanker traffic. For example, the committee chose a distribution of vessel speeds that are likely to occur in the areas where tankers operate. This distribution of speeds was then used to construct a distribution of accidents that are more or less likely to occur at those speeds.

Once the collision and grounding events have been defined, ship damage models are used to determine the structural damage for each accident and each design. The inputs into the models include the accident factors and a description of the vessel (definition of the hull form, compartments, and hull structure).[2] The output from the damage models is the damage extent and location, in other words, the size of the hole and its location on the hull of the ship. Once the size and location of the hole on the bottom or side of the ship are known, the resulting oil outflow can be determined. The calculation is carried out for each accident scenario.

Consequence Assessment

The second component of the evaluation process is the assessment of environmental consequences from an accidental spill. If the environmental impact of a spill were to increase linearly with the volume spilled, the oil outflow could be used to measure the performance of alternative designs. However, since the impact of the spill is dependent on many factors other than the volume (e.g., product type, environmental conditions, location), one cannot assume that the relationship between the spill volume and the consequences is linear (see Chapter 2). Therefore,

[2] The committee developed this methodology for evaluating new tankers. If several simplifying assumptions about aging and fatigue can be made, however, it may be possible to study retrofit options for existing ships as well.

to perform an unbiased evaluation of alternative designs, it is necessary to assess the consequences of the oil outflow by taking into account all relevant variables that affect the outcome.

The committee concluded that past efforts to use the reported cost of a spill as a surrogate for its overall consequences did not provide a rational basis for comparison of designs. Therefore, the committee decided to carry out environmental impact modeling using SIMAP, a modification of a stochastic version of the National Resources Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME).[3] SIMAP models oil fate and transport and allows for random sampling of weather conditions on the basis of historical weather data. It provides a number of consequence measures, such as the area of the sheen, the toxicity in the water column, and the length and area of oiled shoreline. Spill cleanup costs were included in the analysis at first but were later excluded because of the uncertainty in the cost models. The economic impacts due to cargo loss and third-party damages are excluded from the methodology: the impact of cargo loss is considered negligible compared with the environmental impact, while third-party costs, which can be significant, are assumed to be linear with the environmental consequence measures. These assumptions are discussed in more detail later in the report.

Because a distribution of weather events is included, the environmental impact modeling produces distributions of values for each consequence measure and for each simulated spill. In addition, the consequences are measured at a number of threshold levels, which represent the intensity or the quantity of the physical measure (e.g., the concentration of toxic components in the water column or the thickness of the slick on the water). The committee decided to limit the evaluation of the consequences to the physical measures instead of extending it to the impact on biological resources. The intent was to keep the analysis as rigorous as possible without necessitating difficult decisions on what threshold levels would damage biological resources and how different types of biological resources are valued. This decision is also addressed in more detail in later sections of this chapter. These distributions of impacts are then compared with each other to determine a single overall consequence metric (or function) that will capture the relative damage caused by spills of different sizes.

[3] NRDAM/CME and the SIMAP modification were developed by Applied Science Associates (ASA) for the Department of the Interior.

Design Comparison

In the third and final component of the methodology, oil outflow values from the first step are transformed using the consequence metric from the second step. For each accident scenario, the performance of the alternative design is compared with that of the reference double-hull tanker, and a difference is calculated. These distributions of differences capture the difference in the environmental impact of the two designs. Equivalency in performance can be determined by evaluating these distributions either qualitatively or quantitatively.

STRUCTURAL DAMAGE AND OIL OUTFLOW CALCULATION

The determination of oil outflow after collision or grounding is divided into the following tasks:

1. Definition of the collision or grounding event and its probability of occurrence,
2. Determination of the structural damage that results from the given collision or grounding event,
3. Determination of the outflow that results after the structure is damaged, and
4. Evaluation of active systems that modify outflow when applicable.

Each of these tasks is discussed in detail in the following subsections.

Definition of the Collision or Grounding Event and Its Probability of Occurrence

The methodology includes the assumption that the probability of alternative designs encountering a potential collision or grounding scenario is the same. Features of a design that reduce the risk of encountering dangerous situations, such as navigational aids, can be incorporated into any alternative design. However, the probability of occurrence (or frequency) of an event relative to the frequency of all other events is included in the methodology through the description of the accident factors that define the collision and grounding events. In addition, whether the ship runs aground in a given scenario depends on its draft, and the effect of possibly different drafts of alternative designs is taken into account in the methodology. Accident factors, which define the condition of the tanker before the accident and the type of colliding vessel, are described in more detail in Chapter 4.

Accident factors, which are defined by a distribution, must be selected so that they represent conditions in the studied area. For example, vessel speed should have a distribution that includes all possible speeds along with their likelihood. Transit and maneuvering speeds will have a high likelihood in the distribution. Speeds outside of the typical range must also be included, but their likelihood will be small. An example of the distribution for speed is shown in Figure 3-2. Once the initial distributions are known, the factors are sampled from the distributions to generate accident scenarios. Collision and grounding incidents that are more likely will have a higher frequency of occurrence.

Determination of Structural Damage

During a collision between two ships or a grounding (when a ship strikes a fixed object on the bottom), contact forces occur between the two bodies. The magnitude of the contact force depends on a number of characteristics of the striking and struck bodies. The effects of these characteristics are to decelerate the motion of the moving ship, perhaps sufficiently to bring it to a stop, and to damage structural members in the region of contact. In an extreme case, the damage may result in internal flooding, leading to loss of buoyancy and stability. If sufficiently severe, the damage may cause the ship to capsize or founder, resulting in its total loss. Even if the ship remains afloat, interior tank spaces may be penetrated, allowing spillage of any liquids they contain.

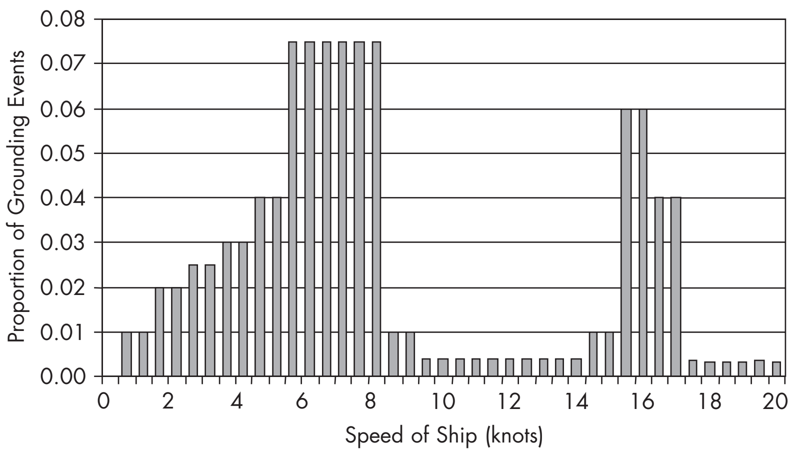

FIGURE 3-2 Distribution of grounding vessel speeds.

Analytical Methods for Assessing Damage During Collision or Grounding

The magnitude and extent of any structural damage depend on the location and magnitude of the forces of contact, as well as the strength properties of the structural members in that vicinity. The collision or grounding event occurs over a time interval ranging from a few seconds to a few minutes, during which time the forces of contact undergo variations in direction and magnitude. The behavior of these contact forces depends on the initial speed and mass, as well as other properties of the ship, and on the behavior of the affected structural members. The forces will change in an irregular manner with time as the ship decelerates and as different structural members undergo deformation and rupture. An analysis of ship behavior in a collision or grounding has the twin goals of predicting the forces of contact and the behavior of the ship structure under the action of those forces. Since these effects, force and structural response, are interrelated, it is necessary to perform simultaneous analyses of the two. This is in contrast to the usual structural design problem in which the forces acting on the structure are predicted first, and the structural members are then designed to withstand those forces.

The basic problem to be solved in the collision or grounding may be stated in terms of energy relations as follows. Before the collision or grounding, the ship is moving forward at velocity V, and its kinetic energy (KE) is given by the following expression:

$$KE = \tfrac{1}{2}(m + m')V^2$$

where m is the actual mass of the ship and m' is the added mass of an equivalent quantity of water, which accelerates with the ship.

During the collision or grounding, KE is transformed or dissipated through several mechanisms. A part of the KE is transformed into potential energy of the ship corresponding to changes in draft, heel, and trim. KE is dissipated through friction, acting principally between the contacting surfaces of the two ships or the ship and the object upon which grounding occurs. KE is also transformed into strain energy of plastic deformation, fracture, and tearing of structural members. Finally, hydrodynamic effects, including water friction and radiating waves, dissipate some of the KE, but this is a minor term and may usually be neglected.

Plastic deformation and fracture of structural members involve highly nonlinear aspects of material behavior; therefore, the forces of contact between ship and ship or ship and ground are strongly nonlinear functions of the relative motions of the two. As a result, the problem of finding the time history of vessel motion (and damage progression) after collision or grounding occurs must usually be solved as a step-by-step integration in time of the equations of vessel motion.

An example is provided by a common model of grounding in which a rock pinnacle is modeled as a circular vertical cone with a rounded vertex. As the bottom of the ship contacts the cone tip, vertical and horizontal forces act on the ship at the point of contact. These forces cause rigid body motions of the ship in its six degrees of freedom, but principally in pitch, heave, roll, and surge. The forces also cause deformation, possibly including yield and fracture, of the ship's structural members in the vicinity of the contact point. The problem is then solved in a series of time steps. At each step, using the velocity at the end of the previous step, an incremental motion is predicted, structural deformations are determined that are consistent with the relative motion between the ship and struck object, and the force associated with those deformations is determined. The integral of this force over the increment of motion equals the work done by the contact force in this step. This work must, in turn, equal the incremental reduction of *KE*. From the remaining *KE*, the velocities at the next step are determined. The entire process ends when the remaining *KE* equals zero and the ship has come to rest.

Obviously, the analysis of a process as complex as this requires certain simplifying assumptions to keep the magnitude of the analysis within practical bounds. These simplifications include assumptions concerning the external kinematics of the ship and the behavior of the material undergoing deformation and fracture. Methods that have been developed and used for this purpose include the following:

- Statistical analysis of previous casualty data,
- Detailed nonlinear finite-element methods, and
- Macroscopic finite-element or superelement methods.

In general, the statistical methods inherently involve the behavior of structures typical of the ships forming the database and may include simplifying assumptions regarding the structural arrangements. They cannot be applied with any confidence to comparative studies in which the subject ship has an innovative structural arrangement. Since such comparison of alternative arrangements with a known arrangement, the double hull, is a key element of the present work, the statistical approximation methods cannot be applied in all evaluations.

Finite-element methods are widely accepted in the analysis of complex structures such as those used in ships. The most advanced implementations are capable of treating nonlinear material and structure behavior, including yield, fracture, and buckling. A detailed nonlinear finite-element analysis requires great effort to build the structural model itself and considerable computational effort to arrive at a solution. The repetitive analyses needed to investigate large numbers of casualty scenarios render these methods impractical for purposes of the present study.

Superelement methods are essentially a variation on finite-element methods. Whereas the latter methods utilize large numbers of small simple elements to represent the structure, superelement methods use relatively few large, sophisticated elements, each incorporating the material and behavioral properties of a relatively large portion of the structure. An example might be the entire stiffened plate panel contained between two web frames. The necessary computational effort is greatly reduced with such methods, yet if appropriately defined elements are used, the results are of sufficient accuracy for the present application.

A limited number of computer codes based on superelement methods have been developed. The program DAMAGE, developed by the Joint Massachusetts Institute of Technology (MIT)–Industry Project on Tanker Safety, which falls into this category, was used to analyze grounding damage during the application of the committee's methodology. DAMAGE is available as software and has the widest range of applicability of published simplified methods (Tikka and Chen 2000). Other published work includes that of Wang et al. (1997), which is applicable to raking damage only, and that of Pedersen (2000) on grounding on soft soil.

The collision study was carried out using a simplified collision analysis tool, SIMCOL, which was developed by Brown and his students at Virginia Tech. Other simplified approaches for analyzing collision include (*a*) the collision module in the program DAMAGE; (*b*) the ALPS/SCOL simplified finite-element code, developed at Pusan National University, Korea; and (*c*) the simplified approach developed at the Technical University of Denmark. (More details on these methods can be found in *Alternative Tanker Designs Collision Analysis* on the accompanying CD.) SIMCOL was selected because of its availability and applicability to analyzing a large number of collision scenarios. The validation and limitations of DAMAGE and SIMCOL are discussed later in this chapter and in Chapter 4.

Limitations of Modeling the Physical Phenomena

Several factors limit the ability to achieve an accurate model of collision or grounding scenarios:

- *Random errors*: Virtually every aspect of any attempt to model the behavior of a ship and its structure in a collision or grounding event is subject to random uncertainties, including
  - *a.* Randomness of the conditions in the environment (e.g., waves, current),
  - *b.* Ship conditions at the time of collision (e.g., speed, draft, heading), and
  - *c.* Structural conditions (e.g., corrosion, construction tolerances, material imperfections).
- *Systematic errors*: These errors are due to shortcomings of analytical methods, imperfect knowledge of the relevant phenomena, and the need to reduce the computations to a manageable level.

The random errors of Types *a* and *b* can be addressed by the choice of conditions under which simulations are run. This is accomplished by conducting simulations for a very large number of cases covering all expected conditions of loading and the environment. Type *c* includes effects that are routinely treated when a reliability analysis is performed on a structure. These effects, such as corrosion, unrepaired dents, and cracks, are a consequence of deterioration of the structure over the life of the ship. Type *c* also includes construction tolerances and material imperfections, which are due to the ship not being built precisely as designed: the thickness of steel plate as received from the mill is not exactly as specified by the designer because of rolling imperfections; welded members are not in the exact locations and alignments shown on the plans; and material properties may not be precisely as assumed or specified as a result of chemistry, heat treatment, and other aspects of the steel-making process. Many of these items are covered by specifications on dimensions plus allowable tolerances in manufacture, and these tolerances can be incorporated in the analysis procedure.

The systematic errors are of more concern since they are characteristic of the analysis methodology. In a complex analysis such as that using DAMAGE or SIMCOL, especially when applied repeatedly to a large number of cases, simplifying assumptions must be made to keep the computational effort within reasonable bounds.

In DAMAGE, simplified analytical expressions are developed for the behavior of the different structural elements under various conditions. For example, for a panel of bottom plating, expressions are derived for plate indentation without fracture in the initial stages of contact with an obstacle, for plate splitting as the ship continues to move over the obstacle with increased penetration, and for tearing and wrinkling of the plate ahead of the obstacle. Similarly, expressions are derived for the behavior of stiffeners and webs attached to the plating.

Two types of assumptions are involved in modeling the response—those concerning the material itself and those concerning the structural deformations. Material behavior is defined by a stress–strain curve, which describes the stress–strain relationship up to the fracture strain. The kinematic assumptions concern the geometry of deformation. An example is the behavior of a plate being deformed by contact with the vertex of the cone, which models the obstruction. The model assumes that the deflected shape consists of "flaps" with plastic hinges at their edges, whereas the real deformation pattern involves curved edges.

The structural model in DAMAGE includes only the cargo block. The effect of the bow and the stern on the structural behavior in the damage region is neglected. The model is built with conventional structural members, and the materials used are limited to those that can be described with the stress–strain curve and the assumed failure modes. Innovative structural designs using new materials would require extensions to the current program.

DAMAGE is limited to modeling powered grounding on a single pinnacle. The obstruction, modeled as a pinnacle, is defined by its apex angle and the tip radius. Other types of obstructions or groundings (e.g., grounding on a reef or soft soil, drift grounding) currently cannot be modeled in DAMAGE.

In general, the validity of the combined assumptions can be tested only by experiment. Validation of DAMAGE has been limited to a few test cases, but it has been found to predict the overall damage extent well. It predicts average forces, but it does not capture peak forces as the ship advances relative to the obstruction. (For details see *Alternative Tanker Designs Grounding Analysis* on the accompanying CD.)

The SIMCOL collision model uses modified procedures derived from the statistical work of Minorsky (1959) to determine energy absorption by the horizontal members; reaction forces on the vertical members are determined by applying simplified analytical models that take into account the mechanics of the structural behavior. Total forces are a superposition of the forces acting on vertical and horizontal members. Only conventional structural members can currently be analyzed by SIMCOL, and assumptions on material are similar to those in DAMAGE.

SIMCOL can be used to analyze collisions between two vessels, but not collisions with a solid object, such as a bridge or a pier. The striking ship bow is modeled in SIMCOL as wedge-shaped and rigid. Only the struck ship deformation is taken into account in the energy absorption. Yaw motions and the relative horizontal rotation of the striking and struck ships are taken into account in the external collision mechanics.

Validation of SIMCOL has been even more limited than that of DAMAGE. Because of a lack of data, testing of the program has been limited to comparisons of its results with those from other simplified methods and finite-element analyses.

The committee found that the various simplified methods for modeling structural damage had not been fully tested, and their range of validity required investigation. However, both DAMAGE and SIMCOL were found suitable to illustrate the role of structural damage calculations in the methodology. (More detailed descriptions of the two programs, including the required input, can be found in *Alternative Tanker Designs Collision Analysis* and *Alternative Tanker Designs Grounding Analysis* on the accompanying CD.)

The accident factors and the description of the vessel are the inputs into both DAMAGE and SIMCOL, and they determine the extent and the location of the damage on the ship's hull. If the damage does not penetrate the cargo block, there will be no spill. The frequency of no spills will be accounted for by proper sampling of the accident factors. For example, if low-energy accidents are more likely to occur than high-energy accidents, the sample will model more of the former. Correspondingly, if one of the designs is shown to spill less oil in low-energy accidents than the other, the number of small-spill events for this design will be higher.

Determination of Oil Outflow

If a vessel hull is damaged, it will lose some of its buoyancy, and its loading condition will change (oil may outflow, seawater may flood in, or both). A rigorous oil outflow calculation includes a full damage stability analysis, which finds a new equilibrium condition for the vessel (that is, its position in the water) after the damage. The oil outflow is calculated in this condition. Since the calculation is iterative, the computation time can be long, and in some cases, no mathematical solutions are found. This type of calculation is not ideal for the large number of computations carried out in the methodology. The committee therefore decided to simplify the calculation of outflow in grounding by assuming that the vessel is stranded on the obstruction in the same condition (draft and trim) it was in before the accident. This type of analysis is called *conceptual analysis*. A more complete analysis, which allows for the vessel to float free from the obstruction and requires a full damage stability analysis, is called *survivability analysis*. The limitations of conceptual analysis are discussed in Chapter 4.

The oil outflow from tanks is governed by the hydrostatic balance between oil and water and by the hydrodynamic behavior of the two liquids. The calculation of oil outflow in a bottom-damage case (grounding) is based on the principles of hydrostatic balance, whereas that in a side-damage case (collision) assumes all oil being lost from a damaged tank. This is a common approach for calculating oil outflow, since a more accurate prediction would require a hydrodynamic calculation of outflow as a function of time. This simplified approach was adopted for the methodology.

The calculation of hydrostatic balance in grounding takes into account the effect of tidal changes, and the outflow is corrected for capture of oil in double-hull spaces. If a damaged cargo tank is adjacent to seawater, the dynamic effects are accounted for with a minimum-outflow correction.

Evaluation of Active Systems

If a design being evaluated includes an active system, the reliability of that system must be included in the outflow calculation. Although a number of active systems have been proposed in the past, they have generally been in the concept stage and lacked the particulars needed for evaluation. Since the necessary information for particular active systems was not available to the committee, it was not possible to develop specific recommendations concerning the evaluation of any active system. From the point of view of an overall risk analysis, however, there is no distinction between active and passive systems. The fact that a system requires some action does not preclude construction of the performance probability density functions needed to evaluate the risk of the system. This is the case even for extremely complex systems. Nonetheless, because of the possibility of misrepresentation, the committee is concerned about the evaluation process for such systems, as well as the need for an ongoing process to ensure that the system will perform as claimed over time. The committee concludes that, to enable a rigorous evaluation, the description of an active system may need to include the following:

- The mechanical design of the system and its components;
- Identification of failure modes for the system and its components;

- Description of system performance as a function of time, including loading profiles and performance of automated and manual operations;
- Analyses of system reliability (life cycle);
- Analyses of system maintenance; and
- Descriptions of tests or simulations, or both, to verify the operation of the system.

By way of general guidance, there should be an overarching principle that active systems are required to undergo a rigorous independent analysis, which may include prototype, model, and/or full-scale testing, before acceptance. An independent risk analysis should be carried out. While this analysis should be the responsibility of the proposer, perhaps with guidance from USCG, it is critical that it be conducted by a competent organization. Evidence should be presented concerning the performance of the system, its operation, its maintenance, and its reliability. The submission for approval should be expected to cover the mechanics, operation, and reliability of the system, and the documentation should include, but not be limited to, the following:

- Naval architecture design;
- Structural drawings;
- Identification of those accident scenarios in which the active system would be engaged;
- Stability;
- Compliance with U.S. and international rules and regulations (USCG and IMO);
- Quantitative risk analysis (for components and the overall system);
- Operational analysis as a function of time (incident to action);
- Crashworthiness; and
- Oil outflow with and without the active system in operation, and the probabilities associated with each.

The mechanics of the system refers not only to the complete system, but also to its components and their interrelationships and interdependency. An analysis of a failure of each salient system component, its probability, and its effect on the complete system should be carried out. The probability of system failure, including all possible failure modes and their consequences, should also be analyzed. An assessment of the effectiveness of the proposed active system in preventing oil outflow should be presented under a variety of scenarios: full operation, time delay, partial effectiveness, and active system failure. The likelihood of these scenarios should also be determined.

An analysis of the performance of the system should include an assessment of the operational aspects. Either the active system constantly maintains a state that is designed to ameliorate the effects of an accident, or the system is required to respond to an accident scenario in some remedial fashion to reduce the accident's impact. In the first case, the feasibility of maintaining the active state of the system and the effort involved must be analyzed. The proposal should include energy, maintenance, testing, and inspection requirements. In the second case, before a response can occur, damage must be detected and a decision made to activate the system; this process can be automated or manual. The effect of the two alternatives on system operation must be included in the risk analysis. Furthermore, the possibility of a false alarm should be assessed and the effect of the active system's response in the absence of damage evaluated. In the case of response to an actual accident, a time element is inherent in any active system, whether automated or manual. The performance assessment should include an analysis of the effect of the time delay in responding. Manual systems will need safety precautions and procedures to control the time delay. A formal failure modes and effects analysis may be appropriate.

The reliability of the system over its life must also be addressed. A fundamental reservation about active systems involves possible performance deterioration over time. System behavior over the life of the ship should be analyzed, including the differing deterioration rates of the individual components. In addition to addressing the deterioration issue, the proposal should indicate the maintenance, inspection, and testing necessary to ensure the continued integrity of the system. Complex systems may require specialized personnel for maintenance, and therefore the competency of the personnel involved should be addressed as well.

Finally, the committee concludes that it is difficult at this time to establish all of the necessary guidelines and procedures for the analysis of active systems. The above discussion indicates many of the areas that need to be addressed in a proposal involving such a system, but depending on the types of active systems that may be proposed in the future, other criteria may also need to be assessed. The critical point is that active systems differ from passive systems in that they either need to be operated continuously or must allow for an automated or manual response to a damage scenario. This characteristic introduces additional risks that necessitate a higher degree of evaluation of the performance of these systems.

CONSEQUENCE ASSESSMENT

While the first component of the methodology (damage and outflow calculation) is based on techniques that have been developed previously, the consequence assessment component is a new approach. As discussed in Chapter 2, the committee determined that data on historical spills were not sufficient to allow for the development of a response function describing the relationship of spill volume, oil type, and other factors to spill consequence. Instead, the committee chose to apply existing models of oil spill transport and fate, as well as consequence, to generate such a relationship. The committee's approach to this effort, which involved the following three tasks, is described in this section.

1. Selection of an existing oil fate and transport model and its application to generate estimates of the expected physical consequences of a broad range of hypothetical spills (e.g., meters of shoreline oiled, area of slick).
2. Consideration of whether response functions could be developed that describe the relationship of spill size to
   - Value of lost product,
   - Response cost,
   - Environmental consequence, and
   - Economic and social consequences.
3. Using the results of Tasks 1 and 2, establishment of equivalency ratios that describe the expected consequence of a spill in terms of the consequence of a standard-sized spill (referred to as the *reference spill*).

These tasks are discussed further below.

It is important to note that this approach to spill consequence modeling differs significantly from earlier efforts (e.g., Astrup et al. 1995; Michel and Moore 1995; Michel et al. 1996; Sirkar et al. 1997). These other efforts involved using reported costs of historical oil spills as surrogates for environmental damage, an approach rejected by the committee. Sirkar et al. also recognized the limitations of available cost data and instead considered a range of hypothetical cost curves. They called for the compilation of additional data on spill costs to support the generation of experience-based cost relationships. However, the committee does not believe that an accurate and consistent set of cost data can be compiled for purposes of consequence assessment, and thus pursued the alternative approach described below.

Modeling of Oil Spill Transport and Fate

Three primary decisions were required to model the expected physical consequences of a broad range of hypothetical spills. First, a tool to model the fate of oil in the environment had to be selected. Such tools allow for an understanding of the likely trajectory of oil in the environment under any number of hypothetical conditions. Second, the parameters of this model needed to be defined, including the case study locations for which the model would be run, spill sizes, oil type, and weather. Finally, the metrics that would be used to describe the physical consequences of each modeled release event had to be identified.

Several models are available that simulate the transport and fate of oil in the marine environment. Three were considered by the committee: (*a*) NRDAM/CME, developed by the U.S. Department of the Interior for purposes of natural resource damage assessment; (*b*) the Outer Continental Shelf model, developed by the Department of the Interior's Minerals Management Service for use in assessing the environmental implications of decisions concerning off-shore oil leases; and (*c*) USCG's TAP model, developed for oil spill response planning.

Of these three models, NRDAM/CME is the only one that (*a*) addresses a range of sites throughout the United States (the TAP model is available only for San Francisco Bay) and (*b*) allows for thresholds of concern to be varied. In addition, as noted earlier, ASA has developed a stochastic version of NRDAM/CME, SIMAP, that makes it possible to effectively generate a large number of modeled scenarios with a reasonable level of effort. It is this model that the committee applied to the present analysis.

The SIMAP model is described in detail by French et al. (1996, 1999) and French and McCay (2001). The model has undergone extensive peer review, been applied widely for both damage assessment and spill response planning purposes, and been accepted for use in natural resource damage assessment by both the U.S. Department of the Interior and NOAA.

The physical consequences of a spill event will depend largely on the location of the event, the volume and type of oil spilled, and the weather at the time of and following the spill. For example, the location of a spill will determine shoreline oiling potential; the characteristics of the product will determine the extent to which it partitions to the water column and sediments; and the weather following a spill will determine the direction and speed at which the slick will travel, the distance it will travel, and the extent to which the oil will be dispersed in the environment.[4] The committee selected ranges for each of these factors in modeling spill consequence across various spill volumes, as discussed in Chapter 4.

The physical consequences of a spill can be described by a range of metrics. Commonly used measures include extent of shoreline oiling, area of slick, oil constituent concentrations in the water column, residual oil constituent concentrations in sediments, and various measures of the "dose" of oil borne by different environmental media [e.g., hours of exceedance of a threshold polycyclic aromatic hydrocarbon (PAH) concentration in the water column]. The committee used four physical consequence metrics (the area of the slick, the length and area of oiled shoreline, and the toxicity in the water column) to generate the equivalency ratios, as described in Chapter 4.

Response Functions of Spill Size to Consequence

The ultimate implications of an oil spill are defined in terms of the environmental, economic, financial, and social consequences of the event. For example:

- The owner(s) and insurer(s) of the ship's cargo suffer a financial loss.
- The responsible party and other entities incur costs associated with the response to the spill and its cleanup.
- The public may suffer loss of use of an oiled resource (e.g., a beach closure).
- The public may suffer a loss associated with the reduced quality of an environmental resource (e.g., the loss of nursery habitat for an endangered fish species).
- Private parties may suffer losses (e.g., a commercial fishery may be closed for some period of time).
- An important resource for a local community (e.g., an artesianal fishery) may be lost or diminished in value.

The committee gathered information on the relationship of these factors to spill size. In particular, the committee considered the extent to which

[4] *Weather* here is used to refer to wind, currents, tides, wave energy, and similar factors.

these spill outcomes are more or less a function of the physical consequence measures discussed above.

One option available was to attempt to model each of these measures of consequence individually. For example, it is possible to estimate the likely number of visitor days that would be diminished in value as a result of a hypothetical spill event given information on the location, extent, and duration of beach oiling; the time of year of the spill event; and beach use levels. Similarly, given the volume of oil spilled, the spill location, and the weather conditions at the time of a spill, it is feasible to generate an estimate of expected cleanup costs for a hypothetical spill event. The committee examined a range of measures of spill consequence, as discussed below.

Environmental Impact Measures

The committee considered the use of several environmental impact measures. In particular, SIMAP provides two categories of environmental consequence metrics. The first involves measures of impacts to wildlife, water column organisms, and so on. The second involves measures of impact across shoreline type (e.g., rocky versus wetland). These measures may be better than the physical impact measures discussed above at reflecting the likely true consequence of a spill event. For example, equivalent areas of surface water swept by a slick at two locations may affect dramatically different numbers of biota.

Despite the potential advantages of considering environmental consequences,[5] the committee chose not to do so, for several reasons. First, there is a great deal of uncertainty in the available measures of species abundance and other factors used to describe environmental resources present at each modeled site, and these measures will vary with weather, time of year, and other factors. That is, the environmental consequences predicted by SIMAP may significantly over- or understate the actual consequences that would occur from a given spill. Therefore, the results generated by SIMAP for these measures of damage are generally less well accepted by the professional community than are physical impact measures.

Second, in selecting case study sites for use in modeling spill consequence, the committee's goal was not to obtain precise measures of loss

[5] *Environmental consequences* refer to the impact of an oil spill on the affected habitat, whereas *physical consequences* refer to physical measures of oil concentration in the water or on the shore. In the committee's methodology, physical consequences are used to measure environmental consequences, and the term *environmental impact* is used in the report to describe this measure.

at these specific locations, but to model consequence under a range of possible physical conditions. Including the environmental consequence measures in the model would result in an increased risk of assigning too much weight to the specific conditions found at these sites.

Finally, there is reason to believe that environmental consequence will, on average, be linearly related to physical consequence. That is, the physical consequence measures discussed above probably serve as good indicators of likely environmental consequence when considered across all potential spill locations and conditions.

Value of Lost Product

One category of economic loss associated with oil spills is the value of the lost product. Early in the analysis, the committee determined that, while larger quantities of product may have lower value per unit (and thus the value of lost product from a large spill may not be as great as that from a small spill, per unit volume), the overall effect of omitting this factor from the analysis would be quite small. Thus, this measure was not included in the analysis.

Response Costs

The committee expended a great deal of effort generating a relationship that would describe oil spill response and cleanup cost as a function of spill size. The committee considered historical spill cost data and existing models of spill cleanup and response costs, as well as primary estimates of spill response and cleanup costs generated for each of the hypothetical spill locations. The committee asked a recognized expert in the field, Dr. Dagmar Etkin, to prepare a set of reports summarizing available information on spill response and cleanup costs and to provide information that would make it possible to estimate response costs for each of the modeled spills. (See *Shoreline Cleanup Cost Modeling* and *Mechanical Containment and Recovery Cost Models* on the accompanying CD.) After reviewing these reports, the committee concluded that (*a*) the historical record of spill response and cleanup costs is not sufficient to allow for the estimation of a cost consequence function; (*b*) estimates generated using existing models of spill response and cleanup cost demonstrate a great deal of uncertainty, especially for spills at the low and high ends of the modeled spill size range; and (*c*) in many cases, the best predictive models are simply linear transformations of the physical consequence measures already being considered by the committee.

All efforts to estimate spill response costs for modeled spill events rely to some extent on historical cost data. Since the number of spills for which such data are available is small (especially for larger spills), either inconsistencies in the reported cost estimates or case-specific circumstances could introduce significant bias into the modeling effort. In addition, the committee determined that the degree of uncertainty inherent in any modeled cost estimate will be greatest for the smallest and largest hypothetical spill events, a factor that could have led to additional bias in the final consequence function. Since the best predictive models are linear transformations of physical consequence measures, the committee decided that these measures are sufficient proxies for response and cleanup costs.

As noted below, the committee recommends that additional consideration be given to the development of a robust spill cleanup and response cost function, and that the consequence model developed here be tested for sensitivity to inclusion of alternative measures of consequence.

Third-Party Damages

The committee considered the development of detailed estimates of third-party damage for each of the hypothetical spill events. The focus of this discussion was on such consequences as beach closures, recreational fishing closures, interruption of other recreational activities, commercial fishing/shellfishing closures, and interruption of marine transportation.

As for the biological consequence metrics discussed above, the committee determined that (*a*) the level of precision that could be achieved in establishing these consequence measures would be low and could vary significantly across case study sites (e.g., determining the impacts of a beach closure would require information on numbers of visitors to the beach at the time of the spill, which would generally not be known with any certainty); (*b*) there is good reason to believe that these measures of consequence are, in general, linearly related to physical consequence, already captured in the modeling efforts as described above; and (*c*) the case study sites were not chosen as specific locations, but as indicative of the kinds of locations at which oil might be spilled (that is, shifting the case study site a few miles could result in a different pattern of expected third-party losses). Thus, as for specific measures of environmental consequence, consideration of site-specific third-party losses might have resulted in assigning disproportionate weight to a particular modeled location.

Establishment of Equivalency Ratios

As discussed above, the committee ultimately selected a modeling approach that (*a*) uses SIMAP to estimate the physical consequences of a range of hypothetical oil spills at a set of case study sites and (*b*) assumes that a set of physical consequence measures are reasonable proxies for the financial, economic, social, and environmental consequences of oil spills.

Since the committee's approach does not rely on a single metric to report consequence (such as dollar damages), it was necessary to combine the physical consequence measures used into a single measure that could be employed to compare the relative consequences of spills of different sizes. The approach selected involves the use of "equivalency ratios," which define the expected consequence of a spill of a given size relative to the expected consequence of a standard reference spill. That is,

$$\text{Equivalency ratio} = \frac{\begin{array}{l}\text{physical consequence of modeled spill}\\ \text{(e.g., meters of shoreline oiled)}\end{array}}{\begin{array}{l}\text{physical consequence of reference spill}\\ \text{(e.g., meters of shoreline oiled)}\end{array}}$$

If consequence is constant across spill size per gallon spilled, the equivalency ratio should equal the ratio of the size of the modeled spill to the size of the reference spill. That is, if the equivalency ratio is greater than the ratio of spill size, the consequence per gallon of oil spilled is greater for the modeled spill than for the reference spill. If the equivalency ratio is less than the ratio of spill size, the consequence per gallon of oil spilled is less for the modeled spill.

The specific analytic steps the committee followed in generating these ratios and the ultimate consequence function are described in Chapter 4.

DESIGN COMPARISON

The design comparison involves combining the results of the other two steps in the methodology (outflow and consequence analyses). Since both the alternative design and the reference double-hull vessel have been run through the same set of accident scenarios, their performance for each scenario can be directly compared. However, since the consequence analysis showed that a direct oil outflow comparison would not be adequate, the outflow values need to be transformed using an overall summary consequence metric based on the equivalency ratio. By taking this step for each accident scenario, not only can the better design be determined, but also the relative impact on the environment can be assessed. If both designs perform poorly for a particularly severe accident scenario, both may spill considerable, though different, amounts of oil into the environment. This difference in environmental impact may not be significant; massive damage has already occurred. However, the same difference could be very important if one design did not leak and the other did for a much less severe accident scenario. When repeated across thousands of realistic scenarios, this pairwise analysis done at the scenario level using the overall consequence metric allows for a comprehensive evaluation of the designs. The resulting distribution of differences describes the relative environmental performance of the alternative design and allows for a determination of equivalency.

LIMITATIONS OF THE METHODOLOGY

While the committee's methodology is sound, it has some limitations in its current stage of development. The four most significant limitations are discussed below, along with suggestions for further development work to address them.

Vessel Structure

Analysis of a vessel of nonsteel or nonconventional construction would require the use of material performance characteristics dissimilar to those used in the methodology and would necessitate modifications to the formulae used in the analysis. To this end, the programs used in the analysis of outflow, DAMAGE and SIMCOL, would have to be modified. Making these modifications would require specific determination of both the material properties and the performance of those materials.

Site-Specific Factors

The committee's approach involves modeling a large number of hypothetical releases from tanker accidents at given case study sites. To the extent that these case study sites are not representative of typical spill locations, this approach will produce biased results. The sensitivity of the final consequence function to the chosen set of sites could, however, be tested by considering a larger number of case study sites.

Physical Consequence Measures

The committee's approach involves estimating the extent to which physical consequence predicts total consequence. As noted above, the committee assumed that various physical consequence metrics can be used as proxies for the expected environmental and third-party costs of a spill, as well as the expected response and cleanup costs. Several limitations may be introduced by this assumption. The most significant of these is that third-party costs and response and cleanup costs are likely to be disproportionately larger for small spills. That is, the physical consequence measures used by the committee are likely to understate third-party and response and cleanup costs for small spills. Further investigation of this limitation could lead to more confidence in the final outcomes.

Modeled Grid Size Used in SIMAP

SIMAP estimates the physical consequences of spills using a geographic grid size that varies by location. In the case of small spills, the amount of oil in the water may not be sufficient to register the physical consequence measures. Thus while small spills do cause environmental harm, the version of SIMAP used by the committee assigns some modeled spills a physical consequence of zero. The result is understatement of the consequences of some small spills. The SIMAP modeling approach does adjust for this factor to a certain extent by assuming that the physical consequence of a spill can never be less than the smallest measurable unit. However, it would be useful to do additional modeling with smaller grid sizes to understand the potential bias introduced by this factor and possibly modify the model for future uses.

SUMMARY OF THE METHODOLOGY

In summary, the methodology proposed by the committee involves two initial steps—one to calculate oil outflow following a tanker accident and the other to assess the consequence or impact of an oil spill. These two steps are then combined in a third and final step—the comparison of tanker designs.

The oil outflow calculation involves the computation of a series of accident scenarios causing specific damage to a ship that, in turn, results in a specific quantity of oil spilled. Each design to be evaluated will be subjected to the same series of accident scenarios, but because they are different designs, different amounts of oil will be spilled.

The consequence assessment involves assigning a rational metric for the environmental consequence of a series of oil spill events of varying quantities, locations, and conditions, and then constructing and using a multiplier to transform the outflow differences for two designs determined in the first step into consequence differences. The committee carried out this step, and the resulting consequence curve can be applied to different design comparisons. The consequence curve needs further refinement, as discussed above, but once the refinement has been completed, this step does not need to be repeated for each design comparison.

The third and final step, design comparison, involves comparing the results of the measurement of differences in consequence for the design being evaluated with the reference vessel. Under some conditions, one design may have lower consequences and thus be a better performer, but under other conditions the opposite may be true. The methodology provides the data and analyses needed to make this comparison for a large number of individual conditions and to conclude whether one design is equivalent, inferior, or superior to another.

As noted above, the committee believes its methodology is sound, systematic, and well specified, and represents a significant improvement over methods proposed and used in the past. Chapter 4 describes the application of the committee's methodology in more detail and provides examples of the necessary computations, descriptions of the analyses, and illustrations of the resulting graphics that would be used to compare actual designs.

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ABBREVIATION

SNAME	Society of Naval Architects and Marine Engineers

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4
APPLICATION OF THE METHODOLOGY

The methodology developed by the committee was applied to evaluate two 150,000–deadweight ton (DWT) tanker designs—one single- and one double-hull—and two 40,000-DWT tankers—one single- and one double-hull. The application involved structural damage and outflow calculations for each tanker, oil-spill fate and transport simulations in four geographic locations, combining of the outflow and spill simulation results into a consequence measure, and design comparisons. The application and its results are described in this chapter: the selection of vessels and collision and grounding scenarios, the collision and grounding analyses and their results, the selection of hypothetical spill scenarios and consequence measures, limitations of the consequence analysis, and finally the design comparison. It is important to keep in mind that the work presented is only an illustration of the use of the methodology. As discussed in Chapter 3, further refinement and testing of the methodology are recommended, particularly if the alternative design in question includes innovative design features.

SELECTION OF VESSELS AND COLLISION AND GROUNDING SCENARIOS

The selection of vessels for use in testing the methodology was based on the following criteria:

- The vessels to be compared had to have the same cargo capacity.
- Detailed structural information about the vessels had to be available (to demonstrate how the methodology models structural resistance during accident scenarios).
- Vessel drawings and other relevant information had to be available to the committee.

Because of the above requirements, alternative designs lacking sufficient design detail had to be excluded from consideration. The profiles and midship sections of the 150,000-DWT and 40,000-DWT vessels included in the study and their subdivisions into cargo and ballast spaces are shown in Figures 4-1 and 4-2, respectively.

It is important to note that the double-hull ships have a deeper draft than the single-hull ships, which is typical for existing single- and double-hull ships of the same capacity. The draft and subdivision of the reference double-hull vessels are important for the outflow results and must be carefully evaluated when selecting the standard double-hull ships.

The programs SIMCOL and DAMAGE were selected for the collision and grounding analyses, respectively. These programs use a simplified approach to calculate resistance and therefore are suitable for analyzing a large number of collision and grounding events. Oil outflow from damaged cargo tanks is a part of the SIMCOL output, whereas DAMAGE provides information on structural damage only. A program was written to allow batch runs of a large number of grounding cases and to add an outflow calculation based on the structural damage output from DAMAGE. These damage modeling programs were used in the committee's illustration of the methodology, but other programs could be incorporated into the methodology as well.

As discussed in Chapter 3, SIMCOL and DAMAGE each use a simplified approach to analyze collision and grounding damage, and they include assumptions that limit their application. The main limitations of SIMCOL are as follows:

- The bow of the striking vessel is assumed to be rigid. The energy absorbed by the deformation of the striking bow is neglected.
- Analytical models in SIMCOL are based on empirical data, and they may not be applicable to analysis of innovative structural designs.
- SIMCOL models collisions between two vessels. Collisions with solid objects, such as bridges or docks, cannot be modeled.
- SIMCOL has limitations in modeling raking damage.

The main limitations of DAMAGE are as follows:

- The structural model includes only the cargo block. The effect of the bow and stern on structural behavior in the damage region is neglected.
- The model is built with conventional structural members, and the material used is limited to that which can be described with the stress–strain

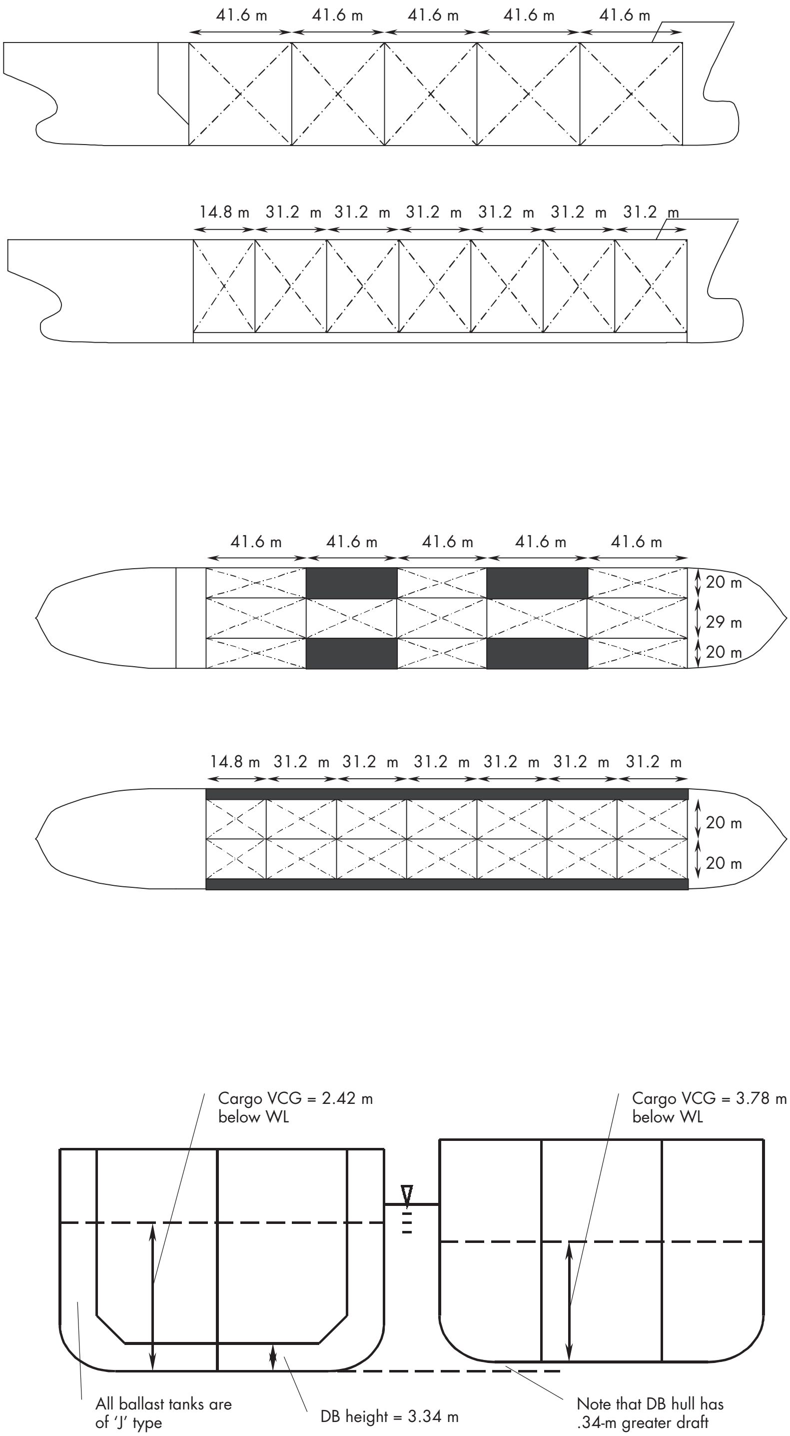


FIGURE 4-1 Profile, plan, and midship section for 150,000-DWT ships (VCG = vertical location of the center of gravity; WL = waterline).

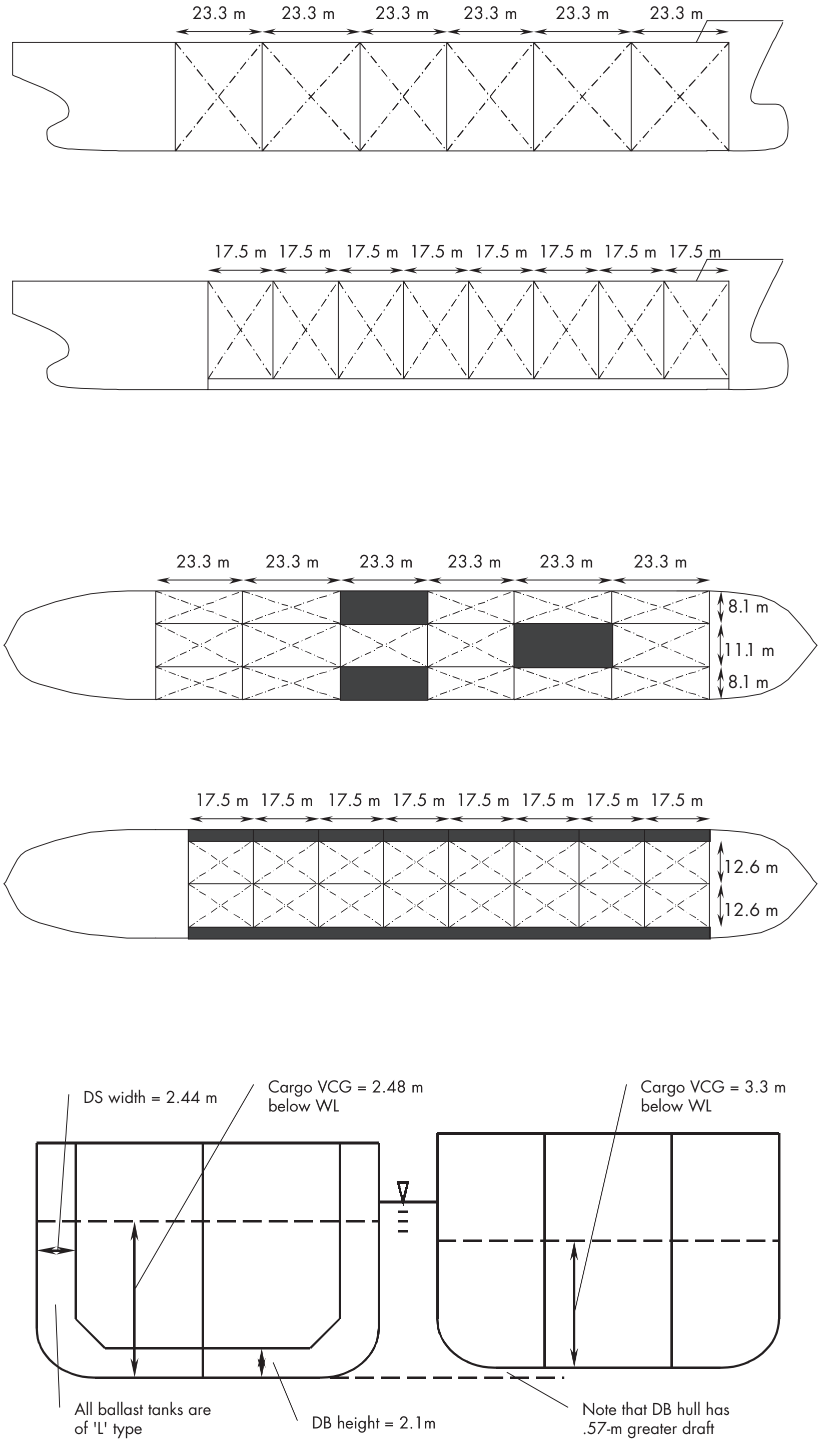


FIGURE 4-2 Profile, plan, and midship section for 40,000-DWT ships (VCG = vertical location of the center of gravity; WL = waterline).

curve and the assumed failure modes. Innovative structural designs using new materials would require extensions to the current program.

- DAMAGE is limited to modeling powered head-on grounding on a single pinnacle. Other types of obstruction or grounding (e.g., grounding on a reef or soft soil, drift grounding) currently cannot be modeled in DAMAGE.

A more detailed description of the programs and their validation can be found in the *Alternative Tanker Designs Collision Analysis* and *Alternative Tanker Designs Grounding Analysis* reports included on the accompanying CD.

The collision and grounding incidents to be used were defined by accident factor distributions, which were selected to sample conditions in U.S. waters with a high density of tanker traffic. Data were collected for the selected hypothetical spill locations, and it was assumed that the vessels had an equal likelihood of being in each of the geographic locations. Available data were inadequate for many of the variables, and further refinement of the accident-factor distributions is recommended.

Four hypothetical spill locations were used in the application (their selection is discussed later in this chapter):

- Big Stone Anchorage, Delaware Bay;
- Galveston lightering area, Gulf of Mexico;
- Carquinez Strait Bridge, San Francisco Bay; and
- Farallon Islands, offshore San Francisco.

Accident factors for grounding were collected from the following sources:

- The speed distribution was based on information received from pilots and operating personnel on typical speeds in the Galveston lightering area, in San Francisco Bay near Carquinez Strait Bridge, and outside of San Francisco Bay. No speed data were available for Delaware, but speeds were assumed to be similar to those in San Francisco Bay.
- The tidal distribution was based on information on the four locations obtained from NOAA (tidesonline.nos.noaa.gov).
- Obstruction depths were based on data for Galveston, Delaware, and San Francisco Bay. These data were received from USCG vessel traffic service (VTS) centers and NOAA charts. No data were available on the shape of the obstructions in these locations.

- The distribution for the obstruction tip radius was taken from work by Rawson et al. (1998). The minimum and maximum apex angles were based on the limitations of the theory in DAMAGE, and a uniform distribution was assumed.
- Inert gas pressure[1] distribution was based on data for a typical range of inert gas pressures provided by INTERTANKO.
- The capture[2] distribution was selected on the basis of model test results presented in an IMO (1992) comparative study.

The accident factors and their distributions for grounding are given in Table 4-1.

Brown provided the committee with accident factors for collision scenarios. His primary data sources were a report by Sandia National Laboratories (1998) and 1993 Lloyd's Worldwide Ship Data provided by the U.S. Maritime Administration. A discussion of the data can be found in the *Alternative Tanker Designs Collision Analysis* report on the accompanying CD. Table 4-2 presents the accident factors and their distributions used in the collision analysis.

COLLISION AND GROUNDING ANALYSES

The accident factors described above were sampled using Monte Carlo simulation to generate 10,000 collision and grounding events. The structural damage and oil outflow were analyzed for each vessel using the same 20,000 scenarios. This allowed direct design comparisons to be made.

The collision calculations were contracted to Brown, the developer of the SIMCOL program. The grounding calculations were obtained from an ongoing Society of Naval Architects and Marine Engineers/ Ship Structures Committee (SNAME/SSC) project on Prediction of Structural Response in Grounding.

The ships were assumed to be in a fully loaded condition, adjusted so that each vessel carried the same quantity of cargo and maintained an even-keel condition. The cargo was crude oil with a density of 0.84 grams per cubic centimeter (g/cm^3), which corresponded to one of the oil types used in the oil fate and transport simulations.[3] The param-

[1] Inert gas pressure is maintained in cargo tanks to avoid explosive conditions.

[2] *Capture* refers to the amount of oil that is captured in ballast spaces adjacent to damaged cargo tanks.

[3] The density of the other oil type (North Cape No. 2 fuel oil) is 0.86. Since the densities of the two oil types are similar, the outflow results will be close as well.

TABLE 4-1 Grounding Accident Factors and Their Distributions

Factor	Minimum	Maximum	Distribution
Speed (knots)	0	20	Probability that the speed is in the range 0 to 5 knots—25% 5 to 8 knots—45% 8 to 15 knots—8% 15 to 16 knots—20% 16 to 20 knots—2%
Obstruction depth from mean low water (meters)	0	19	Probability of depth ranges 0 to 5 m—11% 5 to 10 m—28% 10 to 15 m—31% Larger than 15 m—30%
Obstruction apex angle (degrees)	15	50	Truncated normal distribution. Strong positive correlation with tip radius (0.80). Large apex angles correspond to large tip radii
Obstruction tip radius (meters)	0	10	Truncated normal distribution
Nondimensional rock eccentricity, e/(beam/2), from centerline	0	1	Uniform distribution
Tidal variation (meters from mean low water)	0	2.5	Probability that the ride is in the range 0 to 0.7 m—50% 0.7 to 1.7 m—35% Greater than 1.7 m—15%
Inert tank pressure (millimeters water gauge)	400	1000[a]	Uniform distribution
Capture in ballast tanks (as percent of tank volume)	0	50	Uniform distribution
Minimum outflow (as percent of ruptured tank volume)	0.5	1.5	Uniform distribution. Moderate positive correlation with speed (0.50). Higher speeds are more likely to have higher minimum outflow

[a]Pressure valves preset at 1500 mm water gauge (WG), but to represent industry practice and allow the use of a uniform distribution, the range of 400 to 1000 mm WG was applied.

eters defining the vessel condition and the liquids carried are shown in Table 4-3.

Both the collision and grounding calculations included several simplifying assumptions. These assumptions are discussed in detail in the reports on the accompanying CD; the main assumptions are summarized below.

TABLE 4-2 Collision Accident Factors and Their Distributions

Factor	Minimum	Maximum	Distribution
Ship type	N/A	N/A	Distribution of ship type Tankers—25.2% Bulk cargo—17.6% Freighters—42.4% Passenger—1.4% Container—13.5%
Displacement (metric tons)	Tankers—700 Bulk—1,800 Freighters—500 Passenger—1,000 Container—1,100	Tankers—274,000 Bulk—130,000 Freighters—42,000 Passenger—76,000 Container—59,000	Probability by ship type Tankers—Weibull (0.84, 11.2) Bulk cargo—Weibull (1.2, 21.0) Freighters—Weibull (2.0, 11.0) Passenger—Weibull (0.92, 12.0) Container—Weibull (0.67, 15.0)
Speed of striking ship (knots)	0	20	Distribution based on historical data, approximately Weibull (2.2, 6.5)
Collision angle (degrees)	0	180	Distribution based on historical data, approximately truncated normal (90.0, 29.0)
Strike location relative position from bow	0	1	Beta (1.25, 1.45)
Speed of struck ship (knots)	0	20	Distribution based on historical data, approximately exponential (0.584)

NOTE: N/A = not available.

The collision program SIMCOL solves the external ship dynamics and the internal deformation mechanics simultaneously in the time domain. The external dynamics model in SIMCOL takes into account the yaw motions of the striking and struck vessels, as well as the relative horizontal rotation between the two vessels. Principal dimensions and displacements define the ships. The striking ship's bow is assumed to be wedge-shaped, and the deformation is considered only for the struck ship.

The internal mechanics model uses analytical modeling to determine reaction forces for vertical members, but the reaction forces and absorbed energy for horizontal members are based on empirical results.[4] The structural model of the struck ship includes vertical and horizontal

[4] *Horizontal members* refer to those structural members for which the collision force is applied in the plane of the structure (e.g., the crushing of a deck), and *vertical members* refers to those structural members for which the collision force is applied normal to the plane of the structure (e.g., side shell) or across the axis of a member (e.g., side-shell stiffeners).

TABLE 4-3 Vessel Condition Prior to Collision and Grounding

Parameter	Single-Hull, 150,000 DWT	Double-Hull, 150,000 DWT	Single-Hull, 40,000 DWT	Double-Hull, 40,000 DWT
Displacement (metric tons)	175,907	175,940	47,448	49,410
Cargo oil (metric tons)	149,635	149,635	35,949	35,922
Draft at MS [meters (m)]	16.78	17.12	10.58	11.17
Draft at fore perpendicular (m)	16.78	17.12	10.58	11.17
Draft at aft perpendicular (m)	16.78	17.12	10.58	11.17
Summer load line (m)	16.785	17.205	10.614	11.303
VCG (m)	13.35	14.71	7.526	9.26
Waterplane area [square meters (m^2)]	11,506	11,513	4,800	5,014
Transverse metacentric height (GMt) (m)	6.96	5.15	3.243	2.91
Longitudinal metacentric height (GMl) (m)	306.65	299.75	276.54	263.19
Distance from MS to LCF (LCF relative to MS) (m)	0.85 fwd	0.58 fwd	0.131 aft	2.81 aft
Density [grams per cubic centimeter (g/cm^3)]				
Cargo	0.84	0.84	0.84	0.84
Fuel oil	0.98	0.98	0.98	0.90
Diesel oil	0.90	0.90	0.90	N/A
Lube oil	0.85	0.85	0.85	0.92
Fresh water	1.00	1.00	1.00	1.00
Salt water	1.025	1.025	1.025	1.025
Tanks (% full)				
Cargo tanks (ex slops)	98	98	98	98
Slop tanks	66	89	N/A	N/A
FO	96	96	96/95	96
FO settling, service, overflow	20	20	N/A	N/A
DO	96	96	N/A	N/A
DO service	20	20	N/A	N/A
Fresh water	98	98	98	100
Forepeak ballast tank	3.5	11	0	100/11.2
Other ballast tanks	0	0	0	0

NOTE: DO = diesel oil, FO = fuel oil, LCF = longitudinal center of flotation, MS = midships, N/A = not applicable, VCG = vertical center of gravity.

members on the side. Horizontal members, side shells, and bulkheads (transverse and longitudinal) are modeled by smeared thickness (which includes the effect of stiffeners). Web frames are modeled with additional detail.

Once collision damage calculations have been completed, SIMCOL determines which cargo tanks have ruptured. The outflow calculation assumes that all oil is lost from a damaged cargo tank. No hydrostatic or hydrodynamic effects are taken into account.

The friction coefficient in DAMAGE was assumed to be 0.3.[5] The ship model includes the cargo block without the bow and stern of the ship. Structural resistance is analyzed in a stepwise manner by moving the ship forward and, at each time step, finding the rock penetration and static equilibrium of the ship. Ship motions, excluding sway and yaw, are taken into account. Heave, roll, and pitch motions are calculated on the basis of static equilibrium using a simplified model. Surge motion is based on energy balance. Validation of DAMAGE can be found in work by Simonsen (1998) and Tikka (1998).

The DAMAGE program outputs the vertical, horizontal, and longitudinal extent of damage, and this information was used to determine the damaged tanks. The oil outflow from damaged cargo tanks was calculated according to the principle of hydrostatic balance. The pressure balance was calculated at the lowest point of the damaged tank. Similar to the assumptions in the IMO guidelines (IMO 1996), some oil was assumed to be captured in the ballast tanks, and a minimum outflow was assumed from damaged cargo tanks adjacent to seawater as a result of dynamic effects. The IMO guidelines assume a constant value for capture and minimum outflow, whereas the calculations used by the committee were based on a range of values sampled from the initial distributions for these variables to account for the uncertainty involved.

The outflow calculation was performed in the initial condition (conceptual analysis), and it did not include a damage stability (survivability) analysis.[6] Tikka (1998) compared the conceptual analysis with a survivability analysis for double-hull tankers with a range of tank arrangements in four size ranges. The error in the mean outflow was small for conventional tank arrangements (typically less than 6 percent), and the error in the zero-outflow probability was insignificant (less than 0.1 percent) with no tide when conceptual analysis was used. At lower tides, the error percentages were smaller. Large errors were found for tank arrangements without centerline bulkheads, which can no longer be built according to MARPOL regulations.

Finally, if one of the designs includes an active system, that system's effect should be taken into account in the outflow analysis. As discussed in Chapter 3, a proposal involving an active system must include a reliability analysis. Results of the reliability analysis provide distribu-

[5] Friction coefficient values of 0.3 to 0.4 are typically used in grounding analyses (Simonsen 1998).

[6] Conceptual analysis assumes that the ship is aground on a shelf at a draft equal to the initial intact draft. Survivability analysis takes into account changes in the ship's condition and includes a damage stability analysis. If the vessel does not meet the MARPOL damage stability criteria, all oil is assumed lost.

tions for the variables that define the operation of the active system, and these variables and distributions are taken into account in the generation of collision and grounding scenarios. In other words, an active system adds another layer of uncertainty analysis to the methodology, and this is taken into account in the definition of the accident scenarios. Once the accident scenarios have been defined, determination of the outflow volume in each scenario must be adapted to the particular active system, but the basic principles of the methodology apply in the same way to analysis of active and passive systems.

RESULTS OF COLLISION AND GROUNDING ANALYSES

Collision and grounding analyses provided oil outflow for each of the 10,000 collision and grounding events. A summary of the results is provided in Tables 4-4 and 4-5, respectively. The results indicate that a double hull is effective in reducing the number of spills due to collision and grounding. For collision, there were cases in which the double-hull design had a spill, but damage to the single-hull design occurred only to the side ballast tanks and resulted in no spill. For grounding, there were no cases in which the double-hull design spilled and the single-hull did not. The double-hull designs reduced the number of spills (over the single-hulls) by 54 and 67 percent for the 150,000- and 40,000-DWT tankers, respectively. In grounding, the smaller tankers had significantly fewer spills than the larger ones (1,833 versus 5,911 scenarios) because of their shallower drafts. The obstruction depths were the same in both analyses.[7] For collision, the double-hull vessels had a larger average spill size (given a spill) than the single-hulls, but the single-hulls had a larger maximum spill. For the grounding scenarios, in comparing average spill size given a spill, the single-hull vessel had a larger average spill than the double-hull in the 150,000-DWT size, but the reverse was true for the 40,000-DWT size. The double-hull designs had a larger maximum spill than the single-hulls.

The tank subdivision in the transverse direction had a strong impact on the outflow results, given a breach of the cargo block, in both collision and grounding. The analyzed single-hull vessels had three cargo tanks across, whereas the double-hull vessels had two tanks. The side tanks in the single-hulls were smaller than those in the double-hulls. On

[7] Because the depth and size of the obstacles were kept the same for both the 40,000- and 150,000-DWT tanker analyses, comparison across the two tanker sizes could be performed.

TABLE 4-4 Collision Results for 150,000-DWT and 40,000-DWT Single-Hull and Double-Hull Tankers

Result	40,000-DWT Vessel		150,000-DWT Vessel	
	Double	Single	Double	Single
Outflow (millions of gallons)				
Average given a spill	0.94	0.77	4.36	3.36
Average over all scenarios	0.13	0.31	0.45	1.07
Maximum	3.02	4.27	11.65	18.65
Minimum given a spill	0.60	0.49	1.46	1.01
Number of spills	1,404	4,045	1,026	3,183
Probability of no spill[a] (%)	86.0	59.6	89.7	68.2

[a] *Probability of no spill* refers to the likelihood of no spill in all potential collision scenarios, whereas *probability of zero outflow* in the IMO methodology refers to the likelihood of no spill when the outer shell of a tanker has been ruptured. The committee's methodology also takes into account the difference in the vessel drafts.

the other hand, some of the side tanks in the single-hull vessels were ballast tanks, and breaching them did not result in a spill. In collision, the outflow calculation assumed that all oil was lost from a breached tank, and the size of the breached tank determined the outflow. In grounding, all transverse locations of the obstruction were equally likely, and the size of the breached tanks was important for the resulting outflow.

Oil outflow distributions for the single- and double-hull tankers in collision are shown in Figures 4-3 through 4-8.

Oil outflow distributions for the single- and double-hull tankers in grounding are shown in Figures 4-9 through 4-14. As with collision, the single-hull tankers had more small and medium-sized spills than the

TABLE 4-5 Grounding Results for 150,000-DWT and 40,000-DWT Single-Hull and Double-Hull Tankers

Result	40,000-DWT Vessel		150,000-DWT Vessel	
	Double	Single	Double	Single
Outflow (millions of gallons)				
Average given a spill	0.84	0.66	3.91	4.28
Average over all scenarios	0.05	0.12	1.06	2.53
Maximum	5.04	3.25	19.35	17.44
Minimum given a spill	0.16	0.07	0.87	0.86
Number of spills	612	1,833	2,724	5,911
Probability of no spill[a] (%)	94.0	81.7	72.8	40.9

[a] *Probability of no spill* refers to the likelihood of no spill in all potential grounding scenarios, whereas *probability of zero outflow* in the IMO methodology refers to the likelihood of no spill when the outer shell of a tanker has been ruptured. The committee's methodology also takes into account the difference in the vessel drafts.

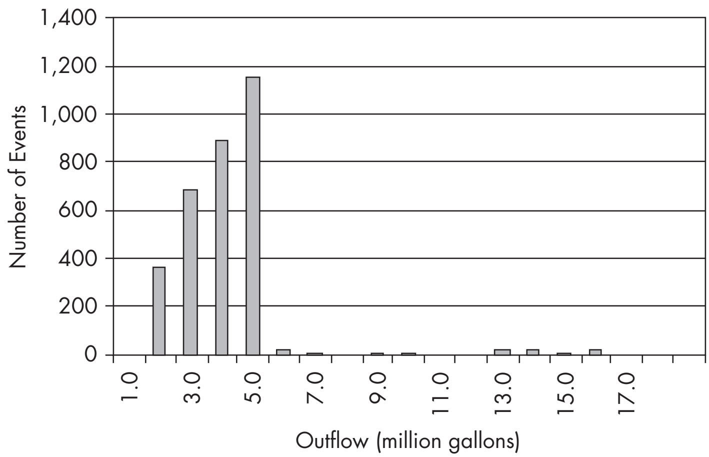


FIGURE 4-3 Outflow distribution for 150,000-DWT single-hull tankers (collision).

double-hulls, but the double-hulls had more very large spills.[8] The distributions for both sizes indicate that the single-hull tankers had a large number of small and medium-sized spills, whereas the double-hulls had more, although still only a few, very large spills. The 150,000-DWT single-hull tanker spilled more oil than the double-hull tanker in 84 percent of the grounding events, while the 40,000-DWT single-hull tanker spilled more than the double-hull tanker in 82 percent of those events.

It is important to note that the distributions shown are specific to the selected scenarios and vessels. No general conclusions on generic single- and double-hull designs can be drawn on the basis of these results alone.

The outflow results from the collision and grounding analyses were used in combination with the results of the consequence analyses in the application of the committee's methodology. The details of the collision and grounding studies can be found in the *Alternative Tanker Designs Collision Analysis* and *Alternative Tanker Designs Grounding Analysis* reports provided on the accompanying CD.

HYPOTHETICAL SPILL SCENARIOS AND CONSEQUENCE MEASURES

The committee conducted an analysis to generate a single consequence function describing the relationship of spill size to spill consequence for

[8] These differences in spill sizes are due, in part, to the subdivision differences between single- and double-hull tankers. The profiles of the midship sections for the single- and double-hull tankers in Figures 4-1 and 4-2 illustrate the differences in size of the internal tanks.

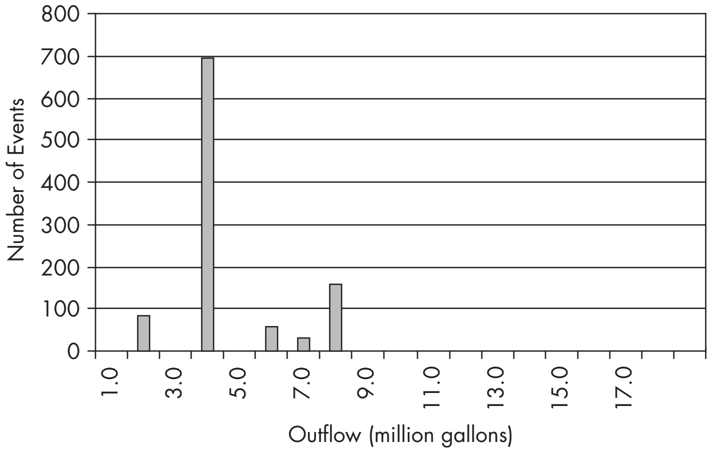


FIGURE 4-4 Outflow distribution for 150,000-DWT double-hull tankers (collision).

use in comparing the environmental performance of alternative tanker designs. In this section, the steps followed to generate this function are described. In the next section, this function, along with the outflow estimates described above, is applied to demonstrate how the approach can be used to compare the environmental performance of alternative tanker designs.

Hypothetical Spill Scenarios

To generate the required model runs, values had to be selected for several modeling parameters. These included the case study locations, weather at the time of and following the spill, oil type, and spill volume.

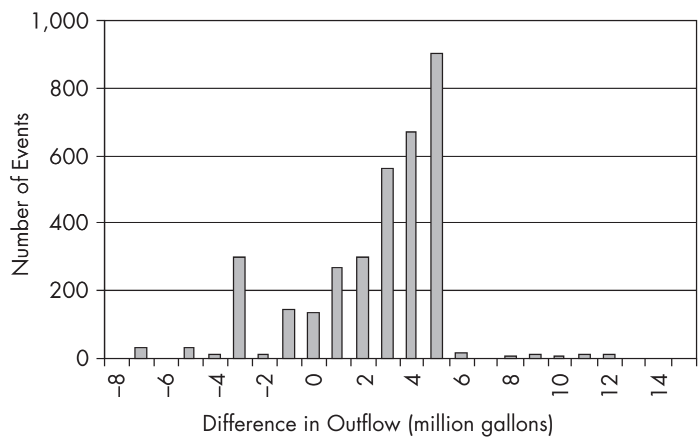


FIGURE 4-5 Distribution of differences in outflow between single- and double-hull (SH minus DH) 150,000-DWT tankers (collision).

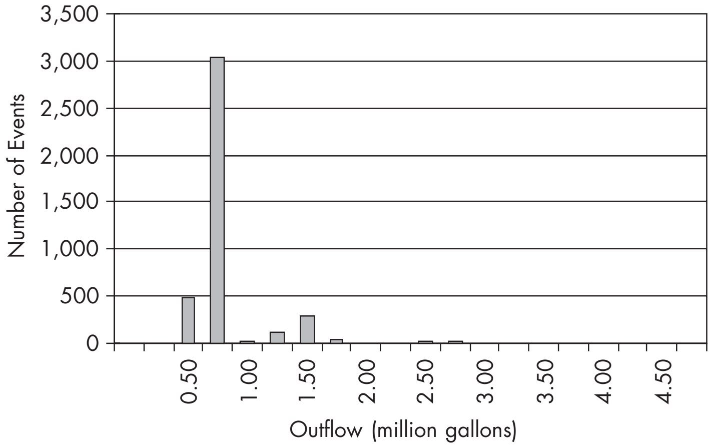


FIGURE 4-6 Outflow distribution for 40,000-DWT single-hull tankers (collision).

Selection of Locations

The committee determined that consideration of four case study locations would reflect sufficiently variable site characteristics to demonstrate the methodology. As discussed below, additional locations could be run and added to the analysis. As noted earlier, the following locations were modeled:

- Big Stone Anchorage, Delaware Bay;
- Galveston lightering area, Gulf of Mexico;

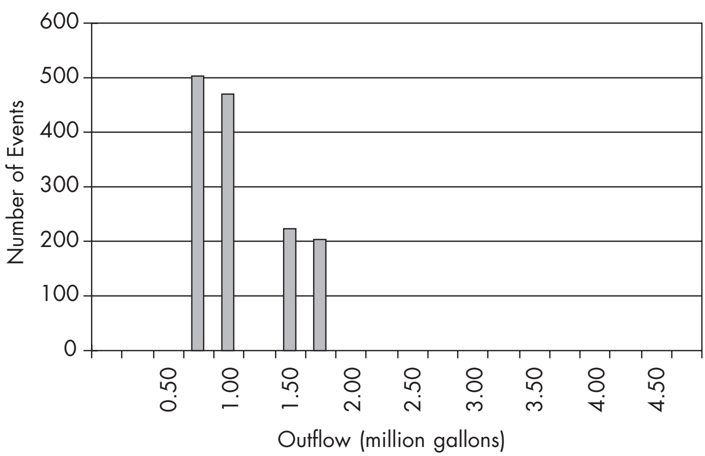


FIGURE 4-7 Outflow distribution for 40,000-DWT double-hull tankers (collision).

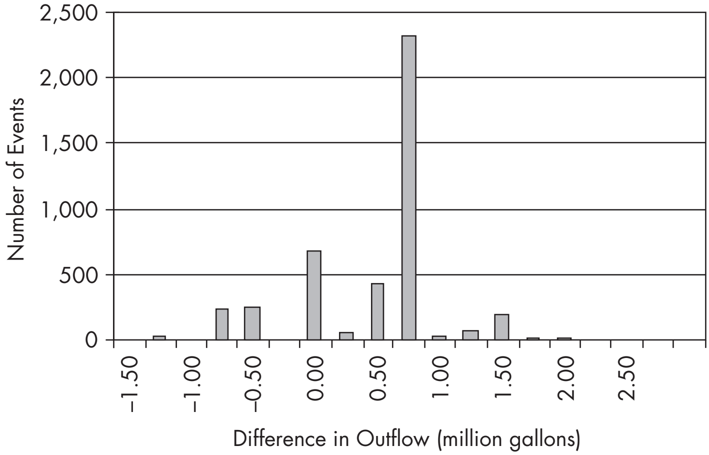


FIGURE 4-8 Distribution of differences in outflow between single- and double-hull (SH minus DH) 40,000-DWT tankers (collision).

- Carquinez Strait Bridge, San Francisco Bay; and
- Farallon Islands, offshore San Francisco.

These four locations were selected because they are known to have a large volume of oil-tanker traffic and because detailed data required for SIMAP[9] (e.g., current information) were available for these locations without a great deal of additional data-gathering effort.

Note that selection of these locations is not meant to imply that they have a higher probability of experiencing an oil spill or that the spills modeled at these sites are likely or even possible. For example, for some grounding scenarios, the vessel speeds considered in the DAMAGE model are highly unlikely to be seen at the model locations. Instead, these locations are intended to be indicative of the waters in which ships operate in terms of bathometry, weather, and geographic conditions.

Selection of Weather

To incorporate weather into the model, the committee developed a random sample of 200 actual meteorological histories, stratified by month (i.e., each month had an equal chance of being selected in the random draw, helping to ensure that a random sample would not be generated that omitted a

[9] SIMAP is a stochastic modification of the NRDAM/CME model. See Chapter 3.

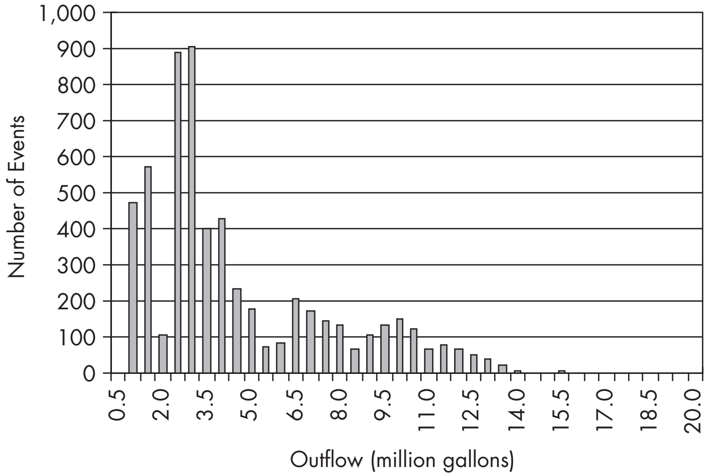


FIGURE 4-9 Outflow distribution for a 150,000-DWT single-hull tanker (grounding).

season of the year). The randomly selected spill date determined the weather situation over the modeled time period.[10] Weather conditions were held constant across oil type and spill size for a given location.

Selection of Oil Types

To bound the range of outcomes from SIMAP, the committee selected two oil types for the modeling exercise. The characteristics of these two oils were established on the basis of data from samples for two recent spills and were intended to cover the range of likely oil characteristics (in terms of volatility, solubility, and so on). The following two types were selected:

- Light crude oil (South Louisiana Crude, Lake Barre sample), and
- North Cape No. 2 fuel oil.

Selection of Spill Volumes

For each oil type, seven spill sizes were modeled to bound the range of estimated quantities released from tankers operating in U.S. waters. The spill sizes considered are shown in Table 4-6.

The maximum spill sizes shown relate to an assumed total loss of cargo from a tanker. The minimum spill size was chosen to represent

[10] ASA considered more than 10 years of weather data in each random draw.

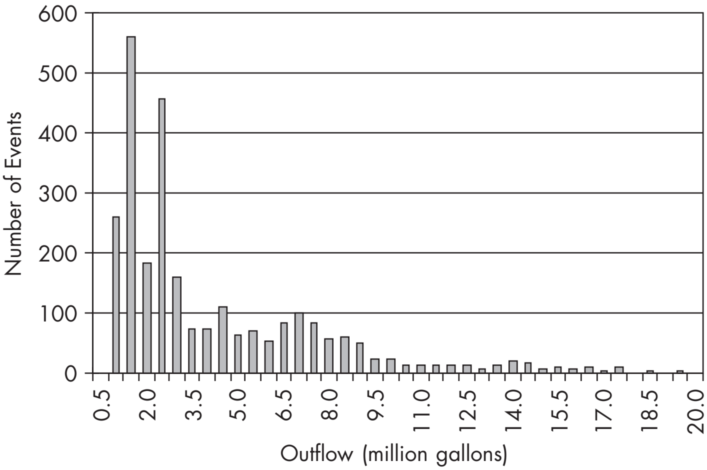


FIGURE 4-10 Outflow distribution for a 150,000-DWT double-hull tanker (grounding).

the lower end of typical tank vessel collision or grounding spills that could reasonably be modeled with SIMAP. In all cases, the release was modeled as an instantaneous event.

It should be noted that the modeling effort assumes no recovery of spilled oil. Historically, only a small percentage of oil spilled in the marine environment is recovered (OTA 1990), and there is no clear pattern

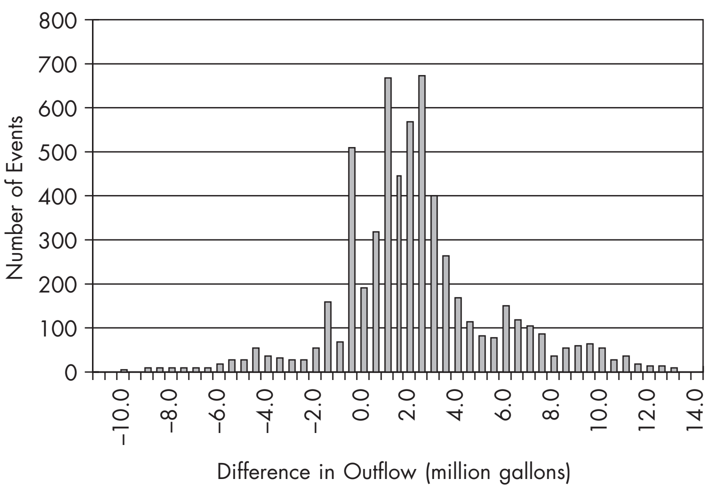


FIGURE 4-11 Distribution of differences in outflow between single- and double-hull (SH minus DH) 150,000-DWT tankers (grounding).

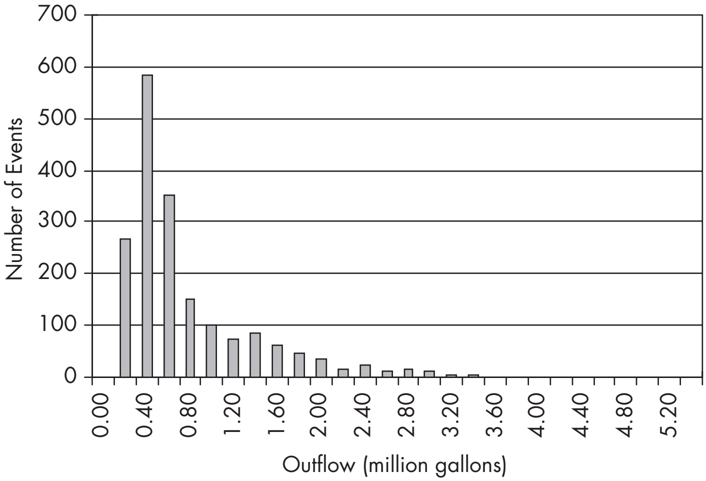


FIGURE 4-12 Outflow distribution for a 40,000-DWT single-hull tanker (grounding).

in terms of the percentage of oil recovered as a function of spill size. More important, the committee did not expect that recovery percentages would differ across tanker designs. If a proposed design offered an advantage over the conventional double-hull tanker in terms of oil recovery, this factor would need to be taken into account in comparing the proposed design with the double hull.

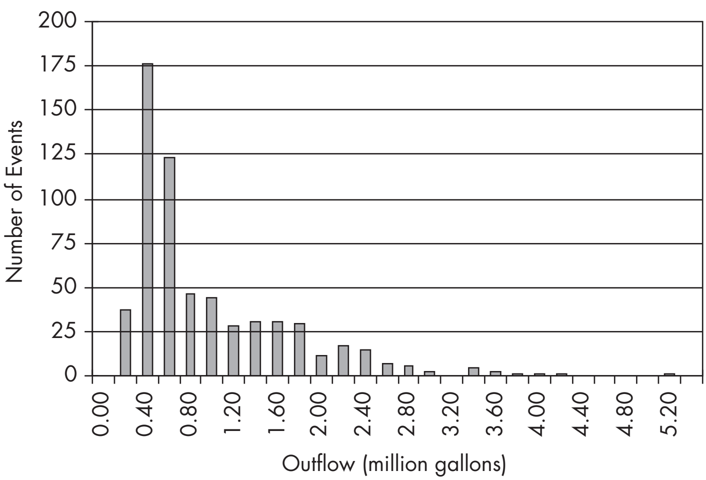


FIGURE 4-13 Outflow distribution for a 40,000-DWT double-hull tanker (grounding).

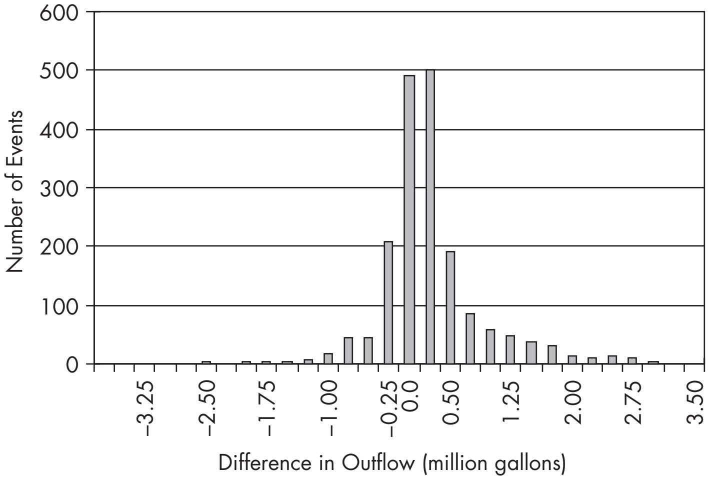


FIGURE 4-14 Distribution of differences in outflow between single- and double-hull (SH minus DH) 40,000-DWT tankers (grounding).

Final Scenarios

With four sites, 200 weather events, two oil types, and seven spill volumes, a total of 11,200 spills was considered. Given limitations in the number of spill scenarios the committee was able to commission, however, only one oil type was run for the Carquinez Strait location. Thus, a total of 9,800 spill scenarios was actually run.

Consequence Measures

As noted in Chapter 3, the committee considered a range of physical consequence measures available from SIMAP and did not include environ-

TABLE 4-6 Modeled Spill Sizes

Crude Carrier (gallons)	Product Carrier (gallons)
80,000,000	25,000,000
40,000,000	10,000,000
10,000,000	5,000,000
5,000,000	1,000,000
500,000	500,000
100,000	100,000
10,000	10,000

mental impact or cost measures. The SIMAP model provides the following physical consequence measures:

- Oil on water surface—measured as the area of water surface exposed to a slick of given thickness at some point following the spill.
- Oil on shoreline—the area or length of shoreline exposed over some thickness threshold.
- Oil in the water column—the volume of water column over some concentration threshold.
- Toxic oil components (i.e., low–molecular weight aromatics) in the water column (the volume of water column over some concentration threshold).
- Oil in bottom sediments—the area of sediments exposed over some concentration threshold.
- Total dosage, including slick thickness times the time present (mass per area-time), and water-column concentration times the time present.

Each of these measures was calculated for each hypothetical event across a range of thresholds. As described in Chapter 3, four measures were chosen for use in generating the consequence function: area of oil on water surface, oil on shoreline—area and length, and toxicity in the water column.[11]

The six thresholds modeled for each physical consequence measure reflect six order-of-magnitude intervals, generally starting one order of magnitude below a conservative estimate of a biological-effects threshold for the measure, and stepping four orders of magnitude above that threshold. For example, surface slicks were modeled at 1.0, 10, 100, 1,000, 10,000, and 100,000 microns. In this case, a surface slick 10 microns thick is considered to be a reasonably conservative biological-effects threshold. The committee adopted this approach to allow for flexibility in the later selection of one or more thresholds to be used as the "best" measure of likely consequence.

Figure 4-15 and Table 4-7 present examples of the information provided by SIMAP for the modeled scenarios. Figure 4-15 shows a spill "rose" generated for one of the case study sites, considering one oil type

[11] Although the committee was aware of recent research on the long-term persistence of even small amounts of oil in the environment (Carls et al. 1999; Heintz et al. 1999), it had no data indicating that persistence varies with spill size or that initial exposure (e.g., area of shoreline above peak concentration) is not a good proxy for long-term exposure, all else being equal. Therefore, no direct measures of persistence, per se, were included in the consequence function calculation.

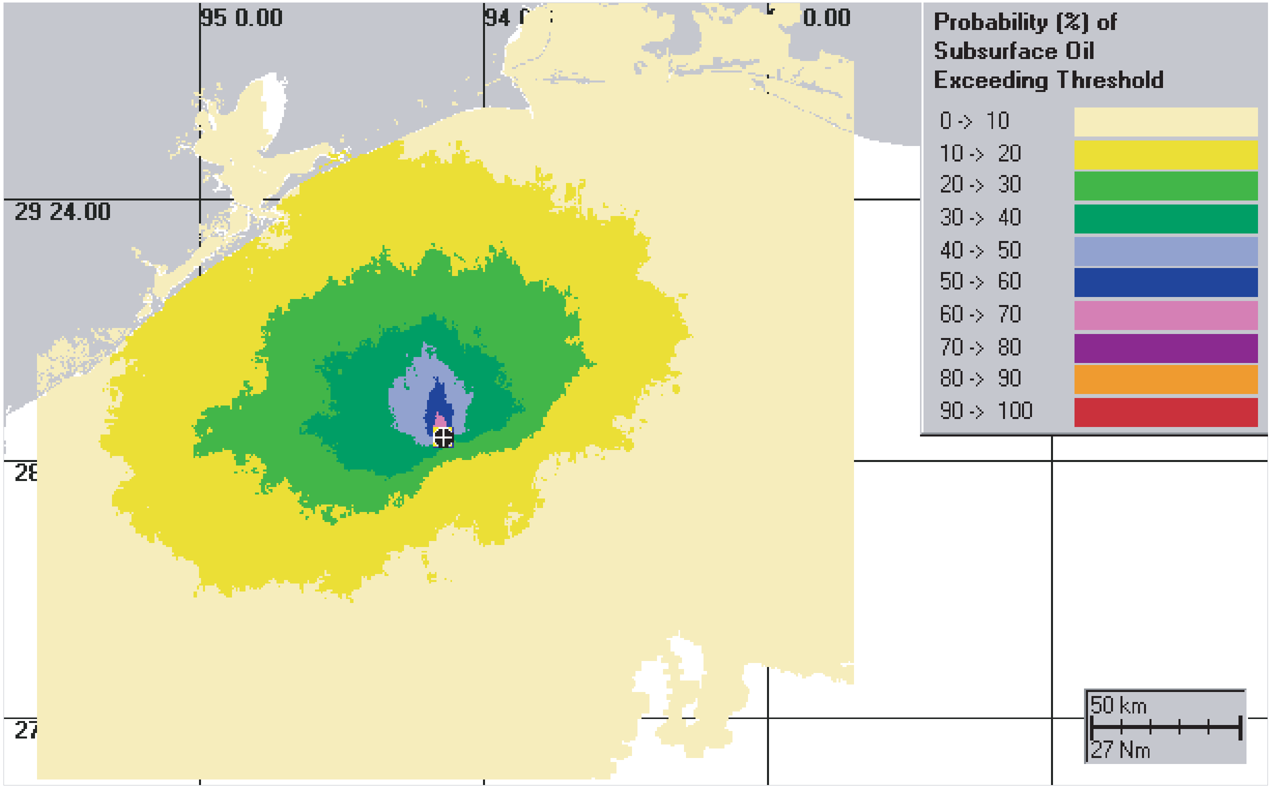


FIGURE 4-15 Texas spill site, 25 million gallons of No. 2 fuel oil (total hydrocarbons) in the water column: probability of exceeding a threshold concentration of 1 part per billion over a 2-week period.

TABLE 4-7 Modeled Physical Consequence: Total Square Meters of Slick Predicted at Galveston Lightering Area Case Study Site, North Cape No. 2 Fuel Oil

Model Run	Threshold 1 (1 micron) (m^2 slick)	Threshold 2 (10 microns) (m^2 slick)	Threshold 3 (100 microns) (m^2 slick)	Threshold 4 (1,000 microns) (m^2 slick)	Threshold 5 (10,000 microns) (m^2 slick)	Threshold 6 (100,000 microns) (m^2 slick)	Sum
1	1.83×10^9	7.60×10^8	2.72×10^7	3.21×10^5	0.00	0.00	2.61×10^9
2	1.76×10^9	1.13×10^9	1.12×10^8	0.00	0.00	0.00	3.01×10^9
3	2.28×10^9	8.99×10^8	3.01×10^7	0.00	0.00	0.00	3.20×10^9
4	1.19×10^9	7.51×10^8	2.82×10^7	0.00	0.00	0.00	1.96×10^9
5	1.76×10^9	1.12×10^9	4.84×10^7	0.00	0.00	0.00	2.93×10^9
6	1.66×10^9	8.04×10^8	3.24×10^7	3.21×10^5	0.00	0.00	2.50×10^9
7	7.96×10^9	3.82×10^8	3.40×10^7	6.41×10^5	0.00	0.00	1.21×10^9
8	1.23×10^9	7.03×10^8	6.60×10^7	1.28×10^6	0.00	0.00	2.00×10^9
9	1.92×10^9	4.09×10^8	4.04×10^7	6.41×10^5	0.00	0.00	2.37×10^9
10	2.85×10^9	5.86×10^8	3.81×10^7	1.60×10^6	0.00	0.00	3.48×10^9
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
200	2.22×10^9	7.05×10^8	5.23×10^7	3.21×10^5	0.00	0.00	2.98×10^9
Average	1.53×10^9	6.69×10^8	4.43×10^7	4.25×10^5	0.00	0.00	2.24×10^9

and spill size. The multiple spill trajectories shown represent the 200 modeled weather events for this site.

Table 4-7 provides an example of the tabular output provided by SIMAP for one case study location/oil type/spill size combination and one consequence measure. The case study site is the Galveston lightering area, the oil type is North Cape No. 2 fuel oil, and the spill volume is 100,000 gallons. For each of the 200 modeled weather events, SIMAP provided an estimate of the total area of surface slick exceeding the six thresholds considered. For example, for Model Run 2, 1.13×10^9 square meters of surface water was exposed to a slick equal to or greater than 10 microns in thickness (this is not the maximum size of the slick at any one moment in time, but the total area of surface water that exceeded that threshold thickness at some point following the spill event). For this spill size, no grid cell was modeled to exceed the fifth or sixth thresholds; thus, these columns are reported as zeros.[12]

Consequence Modeling

In this section, a summary of the steps followed to generate the final consequence function is provided. The first step was to generate a single measure of consequence for each of the four physical consequence measures. As noted, SIMAP provided consequence measures at six alternative threshold levels. The committee considered several approaches to combining these consequence measures. In particular, the committee considered using (*a*) the results presented for a single threshold (with a focus on the second threshold, which was thought to be the level that best represented a threshold for biological effects); (*b*) the sum of the six physical consequence measures, as presented for each of the six modeled thresholds; and (*c*) a sum of the thresholds, weighting each of the measures by factors of 10 [i.e., (consequence at Threshold 1) + (10 × consequence at Threshold 2) + (100 × consequence at Threshold 3) + . . .]. The committee chose the simple sum of consequence across threshold, as shown in the final column of Table 4-7, as the primary measure for this demonstration. The committee also tested the other two approaches to understand the sensitivity of the selected function to this assumption. Thus, for each of the four physical consequence measures, a vector of 200 simulations of consequence was created, reflecting the 200 randomly

[12] Detailed information on all of the model runs commissioned by the committee, as well as the output of these runs, can be found on the accompanying CD.

selected weather events. These simulations were generated for each location, for two oil types within each location, and for seven spill sizes for each location/oil type combination.

The four metrics used should sufficiently address the various environmental media through which consequences occur. By pooling them in an additive fashion, it is assumed that they are each of equal importance in determining consequence, since each can be argued to reflect a potential for ecological, economic, financial, and social effects. For example, the doubling of a slick's surface area is treated as equal to the doubling of the length of shoreline oiled in terms of the increased potential to result in consequence. Larger slicks hold greater potential to cause closure of commercial fisheries, while spills that impact primarily coastline might not result in a fishery closure, but could lead to a recreational beach closure. The relative economic importance of these two effects for any given spill will depend on site-specific and time-specific factors, but lacking detailed information on the location of expected spills, the committee believes these are equally good predictors of potential consequence. It is important to note that by using two shoreline oiling measures, the committee effectively recognized that when shoreline is oiled, a range of consequences can result (e.g., increased cleanup costs, potential for economic consequence).

As described in Chapter 3, the consequence function is expressed in terms of the consequence of each modeled spill relative to the consequence of a reference spill of 500,000 gallons (one of the volumes used in the simulations). The reference spills represent spills at the same location, of the same oil type, and given the same weather patterns as each of the modeled spills (i.e., the only factor that was varied is the size of the spill). Thus for each of the four consequence metrics, consequence ratios were created, as shown in Table 4-8. In this case, the "summed consequence" measures are the same as the measures reported in the last column of Table 4-7. The third column represents the modeled consequence for a series of 500,000-gallon spills of North Cape No. 2 fuel oil at the Galveston lightering area case study site, assuming the same 200 weather events. For example, for Model Run 4, the consequence ratio is 0.66 (i.e., the modeled consequence of a 100,000-gallon spill was 66 percent that of the modeled 500,000-gallon spill). Note that if spill consequence had a one-to-one relationship with spill size, the ratio would be 0.2.

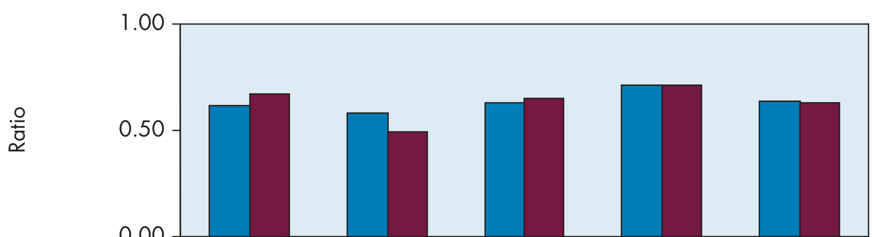
Figure 4-16 presents a set of consequence ratios for the Galveston lightering area, considering both oil types that were modeled and all four selected consequence measures. As shown, for this site the average con-

TABLE 4-8 Comparison of Modeled Spill Consequence: Total Square Meters of Slick Predicted at Varying Thickness Thresholds, 100,000-Gallon Spill Versus 500,000-Gallon Reference Spill, Galveston Lightering Area Case Study Site, North Cape No. 2 Fuel Oil

Model Run	Summed Consequence (100,000 gal)	Summed Consequence (500,000 gal)	Consequence Ratio
1	2.61×10^9	4.12×10^9	0.63
2	3.01×10^9	4.69×10^9	0.64
3	3.20×10^9	5.25×10^9	0.61
4	1.96×10^9	2.98×10^9	0.66
5	2.93×10^9	4.59×10^9	0.64
6	2.50×10^9	3.93×10^9	0.64
7	1.21×10^9	1.75×10^9	0.69
8	2.00×10^9	2.93×10^9	0.68
9	2.37×10^9	4.36×10^9	0.54
10	3.48×10^9	7.20×10^9	0.48
.	.	.	.
.	.	.	.
.	.	.	.
200	2.98×10^9	4.76×10^9	0.63
Average	2.24×10^9	3.66×10^9	0.61

sequence ratios are similar for the two modeled oil types and generally consistent across the four spill consequence measures considered.

A total of 168 average consequence ratios were generated. These ratios represent the four modeled locations, two oil types, four physical consequence measures, and six spill sizes modeled (the seventh spill size, 500,000, was used as the reference spill). Figure 4-17 provides a graph of these 168 consequence ratios, as well as a simple regression line through



	Area of Slick (m^2)	Water Column PAH (m^3)	Shoreline units (m^2)	Shoreline units (m)	Average
North Cape No. 2	0.61	0.58	0.63	0.71	0.63
Light Crude Oil	0.66	0.49	0.65	0.71	0.63

FIGURE 4-16 Comparison of spill consequence ratios: 100,000-gallon spill versus 500,000-gallon reference spill in Galveston lightering area case study.

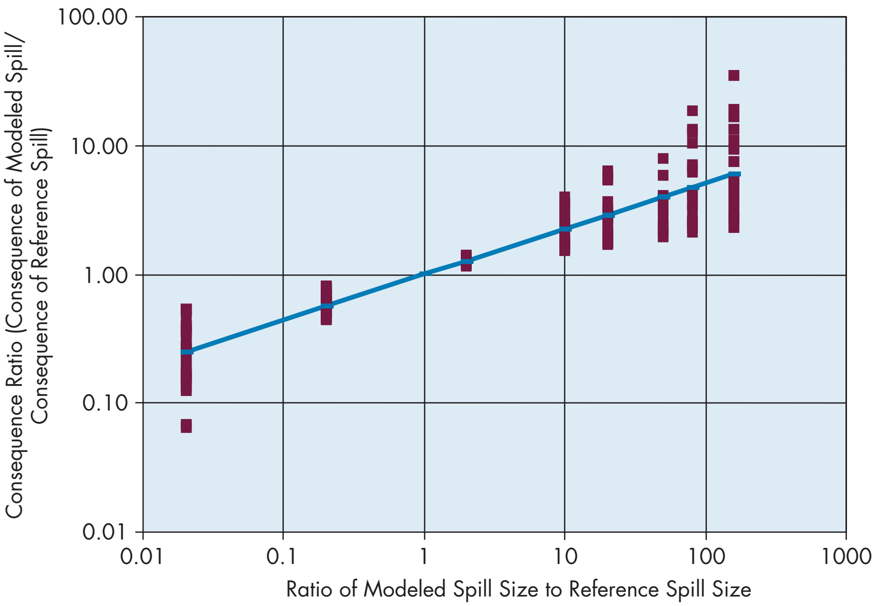


FIGURE 4-17 Physical consequence function expressed as consequence ratios.

these data points (the "consequence function").[13] Note that a one-to-one relationship would imply that the consequence of a gallon of spilled oil would be the same regardless of the total size of the spill. The analysis indicates that this is not the case. For spills of less than 500,000 gallons, the calculated average ratios were all significantly greater than what they would have been if the relationship were one-to-one; that is, the consequence of each gallon of oil spilled in smaller spills was greater than the consequence of each gallon of oil spilled in a comparable reference 500,000-gallon spill event. Inversely, the consequence of each gallon of oil spilled in the largest modeled spills was much smaller than the consequence of each gallon spilled in a reference 500,000-gallon spill event.

Figure 4-18 presents a subset of these data points and an alternative consequence function, considering modeled spills of less than 25 million gallons. For the committee's simulated collision and grounding events, in no case was the calculated outflow greater than 25 million gallons. Thus the consequence function shown in Figure 4-18 was applied in conducting the next step in the analysis.

[13] Note that the consequence curves are presented in log-log scale.

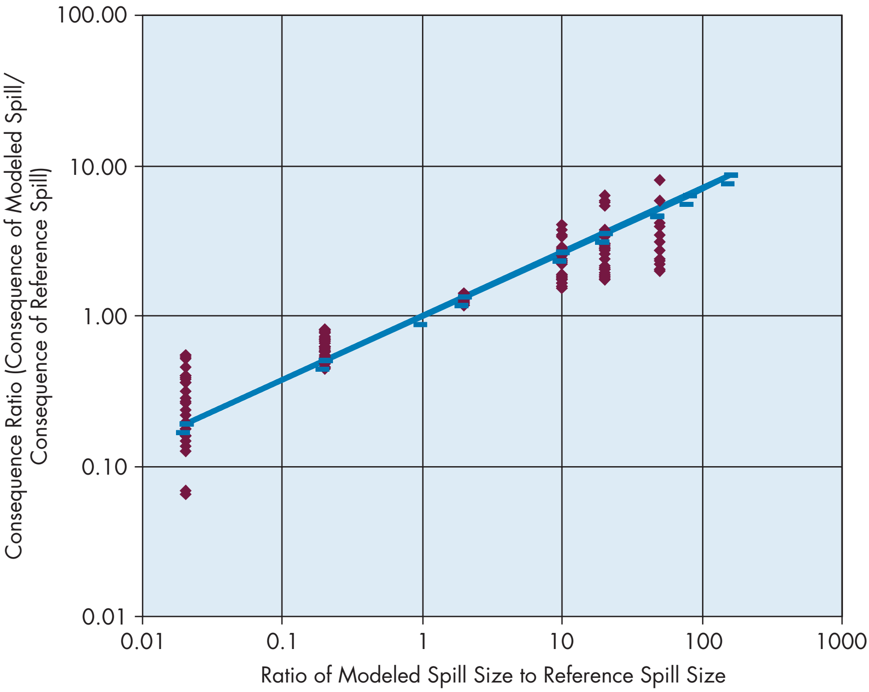


FIGURE 4-18 Physical consequence function expressed as consequence ratios for modeled spills of less than 25 million gallons.

The committee considered the sensitivity of the consequence function to the modeling assumptions. Figure 4-19 presents consequence functions for the modeled crude oil and product separately. This figure shows that the model outcome was relatively indifferent to assumptions concerning the characteristics of the spilled product. Figure 4-20 presents an alternative set of consequence functions, separately considering each of the case study sites. In this instance, some significant differences emerge. In particular, the Galveston lightering area and Carquinez Strait Bridge case study sites, when considered separately, provide very different consequence functions. The Carquinez Strait Bridge equation most closely matches the null hypothesis of a one-to-one relationship of consequence to spill size, probably reflecting the closed nature of San Francisco Bay.

Figure 4-21 provides separate consequence functions for each of the four physical consequence metrics considered. Figure 4-22 provides upper and lower bounds of the consequence ratio, as well as the best-fit model for the range of values assumed. Figure 4-23 presents the sensitivity of the consequence function to the alternative weighting of conse-

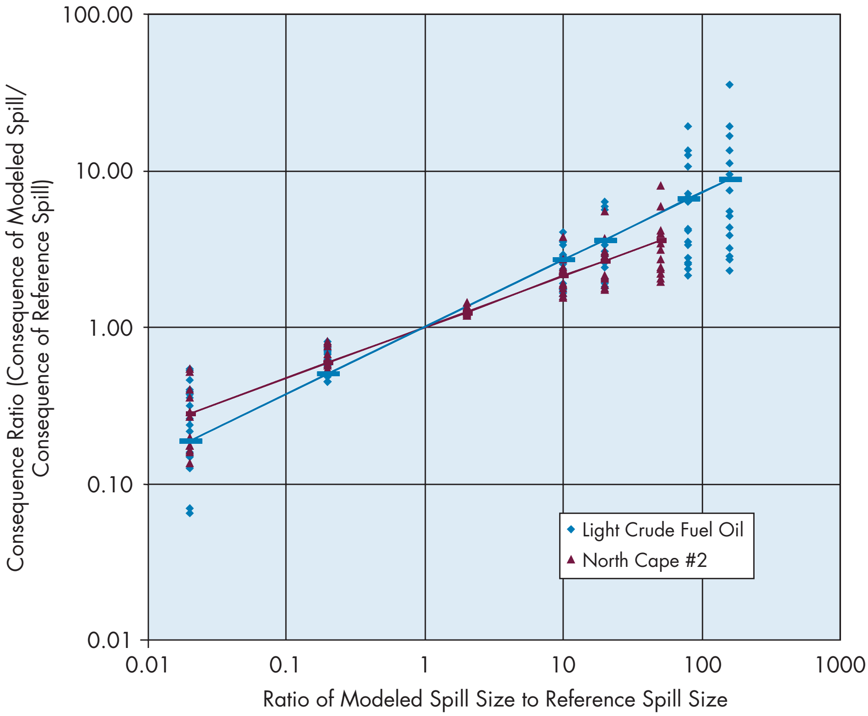


FIGURE 4-19 Physical consequence function sensitivity analysis: comparison of consequence ratios for two oil types.

quence across threshold measures. This figure considers three alternative weightings of modeled consequence across the six thresholds considered for each physical consequence metric: consequence measures based on summing of consequence across each of the thresholds, with equal weight applied to each threshold's value (the committee's selected approach); calculation of consequence based solely on exceedance of the second threshold for each consequence metric; and summing of consequence across each of the thresholds, with estimated consequence weighted by factors of 10 as the thresholds increase. Not surprisingly, the consequence values based on the second threshold have a pattern similar to that of the values based on the equal-weight model, but with a broader distribution within each spill size. This broader range reflects the greater variability in consequence obtained by relying on a single threshold. The consequence values generated using the factors-of-10 weighting scheme approximate more closely a one-to-one model of consequence and spill size than the values generated through the other two approaches. Even with this extreme weighting function, however, a consequence function would be

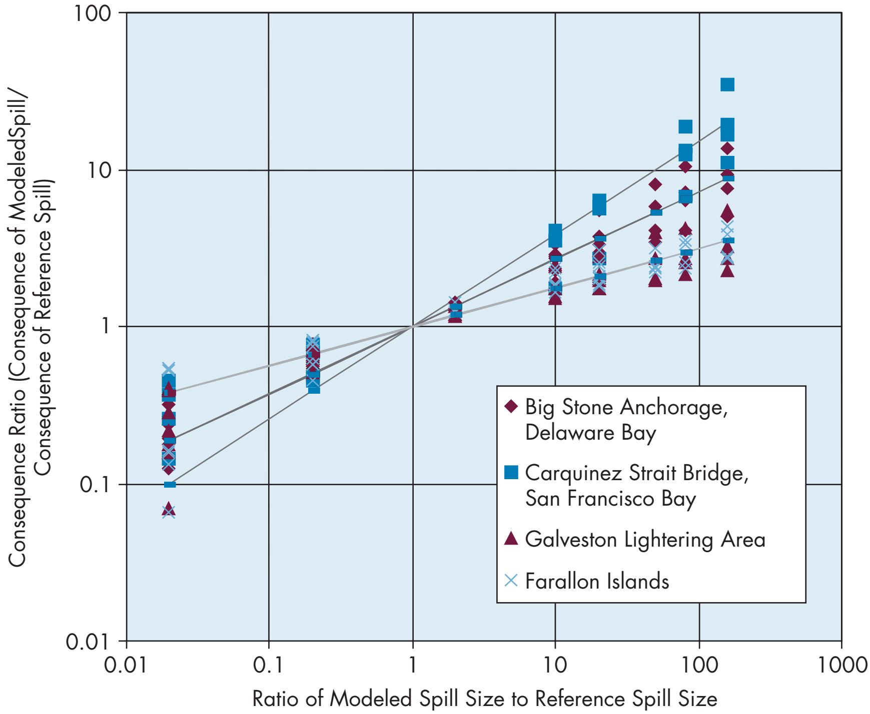


FIGURE 4-20 Physical consequence function sensitivity analysis: comparison of consequence ratios across case study sites.

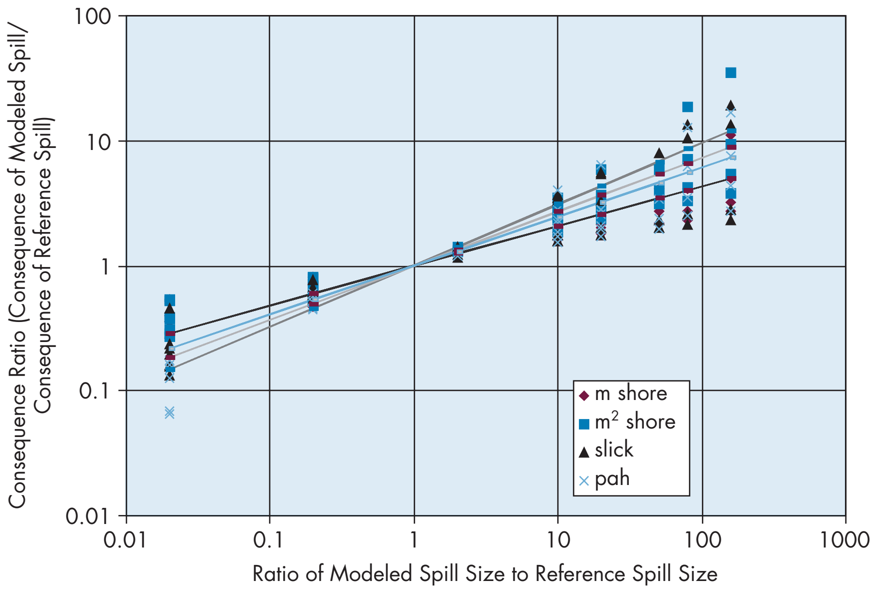


FIGURE 4-21 Physical consequence function sensitivity analysis: comparison of different consequence metrics.

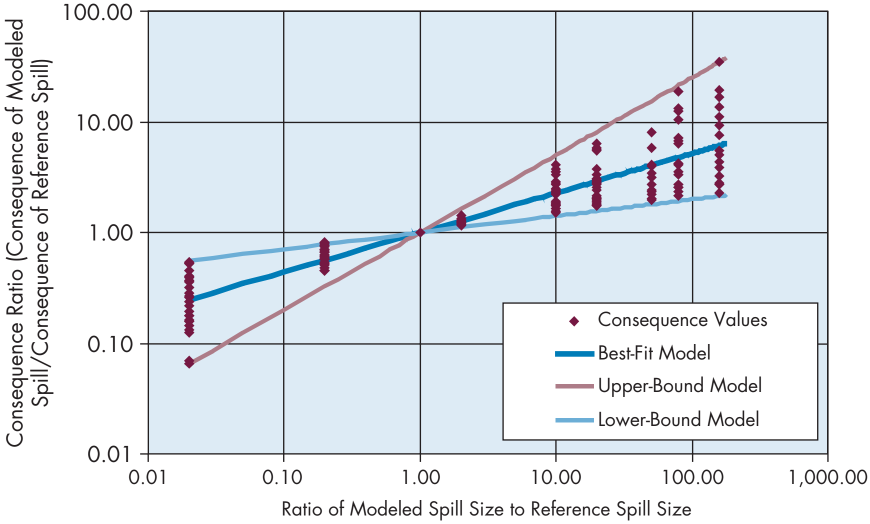


FIGURE 4-22 Physical consequence sensitivity analysis: comparison of upper and lower bounds.

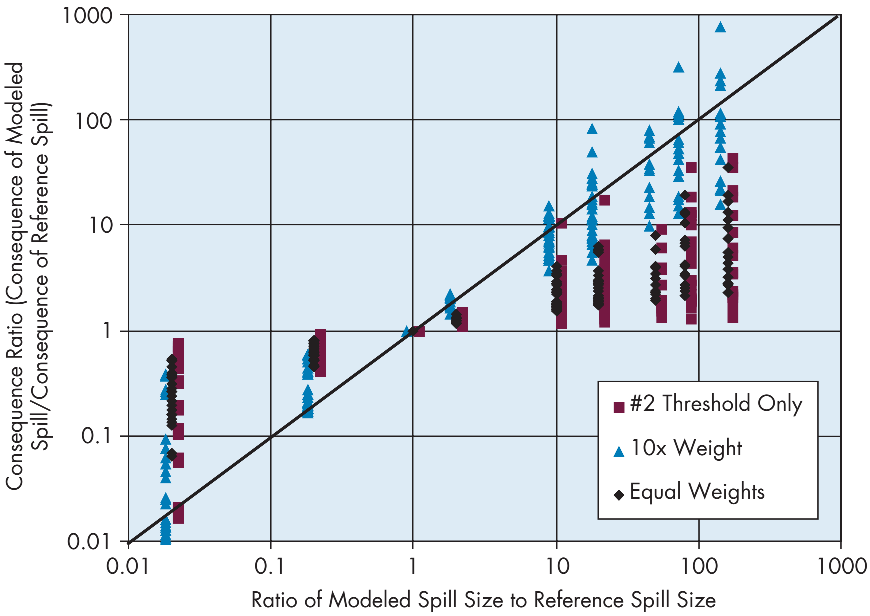


FIGURE 4-23 Physical consequence function sensitivity analysis: alternative weighting of consequence across threshold measures.

generated that would predict increased consequence per gallon spilled as spill size decreases.

In conducting the tanker comparison, the committee selected best-fit, upper-bound, and lower-bound consequence functions. The best-fit model was generated using a simple regression through the average consequence ratios for all spills of less than 25 million gallons. The upper bound was a function that incorporated the uppermost average values, while the lower bound represented a function that incorporated the lowermost values (as shown in Figure 4-22). Note that each of the points on Figure 4-22 (and the previous figures) reflects an average value generated from 200 data points. Thus, the actual range of values generated is much greater than that shown on these graphs, and some data points for specific individual weather events and locations lie outside the upper- and lower-bound consequence functions.

LIMITATIONS OF THE CONSEQUENCE ASSESSMENT

In addition to the limitations of the committee's methodology described in Chapter 3, there are several limitations of this specific application. First, given the resources available to the committee, the release of only one oil type at the Carquinez Strait Bridge case study site was modeled. Second, in light of the large number of smaller releases predicted by the collision and grounding simulations, consideration should be given to additional modeling of smaller spills, possibly using smaller grid-cell sizes. Third, no attempt was made to model oil recovery in the context of spill-response actions; to the extent that the recovered percentage differs across spill sizes, this factor may result in bias in the consequence function. Fourth, more sophisticated statistical models could be applied to the data generated by this exercise to produce upper- and lower-bound consequence functions for use in comparing alternative tanker designs. Because of the grid size used in SIMAP, the oil fate and transport model described in this report tends to underestimate the consequences of small spills. Therefore, more work is needed to refine the model. The sensitivity of the model to grid size and spill size should be further investigated to quantify the effect of this possible underestimate.

DESIGN COMPARISON

A total of 80,000 accident scenarios and outflow calculations were run—10,000 collision and 10,000 grounding events for each of two designs (single-hull and double-hull) and two different ship sizes (40,000-DWT and 150,000-DWT). Because identical accident scenarios across designs were used, the committee was able to compare outflow performance at the individual scenario level; it was not necessary to resort to comparison of the distributions of outflows. A fraction of the 80,000 scenarios resulted in outflow, which was converted to the consequence measure, the 500,000-gallon spill equivalent. By calculating and analyzing the differences in this measure across the scenarios, it was possible to determine whether an alternative design was equivalent to the target double-hull design.

Transforming the outflow gallons into 500,000-gallon spill equivalents made small spills look relatively more damaging than large spills. This point becomes important when one is examining the difference in outflow consequences: differences in large spills will appear less important than equal-sized differences in small spills. Table 4-9 provides an example of this effect. Even though the difference in spill amounts between the two designs is a constant 100,000 gallons, this difference has decreasingly less consequence as the absolute spill size increases. A 100,000-gallon difference in outflow when one design does not leak is equivalent to 0.563 times the consequence of a 500,000-gallon spill, whereas a 100,000-gallon difference when both designs spill about 20,000,000 gallons is equal to 0.007 times the consequence of a 500,000-gallon spill.

Table 4-10 provides a summary of the outflow and consequence measures for each of the design comparisons. In this table, the 80,000 accident scenarios are broken down by accident type, ship size, and performance measures (i.e., which design spilled more oil). For example, in comparing the 40,000-DWT designs, neither design spilled oil in 8,167 of 10,000 grounding scenarios; of the remaining scenarios, only the single-hull design spilled in 1,221 cases, and both spilled in 612 cases. In no case did the double-hull spill and the single-hull not spill. For the 612 cases in

TABLE 4-9 Demonstration of the Consequence Function

Outflow in Gallons			500,000-Gallon Spill Equivalents		
Design 1	Design 2	Difference	Design 1	Design 2	Difference
0	100,000	100,000	0.000	0.563	0.563
500,000	600,000	100,000	1.000	1.067	0.067
1,000,000	1,100,000	100,000	1.281	1.325	0.044
5,000,000	5,100,000	100,000	2.275	2.291	0.016
10,000,000	10,100,000	100,000	2.914	2.924	0.010
20,000,000	20,100,000	100,000	3.732	3.739	0.007

TABLE 4-10 Characteristics of the 80,000 Accident Analyses

			One Design Spills		Both Designs Spill			
					SH > DH		DH > SH	
Event	Measures[a]	No Spill	Only SH	Only DH	SH	DH	SH	DH
Collision								
40,000-DWT	Count[b]	5,711	2,885	244	219		941	
	Avg. mil. gal.	N/A	0.72	0.74	1.62	0.92	0.73	0.99
	Avg. 500k equiv.	N/A	1.13	1.14	1.50	1.22	1.14	1.26
150,000-DWT	Count[b]	6,567	2,407	250	365		411	
	Avg. mil. gal.	N/A	3.10	4.20	5.79	3.86	2.77	4.83
	Avg. 500k equiv.	N/A	1.89	2.12	2.32	2.07	1.80	2.19
Grounding								
40,000-DWT	Count[b]	8,167	1,221	0	273		339	
	Avg. mil. gal.	N/A	0.62	0.00	0.90	0.68	0.60	0.96
	Avg. 500k equiv.	N/A	1.00	0.00	1.15	1.02	1.00	1.18
150,000-DWT	Count[b]	4,089	3,187	0	1,622		1,102	
	Avg. mil. gal.	N/A	4.06	0.00	5.42	3.24	3.22	4.88
	Avg. 500k equiv.	N/A	2.00	0.00	2.25	1.83	1.82	2.06

NOTE: N/A = not applicable.

[a]Measures shown are count of scenarios in each spill category (count), average outflow in millions of gallons (avg. mil. gal.), and average outflow in 500,000-gallon spill equivalent units (avg. 500k equiv.).

[b]Each count represents a comparison between the results of two accident scenarios, one for a double-hull and one for a single-hull design.

which both spilled, the single-hull spilled more in 273 cases, and the double-hull spilled more in 339.[14] Also shown in the table are the average spill sizes (in millions of gallons) and average consequence (in 500,000-gallon spill equivalents). Note that average outflow for the case in which only the single-hull tanker spilled was 0.62 million gallons and that the values for both designs' spills were generally larger (0.60 million to 1.18 million gallons). The fact that when both designs spilled, the outflow numbers were large but relatively close to each other means that when these outflow values are expressed in terms of 500,000-gallon spill equivalents, the average equivalent units are very close (1.00 to 1.15). This pattern of relationships is generally repeated across the remainder of the table. The only major difference is that with the collision analysis, there was a small number of accidents that caused the double-hull design to spill but not the single-hull (244 for the 40,000-DWT design and 250 for the 150,000-DWT design).

[14] These numbers are specific to the selected designs and cannot be used to draw general conclusions on all double- and single-hull designs. The choice of the reference ship to be used in the evaluation of equivalency is important.

To determine the equivalency of two designs, differences measured in consequence units taken at the accident scenario level must be analyzed. Table 4-11 provides summary data for these differences. This table depicts benefit measures for use of the different designs. For example, for 40,000-DWT vessels involved in groundings, the double-hull design spilled less oil than the single-hull in 1,494 scenarios (when at least one design spilled), and the single-hull outperformed (spilled less than) the double-hull in 339 scenarios (in the remaining 8,167 scenarios, neither design spilled oil; see Table 4-10). In the 1,494 scenarios in which the double-hull design performed better:[15]

- On average, the benefit of having a double hull was 0.55 million gallons per scenario.
- The total amount not spilled because of using a double hull was 816 million gallons.
- On average, the benefit of using a double hull was 0.84 500,000-gallon spill equivalents per scenario.
- The total number of 500,000-gallon spill equivalents saved because of using the double hull was 1,250.

In the 339 scenarios in which the single-hull design performed better:

- On average, the benefit of having a single hull was 0.36 million gallons per scenario.
- The total amount not spilled because of using a single hull was 124 million gallons.
- On average, the benefit of using a single hull was 0.18 500,000-gallon spill equivalents per scenario.
- The total number of 500,000-gallon spill equivalents saved because of using the single hull was 61.

Note that the gallon measures are included only for reference. *It is the committee's strong recommendation that all design comparisons be made using the 500,000-gallon spill equivalent units.*

Thus in comparing the two designs, the double hull had better performance under some scenarios and the single hull under others. To

[15] The "benefits" shown cannot be used to calculate amounts of oil that would not have been spilled in previous real-world accidents had a particular design been in use. These benefits pertain only to the hypothetical accident scenarios used in the simulation.

TABLE 4-11 Design Comparison Using Difference in Outflows

Event	Measures[a]	Double Hull Performs Better[b]	Single Hull Performs Better[b]	Net Advantage to Double Hull[b]	Performance Advantage of Double Hull[c]
Collision					
40,000-DWT	Count	3,104	1,185	1,919	2.62
	Avg. mil. gal.	0.72	0.36	0.36	1.99
	Sum mil. gal.	2,237	429	1,808	5.22
	Avg. 500k equiv.	1.07	0.33	0.74	3.22
	Sum 500k equiv.	3,326	394	2,932	8.44
150,000-DWT	Count	2,772	661	2,111	4.19
	Avg. mil. gal.	2.94	2.89	0.05	1.02
	Sum mil. gal.	8,144	1,910	6,234	4.26
	Avg. 500k equiv.	1.67	1.04	0.63	1.61
	Sum 500k equiv.	4,627	687	3,940	6.73
Grounding					
40,000-DWT	Count	1,494	339	1,155	4.41
	Avg. mil. gal.	0.55	0.36	0.18	1.50
	Sum mil. gal.	816	124	692	6.59
	Avg. 500k equiv.	0.84	0.18	0.66	4.65
	Sum 500k equiv.	1,250	61	1,189	20.50
150,000-DWT	Count	4,809	1,102	3,707	4.36
	Avg. mil. gal.	3.43	1.67	1.76	2.06
	Sum mil. gal.	16,489	1,835	14,654	8.99
	Avg. 500k equiv.	1.46	0.26	1.20	5.62
	Sum 500k equiv.	7,033	287	6,746	24.54

[a] Measures shown include number of scenarios in each spill category (count), average benefit in millions of gallons (avg. mil. gal.), sum of benefits in millions of gallons (sum mil. gal.), average benefit in 500,000-gallon spill equivalent units (avg. 500k equiv.), and sum of benefits in 500,000-gallon spill equivalent units (sum 500k equiv.).

[b] Values given indicate benefits of the design.

[c] Values given indicate how many times better the performance of the double-hull design is relative to that of the single-hull overall.

determine which design is superior overall (i.e., has the smaller total consequence), the difference between the measures can be calculated. For the designs analyzed in this report, the double hull was clearly superior. Table 4-11 indicates that, for the 40,000-DWT tankers involved in grounding incidents, use of a double-hull design in the 10,000 scenarios saved 1,189 500,000-gallon spill equivalent units over use of a single-hull design. Note that all of the other measures in the table also show a considerable advantage for the double-hull design. This will not necessarily be the result if the methodology is applied in other comparisons. For example, a mid-deck design could have a positive benefit relative to a double-hull design with regard to total gallons spilled but be inferior according to the 500,000-gallon spill equivalent measure. To demonstrate how this could happen, the last column in Table 4-11 shows the relative benefit of the double-hull design across the different measures and scenarios. Referring back to the 40,000-DWT tankers in grounding incidents, the double-hull tanker was superior to the single-hull in 4.41 times more scenarios, spilled 6.59 times less oil, and caused 20.50 times less damage according to the 500,000-gallon spill equivalent measure. These differing ratios show how different measures could lead to apparently conflicting results. *This is precisely why the committee believes the consequence measure should be the final determinant of design equivalency with the double hull.*

Figures 4-24 through 4-27 depict the 500,000-gallon spill equivalent results shown in Table 4-10. They also demonstrate how sensitive the results are to assumptions about the consequence function. Figure 4-24*a* shows the results for the 40,000-DWT tankers involved in grounding scenarios using the best-fit consequence function. The light gray region in the lower left corner of the figure represents the 339 scenarios in which the single-hull design outperformed the double-hull. The height of the region indicates the number of 500,000-gallon spill equivalent units saved by using the single-hull design in each scenario. The larger black area represents the 1,494 scenarios in which the double-hull design outperformed the single-hull. The area of the two regions represents the sum of 500,000-gallon spill equivalent units (1,250 for the black region and 61 for the gray). If the designs were equivalent, the two regions would be equal in size.

Figures 4-24*b* and *c* show the same results using the lower- and upper-bound consequence functions from Figure 4-22, respectively. The lower-bound function is even more concave, increasing the relative impact of smaller versus bigger spills, while the upper-bound function is closer to a linear relationship between spill size and consequence. The effect of these different functions is not significant in determining the equivalency of the two designs: the double hull is clearly superior in all figures. However, the changes in the shaded areas highlight the importance the functional form could have for future comparisons. In Figure 4-24*b* it is easy to identify the 1,221 scenarios from Table 4-10 in which only the single-hull design spills (the steep "cliff" in the black region just beyond 1,200). This cliff disappears when the flatter upper-bound consequence function is applied. This is an example of the effect demonstrated in Table 4-9. Figure 4-25 shows the same analysis for the 150,000-DWT designs.

Figures 4-26 and 4-27 show the results of the collision analysis for the 40,000-DWT and 150,000-DWT vessels, respectively. Note that in a few 150,000-DWT scenarios the single-hull has a larger advantage over

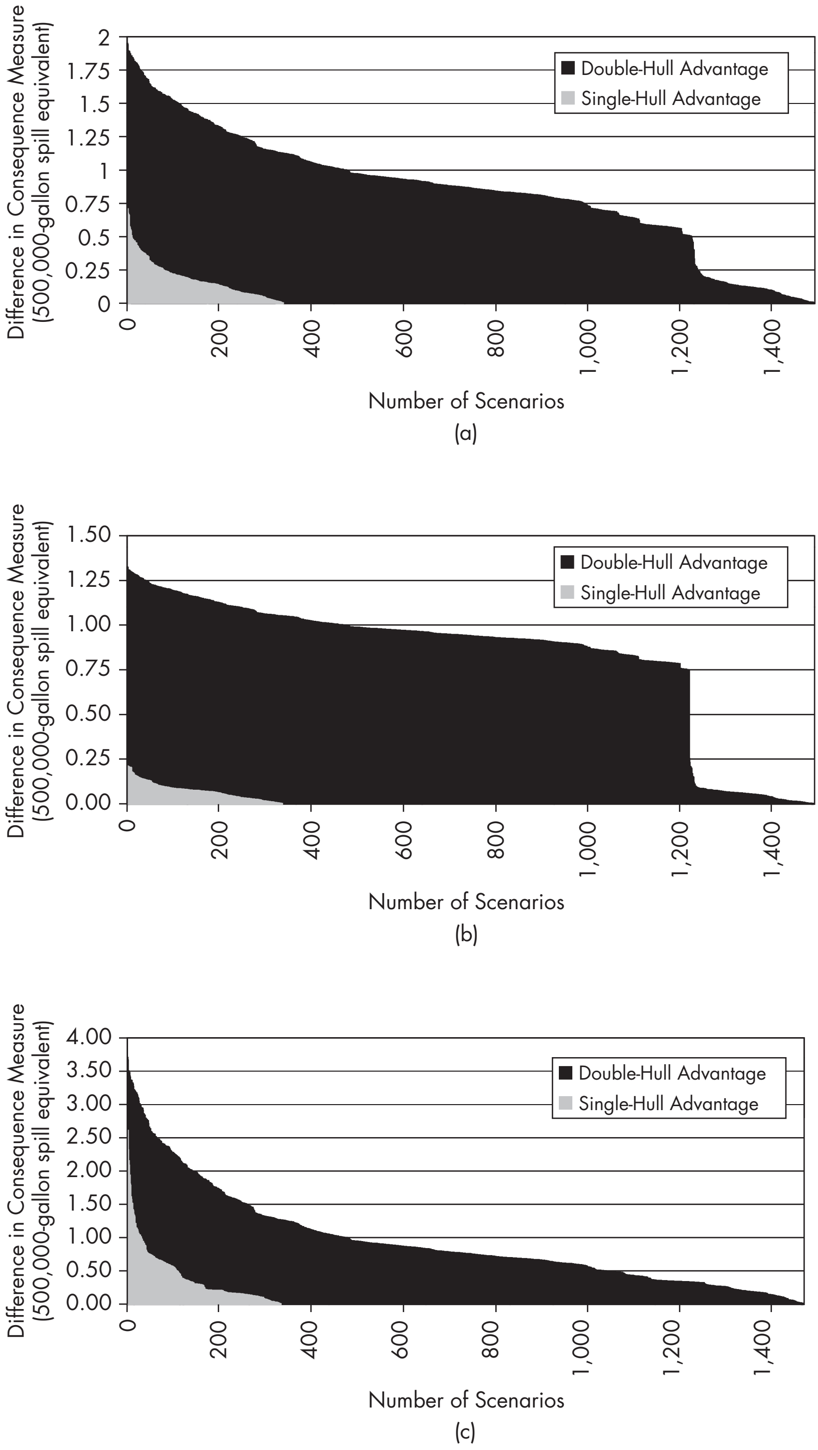


FIGURE 4-24 Comparison of 40,000-DWT vessels in grounding scenarios using three models: (*a*) best fit, (*b*) lower bound, and (*c*) upper bound.

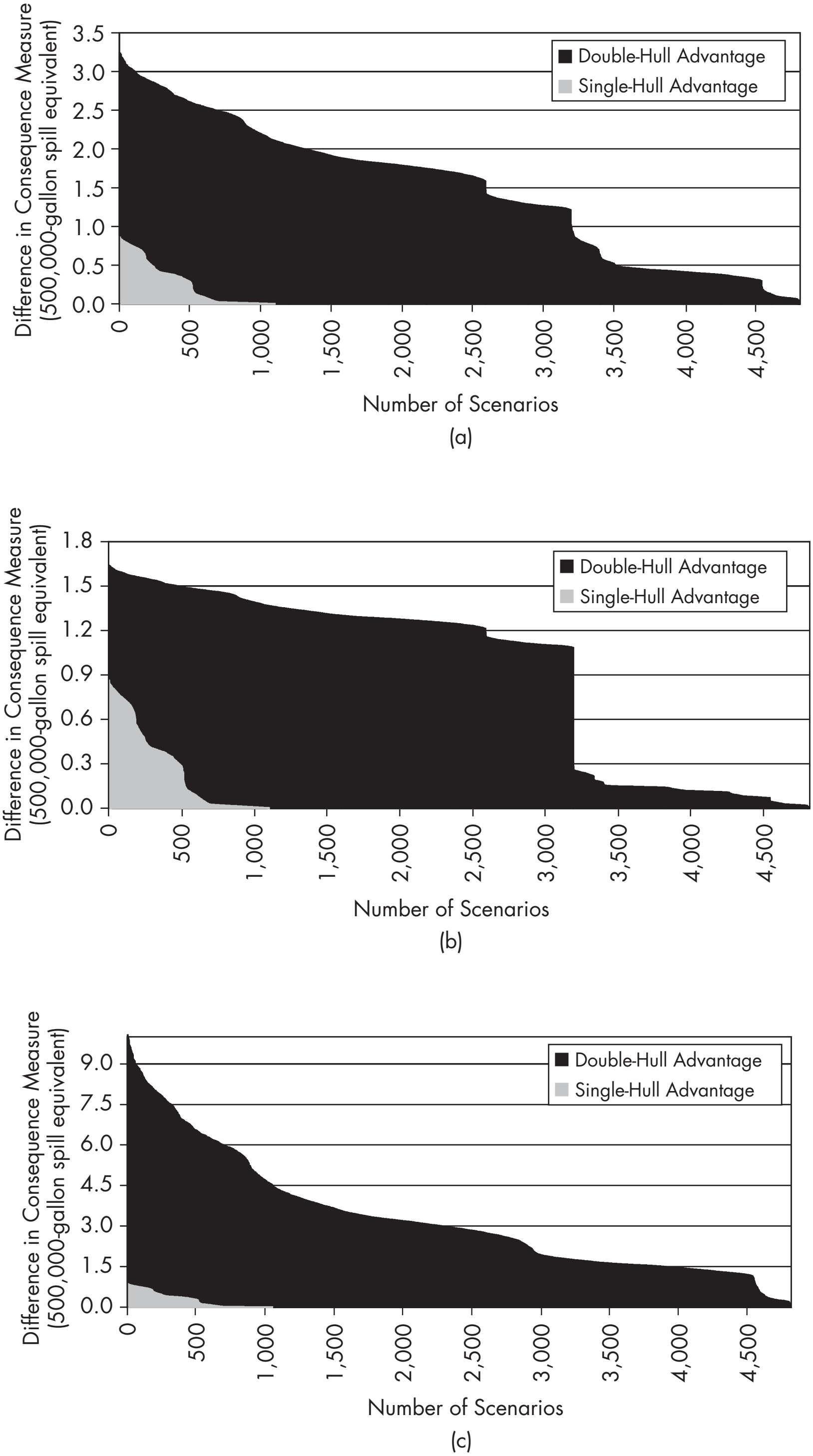


FIGURE 4-25 Comparison of 150,000-DWT vessels in grounding scenarios using three models: (*a*) best fit, (*b*) lower bound, and (*c*) upper bound.

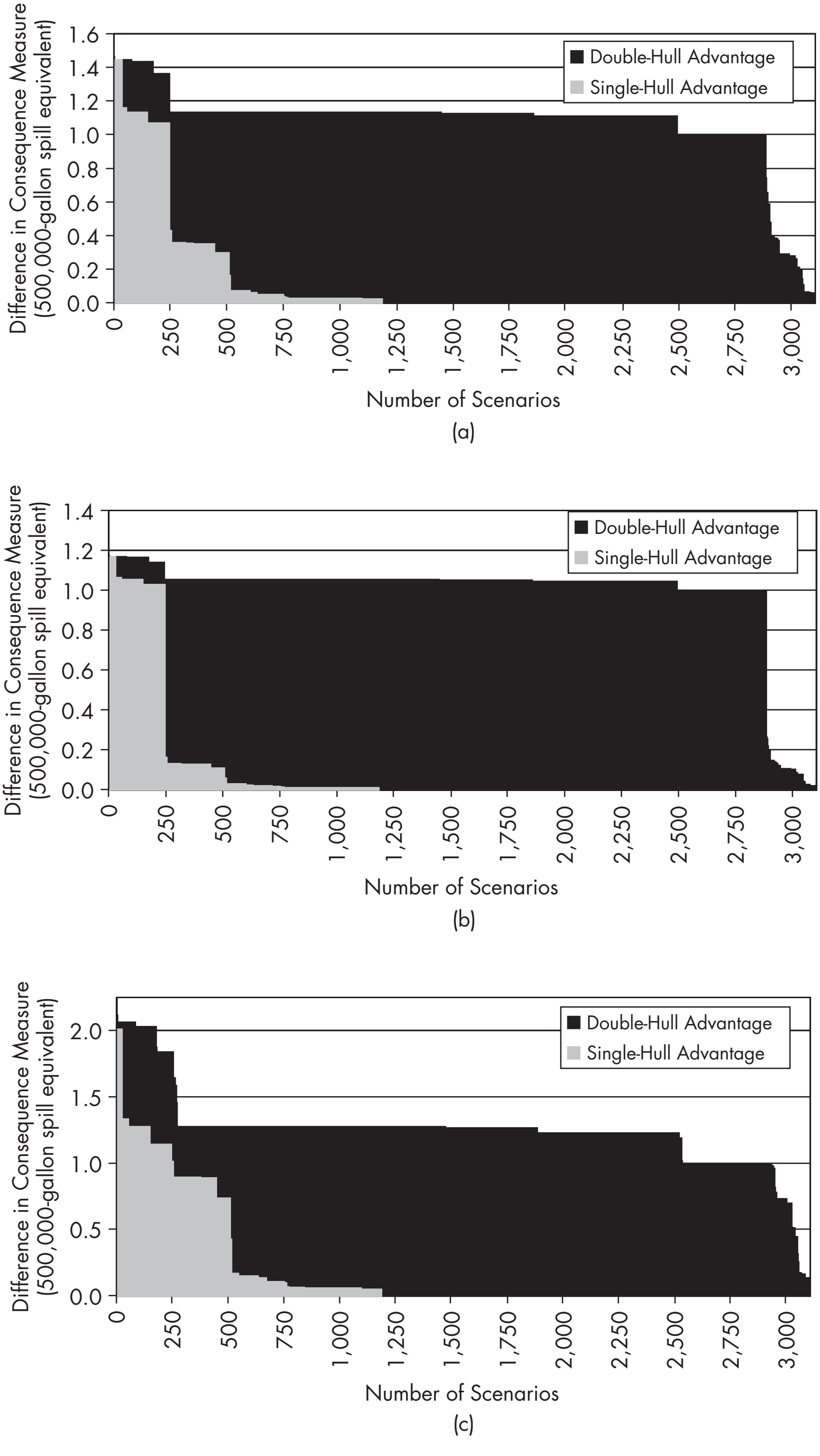


FIGURE 4-26 Comparison of 40,000-DWT vessels in collision scenarios using three models: (*a*) best fit, (*b*) lower bound, and (*c*) upper bound.

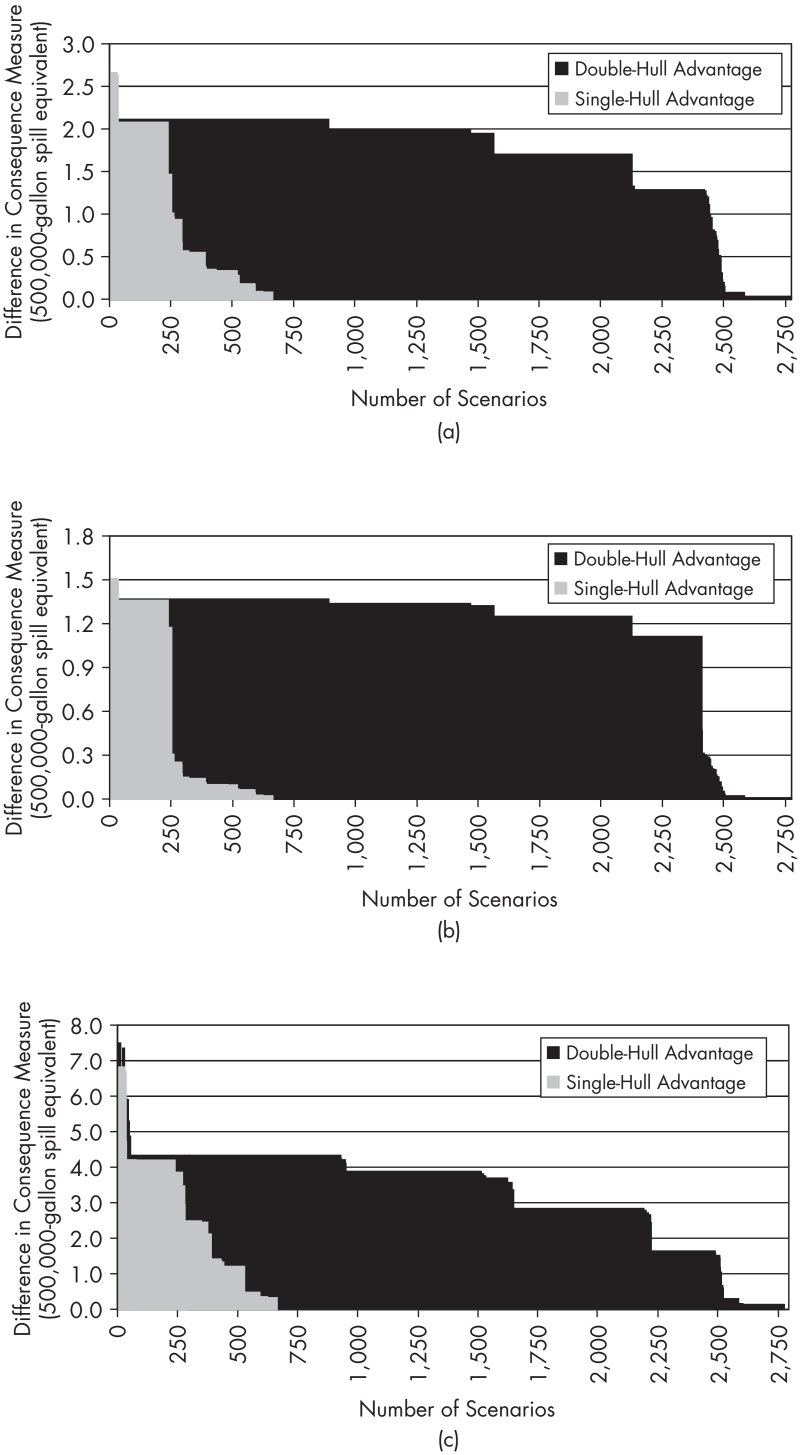


FIGURE 4-27 Comparison of 150,000-DWT vessels in collision scenarios using three models: (*a*) best fit, (*b*) lower bound, and (*c*) upper bound.

the double-hull than the double-hull has over the single-hull in any scenario. Nonetheless, a comparison of the two shaded regions shows the overall benefits of using the double-hull design.

Since the committee did not attempt to determine the likelihood of any of the scenarios actually occurring, the above analysis cannot be used to determine the actual savings that might be incurred by using a fleet of double-hull designs in a given time period. This is a very different and more difficult problem that would require a detailed risk analysis of a specific port area with defined operations and traffic patterns—the type of analysis that would be required if one wanted to determine the relative costs and values of a double-hulled fleet.

SUMMARY

By performing the applications described in this chapter, the committee has demonstrated that its methodology can be used to compare tanker designs and determine their relative environmental performance. The applicability of available computational tools to the prediction of structural damage and resulting oil outflow in multiple accident scenarios has also been shown. The applications involved single-hull and double-hull designs of two different sizes. The committee checked the outflow results for two vessel sizes to show that the methodology provides consistent results for a range of possible conditions, as well as reasonable distributions of the differences when two designs are compared. The committee then tested its approach to the development of a consequence metric that can be used to modify the outflow results and represent a rational measure of environmental consequence differences in a design comparison. The committee also conducted sensitivity analyses to test the rigor of the consequence function. Finally, the committee illustrated its methodology for comparing designs for a range of both collision and grounding events. The final design comparisons showed that the methodology can be applied to designs with different features, and the results can be depicted graphically to determine which design exhibits superior performance.

The committee understands that its methodology will lead to unambiguous results only when the factors used in the comparison of designs, taken together, show clearly that one design has superior performance over another. In the illustration in this report, that appears to be the case. There could be instances, however, in which the relative performance of one design versus another is not obvious using this methodology alone. In those cases the regulatory authority must exercise its judgment, take into account other factors in the comparison, and make a determination that is consistent with its public mission. The committee believes that any proposed methodology would require a similar process.

REFERENCES

ABBREVIATIONS

IMO	International Maritime Organization
OTA	Office of Technology Assessment, U.S. Congress
SNAME	Society of Naval Architects and Marine Engineers

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CONCLUSIONS AND RECOMMENDATIONS

The committee has carried out its charge to develop a rationally based methodology for assessing alternative tanker designs on the basis of their relative ability to prevent environmental damage from oil spills following collision and grounding accidents. The committee has tested this methodology by applying it to two existing tanker designs and presented the results of those applications. Finally, the committee has researched and produced related analyses that support, explain, and demonstrate the methodology, including its limitations. The committee's conclusions concerning these efforts are presented in this chapter. Also presented are the committee's recommendations for further refinement of the methodology and other actions to enhance its future use, as well as for its application by USCG in making decisions about the acceptability of alternatives to the double-hull design for operation in U.S. waters.

OVERALL METHODOLOGY

The methodology developed by the committee for comparing alternative tanker designs is described in Chapter 3; its application for comparing two designs is illustrated in Chapter 4. The committee concludes that the methodology can be used as a tool by a regulatory authority for considering alternative designs and represents a significant improvement over existing methods. The methodology could also be used by both the industry and regulatory authorities to rate the relative environmental performance of two designs following collision and grounding accidents. At the same time, the methodology needs further refinement to enhance its accuracy and reliability. Such efforts should encompass peer review of the methodology; testing of the methodology; and a comprehensive review by stakeholders, including the tanker industry, environmental groups, and regulators. The methodology is not dependent on the software used by the committee. If other software is found to provide more accurate results for structural damage and outflow or the consequences of spills, it can be used instead.

The discussion in Chapters 3 and 4 reviews those refinements the committee believes to be most critical, as well as factors that will limit the implementation of the methodology until further refinement is accomplished. In developing the methodology, for example, the committee used a limited set of model specifications concerning spill size and location, as described in Chapter 4. The committee believes that the construction of additional model scenarios would yield more information about the relative effects of spill size and location and thus improve the accuracy of the modeling technique. Furthermore, certain applications of the methodology may require enhancements to accommodate various design features. For example, the tool used to calculate structural damage must be modified if a subject vessel under review is not of conventional steel construction.

Recommendation 1: **USCG should use the proposed methodology for evaluating alternative tanker designs and at the same time undertake a program to refine the methodology to address the issues discussed in this report.**

Recommendation 2: **USCG should institute a standard procedure for evaluating specific designs submitted as equivalent to a double-hull design. This procedure should include the methodology proposed by the committee for assessing equivalency on the basis of environmental consequences from oil spills following collision and grounding accidents. Other appropriate factors, such as those associated with the safety and operation of the vessel, will have to be evaluated in conjunction with the use of this methodology.**

Recommendation 3: **To continue and validate the work of the committee, USCG should apply the committee's methodology to compare other alternative designs with the double hull. The committee suggests that one alternative assessed be the mid-deck design, which is available in a detailed form and has already been evaluated by IMO.**

DOUBLE-HULL REFERENCE SHIPS

Although the committee's charge referred to comparing alternative designs with the double-hull standard, the committee did not select a standard double-hull design. To test its methodology, the committee selected one available double-hull design without regard to whether it represented an accepted standard. Since each design may have qualities and characteristics that differ from a minimum standard in a significant way, selection of one standard by which all alternatives would be measured in the future would represent a policy decision. In using the methodology, however, a critical first step is to define such standard double-hull reference ships in a number of size ranges, thus enabling all proposed new designs to be measured on the same basis.

> ***Recommendation 4:*** **USCG should define in sufficient detail and make available the standard reference ships needed for the methodology. This concept is similar in nature to the reference ships currently used by IMO. In developing the standard reference ships, USCG should refer to the discussion of design of double-hull tank vessels in the 1998 NRC report entitled *Double-Hull Tanker Legislation: An Assessment of the Oil Pollution Act of 1990.***

NEED FOR VESSEL DESIGN DETAILS

The committee's approach to developing this methodology entailed rigorous computational methods that included analyzing the crashworthiness of ship structures, calculating oil outflows in specific accident scenarios, and modeling spills and their complex behaviors while reducing the results to numerical values. The methodology is necessarily complex and requires substantial detail in all input values, including complete design details for any vessel to be evaluated. Given these complexities, it would be unreasonable to expect that the methodology could be used to evaluate a concept in the absence of a complete ship design. The committee concludes that if an alternative design is to be evaluated by USCG, sufficient design and analysis detail must be available.

> ***Recommendation 5:*** **Anyone proposing an alternative design should be required to submit to USCG not only a complete description, including design plans, but also an analysis of the design and its performance within the framework of the models used in the proposed methodology, including such aspects as outflow under different accident scenarios. Sufficient information should also be provided to allow USCG to perform an independent review of the proposed design. In addition,**

USCG should prepare specific instructions for those who wish to submit alternative designs, including a list of required design plans, structural and mechanical details, and relevant calculations. The format and organization of a submission should also be specified.

CONSIDERATION OF ACTIVE SYSTEMS

Several designs for oil tankers, including the double hull, protect against oil spills by creating an arrangement of the ship's structure that will prevent or mitigate oil outflow. These "passive" approaches may create a void space between cargo oil tanks and the sea, or locate tanks where they are less likely to leak or be punctured, or use hydrostatic pressure balance to prevent leaks after a puncture. In contrast to passive systems, some alternative designs incorporate "active" systems with the use of valves, sensors, piping, pumps, or other mechanical devices that would be activated after an accident to mitigate oil outflow. Active systems present additional factors to be considered when evaluating alternatives. Their unique characteristics pose multiple types of risks that need to be considered in conjunction with relevant operational protocols. These complexities add an overlay to the proposed methodology that the committee could not test within this study because of a lack of sufficient detail on any active system. In particular, a quantitative life-cycle risk analysis conforming to requirements specified by USCG would be needed as part of the approval process for an active system. The committee believes that the techniques for conducting such an analysis exist; however, it could not apply these techniques within the limited resources available for this study.

Recommendation 6: **Any submittal to USCG of an alternative design that includes an active system should contain a quantitative life-cycle risk analysis, along with supporting information, so that independent verification can be accomplished by either USCG or others. In addition, USCG should develop the capability to review and evaluate all of the risk assessment factors that might be presented in such a submittal.**

COMPONENTS OF THE METHODOLOGY

The methodology developed by the committee has three components or steps: (*a*) analysis of oil outflow following a collision or grounding accident, (*b*) analysis of the consequences of the oil outflow, and (*c*) comparison of the design relative to the environmental performance of the double-hull standard.

Outflow Analysis

The committee concluded that the use of historical data, and therefore the IMO methodology and other methods based on such data, is not appropriate for evaluating new tanker designs. Accordingly, the methodology proposed by the committee uses direct computational tools instead of historical data to determine the crashworthiness of either double-hull or alternative designs. The structural damage databases currently available, including the one updated by the committee, include only single-hull tankers and combination carriers. Collecting new data would not provide a usable database for the purposes of this methodology since data on innovative designs simply do not exist.

In addition, in developing the methodology, the committee concluded that existing computational tools for determining damage extent and outflow are not fully validated, and their applicability is limited to evaluating structural arrangements that use conventional members and materials—plates, webs, girders, and steel. Grounding types are limited to powered groundings on a single pinnacle. Methods are based on simplifying assumptions whose effects on the results are not yet entirely understood. The committee believes that the computational tools used for this study provide a better comparative method than the current approach based on the use of historical damage data, although further work is needed to validate and improve these tools.

> ***Recommendation 7:*** **USCG should undertake a program to collect collision and grounding data in sufficient detail for use in validating both collision and grounding analyses. The USCG accident investigation report should routinely include data of the detail and extent necessary for this purpose. The data should be stored in a format that is easily accessible and conveniently usable by researchers. USCG should encourage others, through IMO, to collect detailed accident investigation data in a uniform manner. In addition, USCG should initiate a program for the continued development of grounding and collision analyses. The following areas need the most development:**
>
> - **Addition of other than powered grounding on a single pinnacle**,
> - **Addition of collision with solid objects,**

- **Addition of a deformable bow in the collision model, and**
- **Further development of the collision model at the structural member level.**

As more data become available, USCG should maintain a continuing program of testing and validation of the collision and grounding analysis tools.

Consequence Analysis

The consequence analysis performed by the committee indicated that the relationship between spill size and environmental consequence is not linear. The committee's application of the methodology demonstrated that the consequence of each additional gallon spilled is greater for small than for large spills. In other words, the impact of spills increases with volume, but the marginal impact of each additional gallon spilled decreases. Thus the evaluation of an alternative design based on outflow alone would not be valid and could yield a misleading result. This conclusion led the committee to select an approach that could relate measures of environmental damage to each oil spill scenario.

The existing data on cost for past oil spills have been gathered irregularly and are difficult or impossible to obtain. Because of extreme variability in the cost data associated with environmental damage assessment, as well as in third-party cost data (which together constitute the preponderance of costs in most spills), past data are neither reliable nor comparable. Therefore the committee chose to use physical consequence instead of historical spill costs as the most consistently measurable and comparable method of evaluating environmental consequences. The committee does not believe that further efforts to collect and analyze historical data on spill costs would lead to any improvements in the development or application of its methodology or other similar efforts.

Recommendation 8: **The committee recommends that USCG take the committee's findings on evaluating environmental consequences of spills into account in its regulatory initiatives relative to environmental impacts of oil spills, including cost–benefit analyses.**

Design Comparison

The committee concludes that a complete distribution of the differences in environmental impact (impact differences) is necessary for comparison of designs because it provides information on the regions where one design performs better than another. The use of simple descriptive statistics, such as the mean, is not sufficient and can be misleading. Furthermore, it is important to compare the impact differences event by event instead of comparing the cumulative impacts of designs for all events. As noted above, the impact difference is not a linear function of the outflow difference. For example, the impact difference for an event in which one design spills 200,000 gallons and the other spills no oil can be larger than that for an event in which one design spills 60 million gallons and the other 70 million, even though the outflow difference is larger in the latter case. The methodology proposed by the committee yields a distribution of impact differences for each event, which in turn provides information on the magnitude of the impact differences as well as their frequency.

***Recommendation 9:* The committee recommends that USCG propose to IMO that it replace its current guidelines with a rational methodology for evaluating alternative tanker designs based on the principles presented in this report.**

The committee understands that to implement all of its recommendations will require substantial time and effort on the part of USCG but has neither estimated the cost involved nor determined whether USCG has the necessary resources available. Therefore, the committee cannot propose an appropriate schedule for the recommended tasks, nor can it set priorities for this work relative to USCG's other responsibilities. The committee does, however, believe that the work presented to illustrate the proposed methodology provides a foundation that can be used by USCG in its implementation efforts.

APPENDIX A

PRESENTATIONS AT COMMITTEE MEETINGS

First Committee Meeting, June 17–18, 1999, Washington, D.C.

The following presentations were given by guest speakers:

Sponsoring agency goals and expectations for the study
RADM Robert C. North, USCG

Background on the congressional request for this study
Jim Sartucci, Legislature Assistant, Office of Senator Trent Lott

Review of background material and technical status of work
Peter Johnson, project consultant

Overview of risk analysis research on tanker grounding and collision accidents
Preben Pedersen, Technical University of Denmark (conference call)

Evolution and actions related to double-hull requirements and alternatives
RADM Joel D. Sipes (USCG, retired), Marine Safety Systems, Inc.

Background on methodologies for establishing equivalency and evaluation of their strengths and weaknesses
Keith Michel, Herbert Engineering

Status of Society of Naval Architects and Marine Engineers' (SNAME) assessment of research on crashworthiness of tank vessel structures and damage statistics
Alan Brown, Virginia Polytechnic Institute and State University

Overview of available spill cost data and analyses, and what is needed to develop a spill cost metric for evaluating relative performance
Dagmar Etkin, Environmental Research Consulting

Proposed alternative design and results of analyses of its performance
CAPT Edward K. Roe (USCG, retired), Marine Safety Systems, Inc.

Second Committee Meeting, September 27–28, 1999, Washington, D.C.

The following presentations were given by guest speakers:

Information on alternative tanker design proposals
Paul Cojeen, USCG

Key issues from 1997 SNAME paper "A Framework for Assessing Environmental Performance of Tankers in Accidental Groundings and Collisions"
Jaideep Sirkar, USCG, and Wayne Willis, ICF Kaiser International

Oil spill cost models
Robert Unsworth, Industrial Economics; Heidi Schuttenberg, Applied Science Associates

Tanker industry perspective
John Burke, Mobil Shipping and Transportation Company (retired)

International tanker fleet's adoption of double hulls and consideration of alternatives
William O. Gray, Gray Maritime Company

New double-hull design standards from IMO
Keith Michel, Herbert Engineering (conference call)

Update on status of SNAME assessment of research on crashworthiness of tank vessel structures and damage statistics
Alan Brown, Virginia Polytechnic Institute and State University (conference call)

Third Committee Meeting, January 26–28, 2000, Irvine, California

The following presentations were given by guest speakers:

Double-hull tankers and alternative designs
Frank Nicastro, Exxon Company, International (retired)

Risk in active systems
B. John Garrick, Garrick Consulting

Long-term effects of oil spills in marine and coastal habitats
Stan Rice and Ron Heintz, Auke Bay Laboratory, National Marine Fisheries Service/National Oceanic and Atmospheric Administration, Juneau, Alaska

Fourth Committee Meeting, September 25–26, 2000, Washington, D.C.

The following presentations were given by guest speakers:

Modeling of damage and oil outflow in collisions and groundings
Alan Brown, Virginia Polytechnic Institute and State University; Kirsi Tikka, Committee Chair

Spill consequence modeling
Robert Unsworth and Paul Fischbeck, Committee Members

Fifth Committee Meeting, January 17–19, 2001, Irvine, California

This was a closed session with no guest speakers.

APPENDIX B

THE COAST GUARD AUTHORIZATION ACT OF 1998

Section 423, "Double Hull Alternative Designs Study," states, as follows:

Section 4115(e) of the Oil Pollution Act of 1990 (46 U.S.C 3703a note) is amended by adding at the end thereof the following:

"(3)(A) The Secretary of Transportation shall coordinate with the Marine Board of the NRC to conduct the necessary research and development of a rationally based equivalency assessment approach, which accounts for the overall environmental performance of alternative tank vessel designs. Notwithstanding the Coast Guard opinion of the application of sections 101 and 311 of the Clean Water Act (33 USC 1251 and 1321), the intent of this study is to establish an equivalency evaluation procedure that maintains a high standard of environmental protection, while encouraging innovative ship design. The study shall include:

"(i) development of a generalized cost spill data base, which includes all relevant costs such as clean-up costs and environmental impact costs as a function of spill size;

(ii) refinement of the probability density functions used to establish the extent of vessel damage, based on the latest available historical damage statistics, and current research on the crashworthiness of tank vessel structures;

(iii) development of a rationally based approach for calculating an environmental index, to assess overall outflow performance due to collisions and groundings; and

(iv) application of the proposed index to double hull tank vessels and alternative designs currently under consideration.

"(B) A Marine Board committee shall be established not later than 2 months after the date of enactment of the Coast Guard Authorization Act of 1998. The Secretary of Transportation shall submit to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Transportation and Infrastructure in the House of Representatives a report on the results of the study not later than 12 months after the date of enactment of the Coast Guard Authorization Act of 1998."

APPENDIX C

SUMMARY OF IMO 13F GUIDELINES

[The following are excerpts from a report to the American Bureau of Shipping entitled *Review and Improvement of the IMO Probabilistic Methodology for Evaluating Alternative Tanker Designs,* by K. K. Tikka, Webb Institute, April 1998.]

Regulations 13F and 13G of the 1992 Amendments to Annex I of MARPOL 73/78 mandate the phasing out of single hull tankers and their replacement by double-hull tankers or by tankers whose environmental performance is "equivalent" to double-hull tankers. In order to assess the equivalency of a design concept to a double-hull tanker, the International Maritime Organization (IMO) developed the *Interim Guidelines for the Approval of Alternative Tanker Designs* under Regulation 13F of Annex I of MARPOL 73/78 (*IMO 13F Guidelines*) (IMO 1996). These guidelines employ a probabilistic methodology to evaluate "equivalency" between designs (the methodology is referred to in the text as "IMO methodology").

The *IMO 13F Guidelines* use a "pollution prevention index" to assess the equivalency of designs. The pollution prevention index combines three oil outflow parameters: the "probability of zero outflow" (P_0), the "mean outflow" (O_M) and the "extreme outflow"(O_E). The "probability of zero outflow" indicates the likelihood of no outflow. In other words, it measures the tanker design in terms of its ability to avoid spills. The "mean outflow" is the mean value of outflows from all casualties and it measures the overall outflow characteristics of a design. The "extreme outflow" is the mean of the upper 1/10th of the accidents which measures the performance of a design in severe accidents.

The calculation is based on the assumption that an accident has taken place and that the outer hull is breached. Therefore, no probabilities associated with the accident occurrence are included. The damage scenarios are described by probability density functions provided for damage locations and damage extents. Probability densities are provided for:

- Longitudinal and vertical locations, longitudinal and vertical extent and transverse penetration of side damage due to collision
- Longitudinal and transverse location, longitudinal and transverse extent, and vertical penetration of bottom damage due to grounding.

The probability densities are based on limited historical data (50 to 60 incidents) collected by classification societies for IMO (Lloyd's Register 1991). The data is for single-hull tankers above 30,000 DWT. All the variables describing damage scenarios are assumed to be independent. The variables are non-dimensional: Longitudinal location and longitudinal extent are divided by the ship's length between perpendiculars. Transverse penetration in side damage, as well as transverse extent and location in bottom damage are divided by the ship's breadth. Vertical penetration in bottom damage, as well as vertical extent and location in side damage are divided by the ship's depth.

The outflow parameters are calculated separately for collisions and groundings, and combined in the ratio of 40 percent of collisions and 60 percent of groundings. For the calculation of the outflow parameters, the ship is loaded to the maximum load line with zero trim and heel. The cargo tanks are assumed to be 98 percent full and the cargo density is based on this assumption.

IMO Guidelines include two alternative calculation methods: the conceptual method and the survivability method. The conceptual method is intended for evaluating the environmental performance of a new design concept relative to a reference double-hull tanker. The survivability analysis is intended for the approval of a final shipyard design.

The conceptual method assumes that the vessel survives the damage in each casualty. No damage stability calculations are required. In the side damage cases, the oil outflow is equal to the total amount of oil carried in the damaged compartments. In the bottom damage cases, the vessel is assumed to rest at its initial drafts, with zero trim and heel. Oil outflow from the damaged compartments is calculated based on hydrostatic balance principles, i.e., oil outflows from a compartment until the hydrostatic pressure of the fluid in the tank is equal to the hydrostatic pressure of sea water at the bottom of the compartment.

The survivability method requires damage stability calculations. Survivability is defined in terms of the requirements of the IMO regulation 25(3) of Annex I of MARPOL 73/78. If the vessel does not survive, i.e., it fails to satisfy the requirements, all oil onboard is assumed lost both in side damage and bottom damage cases. If the vessel survives, the oil outflow in side damage cases is equal to the total amount of oil carried in the damaged compartments. In bottom damage cases, the oil outflow is calculated based on hydrostatic balance principles at the equilibrium waterline.

The outflow calculations in bottom damage cases, both in conceptual and survivability analyses, are done for 0 meter, 2 meter and 6 meter tides. However, the maximum tide to be analyzed is 50 percent of the ship's maximum draft. The vessel is assumed stranded at a water depth equal to its draft in the 0-meter tide condition. In the 2-meter and 6-meter tides, the assumed water depth is reduced 2 and 6 meters respectively. The equilibrium condition of the vessel in the damaged condition is found through an iterative calculation in which the oil outflow is calculated based on the hydrostatic balance between oil and surrounding water at the lowest point of the damaged tank. The outflow corresponding to a damage case is a weighted average of the outflows in the three tidal conditions. The relative weights for the tidal conditions are:

- 0.4 for 0 meter tide
- 0.5 for 2 meter tide
- 0.1 for 6 meter tide

An inert tank pressure of 0.05 Bar Gauge is assumed for the hydrostatic balance calculations. The location of pressure balance calculations is the lowest point in the damaged tank.

A minimum outflow of one percent of the total tank volume is assumed for cargo tanks adjacent to the bottom shell to account for initial outflow and dynamic effects due to current and waves.

If the bottom of a damaged cargo tank is adjacent to a ballast tank, the pressure balance calculation is carried out at the lowest point of the damaged cargo tank. The ballast tank is assumed to contain 50 percent of sea water and 50 percent of oil by volume, i.e., 50 percent of the volume is captured oil in a ballast tank that is directly below a cargo tank.

Many of the above assumptions were included in the regulation somewhat arbitrarily (SNAME 1998). The selection of tidal heights was arbitrary, the one percent minimum oil outflow was partially supported by model tests and the 50 percent capture of oil by ballast tanks below cargo tanks was investigated by model tests, but not conclusively.

After the oil outflow calculations are performed, the outflow parameters and the pollution prevention index are determined. The pollution prevention index E is calculated with the following formula:

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

P_0, O_M, O_E are the probability of zero outflow, mean oil outflow and extreme outflow, respectively. These values are determined from the oil outflow calculations where the likelihood of each damage scenario is described by the independent probability densities. P_{0R}, O_{MR}, O_{ER} are the corresponding parameters for the reference double-hull tankers of the same cargo capacity. The reference tankers are defined in the *IMO 13F Guidelines*. The reference tankers were selected as representative of designs with favorable outflow performance in order to require alternative designs to be equal to "good" double-hull tankers (Sirkar et al. 1997). If an alternative concept has a pollution prevention index greater or equal to one, the concept is considered equivalent or better than the reference double-hull tanker.

The pollution prevention index equation contains several factors, which according to those involved in the development have no rigorous basis (SNAME 1998). The factors 0.5, 0.4, and 0.1, which weigh the contribution of the probability of zero outflow, mean oil outflow and extreme outflow to the index, were chosen rather arbitrarily as a compromise that would assure the equivalency of the double-hull and mid-deck concepts (Sirkar et al. 1997). A heavy weight on the probability of zero outflow favors double-hull designs, whereas a heavy weight on mean outflow favors mid-deck tanker designs.

REFERENCES

ABBREVIATIONS

IMO	International Maritime Organization
SNAME	Society of Naval Architects and Marine Engineers

IMO. 1996. *Interim Guidelines for the Approval of Alternative Methods of Design and Construction of Oil Tankers Under Regulation 13F of Annex I of MARPOL 73/78*. MARPOL 73/78 1994 and 1995 Amendments. London.

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APPENDIX D

STRUCTURAL DESIGNS FOR NEW DOUBLE-HULL TANKERS

The world tanker fleet has gradually changed with the construction of double-hull vessels to comply with U.S. regulations that followed passage of the Oil Pollution Act of 1990 (OPA 90). Since the design of a double-hull tanker has an effect on its outflow performance in the case of a grounding or collision, it is important to be familiar with current design practices when selecting a double-hull tanker for use as a reference in comparing alternative designs. An overview of issues related to the structural design and arrangement of new double-hull tankers is provided in this appendix.

STRUCTURAL DESIGN OF DOUBLE-HULL TANKERS

Since only a few double hull-tankers were built prior to OPA 90 and IMO Regulation 13F, designers had to develop new structural layouts, as well as use the experience with double-hull designs for other vessel types, such as containerships. There was very little service experience available for most double-hull construction types and none for the very large vessels. Hence, designs based on requirements expressed in OPA 90 and Regulation 13F benefited little from past experience.

To meet this need, the Tanker Structure Cooperative Forum (TSCF) developed and published the *Guide to Inspection and Maintenance of Double-Hull Tanker Structures* in 1995. The information in this guide is based on experience with operations as reported by the forum membership, which included oil companies and classification societies. This information was collected for a limited number of existing double-hull tankers, double-side tankers, and double-bottom tankers, as well as other types of vessels with similar details. The guidance provided serves as an excellent resource for initial design efforts by indicating details that require special attention in design and construction.

For its 1998 study *Double Hull Tanker Legislation: An Assessment of the Oil Pollution Act of 1990*, a National Research Council study committee conducted a survey of designers, builders, and operators of double-hull tankers to gather information on actual experience. The conclusion of most respondents is that double-hull tankers can be operated as safely as other designs, provided more attention is given to inspection and maintenance.

Classification societies have also looked at their rules to determine how to evaluate double-hull tankers. Most of the societies have made use of detailed analysis methodologies that have become available because of advances in computer design. Experience gained through a better understanding of the failure mechanisms of yielding, buckling, fatigue, and corrosion of single-hull tanker structures has been the basis for many of the requirements applied by the classification societies, and the societies have developed guidance for the evaluation of these failure mechanisms.

The early double-hull tankers designed and built since OPA 90 and Regulation 13F are just now completing their first 10 years of service. Both operators and classification societies are currently gathering data on the performance of the structure of these tankers. In general, the experience has been good, but there have been some areas in which either guidance found in the work of TSCF has not been followed or unexpected structural problems, such as microbial corrosion in cargo tanks, have developed.

ARRANGEMENTS OF DOUBLE-HULL TANKERS

Most new tanker designs have complied with the double-hull requirements of Regulation 13F and also meet USCG's criteria for double-hull designs under OPA 90. Appropriate provisions of these regulations define the minimum size of the double-hull space. The size of the space is based on the deadweight of the vessel for both the side breadth and the bottom depth. The minimum space for the separation of the inner skin is 2 meters for all vessels above 40,000 deadweight tons (DWT).

Tank vessels in common use that are covered by the regulations are generally categorized by size as follows:

- Product tanker—about 40,000 DWT.
- Aframax tanker—about 80,000 DWT.

TABLE D-1 Compliance of Tanker Double-Hull Designs

Type	Regulation Depth of Side (meters)	Regulation Depth of Bottom (meters)	Actual Depth of Side Range (meters)	Actual Depth of Bottom Range (meters)
Product	2.0	2.0	2.0–2.42	2.0–2.18
Aframax	2.0	2.0	2.0–2.28	2.0–2.63
Suezmax	2.0	2.0	2.05–2.7	2.58–2.8
VLCC	2.0	2.0	2.4–3.6	3.0–3.2

- Suezmax tanker—about 135,000 DWT.
- Very large crude carrier (VLCC) tanker—about 250,000 DWT.

All of these vessels will have a minimum space of 2 meters separating the inner and outer hulls of the double hull. The other important arrangement is the number of tanks: they range from 8 to 16 in number and can be further subdivided by one or more longitudinal bulkheads.

Most designs have similar arrangements because both OPA 90 and MARPOL define double-hull and tank size. One significant change that has occurred at IMO since the work of TSCF is stability by design. The early double-hull designs in the Aframax and Suezmax size ranges had only one tank between the inner hulls, either to save weight or maximize operational efficiency. This led to some vessels having stability problems, termed *lolling*, during the discharge of cargo. In 1997, the need to meet stability requirements led to modifications of the Aframax and Suezmax tanker designs, which now include centerline bulkheads to provide port and starboard cargo tanks. A number of other requirements specify tank sizes based on specific design arrangements. A raking damage stability requirement[1] was added to MARPOL regulations to ensure the damage stability of double-hull tankers.

A significant number of double-hull ships have been built for registry outside the United States since OPA 90 and Regulation 13F entered into force. Typical spaces for the double hull for the product, Aframax, Suezmax, and VLCC tankers are indicated in Table D-1.

FUTURE IMPROVEMENTS IN DOUBLE-HULL TANKER DESIGNS

Although classification societies have adequate tools to assess designs and ensure the safe performance of double-hull tankers, there is room for im-

[1] This is a requirement to consider a long extent of bottom damage (about 60 percent of the ship's length) as one possible condition for damage stability calculations.

provement in many areas. Among the critical areas are structural details and fabrication tolerances. Early design evaluation can also lead to structural improvements. Another area for improvement is assessment of structures that have been in service to provide feedback for new designs. Efforts now under way within many organizations to improve design details are expected to bring greater safety and reliability to tankers of the future. If and when newer alternative designs are considered, it will also be necessary to ensure that any new structural details are adequately evaluated.

STUDY COMMITTEE BIOGRAPHICAL INFORMATION

Kirsi K. Tikka, *Chair*, is Professor of Naval Architecture at the Webb Institute in New York, where she lectures and conducts research in ship structures and environmental performance of tankers in collision and grounding accidents. Dr. Tikka received a Ph.D. in naval architecture from the University of California–Berkeley and an M.S. in mechanical engineering from the Helsinki University of Technology. She currently teaches courses in ship design and structures at Webb. Previously she held positions at Chevron Shipping Company as Senior Structural Specialist; Senior Operations Planner; and Senior Analyst, Tanker Planning and Economics. Dr. Tikka served on the NRC (Marine Board) committee that produced the 1998 report *Double Hull Tanker Legislation: An Assessment of the Oil Pollution Act of 1990*. She is active in the Society of Naval Architects and Marine Engineers, where she serves as working group leader for a panel on structural response in grounding and collision. She is also Chair of the Committee on Risk Analysis for the International Ship and Offshore Structures Congress.

Peter F. Bontadelli is a private consultant in natural resources policy issues. From 1992 through March 1999, he served as Administrator of the Office of Oil Spill Prevention and Response of the California Department of Fish and Game, where he directed prevention, removal, abatement, response, containment, and cleanup efforts related to oil spills in the marine waters of California. His previous experience at the Department of Fish and Game included service as Special Assistant to the Director, Chief Deputy Director, and Department Director. During that time, he served on various environmental panels, including the Pacific Flyway Council (of which he is a former President), the North American Wetlands Conservation Council, the Pacific Fishery Management Council, the Pacific States Marine Fisheries Commission, the International Association of Fish and Wildlife Agencies, and the Western Association of Fish and Wildlife

Agencies. Mr. Bontadelli served on the NRC (Marine Board) committee that produced the 1998 report *Double Hull Tanker Legislation: An Assessment of the Oil Pollution Act of 1990*, among others, and is currently a member of the Board. He received a B.A. in political science from the University of California–Davis.

John M. Burke is retired Vice President and Director of Mobil Shipping and Transportation Company and Manager of its Technical and Offshore Divisions. He was responsible for Mobil's new shipbuilding activities. He is a graduate of the University of Michigan with a B.S. in naval architecture and marine engineering. His previous positions include Chartered Fleet Coordinator for Exxon International in New York, Marine Engineering Manager for Exxon USA in Houston, Naval Architect and shipbuilding project manager for Esso International in London, and Design Engineer for aircraft carriers and submarine construction programs with Newport News Shipbuilding Company. Mr. Burke served on the NRC (Marine Board) committee that produced the 1991 report *Tanker Spills: Prevention by Design*. He participated in the United Nations' 1992 IMO Comparative Study on Tanker Design and is a member of the Society of Naval Architects, the Royal Institute of Naval Architects, and the American Bureau of Shipping.

Paul S. Fischbeck is Associate Professor in the Department of Engineering and Public Policy and the Department of Social and Decision Sciences at Carnegie Mellon University. His general research involves normative and descriptive risk analysis. Past and current research includes the development of a risk index for prioritizing inspections of offshore oil-production platforms; an engineering and economic policy analysis of air pollution from international shipping; a large-scale probabilistic risk assessment of the space shuttle's tile protection system; and a geographic information system designed to evaluate the environmental risk, economic potential, and political factors of abandoned industrial sites. Dr. Fischbeck was a member of the Marine Board's Committee on Risk Assessment and Management of Marine Systems and has been a technical advisor to the Ship Structures Committee. He received a B.S. in architecture from the University of Virginia, an M.S. in operations research and systems analysis from the Naval Postgraduate School, and a Ph.D. in industrial engineering and engineering management from Stanford University. Dr. Fischbeck has written extensively on various applications of decision and risk analysis methods and has won several awards from the Institute of Operations Research and Management Sciences. He is a retired Navy Captain.

Alan G. Gavin is Marine Director, Lloyd's Register of Shipping, London, a leading classification society that sets and monitors design and performance standards for commercial ships operating worldwide. He is responsible for global marine technical and commercial policy, as well as for ship research and development activities, classification, and quality matters. He also represents Lloyd's in legal cases. Previously, Mr. Gavin held the posts of Manager of Research and Development and Manager of the Construction Services Department at Lloyd's. He has conducted major structural analysis projects, fatigue analyses, and model tests of tankers and ship containment systems, and published numerous papers on tanker design, ship structures, risk management, and double-hull design details. Mr. Gavin has served with Lloyd's in the United Kingdom and Japan. He currently represents Lloyd's on the Council of the International Association of Classifications Societies (IACS) and has served as Chairman of the IACS Working Party on Strength and as Chairman of the IACS group responsible for preparing the Shipbuilding and Quality Repair Standards. Mr. Gavin received a B.S. (with honors) in naval architecture from Strathclyde University in 1973 and is a member of the Royal Institution of Naval Architects and a Chartered Engineer.

Sally Ann Lentz is Executive Director and General Counsel of Ocean Advocates, a national nonprofit environmental organization that promotes marine policy positions within the U.S. government and international organizations. In that capacity, she develops and coordinates policy positions for coalitions of domestic and international environmental organizations on shipping, coastal, and marine issues, and represents these organizations at international conventions addressing oil pollution from tanker accidents. Ms. Lentz has a diploma in European integration from the University of Amsterdam, a JD from the University of Maryland, and a B.A. in sociology and anthropology from Oberlin College. She is a member of the District of Columbia and Maryland Bars and has served as a member of U.S. and environmental delegations to IMO and other international and regional forums. Ms. Lentz served on the Marine Board committees that produced the 1991 report *Tanker Spills: Prevention by Design* and the 1998 report *Double Hull Tanker Legislation: An Assessment of the Oil Pollution Act of 1990*. She has published extensively in professional and legal journals on marine and ocean environmental protection issues.

J. Randolph Paulling, a member of the National Academy of Engineering (NAE), is Professor Emeritus of Naval Architecture, Department of Naval Architecture and Offshore Engineering, University of California–Berkeley.

Previously, he served at Berkeley as Chairman of the Department of Naval Architecture and Chairman of the Faculty of the College of Engineering. Dr. Paulling has held positions with the research department of Det Norske Veritas, Oslo, Norway and with the National Maritime Institute in London, the University of Tokyo, and the University of New South Wales. He has a B.S. and an M.S. in naval architecture from Massachusetts Institute of Technology and a Dr. Eng. in naval engineering from the University of California–Berkeley. Dr. Paulling is a member of numerous professional societies, including the Society of Naval Architects and Marine Engineers (SNAME), which he served as Vice President from 1985 to 1988. He is a Fellow of the Royal Institution of Naval Architects and a member of the editorial committee of the *Journal of Ship Research*. Dr. Paulling was chairman of the National Academy of Sciences/NAE Committee on Assuring the Safety of Innovative Structures and chaired the 20th International Towing Tank Conference in 1993. He was named as one of four U.S. "Eminent Ocean Engineers" by the American Society of Civil Engineers and Japan Society for the Promotion of Science. In 1985, SNAME awarded him the David W. Taylor gold medal for notable achievement in naval architecture.

Dragos Rauta is Technical Manager of INTERTANKO, Oslo, Norway, an independent association of owners and operators of tank vessels involved in oil and chemical transportation operations worldwide, representing the majority of the world tanker fleet. He is responsible for technical issues related to ship design, operations, regulatory issues, pollution prevention, maintenance and inspection, and accident investigations. Mr. Rauta received an M.S. in naval architecture from the Romanian University and since 1990 has represented INTERTANKO with industry and international maritime organizations in matters related to safety and environmental issues. He is a member of Det Norske Veritas' Nordic Committee for Safety at Sea and an associate member of SNAME. He has served on committees and working groups responsible for developing standards and regulations for tanker designs within IMO, IACS, the International Chamber of Shipping, OCIMF, and SNAME.

Philip G. Rynn is currently Senior Staff Consultant for Engineering Management with ABS (American Bureau of Shipping) Americas, one of the leading ship classification societies in the world. He has been with ABS since 1965. He is responsible for oversight of technical services, including approval of ship designs and appraisal and analysis of designs for compliance with ABS rules and other statutory requirements, such as USCG regulations and IMO requirements. Mr. Rynn received a B.S. in marine engineering from the State University of New York Maritime College and has served on numerous U.S. and international committees that oversee and advise the maritime industry on design and safety issues. He is currently a member of the Tanker Structure Cooperative Forum Work Group, the Ship Structures Committee, and the Chemical Transportation Advisory Committee of USCG, and is Chairman of the SNAME Hull Structure Committee.

Robert Unsworth is a principal with Industrial Economics, Inc., a public policy and economics consulting firm. His specialties include natural resource economics, damage assessment, environmental benefits assessment, and policy analysis. He is a nationally recognized expert in natural resource damage assessments for oil spills and hazardous waste sites and is a leader in efforts to apply regulatory cost–benefit analysis to reduce the effects of environmental pollution. Mr. Unsworth has conducted a variety of assessments of the economic impacts of oil spills, including the *Exxon Valdez* spill and other tanker accidents. He has provided expert testimony in several damage assessment cases and assisted the National Oceanic and Atmospheric Administration in developing regulations and guidance for damage assessment. He also developed a training manual on damage assessment for the Fish and Wildlife Service. Mr. Unsworth has published in the field of environmental economics, lectured at universities and professional meetings, and conducted training sessions for organizations including the Department of the Interior and others. He holds a B.S. in forestry from the New York State College of Environmental Science and Forestry and a master's degree in forest science from Yale University.

Luther W. White is Professor of Mathematics at the University of Oklahoma–Norman. He has worked extensively on statistical analyses related to tanker design issues, particularly with regard to environmental protection guidelines such as those established by IMO. He has organized meetings and seminars on mathematical theory; published widely in professional journals; and consulted with research organizations, publishing companies, engineering instructional groups, and commercial companies such as Marine Safety Systems and Mobil Oil Company. Dr. White received a B.S. from Oklahoma Baptist University and an M.S. and Ph.D. in mathematics from the University of Illinois. He is a member of Sigma Xi, a University of Oklahoma Associates Distinguished Lecturer, and recipient of the Regent's Award for Superior Research.