THE INFLUENCE OF THE OIL POLLUTION ACT OF 1990 ON STRUCTURAL DESIGN AND ECONOMICS OF OIL TANKERS

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In The Name of GOD, The Merciful, The Compassionate

This thesis is dedicated to
The beloved souls of
My mom, Gamra,
and
My dad, Ibrahim,
Who have instilled in me the highest sense of
Responsibility, discipline, achievement, and integrity
Toward faith, life, and my work.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

The transportation of crude oil and petroleum products constitutes the largest component of seaborne cargo movements today, with tanker cargoes accounting for 1.9 billion tons, or 44.6% of the total movements in 1994. Oil tankers of various types and capacities serve as a flexible pipeline for facilitating the global movements of these important commodities. With this active global movement, it is almost impossible to prevent accidents and mishaps. Oil spills, both major and minor, have occurred over the years due to tanker groundings and accidents.

The *Exxon Valdez* incident in March of 1989 was the largest oil spill in U.S. waters. The grounding of the tanker caused the release of nearly 35,600 tons (11 million gallons) of oil in Prince William Sound, in Alaska. The outcome was an environmental catastrophe and damage to the vessel was estimated at $25 million. The cargo lost was worth $3.4 million, but the clean-up cost (not to mention damage to the environment) was about $2.0 billion.

Although this incident was not the largest worldwide, it created worldwide attention and public outcry, and forced the federal government to concentrate efforts on how to increase the effectiveness of spill response and eliminate the possibility of such events in the future. One year after the Valdez disaster, the president of the United States signed the Oil Pollution Act of 1990 (OPA90) into law.

The U.S. Coast Guard (USCAG) asked the National Research Council (NRC) to assess whether alternative tank vessel design would improve maritime safety and provide added protection to the environment. Consequently, the NRC established a special committee to investigate the preparedness for and response to such incidents.

The committee was also asked to carry out a comprehensive review of the safety, economics, and environmental implications of alternative designs, and to determine how these designs might reduce overall accident rates. This NRC special committee completed its report in 1991, and concluded that the primary cause of such incidents is grounding [2]. This report also presented several alternatives to tank design that might be used to prevent oil spills of the size of the *Exxon Valdez* in the future. The report recommended that the most cost-effective design for the prevention of major oil spills is to equip the oil tanker with a double-skinned hull [2]. The expert judgment and simulation, not experience, behind the double-hull concept is that if the outer hull is compromised in an accident, the inner hull will prevent any oil spill into the environment.

Based on these recommendations, Congress included in the OPA90 a requirement that all oil tankers operating in U.S. waters would have a double hull by the year 2015. Other requirements relate to vessel manning and safety, and increased penalties for the discharge of oil within 200 nautical miles of the U.S. coast.

A double hull is basically two skins of steel separated by a small space known as a cofferdam. Within the normal hull envelope is a second inner hull creating a void, approximately 2 meters deep, on the bottom and on the sides. The area between the two hulls contains no oil; therefore, any damage that leaves the inner hull intact will result in no loss of oil. Regulations were also proposed for the modification of existing tankers (retrofits) to reduce the possibility of oil outflow resulting from a collision.

The double-hull concept has created a great deal of controversy both nationally and internationally as to its effectiveness in eliminating an oil spill and its economic consequences in terms of the cost of new designs, operating costs, and so forth. There have been several studies on this issue since the 1991 NRC report; however, none of these studies appears to be detailed enough to draw some solid conclusions. This study will take a fresh look at the entire concept of double-hull oil tankers.

1.1.1 Plan of Study

This study begins with a look at historical oil spills, especially major oil spills such as the *Exxon Valdez*, and the resulting U.S. government actions embodied in the Oil Pollution Act of 1990 and its consequences for the future of oil tankers. The study will discuss and analyze previous studies that were published after the *Exxon Valdez* disaster. The study will investigate alternative designs for double hulls and will discuss the pros and cons of double hulls. The study will focus on economic analysis, including costs and benefits of oil spill prevention through the usage of double-hull tankers. A detailed analysis of the incremental costs of double-hull tankers will be carried out, followed by an analysis of incremental benefits, and net benefits. Policy implications and conclusions, including suggestions for future studies, will end this study.

1.2 Overview of Previous Studies

Costs of oil pollution and government efforts to enforce safety standards and internalize the costs of oil spills have been addressed by many economists. However, there are few recent studies on the economic analysis of tanker design and the projected increase in the cost of shipping oil in double-hull tankers. Although the NRC report is comprehensive and contains a wealth of information, it is widely viewed as inconclusive. For example, while double-hull tanker and alternative hydrostatic designs were discussed in detail, no solid conclusions were drawn about the relative desirability and stability of double hulls versus hydrostatic. The hydrostatic design concept uses natural forces to displace oil from ruptured cargo tanks into specially designed cofferdams. This principle displaces water into the cargo tanks rather than allowing oil to spill out. The hydrostatic design approach appears to be more economical to achieve and involves less drastic change as compared to the double-hull approach. The consortium of ship owners is heavily in favor of the hydrostatic approach.

The few studies which have addressed the issue of double-hull tanker stability and safety while loading and unloading cargo have done so using 3-D models and computer simulations. There is still a lack of industry standards and field experience, however, on how double-hull tankers react to loading and unloading situations at different ports. The shift from single-hull designs to double-hull designs was, on one hand, very drastic to be taken in one step and, on the other hand, left the shipbuilding industry without any clear design standards and/or guidelines. In most other industries, changes are made incrementally over a period of 15 to 20 years. The OPA90 phase-out schedule cannot be considered an incremental change but rather a phase-out schedule to meet the mandated requirements.

In addition to these technical problems, few studies have addressed the incremental costs, incremental benefits, and net benefits, if any, of double-hull tankers as required in the Oil Pollution Act of 1990. One study compared the benefits of reduced spillage with the increased construction and operating costs of double-hulled vessels. In the most probable scenario, the expected benefits were found to be only 20% of the expected costs. According to this study [5], double hulls do not even show a positive net present value in the most favorable circumstances. Even if double hulls prevent all spillage that occurs due to collisions and groundings, and the damage per gallon spilled is as extensive as in the *Exxon Valdez* incident, the benefits are under half of the costs [5]. It should be noted that no formal mathematical models were employed in this study, and some parameters were assumed due to the fact that data are not available or are in considerable dispute. Available data were drawn from government reports in order to avoid any biases from the maritime industry.

Some experts argue that double-hulled tankers may provide extra protection against oil spills, but only at low speeds, known as low-energy grounding, where the ship barely scrapes an underwater reef [6]. In such a scenario, the outer hull may be punctured by sharp rocks but the inner hull, which is nestled six feet or more within the outer skin, remains intact. However, at high speeds, a double-hull tanker can hit a rock or reef that will rip both hulls apart [6]. If the *Exxon Valdez* had been a double-hulled tanker, more, not less, oil would have been spilled because the tanker hit the reef at a high speed, and consequently both hulls would have been ripped [7]. Because of pressure differences, oil will flow out until its pressure equals that of the water [6]. In addition, the ship may sink to the bottom with its full cargo and may cause the oil to spill deep in the water instead of at the surface. This will create even more damage to the environment and marine life.

Double hulls on tankers may not prevent a major catastrophe that could result from combustion. A double-hulled tanker has a void, or empty space, of two meters between the hull and tanks. The theory is that if a ship runs aground, the outer hull may be penetrated, but the inner hull containing the oil will remain intact. However, a cargo tank completely full of oil is quite safe, because there is not enough oxygen in the tank to support combustion. A tank containing oxygen and oil vapors is quite hazardous because, in the correct ratio, an extremely explosive atmosphere may be created. This explosive mixture is avoided in cargo tanks by displacing any oxygen in the cargo tanks with flue gas (exhaust) from the ship's engine, which is inert. Void spaces on ships are not full of inert gas; they are full of air which contains the oxygen required for combustion. Consider the following scenario: A large tank vessel develops a crack in one of its tanks, allowing oil and oil vapor to leak into the void space which is inspected only periodically. Suppose that over a period of weeks or months a considerable amount of vapor accumulates in this space. The tanker runs aground, creating sparks where the hull is penetrated. Clearly, this situation may create the possibility for a devastating explosion, fire, and oil spill. The void space is now a tremendous liability. This may very well happen at some point in time.

1.3. Incremental Costs of Double-Hull Tankers

A review of the costs and benefits of oil spill prevention will be carried out in this study, beginning with the incremental costs of replacing single-hull with double-hull tankers.

1.3.1 Costs of Double-Hull Tankers

1. Tanker Costs
    a. Construction costs (including new design, material, and labor);
    b. Annual operating costs (manning, supplies, routine maintenance

   and repairs, administrative costs, fuel and port costs);
   c. Number of vessels required;
   d. Crew training cost; and
   e. Depreciation and estimates of long-term problems such as corrosion and deterioration of the unreachable places between the hulls.
2. Deadweight losses due to higher costs and prices of crude oil.

1.4. Incremental Benefits of Double-Hull Tankers

The primary benefit of double-hull tankers is to reduce oil spills. Estimations of these benefits will be carried out in three steps:

1. Calculation of the current spillage rate;
2. Estimates of the effect that a double hull would have on the spillage rate; and
3. Valuation of reduced spillage in terms of cost of oil saved, clean-up costs saved, and environmental damage avoided;

1.5 Double-Hull Technology

In the NRC report [2], many design alternatives were investigated using expert judgment and simulation. The top five most feasible designs include:

1. Double-hull: the tanker would have two hulls separated by two meters on both the bottom and the sides. This is the alternative that is mandated by OPA90. The U.S. Coast Guard has been directed to review the NRC study to determine the best alternative to single-hull vessels. Legislation could change the mandate of double hulls if a superior design is found.
2. Double-bottom: the bottom of the tanker would be constructed of two hulls separated by about two meters.
3. Intermediate oil-tight deck with double sides: the tanker would have double sides and a single bottom. There would be a horizontal deck between the top and bottom of the ship. This deck would be oil tight, dividing the ship into two cargo compartments.

4. Single-hull with hydrostatic loading: this tanker would be like the standard single-hull vessel of today but would not be loaded to capacity.
5. Double-hull with hydrostatic loading: this would be a double-hull vessel as described above but would not be loaded to capacity.

The objective of the different designs is to lessen the amount of oil that would be spilled if an accident were to occur. The idea of hydrostatic loading, especially with the conventional single hull vessel, is just to have less oil on the tanker. This would prevent less oil from being spilled, but with the single-hull design it does not really solve the design problem.

After a brief review of the technical contents of OPA 90 and future IMO (International Maritime Organization) regulations, emphasis will be given to the influence of these regulations on the structural design of double hull oil tankers. Technical aspects specific to this type of vessel will be considered and examined in more detail. Some typical structural arrangements of double-hull tankers will be compared to conventional vessels from design, construction and maintenance points of view. Other important factors such as the need for high-strength low-alloy steel, structural integrity and reliability, and corrosion of double hull tankers will also be discussed.

1.6 Conclusions and Policy Implications

The final chapter will compare the detailed analysis of costs and benefits of the double-hull tankers. Based on the findings of this study, major conclusions and policy implications will be given in this chapter.

CHAPTER 2

HISTORY OF OIL SPILLS AND OIL SPILL REGULATIONS

2.1 Regulatory History

The history of oil shipping began shortly after 1859 when hydrocarbon deposits were first discovered at Titusville, Pennsylvania [1]. The main sequence of events that followed this discovery can be summarized as [1]:

1859—Oil discovered

1861—First oil shipped in barrels from Delaware River to London in the brig *Elizabeth Watts*

1886—*Gluckauf* (First Bulk Oil Ship)

1926—International Maritime Conference, Washington, DC

1954—International Convention for the Prevention of Oil Pollution, London

1958—First Law of the Sea Conference

1960—Second Law of the Sea Conference

1967—*Torrey Canyon* Spill, English Channel

1973—IMCO MARPOL '73

1978—IMCO MARPOL 73/78

1978—*Amoco Cadiz* Spill

1989—*Exxon Valdez* Spill

1990—Oil Pollution Act

The *Gluckauf* is believed to be the first ship specifically designed and built (in Newcastle, England, in 1886) to transport crude oil [1]. This ship became the model on which tankers were developed for carrying oil directly inside a single hull. The hull provided far better security for the cargo than barrels or casks, which could split and spill oil, hence creating fire and explosion hazards.

Tanker designs established in the late 1880s remained virtually unchanged until after World War II. Tankers commonly were 10,000 to 15,000 dwt, with a single skin, the engine to the stern, and multiple compartments with either two or three tanks across [2]. Cargoes were usually refined products, most often light or "white" oils, which were not considered polluting as they rapidly evaporated if spilled [2]. The nonpolluting cargo meant that tanks could be rinsed out with water, which at that time was dumped at sea, and the same tanks could be used for ballast (sea water). Separate ballast tanks, other than the peak tanks at the end of the ship, were not developed until after World War II [2].

After World War II, expansion of the world economy resulted in a huge demand for energy in the form of oil. To meet such a worldwide demand, ship sizes steadily increased over the years, reaching about 25,000 dwt shortly after World War II. At the same time, crude oil started to be transported from distant sources such as the Persian Gulf to major marketing areas, namely, North America, Europe, and Japan. These long voyages set the stage for a dramatic increase in ship size, reaching about 300,000 dwt by the late 1960s. By 1975, oil tankers had reached 500,000 dwt and 1,000,000 dwt tankers were on the drawing board [1]. Between 1950 and 1975, the number of single-hull tankers in the world fleet reached about 3,000 tankers [2, 3].

General concerns over oil pollution originated in the 1920s when the United States and the League of Nations sought to obtain explicit international agreements on measures to deal with oil pollution. The first international convention to discuss both the technical and legal aspects of oil pollution was the International Marine Conference in Washington in 1926 [1]. The rising world economy of the 1950s, which demanded an ever increasing supply of crude oil, forced the International Convention on the Prevention of Oil Pollution (known as OILPOL 54) to mandate laws and regulations prohibiting the discharge of oil and oil mixtures in international waters [1]. In 1959, another international conference was held in Copenhagen in a follow-up to the formation of the Intergovernmental Consultative Organization (IMCO) as a specialized body of the UN [1]. The UN Conferences on Law of the Sea, held in Geneva in 1958 and 1960, considered the question of maritime pollution by including the requirements for states (Article 24) in the High Seas Convention [1].

The first major tanker disaster occurred in March, 1967, when the tanker *Torrey Canyon* was grounded off the southwest coast of England, spilling some 119,000 tons of crude oil which spread and polluted a 200-mile arc of the British and French coast lines. It was determined that an error by the ship's captain caused the grounding [1]. As a result of the *Torrey Canyon* accident, IMCO adopted the International Convention for the Prevention of Pollution From Ships in 1973 (MARPOL) [1].

Following the 1967 disaster and a number of serious tanker accidents which occurred between 1974 and 1977, the United States and other coastal nations requested a Conference on Tanker Safety and Pollution Prevention. The Conference, sponsored by IMCO in 1978, resulted in the 1978 MARPOL Protocol to speed up the adoption of MARPOL itself [1]. Within a few weeks of this conference, the Very Large Crude Carrier (VLCC) *Amoco Cadiz* ran aground off Brittany, France, and discharged 223,000 tons of its cargo into the Atlantic ocean [1]. Oil shipping operations continued under the auspices of MARPOL 73 and MARPOL 78 Protocol until the well-publicized grounding of the *Exxon Valdez* in 1989 when 36,000 tons of Prudhoe Bay crude oil were spilled into the Prince William Sound off the Alaskan Coast [1]. The power of the press and the public outcry over this accident led to the enactment of the Oil Pollution Act of 1990 by the U.S. Congress, in which they mandated a number of more stringent requirements for ship design and operation.

The concept of building double-hull oil tankers was first introduced by the US at the 1973 conference on marine pollution after the *Torrey Canyon* disaster [1]. However, the US delegation was forced to drop the double-hull concept, because of the general opposition by other member nations, in favor of the segregated ballast as was reflected in the 1973 Convention for the Prevention of Pollution by Ships (MARPOL) [1]. A group of American experts returned to the issue of double-hulls, however, when preparations were made for the IMCO Conference on Preventing Pollution by Ships in Acapulco in 1976 [1].

Tanker safety and marine pollution were raised again at international discussions in 1976-1977 following a series of tanker accidents in U.S. territorial waters [1]. The need for defensively-located ballast tanks had become urgent. The U.S. delegation to the 1978

Conference on the Safety of Tank Vessels promoted this solution as a compromise to double hulls, and the concept of specially positioned segregated ballast tanks was adopted [1]. The MARPOL Convention required that defensively-located, segregated ballast tanks be used on all new tankers over 20,000 dwt.

As can be deduced from the brief history given above, the legal requirements for vessel design and pollution prevention have been the result of the evolution of international conventions and laws intended to minimize or eliminate oil spills in international waters. Tankers must satisfy a substantial number of requirements at the design stage for safety and pollution prevention purposes. These requirements fall into three broad categories—international legal, domestic legal, and classification society requirements [2].

The International Marine Organization (IMO) is the UN specialized agency responsible for overall marine safety and environmental protection of the oceans. IMO was formed right after World War II and met for the first time on January 6, 1959 [4]. The major tasks of IMO are to [4]:

1. provide an effective machinery for technical, legal, and scientific cooperation among governments in the area of protection of marine environment from pollution caused by ships and other related activities,
2. adopt the highest practicable standards in matters concerning maritime safety and the prevention and control of maritime pollution from ships and other activities, and
3. encourage the widest possible acceptance and effective implementation of these standards at the global level.

Almost all of the world's major shipping nations are members of IMO, and as such are obligated to accept the international agreements adopted by IMO. These include 22 full conventions or treaties and 17 codes, as well as numerous resolutions containing recommendations and guidelines [2].

The procedures for implementing IMO regulations are not straightforward because of variations in vessel requirements and a vessel's flag state [2]. Each oil tanker is governed in design, arrangements, and construction by the international agreements ratified by her flag state. Nations that have formally ratified or approved IMO conventions usually implement the requirements through legislation [2]. When a vessel is judged to have been designed and built to international standards, the flag state issues a certificate for each convention with which the vessel complies. Each certificate is valid for five years, provided the ship has been maintained in accordance with convention requirements through an annual afloat inspection [2]. At the end of five years, the ship undergoes major inspection and renovation as deemed necessary prior to renewal of the certificate [2].

The inspection of vessels in compliance with international or domestic requirements is usually carried out by government agencies such as the Department of Transport in the UK, the Coast Guard in the US, and the Coast Guard in Canada [2]. However, with open registry or "flag of convenience" ships, enforcement and inspection are conducted on a contract basis [2]. Ships must also adhere to any additional domestic requirements imposed by the flag state. These requirements become more complicated when port nations impose unilateral requirements. These unilateral requirements can be related to basic ship design and construction, or can deal with matters such as employment, pilots, hours during which ships can operate in particular channels, and the use of tugs. For example, the U.S. has imposed several unilateral requirements that vary significantly from international standards.

It should be noted that IMO does not have the authority to impose penalties for noncompliance with international conventions. The IMO can revoke or suspend the current ship's certificate and direct penalties—indictment, warning, fine, or imprisonment of the persons(s) responsible for the violation—by the flag state can be imposed [2].

Regulations of ship design for safety and pollution prevention are achieved primarily through international conventions [1, 2, 4]:

1. The International Convention on Load Lines 1966 (ICLL)—concerned with loadlines on ships.
2. The International Convention for Safety of Life at Sea (1974) and its 1978 Protocol (SOLAS)—concerned with the safety of life at sea.
3. The International Convention for the Prevention of Pollution from Ships (1973) and its 1978 Protocol (MARPOL)—concerned with marine pollution.

4. The International Convention on Standards of Training, Certification and Watch-keeping for Safety, 1978 (STCW)—concerned with optimizing crewing standards.

The IMO Conferences produced fundamental changes in the way tankers are designed and operated. The ICLL established and continues to monitor the “Plimsoll Mark loadlines” which can be seen on the sides of ships to ensure that these ships are not overloaded and thus avoid the risk of sinking or creating unsafe working conditions [2].

Current safety legislation on life at sea is partly the result of the SOLAS 1974 Convention and partly of the Protocol established at the Tanker Safety and pollution Prevention (TSPP) Convention of 1978 [4]. The overall objective of SOLAS is to assure the safety of the crew, ports, passengers, ships, and cargo, and hence the environment in an indirect way. The most important structural requirement under SOLAS is the installation of inert gas systems (IGS) on all crude and products carriers of over 20,000 dwt. Some other important provisions of SOLAS are [2]:

1. subdivision and stability requirements to prevent ships from capsizing and to ensure survival under specified collision and grounding situations,
2. general construction principles to ensure the ship’s strength to meet its intended use and trade,
3. safety equipment requirements to assure the carriage of sufficient lifeboats and other safety equipment,
4. fire protection requirements to ensure that ships could withstand certain fire damage and fight fires effectively, and
5. radio telegraphy requirements that specify which communications and navigation equipment ships must carry.

SOLAS was amended in 1981 and 1983. The first set of amendments was concerned with the duplication of steering gear systems and tightening of the IGS rules. The 1983 amendments were concerned with the location and separation of spaces on tanks and with life-saving appliances and arrangements [4].

While ICLL and SOLAS have an indirect effect on preventing oil spills, the MARPOL convention seeks to prevent pollution directly, both from normal operational discharge and accidents [2]. MARPOL specifies design, equipment, and procedural requirements of oil tankers operating in international waters to prevent the pollution of these waters by oil, chemicals carried in bulk, harmful substances carried in packages, sewage, and garbage [2]. Each of these potential sources of pollution is addressed in regulations set out in an "Annex" to MARPOL. MARPOL legislation became effective in October of 1983 with the following installation requirements [2, 4]:

1. Installation of Segregated Ballast Tanks (SBT)—Oil carriers over 20,000 dwt built after dates specified in MARPOL'78 and tankers over 70,000 dwt built after dates specified in MARPOL'73 are required to carry ballast in SBT. Only in severe weather can additional ballast be carried in cargo tanks. In such cases, this water must be processed and discharged in accordance with specified regulations.
2. Protective location of SBT—The required SBT must be arranged to cover a specified percentage of the side and bottom shells of the cargo section. Thus, the protectively located segregated ballast tanks (PL/SBT) are intended to provide a measure of protection against oil outflow in a grounding or collision. Each wing tank or double-bottom tank must meet certain minimum width or depth requirements.
3. Draft and trim requirements—To assure safe operation of the vessel in a ballast condition, the SBT must be of sufficient capacity to permit full submergence of the propeller. The SBTs are to provide a molded draft (d) amidships of not less than $d = 2.0 + 0.02L$, and a trim (horizontal tilt) by stern not greater than $0.015L$, where L is the ship length in meters.
4. Tank size limitations—To minimize pollution in the event of side or bottom damage, the maximum length of cargo tanks is limited to values between 10 meters and $0.20L$, depending on tank location and longitudinal bulkhead arrangements. The maximum volume of each cargo tank may vary up to 22,500 m^3 for side tanks and up to 50,000 m^3 for center tanks, depending on tank arrangements and location.
5. Hypothetical outflow of oil—Formulas establish the maximum allowable hypothetical outflow of oil if a cargo tank is breached at any location on the ship. For the purpose of these calculations, regulations specify certain assumed longitudinal,

transverse, and vertical damage. The key damage parameters, where B is the ship's beam or breadth, are: side transverse extent—B/5 or 11.5 meters, whichever is less; and bottom vertical extent—B/15 or 16 meters, whichever is less.

6. Subdivision and stability—For a specified assumed damage, regulations require the tank subdivision and ship features be such that, under certain specific conditions, the final water line is below any opening leading to progressive down-flooding, and the heeling angle (tilted to one side) does not exceed 25° (or 30° if the deck edge is not submerged).
7. Crude oil washing (COW)—New crude oil tankers must be fitted with an effective tank cleaning procedure that uses cargo oil as the washing medium. COW is a superior system of cleaning cargo tanks that use the dissolving action of crude oil to reduce clingage and sludge. Furthermore, elimination or reduction of water washing helps reduce operational oil pollution of the seas.
8. Inert gas system (IGS)—This system supplies the cargo tanks with an atmosphere free of oxygen so that combustion cannot take place. Treated flue gas from main or auxiliary boilers, inert gas generators, or other sources may be used for that purpose.
9. Slop tanks—Tankers must be fitted with slop tanks of specified capacity to retain on board all slop, cargo drainage, sludge, washing, and other oil residues. Their discharge is monitored in accordance with regulations.

MARPOL was amended in 1984 with changes detailing new requirements for the carriage of oily-water separating equipment and oil discharge monitoring systems [4]. Most important is the fact that the "MARPOL vessel" represented the standard (before OPA 90), against which any further design changes should be measured [2]. MARPOL also established major retrofitting requirements for tankers by applying new equipment requirements (IGS) and either SBT or COW to existing tankers for the first time.

Before the MRPOL regulations were implemented, the control of pollution from operations had been accomplished through the "load on top" or LOT system. This method was highly dependent on the diligence and skills of the crew and was difficult to monitor, so

MARPOL introduced structural means of achieving the same goals with more reliable results [2]. However, the introduction of segregated ballast changed tankers from deadweight-limited carriers to cubic-limited carriers. This, in turn, tended to increase the amount of oil outflow in groundings and thus to increase pollution risks in some accidents for the newly built SBT crude carriers. This drawback was noted by the drafters of MARPOL [2].

Although the implementation of MARPOL and SOLAS requirements began in 1979 and was scheduled to be fully completed by the end of 1986, the world fleet remained a mix of carriers [2]. Many tankers were exempt from these SBT and SBT/PL regulations due to age or year of construction. Only 35% of the world tanker fleet over 10,000 dwt has SBT, and only half of these ships have SBT protectively located, thus meeting full MARPOL requirements [2].

The attempt to satisfy MARPOL requirements in the most economical way led to two changes in new vessel designs [2]:

1. Tankers became deeper in relation to their length to make up for the cubic feet lost to BST. The length-to-depth ratio (L/D) has become lower and the draft-to-depth ratio (H/D) has decreased because of the increase in freeboard.
2. Tankers were generally made broader and shorter, it being more economical to design the vessel wider at the expense of decreasing its length.

In light of this discussion, four general observations can be made [2]:

1. Depth must be increased in SBT ships to obtain enough ballast volume.
2. Ballast volume has increased a great deal in SBT ships for each given cargo volume. This increase is in the range of 234 to 334%, which indicates the additional area that must be protected from corrosion.
3. Expected outflow in groundings has increased by up to 90% in many SBT designs.
4. A greater depth (for a given draft and deadweight) in SBT designs created a reduction in deck and bottom plate thicknesses.

As the size of oil tankers increased, significant design developments were needed to meet safety and load requirements. These technical/design developments include [2]:

1. Riveting was replaced by welding to assure tightness of the tanks. The practice of welding led to some cracking and ships breaking in half, but these problems were solved by improving materials, welding techniques, and design.
2. The empirical (rule-of-thumb) design approach was partially supported by theoretical techniques and the introduction of computers in the 1950s and 1960s to solve complex stress analysis problems. This was necessary due to the growth in ship length from 500 to about 1400 feet, and the corresponding increase in deadweight of over 20 times in less than 20 years. Naval architects were able to quantify loads precisely and to carry out stress analysis computations necessary for ship designs on a theoretical and sophisticated basis. By the late 1970s, reliable theoretical quantification of loads and structural responses were common for tanker designs.
3. Unknown safety factors and design allowables for unknown factors were significantly reduced. This helped to minimize costs and achieve maximum deadweight for minimum draft—the depth of water a vessel can draw. The significant reduction in ratio of lightweight (ship weight without cargo, crew, fuel, or stores) to deadweight directly reduces the cost of a ship per ton of cargo. This means that a ship can carry more cargo for a given draft. It also implies a more efficient structure and, in general, less margin to tolerate construction or maintenance errors or unusual operational events.
4. Structural weight reductions were accompanied by a reduction in the number (and resulting increase in size) of compartments. The intent was to lower cost and simplify operations.

Two key features of modern structural design of oil-carrying tankers were the introduction of new stress analysis techniques by using finite element analysis and 3-dimensional frame analysis, which resulted in better designs and reductions in the structural weight. This, in turn, led to a substantial reduction in cost and a modest increase in load carrying capability. The second feature is the use of improved welding and high strength steel which led to improved and safer tanker hulls [2].

Oil tanker design is a complex task and depends on many factors. However, some basic ship characteristics that must be met include [2]:

- Ship dimensions
- Hull form
- Machinery size, type, and location
- Speed and endurance
- Cargo capacity and deadweight
- Accommodations arrangements
- Cargo/ballast tanks arrangements
- Subdivision and stability accommodations
- Relative amounts of mild or high-tensile steel
- Basic scantling and structural arrangements

Classification societies establish standards, guidelines, and rules for the design and survey of ships [2]. Classification societies are essentially managed through boards of directors composed of ship owners, with some representation from shipbuilders, insurers, and government. There are eleven leading classification societies, as represented by membership in the International Association of Classification Societies (IACS). A ship that has been constructed in accordance with the rules of a society is issued a classification certificate and must be surveyed regularly to maintain its class certificate. Classification requirements do not address safety equipment or crew qualification; they are essentially concerned with structural integrity of the ship and its propulsion and steering systems. Classification requirements include factors such as [2]:

- Materials for hull and key machinery components.
- Structural design requirements including scantling (dimensions of structural elements) and details of all structure and key machinery components (main engine, shafting, propeller, etc.).
- Supervision, inspection, and certification of manufactured steel, welding, machinery components, hull structure, etc.

These requirements must be met for the ship to comply fully with the international convention requirements and to obtain more favorable insurance rates. However, under the SOLAS Convention, each vessel traveling in international waters must have a valid Safety Construction Certificate showing the adequacy of its construction. This implies that being "in class" does not necessarily satisfy SOLAS requirements but, when authorized, a classification society may issue a SOLAS certification on behalf of a flag state [2]. The structural rules developed by classification societies determine the weight and thus a major component of the cost of the ship. "Class" decisions, to a large extent, may dictate the overall cost of the tanker and thus differences among classification societies are important factors that attract clients (ship owners who pay fees to "class" their ships) [2]. Competition among classification societies and among shipyards continues to exert pressure to produce an optimum cost tanker that will perform to an adequate standard [2].

Apart from a few unilateral regulations by some nations, legislation prior to 1990 was always developed under the auspices of IMO. The extent of unilateral safety and pollution legislation has thus far been limited, with the vast majority of nations choosing to implement IMO initiatives rather than to introduce their own schemes. Therefore, regulations initiated at state and port levels have concentrated on ensuring that internationally agreed standards are met in practice. However, the U.S. Oil Pollution Act of 1990 (OPA 90, PL 101-380), was a major departure from the international effort to address improvements in tank vessel design and operation. The US acted unilaterally in promulgating a requirement to change from single-hull to double-hull design. Section 4115 of OPA 90, "Establishment of Double Hull Requirements for Tank Vessels," requires that all ships traveling in U.S. waters meet standards that exceed the construction and design requirements of MARPOL in compliance with a phase-in schedule [2]. The time table to phase out existing ships may be summarized as [2]:

- All new tank vessels (contracted after June 30, 1990, or delivered after January 1, 1994) operating in US waters or the Exclusive Economic Zone must be fitted with double hulls.

- Existing vessels are permitted to operate until the time limits set forth in the Act. The timetable ends January 1, 2010. Existing tank vessels with double bottoms or double sides meet a separate schedule that ends in 2015.

Oil tankers are usually classified by two size ranges, namely, Aframax and Suezmax. Aframax tankers are commonly defined as being 80,000 to 105,000 dwt, whereas Suezmax are in the range of 120,000 to 165,000 dwt. However, upper limits for Aframax are sometimes quoted as 120,000 dwt, and for the Suezmax tankers as 200,000 dwt. In general, all Aframax and most Suezmax tankers without double bottoms or double sides that exceed 23 years of age will be barred from U.S. trade beginning in the year 2000.

Exceptions provided in Section 4115 of OPA 90 to requirements for a double hull are:

- Tankers used exclusively for responding to oil spills and tank vessels under 5000 gross registered tons (GRT) (10,000 dwt) fitted with a double containment system are exempt until the year 2010.
- Tank vessels under 5000 GRT unloading or discharging at a deepwater port or off-loading in a lightering operation more than 60 miles from U.S. coasts are exempt until 2015. (Lightering is the process of transferring cargo at sea from one vessel to another).

In November, 1990, the United States submitted a proposal to the 30th session of the IMO Marine Environment Protection Committee (MEPC30) to establish an international requirement for double-hull tankers [3]. In August, 1992, the international community, through IMO, endorsed the goals of OPA 90 by implementing amendments to The International Convention for the Prevention of Pollution From Ships (adopted in 1973 and modified in 1978 (MARPOL 73/78). These amendments require [3]:

1. Double-hull vessels or other equivalents in virtually all the world's tanker trade (Regulation 13F), and
2. Additional operational and structural measures for single hull vessels (Regulation 13G).

Regulation 13F specifies hull configuration requirements for new tankers contracted on or after July 6, 1993, of 600 dwt capacity or more [3]. Oil tankers between 600 and 5000 dwt must be fitted with double bottoms (or double sides), and the capacity of each cargo tank is specifically restricted. Every oil tanker of more than 5000 dwt is required to have a double hull (double bottom and double sides) or the equivalent [3]. The IMO regulation left the door open for other design alternatives to double hulls, provided these alternatives gave at least the same level of protection against oil pollution in the event of collision or grounding and they are based on the guidelines developed by IMO and approved by the MEPC[3]. These guidelines employ a probabilistic methodology for calculating oil outflow and a pollution prevention index to assess the equivalency of alternative designs.

Regulation 13G addresses existing single-hull vessels in the world fleet. This regulation applies to crude oil tankers of 20,000 dwt and above, and oil product carriers of 30,000 dwt and above [3]. Regulation 13G also specifies a schedule for retrofitting (with double hulls or equivalent measures) or retiring existing single-hull tank vessels within 25 or 30 years after delivery [3]. Tankers not fitted with segregated ballast tanks (SBTs) or fitted with SBTs that are not protectively located (PL) must designate protectively located double-side (DS) or double-bottom (DB) tanks upon reaching 25 years of age [3]. In appropriate locations, SBTs would be acceptable as protectively located spaces. Regulation 13G accepts hydrostatic loading and other alternatives (operational or structural) to protectively located spaces [3]. Tankers built in compliance with regulation I (6) of MARPOL 73/78 have protectively located ballast spaces and require no modification until reaching 30 years of age. At that age, all tankers must be converted to double hulls [3]. OPA 90 requirements and IMO regulations 13F and 13G can be more easily understood using the following two comparisons in *Table 1* [3].

The impact of the double-hull requirement on the international tanker industry will thus be driven by MARPOL 13F and 13G and by Section 4115 of OPA 90. Although the latter will gradually bar single-hull tankers from trading in US waters, it will not necessarily force them into retirement from non-US trade [3]. MARPOL 13G, on the other hand, mandates the retirement of all single-hull tankers in international trade at 30 years of age [3]. To trade beyond 25 years of age, pre-MARPOL tankers must retrofit protectively-located spaces or make use of hydrostatically-balanced loading (HBL) in selected cargo tanks [3]. However, the international fleet governed by MARPOL is to be composed entirely of double-hull vessels (or approved alternatives) no later than 2023.

TABLE 1. OPA REQUIREMENTS AND IMO REGULATIONS

Regulation	Vessel Size	Hull requirement	Enforcement Date
OPA 90 (Sec. 4115)	< 5000 GT	DH or double containment systems	Building contract after 6/30/90 Delivered after 1/1/ 94
	> 5,000 GT	DH (Double Hull)	Building contract after 6/30/90
Delivered after 1/1/94			
IMO	< 600 dwt	Not applicable	Building contract after 7/6/93
(Reg. 13F)	600-5,000 dwt	DH or DS	New construction or major renovation Begun on or after 1/6/94 Delivered after 7/6/96
	> 5,000 dwt	DH or equivalent	Building contract after 7/6/93 New construction or major renovation Begun on or after 1/6/94 Delivered after 7/6/96
OPA 90 (Sec. 4115)	< 5,000 GT	DH or double containment systems	Building contract after 1/2015
	> 5,000 GT	DH (Double Hull)	Per schedule starting in 1995
	> 5,000 DT	Operational and structural measures	No date set
IMO (Reg. 13G)	Crude carriers > 20,000 dwt	DH or equivalent	30 years after date of delivery
	Product carriers > 30,000 dwt	PL/DS or PL/DB or PL/SBT or hydrostatic	25 years after date of delivery

GT: Gross Ton (a measure of the registered tonnage, not directly related to cargo capacity).

PL/DS: protectively located tanks/double sides.

PL/DB: protectively located tanks/double bottoms.

Pl/SBT: protectively located tanks/segregated ballast tanks.

2.2 Sources of Oil Pollution

The transportation of petroleum and petroleum products constitutes the largest component of seaborne cargo movements today, with tanker cargoes accounting for 1.9 billion tons or 44.6% of the total movement in 1994. Oil tankers of various types and capacities serve as a flexible pipeline for facilitating their global movement. More than 80% of these tankers are non-US [2]. With depletion of the present Alaskan oil fields, the production of US-flag oil tankers is likely to decrease further during the coming decade [2].

Although the United States is one of the largest petroleum producers in the world, it consumes far more than it produces. As such, the demand for imported oil has spurred the continued increase in oil tanker traffic in U.S. waters. Projections of up to a 50% increase in imports of crude oil and petroleum products by the year 2000 have been reported [2].

Even with this high traffic volume, only about 1/500 of 1% (about 9,000 tons) of the total oil moving through U.S. waters is spilled each year [2]. Although many of these spills are small and the effects are localized, large spills can be devastating and attract media attention and hence lead to public outcries and debate over "sensitive" environmental issues. Large spills (30 tons and greater) comprise less than 3% of the total amount spilled, but they cause nearly 95% of the accidental spills in U.S. waters [2]. According to the US National Academy of Sciences statistics, oil pollution from tanker operations has fallen 85% in 20 years. This has occurred despite a rise of 5% per annum in the volume of worldwide tanker traffic (ton miles) in the last ten years. It is believed that the publicity given by the media to each oil tanker accident is the reason behind the public outcry and attention given to these accidents.

Land-based wastes from industry, sewage, and tourism, which are being dumped into rivers, harbors, bays and the open seas contribute most to sea pollution. About 1.48 million tons per year, or 61% of the total annual oil pollution of the sea, comes from land. Pollution to the sea water caused by oil spills due to tanker accidents and operations constitutes about 11.3% of the overall pollution problem. This percentage has fallen even lower over the past several decades due to the continued efforts of the oil transportation industry to improve tanker operations and minimize, or even eliminate, tanker accidents. According to some recent estimates, the sources of oil pollution in the sea can be broken down into the following general categories [??]:

1. Industrial waste, etc.	60.8%
2. Natural sources	10.3%
3. Tanker operations	6.6%
4. Tanker accidents	4.7%
5. Offshore production	2.0%
6. Other shipping	14.4%
7. Refineries/terminals	1.2%

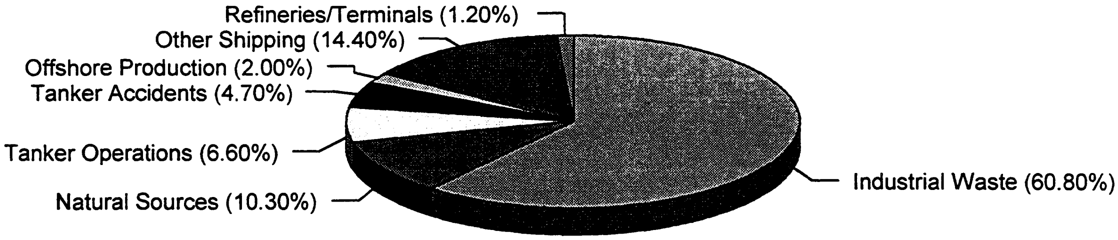


Figure 1. Sources of Oil Pollution

According to a 1985 report by the NRC, accident-related spillage of crude oil and petroleum products from ocean-going tank vessels is not the major source of petroleum input to the seas. This report [2] estimated that tanker accidents accounted for only 13% of the petroleum hydrocarbons entering the marine environment each year from all sources.

2.3. Oil Spills From Tanker Accidents

The most comprehensive database of all accidental oil spills from tankers (carriers and barges), except those resulting from acts of war, has been maintained by the

International Tanker Owners Pollution Federation (ITOPF). This database is used to generate statistics on numbers and sizes of spills, and also to identify causes of spills. This database can be useful for assessing the amount and risk of oil spills. It can also be used for evaluating the possible consequences of changes in tanker design and operation.

The information compiled by the ITOPF comes from published sources, such as the shipping press, magazines and journals, and other special publications issued by vessel owners and their insurers. Data and information on large spills resulting from collisions, groundings, structural damage, fires and explosions are usually contained in published sources. However, the majority of small operational spills are published as individual reports, and therefore, are difficult to obtain and compile. *Table 2* (extracted from an ITOPF database) breaks down the number of oil spill incidents into two categories, namely, 7 to 700 tons and over 700 tons, and gives the annual estimates of the total amount of oil spilled for the years 1970-1996.

Table 2 and *Figure 2* show that the volume of oil spilled each year varies greatly depending on the small number, if any, of major incidents. The vast majority of spills are small (< 7 tons) and contribute relatively little to the total amount spilled each year. Accidental spills from tankers also contribute a relatively small proportion of the annual total volume of oil that enters the world's sea and.

Figure 2 clearly shows that the average number of oil spills that are larger than 700 tons has been dramatically reduced from 24 per year in the period 1970-1979 to about 9 spills per year in 1980-1989. The average number of spills in the years 1995-1996 is 2.5 and the total amount was 89,000 tons.

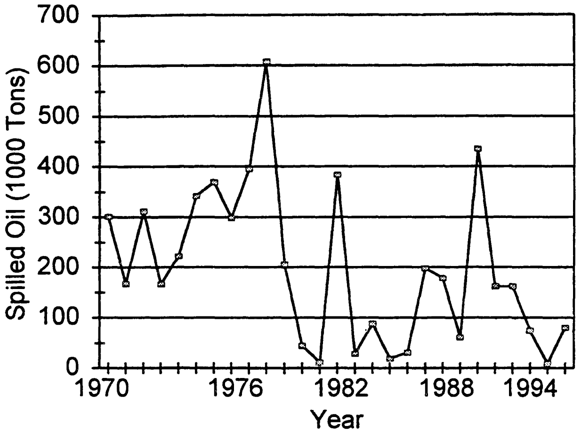


Figure 2. Quantity of Oil Spilled Between 1970 and 1996

TABLE 2. NUMBER OF SPILLS OVER 7 TONS
AND TOTAL QUANTITY OF OIL SPILLED

Year	7-700 Tons	Over 700 Tons	Quantity (1000 Tons)
1970	6	29	301
1971	18	14	167
1972	49	24	311
1973	25	32	166
1974	91	26	222
1975	97	19	342
1976	67	25	369
1977	65	16	298
1978	54	23	395
1979	59	34	608
1980	51	13	206
1981	49	6	44
1982	44	3	11
1983	52	11	384
1984	25	8	28
1985	29	8	88
1986	25	7	19
1987	27	10	30
1988	11	10	198
1989	32	13	78
1990	50	13	61
1991	27	8	435
1992	31	9	162
1993	30	11	144
1994	27	7	74
1995	21	2	9
1996	20	3	80

The U.S. Coast Guard (USCG) compiles data and records of oil spill incidents of all types in U.S. waters. However, the most recent study conducted by the National Research Council [3] concluded that in the USCG database, although well-maintained and managed, contains data that are not of uniform quality from year to year, and the problem has been compounded over the years by three major shifts in the data system structure and emphasis. For example, the USCG oil spill database includes the identity of the vessel for only about 10% of the recorded major casualties [3]. This deficiency prevents the establishment of any correlation between vessel age and oil pollution. Information such as this could have provided some indication of any changes in the risk of oil spills that might be anticipated as a result of the early retirement of tank vessels [3]. Other deficiencies of the USCG database include the failure to record smaller spills (less than 100 gallons) as well as defects in the tracking of larger spills [3]. This NRC study also looked at the database developed and maintained by the Mineral Management Service (MMS) of the U.S. Department of the Interior on oil spills in U.S. waters. The NRC concluded that the MMS database does not include information on spills of less than 1,000 barrels or spills from vessels other than tankers and barges. Therefore, in order to obtain adequate data for an accurate assessment of oil spills in US waters, the new data compiled by the NRC [3] include supplemental data from USCG and MMS databases. The number of spills and volume of spillage in US waters in the period 1973-1995 were extracted from these reports and are presented in *Table 3* [3].

Inspection of *Table 3* reveals that spills from tankers and barges have dominated the statistics over the years, accounting for about 90% of the total volume of oil lost from all vessels since 1973. The table also indicates that large spills of 1 million gallons and more have occurred between 1973 and 1989; however, no large spills involving more that 1 million gallons took place during the period 1991 to date. Moreover, the number of spills and the amount released were at historically low levels during 1991 to 1995. The data have also been plotted in *Figures 3 and 4* to show the general trend.

TABLE 3. NUMBER OF OIL SPILLS AND VOLUME OF SPILLAGE IN US WATERS, 1973-1995*

Year	Number of Spills	Tankers	Barges	Other Vessels
1973	520	3.2	1.0	1.3
1974	530	1.2	2.5	0.5
1975	470	9.0	2.6	1.4
1976	440	9.4	1.6	0.3
1977	480	0.2	1.7	0.2
1978	580	0.8	3.6	0.6
1979	510	13.2	1.2	0.4
1980	490	1.6	1.6	0.5
1981	470	1.2	4.4	0.4
1982	360	1.2	2.0	0.6
1983	330	0.2	2.0	0.3
1984	350	5.0	2.6	2.0
1985	285	0.6	4.0	0.5
1986	295	1.2	1.8	--
1987	280	1.6	0.4	0.8
1989	330	11.6	0.8	0.7
1990	310	5.0	1.0	0.5
1991	290	0.2	0.3	0.3
1992	300	0.3	0.9	0.5
1993	300	0.4	1.1	0.3
1994	210	0.3	1.5	0.5
1995	195	0.4	--	0.4

*In millions of gallons.

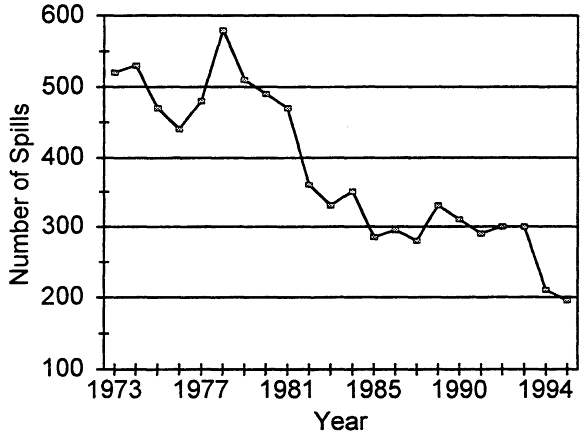


Figure 3. Number of Spills in U.S. Waters

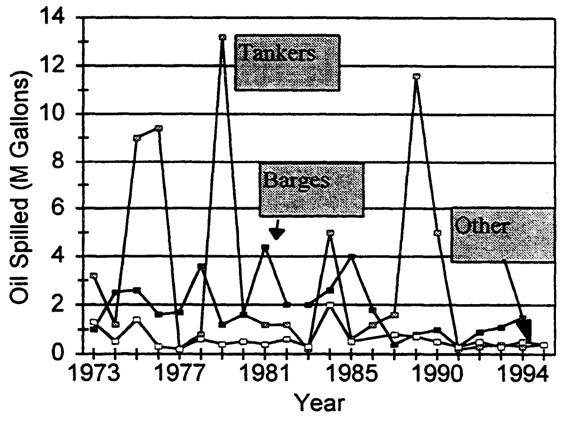


Figure 4. Oil Spilled by Tankers, Barges and Other Carriers

The main types of casualties that resulted in oil spills from tankers and barges during the period 1991 to 1995 are summarized in *Table 4* [3]. The data show that a small fraction of recent oil spills have occurred as a result of tanker collisions and groundings. However, the total volume spilled from barges was significantly greater than oil spilled from tankers. Tankers accounted for only about 10% of the spillage from vessels in US waters whereas barges accounted for about half of the total spillage from vessels and were involved in the majority of spills [3].

TABLE 4. VOLUME OF OIL SPILLED, NATURE OF CASUALTY, AND NUMBER OF SPILLS IN US WATERS FROM TANKERS AND BARGES [3]

Year	Grounding	Collision	All Other	Number of Spills*
Tankers				
1991			100,000	35
1992			120,000	22
1993			80,000	30
1994		50,000	20,000	18
1995	10,000	50,000	70,000	10
Barges				
1991	15,000	150,000	20,000	72
1992	15,000		100,000	28
1993	10,000	300,000	450,000	35
1994	800,000	10,000	110,000	40
1995		10,000	100,000	30

*In gallons.

These casualties, which resulted in oil spills, indicate the need for the development of new vessel designs (type, size, and condition) and operational practices in order to avoid such accidents in the future and protect the environment.

2.4 Major Oil Spills Worldwide

Table 5 gives a brief summary of almost all major oil spills that have occurred worldwide. Despite the large size of some of these incidents, they caused little or no environmental damage because the oil did not impact coastlines. That is probably why some of the tankers' names and incidents are unfamiliar to the general public.

A few very large accidents are responsible for a high percentage of oil spilled. For example, in the ten-year period, 1987-1996, there were 362 spills over 7 tons, totaling 1372 thousand tons; but 992 thousand tons (72%) were spilled in just 10 incidents (less than 3%). The figures for a particular year may therefore be severely distorted by a single large incident. This is clearly illustrated in 1979 (*Atlantic Empress*—287,000 tons), 1983 (*Castillo de Bellver*—252,000 tons) and 1991 (*ABT Summer*—260,000 tons). However, the vast majority of casualties do not result in pollution; only 6% (518) of the accidents reported in a survey of 9,276 accidents worldwide resulted in oil outflow [2]. The survey also shows that worldwide accidents attributed to groundings/strandings and collisions/rammings (contact) of oil tankers 10,000 dwt and larger that resulted in spillage of more than 30 tons of oil caused roughly equal numbers of major pollution incidents [2].

Examining the 50 largest oil spills shown in *Table 5* shows that various causes of accidents—groundings, collisions, structural failure, and fire/explosions—are nearly equal. *Table 5* also shows that a large volume of spillage was the result of a relatively small number of fires and explosions. Fires and explosions, as the initiating cause, produced the greatest outflow of the 50 largest spills [2]. For example, *Khark 5* sustained an explosion which led to fire and the release of 76,000 tons of crude oil off the Morocco coast in 1989 (the 11th largest spill since 1960), and the *Mega Borg* caught fire in the Gulf of Mexico off Texas in 1990 and lost 14,000 tons of crude oil. Fires and explosions may also cause pollution following a collision or other accidents. The data in *Table 5* are plotted in *Figure 5*.

TABLE 5. MAJOR OIL SPILLS WORLDWIDE

Ship Name	Year	Location	Oil Lost (tons)	Tanker Age (in years) and Cause
Atlantic Empress	1979	Off Tobago, West Indies	287,000	5, CO
ABT Summer	1991	700 nautical miles off Angola	260,000	15, N/K
Castillo de Bellver	1983	Off Saldanha Bay, South Africa	252,000	F/E
Amoco Cadiz	1978	Off Brittany, France	223,000	4, S/H
Haven	1991	Genoa, Italy	144,000	18, N/K
Odyssey	1988	700 nautical miles off Nova Scotia	132,000	16, F/E
Sea Star	1972	Gulf of Oman	123,090	4, CO
Torrey Canyon	1967	Scilly Isles, UK	119,000	9, GRN
Urquiola	1976	La Coruna, Spain	100,000	3, GRN
Hawaiian Patriot	1977	300 nautical miles off Honolulu	95,000	S/H
Independenta	1979	Bosphorus, Turkey	95,000	1, CO
Jakob Maersk	1975	Oporto, Portugal	88,000	GRN
Braer	1993	Shetland Islands, UK	85,000	18, N/K
Khark 5	1989	120 nautical miles off Atlantic Coast of Morocco	76,000	15, F/E
Aegean Sea	1992	La Coruna, Spain	74,000	19, N/K
Sea Empress	1996	Milford Haven, UK	72,000	3, N/K
Katina P	1992	Off Maputo, Mozambique	72,000	N/K
Assimi	1983	55 nautical miles off Muscat, Oman	53,000	F/E
Texaco Denmark	1971		102,319	1, N/K
Julius Schindler	1969		92,087	14, N/K
Irenes Serenade	1980	Greece	81,855	15, S/H
Nova	1985	Iran, Persian Gulf	68,213	10, CO
Metula	1974	Magellan Straits, Chile	50,000	GRN
Wafra	1971	Off Cape Agulhas, South Africa	65,000	15, GRN
Exxon Valdez	1989	Prince William Sound, Alaska, USA	37,000	4, GRN
Epic Colocotronis	1975	West Indies	58,000	GRN
Sinclair Petrolore	1960	Brazil	57,000	F/E
Yuyo Maru No 10	1974	Japan	42,000	CO
Andros Patria	1978	Spain, North Coast	48,000	F/E
World Glory	1968	South Africa	46,000	S/H
British Ambassador	1976	Japan	46,000	GRN
Pericles G. C.	1983	Qatar	44,000	F/E
Mandoil II	1969	USA, West Coast	41,000	CO
Burmah Agate	1979	USA, Gulf	41,000	CO
J. Antonio Lavalleja	1970	Algeria	38,000	GRN
Napier	1973	Chile	37,000	GRN
Corinthos	1975	USA, Delaware River	36,000	CO
Trader	1972	Greece	36,000	S/H
St. Peter	1976	Ecuador	33,000	F/E
Gino	1979	France, Atlantic	32,000	CO
Golden Drake	1972	Bermuda	32,000	S/H
Ionnis Angelicoussis	1979	Angola	32,000	F/E
Chryssi	1970	Bermuda	32,000	N/K
Irenes Challenge	1977	Pacific Ocean	31,000	N/K
Argo Merchant	1976	USA, East Coast	28,000	GRN
Heimvard	1965	Japan	31,000	CO
Pagasus	1968	USA, East Coast	25,000	N/K
Pacocean	1969	Northwest Pacific	31,000	S/H

TABLE 5. CONTINUED

Ship Name	Year	Location	Oil Lost (tons)	Tanker Age (in years) and Cause
Texaco Oklahoma	1971	USA, East Coast	29,000	S/H
Scorpio	1976	Mexico, East Coast	31,000	GRN
Ellen Conway	1975	Algeria	31,000	GRN
Caribbean Sea	1976	East Pacific Ocean	30,000	S/H
Cretan Star	1975	India, West Coast	27,000	N/K
Grand Zenith	1975	South Africa	26,000	S/H
Athenian Venture	1987	Canada, Newfound	26,000	F/E
Venoil	1977	South Africa	26,000	CO
Aragon	1989	Madeira	24,000	S/H
Ocean Eagle	1968	Puerto Rico	21,000	GRN
Mega Borg	1990	Gulf of Mexico, off Texas	14,000	F/E

Code: CO—Collision
GRN—Grounding/Stranding
F/E—Fire/Explosion
S/H—Structure, Hull, or machinery Failure
N/K—Cause of accident not known.

Sources: NRC Report, 1991 [1] and International Tanker Owners Pollution Federation Ltd., London, UK.

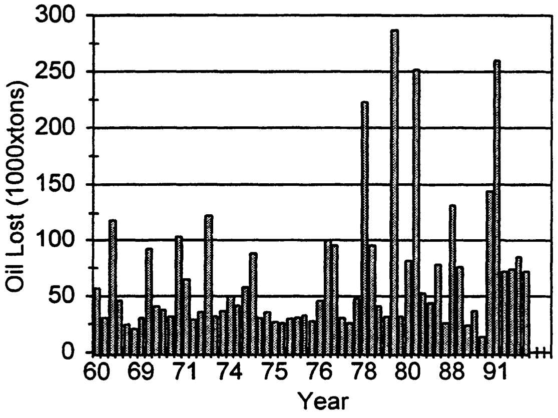


Figure 5. Major Oil Spills Worldwide

Tanker spill databases are often not precise enough to pinpoint the real cause of the oil spill. This can be seen by the *Amoco Cadiz* incident (the 3rd largest) where oil outflow was due to grounding (stranding), while the casualty itself was attributed to steering system failure or machinery failure [2].

The grounding of oil tankers over 10,000 dwt dominated both the number of accidents and volume spilled in U.S. waters. This is not surprising due to the shallow waters of the Gulf of Mexico and the East Coast ports. Groundings caused by shallow-water include the *Argo Merchant* in 1976 (25,000 tons outflow), the *Alvenus* in 1984 (7,389 tons outflow), the *Esso Puerto Rico* in 1988 (4,050 tons), and the *American Trader* in 1990 (975 tons) [2]. These groundings account for a large portion of the accidental spills that have occurred in U.S. waters since 1980 from oil tankers [2]. In addition, the *Burmah Agate* (1979), the *Puertorican* (1984), the *Georgia* (1990), and the *Olympic Glory* (1990) accidents have also dominated the US record [2]. Although not among the top 50 large spills, several additional tanker and barge accidents occurred near the U.S. coast in 1989 and 1990. These are [2]:

- The *World Prodigy*—Grounded and spilled 900 to 1365 tons of light oil off south Rhode Island in 1989. Most of the light oil evaporated quickly, but some local environmental damage was sustained.
- The *Presidente Rivera*—Grounded in the Delaware River near Marcus Hook, Pennsylvania, in 1989, and spilled about 900 tons of fuel oil. Local environmental damage was reported.
- The *Rachel B*—collided with a coastal towed barge and lost more than 800 tons of partially refined crude oil in the intersection of the Houston Ship and Bayport Ship Channels.
- The *American Trader*—Grounded one mile off Huntington Beach, California, in 1990 and spilled about 1200 tons of Alaskan light crude. Although one-third of the crude was recovered, local pollution was reported.
- The *B.T. Nautilus*—Grounded in the Kill van Kull waterway of New York Harbor in 1990 and spilled over 700 tons of fuel oil.

- The barge *Nestucca*—Struck while under tow on Puget Sound in 1988; the hull was breached and resulted in the release of 220 tons of oil. The released oil floated onshore and affected beaches and shorelines in Washington and Vancouver Island, Canada. Significant short-term damage of these shorelines was sustained.

These accidents, in addition to the *Exxon Valdez*, received much public attention and were noted by Congress during the debate that led to the passage of the OPA90.

2.5. Causes of Oil Spills

Most incidents are the result of a combination of actions and circumstances, all of which contribute in varying degrees to the final outcome. *Table 6* is adopted from International Tanker Owners Pollution Federation Limited, London, UK [??]. It analyzes and explores the incidence of spills of different sizes in terms of the primary event or operation in progress at the time of the spill. These "causes" have been grouped into "Operations" and "Accidents". Spills for which the relevant information is not available or where the cause was not one of those given are listed under "Other".

TABLE 6. INCIDENCE OF SPILLS BY CAUSE: 1976-1995 [??]

	< 7 Tons	7-700 Tons	> 700 Tons	Total
Operations				
Loading/Discharging	2753	275	15	3043
Bunkering	541	24	--	565
Other Operations	1145	45	--	1190
Accidents				
Collisions	143	221	83	447
Groundings	216	179	95	490
Hull failures	541	68	36	645
Fires and Explosions	147	14	20	181
Other	2227	158	36	2421
Total	7713	984	285	8982

The general trends shown in *Table 6* can be summarized as follows:

- Most spills from tankers result from routine operations such as loading, discharging, and bunkering which normally occur in ports or at oil terminals.
- The majority of these operational spills are small, with about 93% involving quantities of less than 7 tons.
- Accidents involving collisions and groundings generally give rise to much larger spills, with one-fifth involving quantities in excess of 700 tons.

The IMO database for the world tanker fleet (IMO, 1989), which provides a large sample of incidents (both polluting and nonpolluting), indicates that vessel size and age may play a role in casualties. This database may offer some insight about accidents and tanker characteristics that may be used to improve the design and operations of oil tankers. For example, the size of tankers most commonly used in U.S. waters is in the range of 50,000 to 100,000 dwt. Based on the IMO database, this size range has the worst overall worldwide casualty rate of all size categories [2]. The casualty rate for collisions and groundings for this size range is about equal to that for all tankers, but the rate for fire/explosion exceeds the average by 33% [2]. This figure, however, may be inconclusive due to the lack of related data on causes of many fires and explosions [2]. The IMO database also shows some evidence of a link between vessel age and serious casualties—older vessels tend to have more accidents, particularly fires/explosions and structural/machinery failure [2].

Fires and explosions are the major accidental causes of injuries and deaths aboard tankers. Any consideration of tank vessel hull design configurations and operations must take the risk of fire and explosion to the crew members into account. Despite the importance of the safety of crew members, the data that might relate crew casualties to the cause of the accident or the environment, or that might allow detailed analysis of how the ship structure, compartment arrangements, ventilation, and safety systems to prevent fatalities and injuries are either scarce or nonexistent [2]. However, the 1989 analysis conducted by IMO provides some information on fire accidents to date. Over a 15-year period, 1974-1988, an average of six major cargo fire incidents occurred. *Table*

7 provides the following estimates of the world maritime operational and accidental sources of oil entering the marine environment [2]:

TABLE 7. WORLD MARITIME SOURCES OF OIL ENTERING MARINE ENVIRONMENT

Cause	1990	1981/85	1973/75*
Bilge and Fuel Oil	250,000	310,000	--
Tanker Operational Losses	160,000	710,000	1,080,000
Accidental Spillage			
Tanker Accident	110,000	410,000	200,000
Nontanker Accident	10,000	100,000	
Marine Terminal Operations	30,000	40,000	500,000
Drydocking	--	30,000	250,000
Scrapping of Ships	10,000	--	--
Total	570,000	1,500,000	2,130,000

*In tons per year.

These losses, while large, reflect a major reduction from the nearly 1.5 million tons spilled annually world wide from both tanker operations and accidents during the late 1970s and early 1980s. The reduction in oil spills into the world seas can be attributed to international cooperation in development and execution of rules for tanker design, clean ballasting, and vessel operations, and the supportive action of most maritime nations.

2.6 Double-Hull/Double-Bottom Tanker Accidents

The data and statistics on oil spills from tankers presented in the previous sections did not make any distinction between single-hull, double-hull, or double-bottom. In order to examine the safety and validity of double-hull tankers in preventing or minimizing oil spills, one must examine previous data for trends and behavior. Two data sets have been examined, one from the Finnish Board of Navigation relating to incidents in the

Baltic over the last 25 years, and the other from a major Nordic tanker owner who operated a fleet of 30 to 40 vessels, primarily in Northern Europe but also occasionally in North American waters [1]. Out of a total of 90 grounding/collision incidents in the Baltic, over two-thirds of the incidents involve ships running aground and less than one-third involve colliding, either with other ships or with structures such as lighthouses or piers [1]. This supports the general data that suggest grounding is a much more likely occurrence than collision. Data from the Finnish Board of Navigation on 53 grounding incidents of commercial vessels in the Baltic can be presented as Table 8:

TABLE 8. GROUNDING INCIDENTS
OF COMMERCIAL VESSELS

Damage Penetration	Percentage of Occurrence
1 foot	70.0
2 feet	20.0
3 feet	10.0
4 feet	8.0

These data suggest that the penetration of the bottom shell in most cases (70%) is one foot or less and that no penetration occurred of more than 4 feet. This would suggest that a double-bottom tanker of more than 4 feet would protect the environment from oil spills in the case of grounding [1].

The tanker operator database gives similar support to the benefit of double bottoms with a total of 17 grounding incidents over 25 years [1]. The 11 groundings of double-bottom/double-hull ships resulted in no spill occurrence, whereas the 6 grounding incidents for single-bottom ships resulted in 3 spills [1]. When these data were expanded further to include grounding and collision data, it was found that in 14 incidents of double-bottom/double-hull ships, only 1 spill occurred; in the case of single-bottom ships, 3 spills out of 6 cases occurred [1]. Further investigation of the actual incidents suggest that, in the case of double-bottom ships, spills would have occurred in all but 3 of the 11 cases mentioned if the ships had not been double-bottom fitted [1].

2.7 OPA90 Phase-Out of U.S.-Flag Tanker Fleet

Tankers were traditionally designed with single-skin hulls; however, during the last 20 years increasingly stringent requirements and regulations were developed and implemented in response to oil spills and sea water pollution. From a commercial perspective, tanker markets have traditionally withstood the cyclical ups and downs with remarkable aplomb and dexterity, but the recent institutional and structural changes may threaten their efficiency in future years.

Table 9 shows the OPA90 phase-out schedule of the U.S. flag tanker fleet. This table was compiled by Colton & Company based on information available from the U.S. Coast Guard regulations.

It should be noted that *Table 9* does not list all double-hull tankers that are built or under construction. There are about 50 double hull tankers under construction around the world. In the following section, an attempt is made to list and give as much information as possible on all double-hulled tankers worldwide.

In 1990, Conoco became the first company to voluntarily commit to building only double hull tankers, before U.S. legislation was mandated. Conoco operates five double-hulled oil tankers, and plans to take the single-hull tankers out of service within the next few years.

Mobil Shipping & Transportation Co. contracted Sumitomo Heavy Industries Ltd. to build two double-hull very large crude carriers (VLCCs), each with capacity for as much as 2.2 million bbl of crude oil. The 280,000 dwt, 1100 ft long by 190 ft wide VLCCs was delivered in October 1998 and May 1999. This will bring to four the number of double-hull VLCCs in Mobil's fleet [??].

Bourgas Shipyard Co. Ltd. has finished the construction of a chemical/products tanker for Dubai Maritime Transport Co. The 12,200-dwt tanker is named *Dubai Pride* and features double-hull construction similar to a cargo tank with recessed suction wells in the cargo area's double bottom and 18 fixed cargo pumps [14].

TABLE 9. OPA90 PHASE-OUT OF U.S.-FLAG TANKER FLEET

Name	Operator	DWT (000)	Built or Rebuilt	OPA90 Year
Coastal Corpus Christi	Coastal Tankships	53	1960	Withdrawn
Coastal Eagle Point	Coastal Tankships	53	1960	Withdrawn
Coastal Manatee	Coastal Tankships	31	1961	Withdrawn
Seminole	Mobil Shipping	50	1961	Withdrawn
S/R Baton Rouge	SeaRiver Maritime	77	1970	Withdrawn
S/R Philadelphia	SeaRiver Maritime	77	1970	Withdrawn
Arco Anchorage	ARCO Marine	122	1973	Withdrawn
Chevron Mississippi	Chevron Shipping	71	1972	Withdrawn
Keystone Georgia	Keystone Shipping	27	1964	Withdrawn
Keystone Rhode Island	Keystone Shipping	20	1964	Withdrawn
Overseas Juneau	OSG Bulk Ships	122	1973	1998
Arco Fairbanks	ARCO Marine	123	1974	1999
Arco Juneau	ARCO Marine	122	1974	1999
Trinity	August Trading	38	1966	1999
Arco Independence	ARCO Marine	267	1977	2000
Arco Spirit	ARCO Marine	267	1977	2000
HMI Astrachem	Hvide Shipping	38	1970	2000
Golden Gate	Keystone Shipping	63	1970	2000
Marine Chemist	Marine Transport Lines	37	1970	2000
Overseas Valdez	OSG Bulk Ships	38	1968	Withdrawn
Overseas Vivian	OSG Bulk Ships	38	1969	2000
Overseas Alaska	OSG Bulk Ships	63	1970	2000
Leader	August Trading	38	1969	2000
Willamette	Hvide Shipping	38	1969	2000
Concho	Hvide Shipping	33	1970	2000
Coastal New York	Coastal Tankships	39	1971	2001
Brooks Range	Interocean Ugland	176	1978	2001
Thompson Pass	Interocean Ugland	174	1978	2001
Denali	Keystone Shipping	191	1978	2001
Duchess	Ocean Duchess	38	1971	2001
Overseas Arctic	OSG Bulk Ships	63	1971	2001
Coronado	Keystone Shipping	40	1973	2002
Cherry Valley	Keystone Shipping	40	1974	2002
S/R Benicia	SeaRiver Maritime	176	1979	2002
S/R North Slope	SeaRiver Maritime	175	1979	2002
Seabulk Challenger	Hvide Shipping	41	1975	2003
Chelsea	Keystone Shipping	40	1975	2003
Mormacstar	Mormac Marine	40	1975	2003
Mormacsun	Mormac Marine	40	1976	2003
Patriot	OMI Bulk Management	36	1976	2003
Seabulk Magnachem	Hvide Shipping	41	1977	2004
Mormacsky	Mormac Marine	40	1977	2004
Courier	OMI Bulk Management	36	1977	2004
Rover	OMI Bulk Management	36	1977	2004
Overseas Boston	OSG Bulk Ships	124	1974	2004
Guadalupe	August Trading	30	1978	2004
Sea Princess	Sea Princess Trading	37	1972	2004
Charleston	Amerada Hess	39	1980	2005
Atigun Pass	Keystone Shipping	152	1977	2005
Fredericksburg	Keystone Shipping	40	1980	2005
Marine Duval	Marine Transport Lines	25	1970	2005
New York Sun	Maritrans	31	1980	2005

Overseas Chicago	OSG Bulk Ships	92	1977	2005
Overseas New York	OSG Bulk Ships	92	1977	2005
Overseas Ohio	OSG Bulk Ships	92	1977	2005
Colorado	August Trading	31	1972	2005
S/R Galveston	SeaRiver Maritime	28	1978	2005
Florida Bay	Amoco Oil	25	1981	2006
Georgia Bay	Amoco Oil	21	1981	2006
South Carolina Bay	Amoco Oil	25	1981	2006
Virginia Bay	Amoco Oil	25	1981	2006
Coastal Port Everglades	Coastal Tankships	37	1981	2006
B.T. Alaska	Marine Transport Lines	188	1978	2006
Philadelphia Sun	Maritrans	34	1981	2006
Frances Hammer	Ocean Ships	45	1981	2006
Julius Hammer	Ocean Ships	45	1981	2006
OMI Columbia	OMI Bulk Management	125	1974	2006
Overseas Washington	OSG Bulk Ships	92	1978	2006
Groton	Amerada Hess	47	1982	2007
Jacksonville	Amerada Hess	47	1982	2007
Arco Alaska	ARCO Marine	191	1979	2007
Baltimore	Amerada Hess	47	1983	2008
Mobile	Amerada Hess	47	1983	2008
New York	Amerada Hess	47	1983	2008
Arco California	ARCO Marine	127	1980	2008
Gemini	Cleveland Tankers Inc.	6	1978	2008
Chemical Pioneer	Marine Transport Lines	35	1983	2008
Falcon Leader	Maritime Administration	34	1983	2008
Philadelphia	Amerada Hess	47	1984	2009
Arco Texas	ARCO Marine	91	1973	2009
HMI Dynachem	Hvide Shipping	50	1981	2009
HMI Petrochem	Hvide Shipping	42	1981	2009
Seabulk America	Hvide Shipping	46	1994	2010
S/R Long Beach	SeaRiver Maritime	215	1987	2010
Blue Ridge	Crowley Petroleum Tptn.	42	1981	2011
Coast Range	Crowley Petroleum Tptn.	41	1981	2011
Keystone Texas	Keystone Shipping	41	1981	2011
S/R Charleston	SeaRiver Maritime	49	1983	2011
Energy Ammonia	Energy Transportation	7	1982	2012
Chesapeake Trader	Mormac Marine	51	1982	2012
Delaware Trader	Mormac Marine	51	1982	2012
Overseas Philadelphia	OSG Bulk Ships	44	1982	2012
S/R Baytown	SeaRiver Maritime	59	1984	2012
S/R Wilmington	SeaRiver Maritime	49	1984	2012
Potomac Trader	Mormac Marine	51	1983	2013
Overseas New Orleans	OSG Bulk Ships	44	1983	2013
Keystone Canyon	Keystone Shipping	127	1978	2015
S/R Mediterranean	SeaRiver Maritime	215	1990	2015

Double-Hull Tankers Built Before OPA 90

Prince William Sound	Keystone Shipping	123	1975	DH
Chevron Oregon	Chevron Shipping	40	1975	DH
Chevron Colorado	Chevron Shipping	40	1976	DH
Chevron Washington	Chevron Shipping	40	1976	DH
Chevron Arizona	Maritrans	40	1977	DH
Chevron Louisiana	Maritrans	40	1977	DH
Cornucopia	Keystone Shipping	24	1978	DH
Tonsina	Keystone Shipping	125	1978	DH

Kenai	Keystone Shipping	125	1979	DH
Chilbar	Keystone Shipping	40	1981	DH
Gus W. Darnell	Ocean Ships	30	1985	DH
Paul Buck	Ocean Ships	30	1985	DH
Samuel L. Cobb	Ocean Ships	33	1985	DH
Lawrence H. Gianella	Ocean Ships	33	1986	DH
Richard G. Matthiesen	Ocean Ships	30	1986	DH
Double-Hull Tankers Built or Rebuilt Since OPA 90				
Sulfur Enterprise	Sulfur Carriers	22	1994	DH
Asphalt Commander	Sargeant Marine	34	1995	DH
Captain H. Downing	American Heavy Lift	40	1996	DH
Anasazi	American Heavy Lift	40	1997	DH
New River	American Heavy Lift	40	1997	DH
The Monseigneur	American Heavy Lift	40	1997	DH
American Progress	Mobil Shipping	40	1997	DH

(Source: Shipbuilding: Colton & Company, Arlington, VA.)

Maritrans Inc., Philadelphia, will build as many as six double-hull refined product tankers over the next 3 to 4 years at a cost of about $45 million each. The 40,000-dwt vessels will be used in U.S. trade.

Nippon Yusen Kaisha (NYK), Japan's largest shipping company, has ordered a double-hull VLCC (260,000-dwt) tanker at Ishikawajima Harima Heavy Industries (IHI). The new tanker, which is scheduled for delivery in October 1998, is the second VLCC that NYK has ordered at IHI. The first—the 260,000-dwt *Tajima*—was delivered in September, 1997. Japanese and Korean shipping companies have been the most active in the VLCC new building market this year and account for six of seven VLCC orders placed so far in 1997.

Ishikawajima-Harima Giho/Ihi (IHI) has built four 150,000 MTDW double-hull tankers and two double-hull VLCCs. It is now building a 100, 000 MTDW double-hull tanker. IHI is using high-reliability structural designs based on large-scale structural analysis and long experience, and is constructing high quality tankers which will satisfy design requirements for oil pollution preventive measures on tankers.

The Section 4115 phase-out schedule can also be presented in terms of size, age, and type of construction (single hull, double sides, or double bottom) of vessel as shown in *Table 10*. Vessels of ages shown or older must be phased out.

TABLE 10. SECTION 4115 PHASE-OUT SCHEDULE FOR VESSELS WITHOUT DOUBLE HULLS BY AGE AND SIZE OF VESSEL [3]

Year of D-H Compliance	SH	DS or DB	Year of D-H Compliance	SH	DS or DB	Year of D-H Compliance	SH	DS or DB
5,000 to 14,999 GT Vessel Size			15,000 to 29,999 GT Vessel Size			30,000 GT or More		
1995	40	45	1995	40	45	1995	28	33
1996	39	44	1996	38	43	1996	27	32
1997	38	43	1997	36	41	1997	26	31
1998	37	42	1998	34	39	1998	25	30
1999	36	41	1999	32	37	1999	24	29
2000	35	40	2000	30	35	2000	23	28
2001	35	40	2001	29	34	2001	23	28
2002	35	40	2002	28	33	2002	23	28
2003	35	40	2003	27	32	2003	23	28
2004	35	40	2004	26	31	2004	23	28
2005	25	30	2005	25	30	2005	23	28
2006	25	30	2006	25	30	2006	23	28
2007	25	30	2007	25	30	2007	23	28
2008	25	30	2008	25	30	2008	23	28
2009	25	30	2009	25	30	2009	23	28
2010	25	30	2010	25	30	2010	23	28
2011		30	2011		30	2011		28
2012		30	2012		30	2012		28
2013		30	2013		30	2013		28
2014		30	2014		30	2014		28
2015		30	2015		30	2015		28

DB—double bottom; DH—double hull; DS—double side; SH—single hull.

CHAPTER 3

INCREMENTAL COSTS OF DOUBLE-HULL TANKERS

The purpose of the remaining chapters is to assess the economic impact of Section 4115 of OPA90, and MARPOL 13F and 13G. The economic impact of these regulations will be reflected in the rising costs of oil prices to the consumer as a result of:

- increased capital investments of building double-hull tankers to replace retired single-hull tankers, and
- increased operating costs of double-hull tankers.

These combined costs will be compared with the estimated benefits of double-hull tankers in preventing future oil spills.

In its simplest form, cost/benefit analysis is equivalent to adding up all gains from a policy alternative, subtracting all losses, and choosing the alternative that maximizes net benefits. Thus, cost/benefit analysis is a framework for comparing the pros (benefits) and cons (costs) of choices. However, any data used to quantify these effects will always be based on assumptions, and will always have limitations.

Cost estimates are sensitive to assumptions about future traffic patterns and construction costs, whereas benefit estimates depend on judgments about design effectiveness and spill consequences. Cost estimates can also be looked at from a societal point of view, that is, how much a design change will add to the delivered price of oil in exchange for some added degree of protection against spills. This *societal insurance* may add many benefits such as protecting the environment from oil spills and avoiding the high cost of cleanup and restoration of the damaged environment.

Dollar values can be assigned to costs related to various designs, and the resulting benefits can be expressed in a nonmonetary fashion, e.g., tons of oil not spilled. This approach permits cost-effectiveness analysis: i.e., determination of the cost of new tanker designs, operations, and maintenance that would be incurred per unit of benefit achieved (tons of oil saved as a result of averted accidents). The fundamental question here is how to quantify the reduction in spillage achievable with the chosen design. Here, too, the availability of sufficient and accurate data will be needed in order to arrive at a realistic cost effectiveness analysis of designing, operating, and maintaining double-hull oil tankers.

3.1 Review of Literature on Costs and Benefits of Oil Spill Prevention

Before the passage of the Oil Pollution Act of 1990 (OPA 90), much of the literature on the economics of pollution control focused on regulatory policies that maximize the net social benefits of pollution abatement and prevention [36]. The discussion centered around issues such as emission fees and marketable permits as opposed to a standard-setting approach [36, 37, 38, 39]. However, this approach also attempted to integrate questions of monitoring and enforcement into the theory of environmental regulation [36].

A model to estimate how much care should be taken to prevent an oil spill from occurring, while maximizing the profits of an oil transport firm, was developed by Epple and Visscher [39]. The model showed how vessel size, price of oil, enforcement of pollution control regulations, and risk associated with variance in spill size, can affect the firm's decision regarding spill prevention expenditures. Since the Coast Guard may require a firm to clean up its spills and may assess a penalty for spilling oil, the firm must consider the expected cost of both its action and inaction in preventing spills [39]. Epple and Visscher derived an estimated reduced form expression for the probability and size of spills and found that increased enforcement leads to smaller oil spills [39]. They also showed that it is theoretically possible to isolate the detection effect, but the data required for such a determination were not available at that time. Instead, they estimated the detected probability of an oil spill, and found that increased enforcement actually increased the observed spill rate. This suggests that higher enforcement levels resulted in more new spills being detected than were prevented [39]. In other words, increased enforcement may lead to higher observed spill frequencies because enforcement detects more spills than it deters.

Burrows et al. [38] reviewed the economics of accidental oil pollution by tankers in coastal waters, and provided a theoretical analysis of alternative policy solutions. Accidental pollution of the sea by oil arises from three main sources:

- Accidents to ships at sea, e.g., collision, grounding, or fire. Oil is either spilled from tanker bunkers or from cargo tanks.
- Spillage of oil during transfer, e.g., from ship to shore installations, or from supertanker to smaller vessels, or as a consequence of incorrect operation of valves.
- Escape of oil from underwater reserves associated with drilling activities.

The theoretical framework of their model was based on the assumption that accidental oil spills are an increasing function of oil shipments, keeping other factors unchanged. The public policy problem then exists at two levels [38]:

1. Establishing and enforcing optimal rates of oil shipment, taking the social costs and benefits into account.
2. Establishing an optimal balance between controlling the spill (by an appropriate set of measures) on the one hand, and accepting environmental damage, on the other, once a tanker accident has occurred.

Cohen estimated and compared the social costs and benefits of enforcement of the U.S. Coast Guard's oil spill prevention program [36]. This study attempted to answer the question of whether or not the reduction in spilled oil, from oil-carrying vessels, would be worth the cost to society of preventing those spills [36]. Two types of oil spills associated with vessels were identified: those that occur during an oil transfer operation and those that are the result of a major vessel casualty. Although oil spills are stochastic events, aggregate spill rates for oil transfer operations can be predicted with a good degree of regularity based on previous experience [36]. Estimates of the volume of oil, cleanup costs, and environmental damages that were averted as a result of this program were based on actual spill data, case studies, and various economic assumptions [36]. Based on the models developed in this study, it was estimated that the social benefits of this program exceed its costs, both in the aggregate and at the margin. The marginal cost to society of preventing a gallon of oil from being spilled is estimated to be $5.50 with the marginal benefit being $7.27 [36].

In a subsequent paper, Cohen provided a general framework from which to analyze government monitoring and enforcement of regulations designed to reduce stochastic externalities [37]. Stochastic externalities include many types of pollution, such as nuclear power plant accidents, oil spills, and leakage from hazardous-waste dumps [37]. The author argues that once a regulatory standard has been determined, the problem of the regulator is to design an enforcement scheme that provides incentives for the firm to spend its resources to prevent and control pollution [37]. However, since enforcement is costly, the optimal enforcement mechanism may be one in which the regulator does not observe all polluters. Thus some firms may regret their expenditures on pollution but, ex ante, choose the action desired by regulators on the basis of a subjective probability of being detected [37]. The author viewed this problem as a principal-agent model with moral hazard. The principal is the government with regulatory authority over firms and the agent is a firm that stochastically pollutes the environment. Moral hazard results from the fact that the firm must take some costly action to reduce the likelihood of pollution [37]. The contract is a penalty function that determines the amount that a firm must pay the government if the firm pollutes. The principal-agent model appears to be useful for analyzing many issues associated with the enforcement of government regulations [37].

The following sections present the incremental costs of double-hull tankers as mandated by the Oil Pollution Act of 1990. Data presented here are drawn from the most recent available sources to determine three types of costs:

- Incremental capital costs
- Incremental operating and maintenance costs
- Deadweight loss.

3.2 Incremental Capital Costs of Double-Hull Tankers

The high cost involved in retrofitting existing tankers with double hulls will eventually force most single-hull tankers operating in US waters to be phased out. The retrofitting costs of a 30-year-old U.S.-built tanker would be approximately $1.5 million [5]. The major conversion involved would also require additional safety features. The combined costs of the double-hull retrofit and additional safety features would be about 50 to 80% of the replacement cost of the vessel [5]. Therefore, retrofitting existing single-hull tankers is economically questionable, although some conversions will take place [4]. Given the 25-year period over which requirements of the Act are phased in, it is reasonable to assume that most vessels complying with OPA90 will be newly-constructed and introduced in the normal cycle of vessel replacement [5].

The starting point of the cost analysis is the determination of the annual increase in construction costs from replacing single-hull tankers with double-hull tankers, where

Annual construction costs = Number of double-hull tankers built each year, by vessel size, times the incremental construction cost per double-hull tanker, by vessel size.

Based on data from the NRC [2], it is estimated that 739 tankers of the US fleet will be subject to OPA90. These vessels are categorized by size as: 471 small, 178 medium, and 90 large. Brown and Savage argue that this number conforms to an estimate of 1500 tankers that visited U.S. ports in 1989 [5]. Of these tankers, 80% were foreign-flagged but about 50% were under U.S. ownership or control. The requirements of the Act will effectively segregate the world's tanker fleet into two categories—those that visit U.S. waters and those employed elsewhere in the world.

The 739 oil tankers carry approximately 600 million tons of oil annually. It is estimated, however, that the cargo carrying capacity of a double-hull tanker would be 2.7% less than a comparable single-hull tanker because double-hull tankers are designed to have a cofferdam [2]. This means an additional 2.7% double-hull tankers are needed to meet demand and approximately 20 (739 x 0.027) additional double-hull tankers would have to be built. Therefore, the adjusted total number of tankers operating in U.S. waters would be approximately 760.

Table 11 presents the latest NRC estimates [3] of the costs of constructing single- and double-hull tankers, classified, as in Brown and Savage [5], by tanker size. A small tanker has 40,000 dwt capacity, a medium tanker can carry 80,000 dwt, and a large tanker can transport 240,000 dwt. It should be noted that the costs presented in *Table 10* are mid-range estimates and may vary depending on the country and shipyard that builds the tanker.

TABLE 11. COMPARISON OF CONSTRUCTION COSTS BETWEEN SINGLE- AND DOUBLE-HULL TANKERS [5]

Tanker Size (dwt)	Single Hull ($Million)	Double Hull ($Million)	Cost Increase ($Million)	Incremental Cost Per Ton of Oil Shipped
Small	34.00	39.40	5.4	135.00
Medium	49.70	58.20	8.5	106.25
Large	89.60	105.70	16.10	67.00

We assume, along with the NRC [3], that the average life of a double-hull vessel is 20 years and that they will be replaced at a constant annual rate. Given these assumptions, the annual incremental construction cost is as displayed in *Table 12*.

TABLE 12. DETERMINATION OF ANNUAL INCREMENTAL CONSTRUCTION COST, BY VESSEL SIZE [5]

Size	Total No. Replaced*	No. of Tankers Per Year	Incremental Construction Per Year DH Tanker	Incremental Construction Cost
Small	484	24.2	$ 5.4 M	$ 130.68 M
Mediuum	183	9.1	$ 8.5 M	$ 77.35 M
Large	93	4.6	$ 16.1 M	$ 74.06 M
Totals	760			$ 282.09 M

3.3 Operating/Maintenance Costs

In general, operating costs include manning, supplies, routine maintenance and repairs, administrative costs, fuel, and port costs. Since the double-hull tankers are new and have no track history, insufficient data were available to quantify potential changes in costs of these types associated with double-hull tanker operations. According to operators surveyed by the committee of the NRC, double-hull tankers promise reduced times for discharge of cargo and cleaning of cargo tanks [3]. Until a record of the operating costs of the double-hull tankers is established, however, operating costs of double- and single-hull tankers of similar size and age are assumed to be the same. Maintenance and repair (M&R) and hull and machinery (H&M) insurance premium costs were the only costs that showed significant differences in the NRC study [3]. The NRC report also indicated a difference between double- and single-hull costs of maintaining and repairing the protective coatings in the tanks of double-hull vessels [3]. Such costs occur late in the life of double-hull tankers, however, and are very small in present value terms. Thus they are ignored here.

Insurance premiums are usually based on the estimated costs of marine hull and machinery (H&M) and war-risk insurance per gross ton (GT). Because of the higher purchase cost of a double-hull vessel, the NRC estimated that insurance premiums for a double-hull VLCC or Aframax tanker would be about 6% higher than for a single-hull tanker of comparable size and age [3]. As of 1996, however, there were very small differences in insurance costs between double- and single-hull tankers—on the order of 1 to 4% of insurance costs. Thus incremental insurance premiums, also, can be assumed to have virtually no effect on the present value of costs.

The incremental variable cost of double-hull tankers comes primarily, then, in maintenance and repair of tankers. A double-hull design increases the inspection area on a vessel by approximately 100% over a single-hull design [5]. In addition, the amount of steel surface subject to corrosion and fatigue is increased by a factor of 3, which leads to a significant increase in the amount of steel replacement [5]. These differences produce the cost differential indicated in *Table 13.*

TABLE 13. ANNUAL MAINTENANCE AND REPAIR COSTS PER TANKER [5]

Vessel Size	Single Hull	Double Hull	Incremental M&R Costs Per Tanker
Small (40,000 dwt)	\$3.07 M	\$3.28 M	\$ 0.21 M
Medium (80,000 dwt)	\$4.08 M	\$4.33 M	\$ 0.25 M
Large (240,000 dwt)	\$6.29 M	\$6.65 M	\$ 0.36 M

Given the number of new tankers estimated in *Table 13*, the annual increase in maintenance and repair costs is as displayed in *Table 14*.

TABLE 14. DETERMINATION OF ANNUAL INCREMENTAL MAINTENANCE/REPAIR COSTS, BY VESSEL SIZE

Vessel Size	No. of Tankers Per Year	Incremental M&R Costs Per Tanker	Incremental M&R Costs Per Year
Small	24.2	\$ .210 M	\$ 5.082 M
Medium	9.1	\$ .250 M	\$ 2.275 M
Large	4.6	\$ .360 M	\$ 1.656 M
Total			\$ 9.013 M

3.4 Deadweight Loss

According to the above analysis, annual costs of oil transport will increase by approximately \$291 million per year. In a long-run, constant-cost, competitive environment, these costs will be shifted to consumers in the form of higher prices (P_0 to P_1 in *Figure 6*). The increase in prices will create a deadweight, or consumers' surplus, loss equal to the area, ABC. The value of this area is determined as follows for 1995:

(1) $DWL = .5\ (\Delta P) * (\Delta Q)$

(2) $\Delta P = \Delta AC = \Delta TC \div Q_0$

where Q_0 = 600 million tons x 7.33 barrels per ton, or 4398 million barrels. Thus,

ΔP = \$ 291M ÷ 4398 barrels = \$ 0.066 per barrel

(3) $\% \Delta Q = PED (\% \Delta P) = .36 * (.3)$,

where $\% \Delta Q$ = \$0.666 (\$20) = .3%, assuming P_0 = \$20 per barrel, and PED = .36. Thus, $\% \Delta Q = .00108$. It follows that:

(4) $\Delta Q = \% \Delta Q (Q_1)$, or

$\Delta Q = 4398 * .00108 =$ 4.75 million barrels. Thus,

DWL = .5 (4.75 million barrels) (\$ .066) = \$ 157,000.

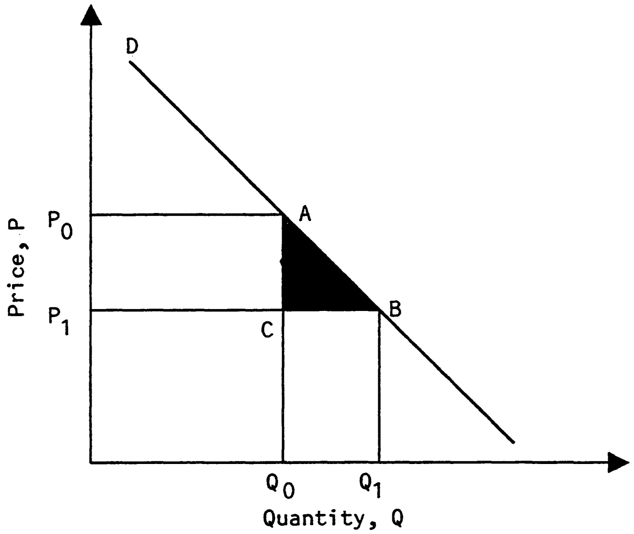


Figure 6. Deadweight Loss From Increased Construction and Maintenance/Repair Costs

This is the DWL for the first year single-hull tankers are replaced. It increases each year as long as total maintenance and repair costs are increasing. Maintenance and repair costs are cumulative; that is, they are \$9 million per year for each increment to the fleet. So, total maintenance and repair costs increase by \$9 million each year until the fleet is replaced (see column 3 of *Table 13*) in 2015.

3.5 Present Value of Construction, Maintenance/ Repair, and Deadweight Costs

Because costs occur at different points in time, it is necessary to calculate the present value of costs (PVC). Doing so requires the use of an appropriate discount rate. According to Gramlich's [43] review of the discount rate issue, the appropriate discount rate depends on whether the resources used to comply with a regulation subtract resources from consumption or investment. In the case at issue, the most likely possibility is that resources used to comply with the double-hull regulations would have otherwise been invested by private firms. If so, the appropriate discount rate is the real rate of return on private investment before taxes.

As indicated by the US stock market performance, the real rate of return on private equities has averaged approximately 7% over the last 75 years. Using this rate and assuming a 50-year period of analysis (long enough to replace the single-hull fleet and fully depreciate the double-hull replacements) and a 1995 base year, the present value of costs is as displayed in *Table 15.*

3.6 Intangible Costs

With any new major design or redesign, there are always hidden problems and risks that can only be found and detected by experience and over a long period of operational time. The redesigning of oil tankers is no exception. For example, double-hull tankers may pose a major threat of explosion and combustion. A double-hull tanker has a void, or empty space, between the hull and tanks. The theory is that if a ship runs aground, the outer hull may be penetrated, but the inner hull, containing the oil, will remain intact. A single-hull cargo tank completely full of oil is quite unlikely to explode because there is not enough oxygen in the tank to support combustion. A tank containing oxygen and oil vapors is quite hazardous because, in the correct ratio, an extremely explosive atmosphere may be created. This explosive mixture is avoided in cargo tanks by displacing any oxygen in the cargo tanks with flue gas (exhaust) from the ship's engine, which is inert. The void spaces on double-hull tankers are not full of inert gas, but are

TABLE 15. PRESENT VALUE OF INCREMENTAL COSTS OF DOUBLE-HULL TANKERS*

Year	Increase in Construction Costs	Increase in Maintenance/ Repair Costs	Deadweight Loss (dwl)	Increase in Total Costs	Present Value of Total Costs
1995	$ 282.09	$ 9	$ 0.157	$ 291.247	$ 272.19
1996	$ 282.09	$ 18	$ 0.172	$ 300.262	$ 262.26
1997	$ 282.09	$ 27	$ 0.187	$ 309.277	$ 252.46
1998	$ 282.09	$ 36	$ 0.202	$ 318.292	$ 242.82
1999	$ 282.09	$ 45	$ 0.217	$ 327.307	$ 233.37
2000	$ 282.09	$ 54	$ 0.232	$ 336.322	$ 224.11
2001	$ 282.09	$ 63	$ 0.247	$ 345.337	$ 215.06
2002	$ 282.09	$ 72	$ 0.262	$ 354.352	$ 206.24
2003	$ 282.09	$ 81	$ 0.277	$ 363.367	$ 197.65
2004	$ 282.09	$ 90	$ 0.292	$ 372.382	$ 189.30
2005	$ 282.09	$ 99	$ 0.307	$ 381.397	$ 181.20
2006	$ 282.09	$ 108	$ 0.322	$ 390.412	$ 173.35
2007	$ 282.09	$ 117	$ 0.337	$ 399.427	$ 165.75
2008	$ 282.09	$ 126	$ 0.352	$ 408.442	$ 158.40
2009	$ 282.09	$ 135	$ 0.367	$ 417.457	$ 151.31
2010	$ 282.09	$ 144	$ 0.382	$ 426.472	$ 144.46
2011	$ 282.09	$ 153	$ 0.397	$ 435.487	$ 137.86
2012	$ 282.09	$ 162	$ 0.412	$ 444.502	$ 131.51
2013	$ 282.09	$ 171	$ 0.427	$ 453.517	$ 125.40
2014	$ 282.09	$ 180	$ 0.442	$ 462.532	$ 119.53
2015	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 113.88
2016	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 106.43
2017	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 99.47
2018	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 92.96
2019	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 86.88
2020	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 81.20
2021	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 75.89
2022	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 70.92
2023	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 66.28
2024	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 61.95
2025	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 57.89
2026	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 54.11
2027	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 50.57
2028	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 47.26
2029	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 44.17
2030	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 41.28
2031	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 38.58
2032	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 36.05
2033	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 33.69
2034	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 31.49
2035	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 29.43
2036	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 27.50
2037	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 25.71
2038	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 24.02
2039	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 22.45
2040	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 20.98
2041	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 19.61
2042	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 18.33
2043	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 17.13
2044	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 16.01
2045	$ 282.09	$ 189	$ 0.457	$ 471.547	$ 14.96
Totals			**$ 395,235**		**$ 5,311.30**

*All costs in millions.

full of air which contains the oxygen required for combustion. Consider the following scenario: a large tank vessel develops a crack in one of its tanks, allowing oil and oil vapor to leak into the void space, which is inspected only periodically. Suppose that over a period of weeks or months, a considerable amount of vapor accumulates in this space. The tanker runs aground and creates sparks where the hull is penetrated. Clearly, this situation sets the stage for a devastating explosion, fire, and oil spill. The void space is now a tremendous liability, but available data do not permit a determination of the costs due to this factor.

Hull failures can also result from improper loading, design or construction flaws, and corrosion. Ship designers are aware of these problems and may take into account all design safety factors to prevent an accident as a result of these factors. However, the designers' knowledge in these areas is only theoretical. In practice, they are limited to simplified definitions of loads, theoretical 3-D models, and past experience and data.

Greater corrosion-induced structural deterioration is a real possibility. All ship building steel corrodes at the same rate unless effective protective measures, such as coatings and/or anodes, are applied and maintained. The double-hull tankers could face two problems in this regard: (1) if the thickness of plates and stiffening members is reduced, due to changes in design criteria and materials, there will be less margin left to corrode before the structure is subjected to possible premature failure; and (2) areas between the outer skin of the tanker and inner hulls will be inaccessible for maintenance and reapplication of anti-corrosion detergents and coatings.

Other possible risk factors that may arise as a result of lack of experience and design data for double-hull tankers are greater instability of double-hull tankers in severe weather conditions and more maneuvering difficulty in shallow waters. Double-hull tanker risk analysis, tanker explosion hazards, and navigation risk are all legitimate concerns and should be addressed in depth. These three factors require a detailed study (both technical and economical) which, however, is above and beyond the scope of this study. In any event, such a study holds the possibility that the cost estimate in *Table 15* is biased downward.

CHAPTER 4

EXPECTED BENEFITS OF DOUBLE-HULL TANKERS

The primary source of benefits of double-hull tankers is the reduction in the amount of crude oil spilled relative to single-hull tankers. Such a reduction saves oil that would otherwise be lost, reduces environmental clean-up costs, and lowers the cost of damages to the environment as a result of oil spills. Double-hull tankers may reduce fatalities or injuries that may occur as a result of fire or explosion, but existing evidence on this point is inconclusive.

The nature and extent of costs arising from oil spills vary significantly, depending on type of oil involved, location and size of the spill, weather conditions during the spill, scope and intensity of clean-up activities, and level of clean-up efficiency (degree of restoration to the original environment). The estimation of costs in economic terms is a developing science. In this chapter, we draw upon existing, although imperfect, estimates to determine the expected range of costs saved or benefits likely to be realized by substituting double-hull tankers for single-hull tankers.

4.1 Benefit Measures

The correct measure of benefits is the amount that people are willing to pay for the extra protection against oil spills provided by double-hull tankers relative to single-hull tankers. Estimates to date, however, have been based on less accurate but more practical measures of costs saved. Costs saved consist of the following:

1. Value of Crude Oil Saved—The value of crude oil lost due to single-hull accidents minus the value of crude oil lost due to double-hull accidents.
2. Clean-Up Costs Avoided—Clean-up costs from single-hull accidents minus clean-up costs from double-hull accidents.

3. Environmental Damage Avoided—Environmental damage from single-hull accidents minus environmental damage from double-hull accidents.
4. Value of Loss of Life and Injuries Avoided—The value of loss of life and injuries from single-hull accidents minus the value of loss of life and injuries from double-hull accidents.

4.2 Value of Oil Saved

4.2.1 Oil Spilled in Single-Hull Tanker Accidents

The volume of oil spilled annually from accidents larger than 10,000 gallons (approximately 30 metric tons) during the ten years 1980 through 1989 averaged about 9,000 tons. During the worst year about 40,000 tons was spilled [2]. To place these spills in perspective, they can be compared to total volumes shipped annually of roughly 600 millions tons in U.S. waters [2].

These spill volumes are assumed to be the average and worst possible cases for 1995, the first year in our evaluation horizon. We assume, further, that each spill volume will grow at an annual average rate of 3% for the entire evaluation horizon from 1995 to 2045. This will be due to the increased probability of accidents caused by scheduling more trips, since the use of double-hull tankers will lower the quantity shipped per tanker as compared to the shipment of a single hull and thus increase tanker traffic that may result in collision or accidents. This increased demand for oil plus increased traffic led the NRC to estimate an increase in oil spills between 3 and 14% [2].

4.3 Effectiveness of Double-Hull Tankers in Reducing Oil Spills

There is general consensus in the marine engineering community that double-hull tankers will only protect against low velocity impacts due to collisions or groundings [7, 8, 9]. A study commissioned by the National Research Council, on the simulation of oil loss from tankers, concluded that 85% of spillage due to groundings and 50% of spillage due to collisions would be prevented by a double-hull tanker [2]. For example, a double-hull tanker would not have entirely prevented the spill from the *Exxon Valdez* accident.

According to Brown and Savage [5], this means that double hulls would reduce spills by 23% in the most probable (average) case and by 30% in the maximum spillage case. The latter assumes that double-hull tankers prevent all spillage that occurs in collisions and groundings [5].

In *Table 16*, we apply Brown and Savage's estimated percentages of the effectiveness of double hulls to the projected oil spills in *Table 17*, with the additional proviso that only 5% of the single-hull tanker fleet will be replaced each year over the period 1995-2015. By placing a dollar value on each ton of oil saved, the benefits of double hull tankers in terms of value of oil saved can be easily determined. Using a constant real price of $146.60 per ton (1990 OPEC average price), the value of oil saved is shown in *Table 18*.

4.4 Clean-Up Costs Saved

The International Maritime Organization (IMO) has estimated the costs of clean up at $4000 a ton, or about $16 a gallon in 1990 prices [5]. By comparison, the Exxon Corporation spent approximately $2 billion in cleaning up the *Exxon Valdez* oil spill, or about $200 per gallon or $50,000 per ton spilled. The *Exxon Valdez* accident was clearly an exceptional case, however, due to the confined nature of Prince William Sound, its remote location, and pristine condition.

The actions of waves and sun often break up smaller spills and evaporate the oil before the slicks encounter land. Double-hull tankers would mitigate collisions and groundings that most likely occur in in-shore areas. In fact, the *Exxon Valdez* clean-up costs should not be used as a typical guide because the magnitude of the damage to the tanker was such that even a double-hull tanker would not have averted the disaster.

Brown and Savage have also estimated that the costs of clean-up are $16 a gallon ($4,000 per ton) in the most probable case, but they argue that they could be as high as $100 a gallon or $25,000 per ton in a worst case scenario [5]. Other estimates for spills prior to the *Exxon Valdez* put clean-up costs in the range of $1,500 to $38,000 per ton [2]. Our calculations for the value of clean-up costs avoided are based on $4,000 per ton in the average case and $25,000 per ton for the maximum case, following Brown and Savage. *Table 19* shows the projected values for the period 1995 through 2045.

TABLE 16. PROJECTED OIL LOST FROM SINGLE-HULL ACCIDENTS, 1995-2045, AVERAGE AND MAXIMUM POSSIBLE LOSSES IN TONS

Year	Average Losses	Maximum Losses
1995	9,000	40,000
1996	9,270	41,200
1997	9,548	42,436
1998	9,835	43,709
1999	10,130	45,020
2000	10,433	46,371
2001	10,746	47,762
2002	11,069	49,195
2003	11,401	50,671
2004	11,743	52,191
2005	12,095	53,757
2006	12,458	55,369
2007	12,832	57,030
2008	13,217	58,741
2009	13,613	60,504
2010	14,022	62,319
2011	14,442	64,188
2012	14,876	66,114
2013	15,322	68,097
2014	15,782	70,140
2015	16,255	72,244
2016	16,743	74,412
2017	17,245	76,644
2018	17,762	78,943
2019	18,295	81,312
2020	18,844	83,751
2021	19,409	86,264
2022	19,992	88,852
2023	20,591	91,517
2024	21,209	94,263
2025	21,845	97,090
2026	22,501	100,003
2027	23,176	103,003
2028	23,871	106,093
2029	24,587	109,276
2030	25,325	112,554
2031	26,085	115,931
2032	26,867	119,409
2033	27,673	122,991
2034	28,503	126,681
2035	29,358	130,482
2036	30,239	134,396
2037	31,146	138,428
2038	32,081	142,581
2039	33,043	146,858
2040	34,034	151,264
2041	35,055	155,802
2042	36,107	160,476
2043	37,190	165,290
2044	38,306	170,249
2045	39,455	175,356

Based on a 3% annual increase.

TABLE 17. OIL SAVED FROM REPLACING SINGLE-HULL WITH DOUBLE-HULL VESSELS

Year	Proportion of Single Hulls Replaced	Proportionate Reduction in Oil Spilled		Expected Reduction in Oil Spilled (tons)	
		Average	Maximum	Average	Maximum
1995	0.05	0.012	0.015	108	600
1996	0.10	0.023	0.030	213	1,236
1997	0.15	0.035	0.045	329	1,910
1998	0.20	0.046	0.060	452	2,623
1999	0.25	0.058	0.075	582	3,377
2000	0.30	0.069	0.090	720	4,173
2001	0.35	0.081	0.105	865	5,015
2002	0.40	0.092	0.120	1,018	5,903
2003	0.45	0.104	0.135	1,180	6,841
2004	0.50	0.115	0.150	1,350	7,829
2005	0.55	0.127	0.165	1,530	8,870
2006	0.60	0.138	0.180	1,719	9,966
2007	0.65	0.150	0.195	1,918	11,121
2008	0.70	0.161	0.210	2,128	12,336
2009	0.75	0.173	0.225	2,348	13,613
2010	0.80	0.184	0.240	2,580	14,956
2011	0.85	0.196	0.255	2,823	16,368
2012	0.90	0.207	0.270	3,079	17,851
2013	0.95	0.219	0.285	3,348	19,408
2014	1.00	0.230	0.300	3,630	21,042
2015	1.00	0.230	0.300	3,739	21,673
2016	1.00	0.230	0.300	3,851	22,324
2017	1.00	0.230	0.300	3,966	22,993
2018	1.00	0.230	0.300	4,085	23,683
2019	1.00	0.230	0.300	4,208	24,394
2020	1.00	0.230	0.300	4,334	25,125
2021	1.00	0.230	0.300	4,464	25,879
2022	1.00	0.230	0.300	4,598	26,655
2023	1.00	0.230	0.300	4,736	27,455
2024	1.00	0.230	0.300	4,878	28,279
2025	1.00	0.230	0.300	5,024	29,127
2026	1.00	0.230	0.300	5,175	30,001
2027	1.00	0.230	0.300	5,330	30,901
2028	1.00	0.230	0.300	5,490	31,828
2029	1.00	0.230	0.300	5,655	32,783
2030	1.00	0.230	0.300	5,825	33,766
2031	1.00	0.230	0.300	5,999	34,779
2032	1.00	0.230	0.300	6,179	35,823
2033	1.00	0.230	0.300	6,365	36,897
2034	1.00	0.230	0.300	6,556	38,004
2035	1.00	0.230	0.300	6,752	39,144
2036	1.00	0.230	0.300	6,955	40,319
2037	1.00	0.230	0.300	7,164	41,528
2038	1.00	0.230	0.300	7,379	42,774
2039	1.00	0.230	0.300	7,600	44,057
2040	1.00	0.230	0.300	7,828	45,379
2041	1.00	0.230	0.300	8,063	46,741
2042	1.00	0.230	0.300	8,305	48,143
2043	1.00	0.230	0.300	8,554	49,587
2044	1.00	0.230	0.300	8,810	51,075
2045	1.00	0.230	0.300	9,075	52,607
				218,866	1,268,762

TABLE 18. VALUE OF OIL SAVED BY DOUBLE-HULL VESSELS

Year	Expected Oil Saved		Price of Oil Per Ton	Expected Value of Oil Saved	
	Average	Maximum		Average Benefit	Maximum Benefit
1995	108	600	$146.60	$15,833	$87,960
1996	213	1,236	$146.60	$31,257	$181,198
1997	329	1,910	$146.60	$48,291	$279,950
1998	452	2,623	$146.60	$66,320	$384,465
1999	582	3,377	$146.60	$85,387	$494,999
2000	720	4,173	$146.60	$105,539	$611,818
2001	865	5,015	$146.60	$126,822	$735,202
2002	1,018	5,903	$146.60	$149,288	$865,438
2003	1,180	6,841	$146.60	$172,987	$1,002,826
2004	1,350	7,829	$146.60	$197,975	$1,147,678
2005	1,530	8,870	$146.60	$224,305	$1,300,320
2006	1,719	9,966	$146.60	$252,037	$1,461,087
2007	1,918	11,121	$146.60	$281,232	$1,630,329
2008	2,128	12,336	$146.60	$311,951	$1,808,411
2009	2,348	13,613	$146.60	$344,260	$1,995,711
2010	2,580	14,956	$146.60	$378,227	$2,192,621
2011	2,823	16,368	$146.60	$413,922	$2,399,550
2012	3,079	17,851	$146.60	$451,419	$2,616,921
2013	3,348	19,408	$146.60	$490,793	$2,845,174
2014	3,630	21,042	$146.60	$532,122	$3,084,768
2015	3,739	21,673	$146.60	$548,086	$3,177,311
2016	3,851	22,324	$146.60	$564,529	$3,272,630
2017	3,966	22,993	$146.60	$581,465	$3,370,809
2018	4,085	23,683	$146.60	$598,909	$3,471,933
2019	4,208	24,394	$146.60	$616,876	$3,576,091
2020	4,334	25,125	$146.60	$635,382	$3,683,374
2021	4,464	25,879	$146.60	$654,443	$3,793,875
2022	4,598	26,655	$146.60	$674,077	$3,907,692
2023	4,736	27,455	$146.60	$694,299	$4,024,922
2024	4,878	28,279	$146.60	$715,128	$4,145,670
2025	5,024	29,127	$146.60	$736,582	$4,270,040
2026	5,175	30,001	$146.60	$758,679	$4,398,141
2027	5,330	30,901	$146.60	$781,440	$4,530,086
2028	5,490	31,828	$146.60	$804,883	$4,665,988
2029	5,655	32,783	$146.60	$829,029	$4,805,968
2030	5,825	33,766	$146.60	$853,900	$4,950,147
2031	5,999	34,779	$146.60	$879,517	$5,098,651
2032	6,179	35,823	$146.60	$905,903	$5,251,611
2033	6,365	36,897	$146.60	$933,080	$5,409,159
2034	6,556	38,004	$146.60	$961,072	$5,571,434
2035	6,752	39,144	$146.60	$989,905	$5,738,577
2036	6,955	40,319	$146.60	$1,019,602	$5,910,734
2037	7,164	41,528	$146.60	$1,050,190	$6,088,056
2038	7,379	42,774	$146.60	$1,081,695	$6,270,698
2039	7,600	44,057	$146.60	$1,114,146	$6,458,819
2040	7,828	45,379	$146.60	$1,147,571	$6,652,583
2041	8,063	46,741	$146.60	$1,181,998	$6,852,161
2042	8,305	48,143	$146.60	$1,217,458	$7,057,726
2043	8,554	49,587	$146.60	$1,253,981	$7,269,458
2044	8,810	51,075	$146.60	$1,291,601	$7,487,541
2045	9,075	52,607	$146.60	$1,330,349	$7,712,167
	218,866	1,268,762		$32,085,742	$186,000,478

4.5 Value of Environmental Damages Avoided

Damages can remain even in the face, or aftermath, of clean-up efforts. Oil spills can impair commercial activities, such as fishing, and recreational activities such as boating. Oil spills can also cause long-run harm to eco-systems.

Court awards for uncompensated damages provide one indication of environmental damages involving oil spills. An analysis of 38 large oil spills in U.S. waters found that, in 1990 dollars, claims have clustered at around $28,000 per ton of oil spilled [2]. The exception here is the *Exxon Valdez* case, where settlement costs could reach $90,000 per ton or higher [2].

It should be noted that the amounts paid are determined under international and domestic laws and, as such, may include only partial compensation for environmental damages but also include clean-up costs. An example of covered costs is provided by the International Oil Pollution Compensation (IOPC) Fund, established in 1978 pursuant to a 1971 international convention. (The United States is not a party to this convention.)

The fund generally covers claims for clean-up costs, consequential losses for owners or users of contaminated or damaged property, and claims for economic losses suffered by persons such as fishermen who depend directly on earnings from coastal or sea-related activities [2], but not the value of environmental impairment, per se. It appears, therefore, that the use of court awards for environmental damage estimates may include some double-counting of clean-up costs, and it is clearly debatable whether these awards accurately reflect all of the environmental damage caused by spills.

Cohen [38, 39] estimated uncompensated environmental damage costs in the range of $1,500 to $10,500 a ton. These estimates, which are for spills prior to the *Exxon Valdez*, did not attempt to take all environmental effects into account. A full accounting of environmental effects now would produce estimates, according to Cohen, in the range of $10,000 to $20,000 per ton, particularly in light of increasing public concern about environmental degradation and nonuse values [2]. One government analyst believes a $30,000 per ton upper-bound figure now would be credible. Brown and Savage assumed $2500 a ton for the most probable case of uncompensated environmental damage and $8,750 a ton in the most favorable (highest benefit) case [5].

TABLE 19. VALUE OF CLEAN-UP COSTS AVOIDED

Year	Expected Oil Saved		Clean-Up Cost Per Ton		Value of Clean-Up Costs Saved	
	Average	Maximum	Average	Maximum	Average	Maximum
1995	108	600	$4,000	$25,000	$432,000	$15,000,000
1996	213	1236	$4,000	$25,000	$852,840	$30,900,000
1997	329	1910	$4,000	$25,000	$1,317,638	$47,740,500
1998	452	2623	$4,000	$25,000	$1,809,556	$65,563,620
1999	582	3377	$4,000	$25,000	$2,329,803	$84,413,161
2000	720	4173	$4,000	$25,000	$2,879,637	$104,334,667
2001	865	5015	$4,000	$25,000	$3,460,364	$125,375,491
2002	1,018	5903	$4,000	$25,000	$4,073,342	$147,584,864
2003	1,180	6841	$4,000	$25,000	$4,719,985	$171,013,961
2004	1,350	7829	$4,000	$25,000	$5,401,761	$195,715,978
2005	1,530	8870	$4,000	$25,000	$6,120,195	$221,746,203
2006	1,719	9966	$4,000	$25,000	$6,876,874	$249,162,097
2007	1,918	11121	$4,000	$25,000	$7,673,445	$278,023,373
2008	2,128	12336	$4,000	$25,000	$8,511,621	$308,392,080
2009	2,348	13613	$4,000	$25,000	$9,393,182	$340,332,688
2010	2,580	14956	$4,000	$25,000	$10,319,976	$373,912,180
2011	2,823	16368	$4,000	$25,000	$11,293,924	$409,200,142
2012	3,079	17851	$4,000	$25,000	$12,317,021	$446,268,861
2013	3,348	19408	$4,000	$25,000	$13,391,338	$485,193,422
2014	3,630	21042	$4,000	$25,000	$14,519,030	$526,051,816
2015	3,739	21673	$4,000	$25,000	$14,954,601	$541,833,370
2016	3,851	22324	$4,000	$25,000	$15,403,239	$558,088,372
2017	3,966	22993	$4,000	$25,000	$15,865,336	$574,831,023
2018	4,085	23683	$4,000	$25,000	$16,341,296	$592,075,953
2019	4,208	24394	$4,000	$25,000	$16,831,535	$609,838,232
2020	4,334	25125	$4,000	$25,000	$17,336,481	$628,133,379
2021	4,464	25879	$4,000	$25,000	$17,856,576	$646,977,380
2022	4,598	26655	$4,000	$25,000	$18,392,273	$666,386,702
2023	4,736	27455	$4,000	$25,000	$18,944,041	$686,378,303
2024	4,878	28279	$4,000	$25,000	$19,512,362	$706,969,652
2025	5,024	29127	$4,000	$25,000	$20,097,733	$728,178,741
2026	5,175	30001	$4,000	$25,000	$20,700,665	$750,024,104
2027	5,330	30901	$4,000	$25,000	$21,321,685	$772,524,827
2028	5,490	31828	$4,000	$25,000	$21,961,336	$795,700,572
2029	5,655	32783	$4,000	$25,000	$22,620,176	$819,571,589
2030	5,825	33766	$4,000	$25,000	$23,298,781	$844,158,736
2031	5,999	34779	$4,000	$25,000	$23,997,745	$869,483,498
2032	6,179	35823	$4,000	$25,000	$24,717,677	$895,568,003
2033	6,365	36897	$4,000	$25,000	$25,459,207	$922,435,043
2034	6,556	38004	$4,000	$25,000	$26,222,983	$950,108,095
2035	6,752	39144	$4,000	$25,000	$27,009,673	$978,611,338
2036	6,955	40319	$4,000	$25,000	$27,819,963	$1,007,969,678
2037	7,164	41528	$4,000	$25,000	$28,654,562	$1,038,208,768
2038	7,379	42774	$4,000	$25,000	$29,514,199	$1,069,355,031
2039	7,600	44057	$4,000	$25,000	$30,399,625	$1,101,435,682
2040	7,828	45379	$4,000	$25,000	$31,311,614	$1,134,478,752
2041	8,063	46741	$4,000	$25,000	$32,250,962	$1,168,513,115
2042	8,305	48143	$4,000	$25,000	$33,218,491	$1,203,568,509
2043	8,554	49587	$4,000	$25,000	$34,215,046	$1,239,675,564
2044	8,810	51075	$4,000	$25,000	$35,241,497	$1,276,865,831
2045	9,075	52607	$4,000	$25,000	$36,298,742	$1,315,171,806
	218,866	1268762			$875,463,635	$31,719,044,748

Following the revised views of Cohen, we assume that the average value of uncompensated environmental damages is somewhere between $10,000 and $20,000 per ton; we choose the midpoint, or $15,000. Based on court award data, we think it is unlikely that the maximum figure is larger than $30,000 per ton. Given these values, we projected the value of environmental damages likely to be avoided by substitution of double-hull tankers for single-hull tankers. These projections are displayed in *Table 20.*

4.5 Loss of Lives and Injuries

Double-hull designs require more periodic inspections, especially to void spaces, an increased risk of fire and explosion, greater instability for the tanker after an accident, and higher risks of sinking. These and other factors increase the hazard to personnel during normal operations [2]. There are no available data for estimating these effects, however.

4.6 Present Value of Benefits

Application of a 7% rate of discount (as in Chapter 4 for the calculation of the present value of costs) to the sum of the three types of benefits (oil saved, clean-up costs saved, and environmental damages avoided) results in the present value of total benefits displayed in *Table 21*. In this table, columns 2 and 3 are the sums of the three types of benefits from *Tables 18, 19, and 20.*

It should be emphasized that estimates of these benefits are quite uncertain, even in situations where all the impacts are known. Even more speculative are judgments about decreases in environmental impact due to design changes (from single-hull tankers to double-hull tankers). Pending a proven record of double-hull performance, however, we are reasonably confident that the true value lies within this range.

TABLE 20. VALUE OF ENVIRONMENTAL DAMAGE AVOIDED

Year	Expected Oil Saved		Environmental Damage Per Ton		Environmental Damage Avoided	
	Average	Maximum	Average	Maximum	Average	Maximum
1995	108	600	$15,000	$30,000	$1,620,000	$18,000,000
1996	213	1236	$15,000	$30,000	$3,198,150	$37,080,000
1997	329	1910	$15,000	$30,000	$4,941,142	$57,288,600
1998	452	2623	$15,000	$30,000	$6,785,835	$78,676,344
1999	582	3377	$15,000	$30,000	$8,736,762	$101,295,793
2000	720	4173	$15,000	$30,000	$10,798,638	$125,201,600
2001	865	5015	$15,000	$30,000	$12,976,363	$150,450,589
2002	1,018	5903	$15,000	$30,000	$15,275,033	$177,101,837
2003	1,180	6841	$15,000	$30,000	$17,699,945	$205,216,753
2004	1,350	7829	$15,000	$30,000	$20,256,604	$234,859,173
2005	1,530	8870	$15,000	$30,000	$22,950,732	$266,095,443
2006	1,719	9966	$15,000	$30,000	$25,788,277	$298,994,516
2007	1,918	11121	$15,000	$30,000	$28,775,419	$333,628,048
2008	2,128	12336	$15,000	$30,000	$31,918,580	$370,070,496
2009	2,348	13613	$15,000	$30,000	$35,224,433	$408,399,226
2010	2,580	14956	$15,000	$30,000	$38,699,911	$448,694,616
2011	2,823	16368	$15,000	$30,000	$42,352,215	$491,040,170
2012	3,079	17851	$15,000	$30,000	$46,188,827	$535,522,633
2013	3,348	19408	$15,000	$30,000	$50,217,519	$582,232,107
2014	3,630	21042	$15,000	$30,000	$54,446,363	$631,262,179
2015	3,739	21673	$15,000	$30,000	$56,079,754	$650,200,044
2016	3,851	22324	$15,000	$30,000	$57,762,146	$669,706,046
2017	3,966	22993	$15,000	$30,000	$59,495,011	$689,797,227
2018	4,085	23683	$15,000	$30,000	$61,279,861	$710,491,144
2019	4,208	24394	$15,000	$30,000	$63,118,257	$731,805,878
2020	4,334	25125	$15,000	$30,000	$65,011,805	$753,760,055
2021	4,464	25879	$15,000	$30,000	$66,962,159	$776,372,856
2022	4,598	26655	$15,000	$30,000	$68,971,024	$799,664,042
2023	4,736	27455	$15,000	$30,000	$71,040,154	$823,653,963
2024	4,878	28279	$15,000	$30,000	$73,171,359	$848,363,582
2025	5,024	29127	$15,000	$30,000	$75,366,500	$873,814,490
2026	5,175	30001	$15,000	$30,000	$77,627,495	$900,028,924
2027	5,330	30901	$15,000	$30,000	$79,956,320	$927,029,792
2028	5,490	31828	$15,000	$30,000	$82,355,009	$954,840,686
2029	5,655	32783	$15,000	$30,000	$84,825,659	$983,485,906
2030	5,825	33766	$15,000	$30,000	$87,370,429	$1,012,990,484
2031	5,999	34779	$15,000	$30,000	$89,991,542	$1,043,380,198
2032	6,179	35823	$15,000	$30,000	$92,691,288	$1,074,681,604
2033	6,365	36897	$15,000	$30,000	$95,472,027	$1,106,922,052
2034	6,556	38004	$15,000	$30,000	$98,336,188	$1,140,129,714
2035	6,752	39144	$15,000	$30,000	$101,286,273	$1,174,333,605
2036	6,955	40319	$15,000	$30,000	$104,324,862	$1,209,563,613
2037	7,164	41528	$15,000	$30,000	$107,454,607	$1,245,850,522
2038	7,379	42774	$15,000	$30,000	$110,678,246	$1,283,226,037
2039	7,600	44057	$15,000	$30,000	$113,998,593	$1,321,722,818
2040	7,828	45379	$15,000	$30,000	$117,418,551	$1,361,374,503
2041	8,063	46741	$15,000	$30,000	$120,941,107	$1,402,215,738
2042	8,305	48143	$15,000	$30,000	$124,569,341	$1,444,282,210
2043	8,554	49587	$15,000	$30,000	$128,306,421	$1,487,610,677
2044	8,810	51075	$15,000	$30,000	$132,155,613	$1,532,238,997
2045	9,075	52607	$15,000	$30,000	$136,120,282	$1,578,206,167
	218,866	1268762			$3,282,988,631	$38,062,853,698

TABLE 21. PRESENT VALUE OF BENEFITS FROM REPLACING SINGLE-HULL VESSELS WITH DOUBLE-HULL VESSELS

	Expected Value of Oil Saved		Values of Clean-Up Costs Saved		Environmental Damage Avoided		Total Benefits		PV of Total Benefits	
Year	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
1995	15,833	87,960	432,000	15,000,000	1,620,000	18,000,000	2,067,833	33,087,960	1,932,554	30,923,327
1996	31,257	181,198	852,840	30,900,000	3,198,150	37,080,000	4,082,247	68,161,198	3,565,592	59,534,630
1997	48,291	279,950	1,317,638	47,740,500	4,941,142	57,288,600	6,307,071	105,309,050	5,148,449	85,963,554
1998	66,320	384,465	1,809,556	65,563,620	6,785,835	78,676,344	8,661,711	144,624,429	6,607,978	110,333,284
1999	85,387	494,999	2,329,803	84,413,161	8,736,762	101,295,793	11,151,953	186,203,952	7,951,188	132,760,845
2000	105,539	611,818	2,879,637	104,334,667	10,798,638	125,201,600	13,783,813	230,148,085	9,184,737	153,357,387
2001	126,822	735,202	3,460,364	125,375,491	12,976,363	150,450,589	16,563,549	276,561,282	10,314,946	172,228,467
2002	149,288	865,438	4,073,342	147,584,864	15,275,033	177,101,837	19,497,664	325,552,138	11,347,818	189,474,308
2003	172,987	1,002,826	4,719,985	171,013,961	17,699,945	205,216,753	22,592,918	377,233,540	12,289,050	205,190,051
2004	197,975	1,147,678	5,401,761	195,715,978	20,256,604	234,859,173	25,856,339	431,722,829	13,144,052	219,465,995
2005	224,305	1,300,320	6,120,195	221,746,203	22,950,732	266,095,443	29,295,232	489,141,965	13,917,954	232,387,824
2006	252,037	1,461,087	6,876,874	249,162,097	25,788,277	298,994,516	32,917,188	549,617,699	14,615,625	244,036,832
2007	281,232	1,630,329	7,673,445	278,023,373	28,775,419	333,628,048	36,730,096	613,281,750	15,241,684	254,490,123
2008	311,951	1,808,411	8,511,621	308,392,080	31,918,580	370,070,496	40,742,153	680,270,987	15,800,509	263,820,817
2009	344,260	1,995,711	9,393,182	340,332,688	35,224,433	408,399,226	44,961,876	750,727,625	16,296,253	272,098,239
2010	378,227	2,192,621	10,319,976	373,912,180	38,699,911	448,694,616	49,398,114	824,799,417	16,732,850	279,388,099
2011	413,922	2,399,550	11,293,924	409,200,142	42,352,215	491,040,170	54,060,061	902,639,862	17,114,031	285,752,664
2012	451,419	2,616,921	12,317,021	446,268,861	46,188,827	535,522,633	58,957,266	984,408,414	17,443,328	291,250,929
2013	490,793	2,845,174	13,391,338	485,193,422	50,217,519	582,232,107	64,099,650	070,270,704	17,724,087	295,938,768
2014	532,122	3,084,768	14,519,030	526,051,816	54,446,363	631,262,179	69,497,516	1,160,398,763	17,959,479	299,869,091
2015	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	17,288,096	288,659.032
2016	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	16,157,099	269,774,796
2017	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	15,100,093	252,125,978
2018	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	14,112,236	235,631,755
2019	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	13,189,006	220,216,593
2020	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	12,326,174	205,809,900
2021	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	11,519,789	192,345,701
2022	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	10,766,157	179,762,337
2023	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	10,061,829	168,002,185
2024	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	9,403,579	157,011,387
2025	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	8,788,392	146,739,614
2026	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	8,213,450	137,139,827
2027	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	7,676,122	128,168,062
2028	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	7,173,945	119,783,236
2029	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	6,704,622	111,946,949
2030	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	6,266,002	104,623,317
2031	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	5,856,076	97,778,801
2032	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	5,472,969	91,382,057
2033	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	5,114,924	85,403,792

TABLE 21. CONTINUED

	Expected Value of Oil Saved		Values of Clean-Up Costs Saved		Environmental Damage Avoided		Total Benefits		PV of Total Benefits	
Year	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
2034	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	4,780,303	79,816,628
2035	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	4,467,573	74,594,979
2036	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	4,175,301	69,714,934
2037	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	3,902,151	65,154,144
2038	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	3,646,870	60,891,723
2039	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	3,408,290	56,908,152
2040	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	3,185,318	53,185,189
2041	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	2,976,932	49,705,784
2042	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	2,782,180	46,454,004
2043	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	2,600,168	43,414,957
2044	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	2,430,063	40,574,726
2045	548,086	3,177,311	14,954,601	541,833,370	56,079,754	650,200,044	71,582,441	1,195,210,726	2,271,087	37,920,305
	21,670,638	125,623,062	591,286,165	21,422,759,585	2,217,323,117	25,707,311,502			476,148,959	7,948,906,078

CHAPTER 5

DOUBLE-HULL TANKERS: THE SEARCH FOR MORE EFFECTIVE TECHNOLOGY

5.1 Background

OPA90 requires DH tankers. It is another example of the technology-forcing that has characterized U.S. environmental legislation. Technologies specified in such legislation are typically chosen on the basis of noneconomic criteria. Thus, it should not be surprising when technology fails a benefit-cost test, as clearly appears to be the case for DH tankers. Such a verdict does not exhaust the economists' contributions, however. Although OPA90 may impose net losses on society, there may be ways to reduce these losses. One option is to create an environment in which various parties affected by a technology requirement are not restricted from, and may even be encouraged to, a search for more cost-effective variations of the technology.

This option is more attractive, the larger the scope for alternative variations of the technology. In this chapter we review the research and development literature related to DH tankers to determine if there is significant scope for such variations. The review indicates that there is, suggesting some simple, yet powerful, guidelines for the further design of DH tanker technology.

5.2 History of Double-Hull Tanker Development

The double-hull concept for oil tankers is not a new idea. For example, double hulls and double bottoms for Exxon tankers (formerly Esso) were first investigated in the mid-1960s. At the 1973 International Convention for the Prevention of Pollution from Ships (ICPPS), the United States proposed double-bottomed tankers. However, the proposal was never given any serious consideration by ICPPS members [8].

After the *Amoco Cadiz* accident in 1978, which resulted in the spillage of 223,000 tons of oil (see *Table 4*), double hulls were considered as part of a protocol on marine pollution negotiated under the International Maritime Organization (IMO) [1]. The idea was rejected as being a less safe way to prevent spills. A careful rearrangement of ballast tanks, which involves placing these tanks in the parts of a ship most likely to be holed in an accident along with partial double bottoms, were believed to be much better safety measures. These safety measures have been introduced on all tankers built since 1979 [2]. However, since the average age of the tanker fleet is now nearly 13 years, relatively few vessels have them, including the *Exxon Valdez* [2].

Finland was the first country to take unilateral action to encourage the use of double-hull tankers [9]. In January of 1990, it imposed a charge of 2.20 markka (55 cents) a ton on oil delivered to its ports by tankers without double bottoms [9].

5.3 Alternative Designs of Double-Hull Tankers

A double-hull tanker is basically two skins of steel separated by a small space known as a cofferdam (see *Figure 6*). Within the normal hull envelope is a second inner hull creating a void, approximately 2 meters deep, on the bottom and on the sides. The area between the two hulls contains no oil; therefore, any damage that leaves the inner hull intact will result in no loss of oil. Regulations were also proposed for the modification of existing tankers (retrofits) to reduce the possibility of oil outflow resulting from a collision.

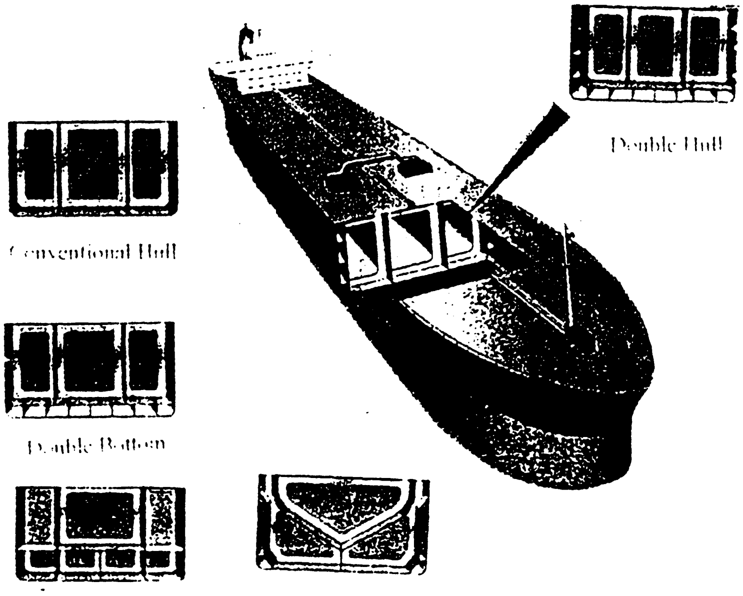


Figure 6. New Designs for Oil Tankers [8]

Double hulls are just one of many proposed methods for preventing oil spills and the environmental tragedies that follow; other modifications are also on the drawing board [8]. *Figure 6* gives a schematic illustration of several deign alternatives. For example, in the Coulombi Egg design, wing ballast tanks guard against side impact, while the mid-deck prevents most oil from leaking out if the bottom ruptures [8].

The International Maritime Organization (IMO) concluded that a mid-deck (or H-deck) design offers as much protection as a double hull [1, 8]. The mid-deck design, the Y-shaped Polmis (pollution minimization system), shown in *Figure 6*, divides the cargo tanks into separate upper and lower chambers. Ballast tanks along the sides provide some protection from collisions. In the event of bottom damage, the upward pressure from water beneath the tanker is greater than the downward pressure of oil in the lower chambers, so oil tends to stay inside the vessel [2].

The Coast Guard evaluated the two mid-deck variations, namely, the Polmis and the Coulombi Egg. As described above, the Polmis features a Y-shaped division that isolates the large center tank from the ship's bottom. Two large rescue tanks with the same shape rest between the cargo tanks [2]. Oil is pumped into these vacuum tanks in an emergency. The Coulombi Egg uses wing tanks with a width exceeding 20% of the vessel's beam, which is supposed to provide protection against collision, with the mid-deck guarding against damage from grounding [2].

Other concepts under consideration include hydrostatic loading, which involves lowering the tank levels until the pressure of the oil is less than that of the water outside the tanker [2]. If a rupture occurs, the incoming water will block oil leakage. The major drawback of this technique is that it reduces cargo capacity by 15% or more [2].

The Coast Guard study also evaluated another approach called an “underpressure system.” The theory behind the underpressure system is that if the tightly sealed tank ruptures, a small amount of oil may escape, hence creating a vacuum that keeps most of the oil from gushing out [2]. However, the concern here is that the system might cause tanks to collapse, thus creating a major oil spill. The Coast Guard agreed with the findings to this effect in the NRC report [2].

The most common types of tanker accidents in U.S. waters are caused by groundings. After studying all design alternatives, the Coast Guard concluded in its December, 1992, report that a double hull is still the best way to prevent oil spills [2].

5.4 Research and Development on Double-Hull Tankers

Since the passage of OPA90 by the United States Congress, research activities in the areas of structural design, response to collisions and groundings, and fatigue life of double-hull tankers have been intensified. Major research projects in double-hull technology have been carried out principally by the United States, Japan, Denmark, and Norway. The Association for Structural Improvement of Shipping Industry in Japan initiated a major seven-year research program aimed at the structural design of double-hull tankers and their potential for preventing oil spills [3]. Most of the research in the United States has been performed at the Massachusetts Institute of Technology (MIT), the Interagency Ship Structure Committee (ISSC), and the Society of Naval Architects and Marine Engineers [3]. The ISSC consists of agencies such as the American Bureau of Shipping, Defense Research Establishment Atlantic (Canada), Maritime Administration, Military Sealift Command, Naval Sea Systems Command, Transport Canada, and the United States Coast Guard (USCG) [3]. The committee's purpose is to pursue and fund research programs aimed at improving the hull structures of ships and other maritime carriers.

Results of the research activities in the countries mentioned above are usually reported at international meetings such as the *International Ship and Offshore Congress* and *the International Symposia on Practical Design of Ships and Mobile Units*. Some other results are also published in international journals and magazines.

The rest of this section reviews and summarizes some of the latest R&D developments in double-hull tanker design, response to collisions/groundings, reliability/producibility, dynamic load approach and fatigue strength, and economic analysis of oil spills and prevention.

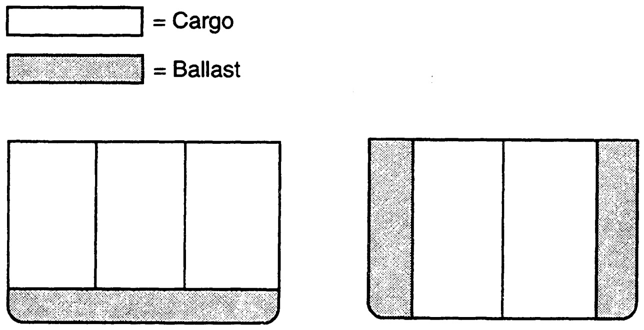
Studies of tanker design and prevention of oil spills carried out since the grounding of the *Exxon Valdez* have highlighted two main points [14]:

- No design is ideal in all circumstances.
- There has been insufficient research into structural and cargo behavior during and after an accident.

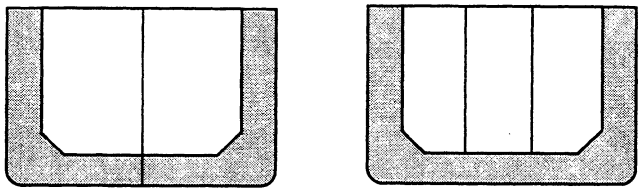
The size and arrangement of cargo tanks are significant factors in the design of double bottoms, double sides, and double hulls (the design proposed by the NRC report [2], and approved by the USCG as being the best design to reduce pollution risks). Each of these alternatives has advantages and disadvantages [2]. To clarify this point, *Figure 7* shows various configurations of tanks in double sides, double bottoms, and double hulls [14]. The shaded area shows the ballast. Most ships without double sides (illustration a of *Figure 7*) will have three tanks across because of the penetration rule (side damage is assumed to extend transversely to 1/5 of the beam or breath of the ship, i.e., total width/5) [2]. Double-sided ships (illustration b) can be more flexible in tank arrangement as long as stability remains sufficient with a penetrated cargo tank side [2]. The common double-hull (L tank shown in illustration c) arrangement has the disadvantage of potentially large off-center weights if damaged [2]. The U-tank arrangement shown in illustration d avoids this large off-center problem, but the disadvantage here is that the total added weight in most damaged cases is doubled. The U-tanks also can have a large free surface, which could create some problems when loading and unloading oil [2].

Separating the side and bottom ballast tanks could reduce the amount of oil off-center and the total added weight for most damage scenarios. This can be achieved in a double-bottom, double-side arrangement (illustration e), and a double-side, double-bottom arrangement (illustration f). The NRC report [2] concluded that a double-bottom, double-side arrangement (e) is more resistant to grounding damage while a double-side, double-bottom arrangement (f) is more resistant to collision damage.

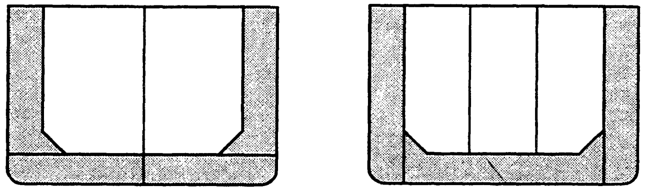
The NRC report [2] has also described another tank arrangement, the intermediate oil-tight deck (IOTD), as receiving considerable attention. The cargo section is divided by a deck or a flat (horizontal bulkhead) where oil is carried in both upper and lower chambers. This is essentially a double bottom that is loaded with oil [2]. This tank arrangement reduces the volume of oil exposed to a bottom rupture, in addition to having a hydrostatic advantage over the conventional MARPOL single-hull tankers [2].



a. Double bottom b. Double sides



c. Double hull "L"arrangement c. Double hull "U"arrangement



e. Double bottom, double side f. Double side, double bottom

Figure 7. Tanker Ballast Tank Arrangement [14]

The structural design procedures for double-hull tankers, and some specific features, were reviewed and compared with conventional single-hull tankers by Niho, Yanagibayashi, and Akashi [18]. This study concluded that the structural design of the double-hull VLCC (very large crude oil carrier) requires two inner longitudinal bulkheads in addition to side double hulls in order to provide the needed high shear force of hull girder and long span of horizontal girders on the transverse bulkhead [18]. The ultimate longitudinal strength of a hull girder was analyzed through a simplified method under both sagging and hogging conditions. Their results show that sagging conditions give lower ultimate bending moment than hogging conditions due to buckling of a single upper deck [18]. This study also looked at the quality and strength of steels needed for the construction of VLCC. They found that high tensile steel with yield strength designations of HT36 and HT32 would be more appropriate than HT40 due to buckling effects [18]. Other design factors reviewed in this study include fatigue strength, corrosion, and reliability analysis [18].

A new double-hull tanker of 90,000 DWT, with a transverseless structural system, that satisfies the requirements of the U.S. OPA90, was developed by Paik et al. [19]. The design philosophy focused on oil pollution prevention by adopting a double-hull arrangement, and producibility due to mechanized fabrication with the help of quite simple structures, taking into account a transverseless system. To evaluate the structural safety of the hull in both the intact and damaged conditions, deterministic and probabilistic approaches were employed on the basis of ultimate hull girder strength [19]. In this case, the mean and coefficient of variation (COV) of both loads and strengths should be known. The mean of extreme vertical bending moment is estimated by direct calculation methods and the COV values are assumed based on existing data. The mean of ultimate hull girder strength is analyzed by using the idealized structural unit method and the COV is estimated by sensitivity analysis with variation in the individual parameters affecting ultimate hull girder strength. Then, a safety assessment of the hull girder in the intact and damaged conditions is carried out based on both deterministic and probabilistic measures of safety. It was concluded that the present hull girder has relatively sufficient safety with respect to applied bending moments in the damaged as well as the intact conditions [19].

A wide range of strength analyses and various experiments using structural models developed at Kawasaki Heavy Industries and applied to the structural design of a new

280,000 DWT double-hull VLCC were discussed in a paper by Taniguchi et al. [20]. The study observed that connections between longitudinal and transverse webs in a ship structure have been weak points in the fatigue strength and bottlenecks in construction. The authors have developed a new slot structure KAWASAKI APPLE SLOT that can ensure structural safety and constructional convenience [20]. The new slot structure has no connections between longitudinals and stiffeners on the transverse web which are hard spots in the conventional slot structure, having special-shaped slots (apple shape) suitable for stress relaxation to compensate for the elimination of stiffeners on the transverse web [20]. This study also performed static strength analysis using finite element calculations, carried out fatigue strength tests using scale models, and evaluated fatigue strength and buckling effects of an actual ship [20]. All tests and analyses verified that the new slot structure can be applied to actual VLCC structures [20].

The procedures and results of a Dynamic Load Approach (DLA) were applied to a recently designed 280,000 DWT VLCC double-hull tanker by Kawachi, Shigematxu, and Kushima [21]. This is the first tanker to be classed with a DLA notation. DLA notation is recently offered by the American Bureau of Shipping as a new class notation because dynamic loads acting on ship structures are more exactly computed by ship motion analysis and are applied in a more precise finite element analysis. The dynamic loads are calculated in ship loading conditions close to the actual ship operation and in the most severe waves possibly encountered in a ship's life [21]. In the DLA, corresponding reduction of scantlings is not permitted; hence the increase of scantlings by DLA can be expected to give a more rational safety margin and higher reliability of the hull strength [21].

Zosen reported that it has successfully constructed and delivered the first double hull VLCC of 290,000-ton deadweight (DWT) [22]. Their published paper introduced the design features that were specially considered in the design of double-hull VLCCs such as tank and structural arrangements and provisions for safety and easy maintenance

[22]. In addition, the paper described the construction procedure that achieved high productivity in the advanced facilities of the Ariake shipyard by [22].

The development of new steels for use in shipbuilding was discussed by Dexter et al. [23]. The use of high-strength low-alloy thin-steel plate in a double-hull configuration led to differences relative to traditional ship construction in manufacturing sequence, welding, and failure modes. Welded joint designs and welding parameters were investigated. Experiments on large-scale beam sections determined the effect of new materials on fatigue strength and added to the existing database information on the effect of structural configuration, loading parameters, residual stresses, and welding defects [23]. Preliminary fatigue data for longitudinal fillet welds were described in this study along with analytical and experimental studies in plate instability, beam-column instability, and cellular grillage instability [23].

A cellular ship structure consisting of inner and outer hulls connected by longitudinal web members has been developed at the Naval Surface Warfare Center, Bethesda, Maryland, by Sikora et al. [24]. Celluar structures have such inherent strength that transverse web frames on conventionally framed ships become unnecessary. The elimination of transverse structures has many potential benefits for fabrication (fewer pieces and simpler structural details) and life cycle costs (fewer crack initiation sites). However, the structural behavior of such ships is markedly different from conventional ones so that new design methods are required [24]. Because the designing processes of advanced double hull tankers are still in the learning stage, the structural behavior of these vessels is not completely understood. Classical approaches for stress analysis cannot be used. This paper developed design methods for double-hull, no-frame ships and provided validations of structural behavior through numerical and experimental studies [24]. Further validation is needed to increase confidence levels of producibility benefits and structural reliability; hence future work is planned to include large-scale models for buckling tests, fatigue tests, grounding-resistance tests, and corrosion control [24].

A study by Garside, Horn, and Kotte [25] reviewed the structural integrity verification approach required for double-hulled tankers, considering both the basic stress response to extreme seas and fatigue life aspects [25]. While a conventional rules-type approach can be employed for the determination of local scantlings, an overall demand and capability assessment is preferred for the hull girder response. The design analysis approach for double hulled tankers is similar to that for conventional tankers; however, the more complex cargo and ballast tankage arrangements which can occur in double-hulled vessels adds to the analytical complexity [25]. This study concluded with a review of some of the fundamental response differences between double-hulled and more conventional tanker designs [25]. In order to produce an efficient steelwork design, including the avoidance of fatigue, it is anticipated that the double-hull design will require more analytical effort compared with conventional and double-bottom designs [25].

A joint MIT-industry program was carried out to study tanker safety by providing experimental force data for the cutting by a wedge of advanced double hull (ADH) small-scale models [26]. A total of six cutting experiments were performed with six different wedge geometries. Complex deformation patterns observed in the damaged specimens were simplified to obtain a closed-form upper bound for the steady-state cutting force. A theoretical expression for the steady-state cutting force of a simplified kinematic model of the ADH specimen was formulated using an upper-bound approach [26]. The ADH steady-state cutting force solution varied from 6% above to 12% below the experimental mean steady-state force [26].

A method for analysis of structural damage due to ship collisions was developed by Jeom and Pedersen [27] to understand the mechanism of deformation and reduce the cargo spillage. This method was based on the idealized structural unit method (ISUM). Longitudinal/transverse webs that connect the outer and inner hulls were modeled by rectangular plate units [27]. The responses to collisions were determined by taking into account yielding, crushing, and rupture. Some plates of the outer and inner shells subjected to large membrane tensions were modeled by membrane tension triangular/ rectangular plate units, while the remaining shell panels were modeled by usual plate units [27]. The effect of stiffeners on unit stiffness and strength was considered as well. The nonlinear finite-element technique was applied to include coupling effects between local and global failure of the structure. In order to deal with gap and contact conditions between the striking and struck ships, gap/contact elements were employed [27]. Dynamic effects were considered by inclusion of the influence of strain-rate sensitivity in the material model. On the basis of the theory, a computer program was developed, and the procedure was verified by a comparison of experimental results obtained from test models of double-skin plated structures in collision/grounding situations with the present solutions [27]. As an illustrative example the procedure was used for analysis of a side collision of a double-hull tanker. Several factors affecting the ship collision response—namely collision speed and scantlings/arrangements of strength members—were also discussed in this study [27].

A full-scale prototype double-hull module was fabricated as part of the U.S. Navy's interest in studying the use of double-hull designs in high-strength, low-alloy (HSLA) steels for surface combatant ships by Pang et al. [28]. Multicellular box column specimens were cut for compressive tests to failure. Initial imperfections (in-plate deflections and welding residual stresses) were found to affect stiffness and strength of welded members. Their paper described measurement of these imperfections and analysis of their effects on component plates of the cellular box specimens [28]. Initial deflections were measured in the laboratory where maximum values did not exceed the Navy's guidelines or proposed values of several researchers. Residual stresses in a box specimen were also measured in the laboratory under more controlled conditions. Using measured imperfections, plate arrangements were analyzed using the finite element method. The imperfections were found to reduce stiffness and strength of the plates [28]. The results show that for accurate prediction of strength of welded plates, initial imperfections must be taken into account [28].

The results of the "Safe Hull" rule restatement phase of the ABS RULES 2000 project, undertaken by the American Bureau of Shipping (ABS) to develop structural criteria for double-hull tankers based on a first-principles approach, were reported by

Chen et al. [29]. The paper first discussed philosophical concepts and loading cases, followed by a strength assessment with respect to the dominant failure modes [29]. The load components considered in the load criteria consist of still water and cargo loading, internal hydrostatic and dynamic tank cargo loading, as well as sloshing load. The dominant failure modes were found to include yielding, bulking, and fatigue. Strength requirements developed in the Safe Hull System focused on both initial design and design evaluation. Comparisons of the newly developed requirements with service experience were also given to illustrate the applications of the criteria [29].

The mechanics of, and the raking damage estimates from the grounding of double-hull tankers, were proposed by Paik and Lee [30]. The accuracy and applicability of the model were verified by a comparison with experimental results. The progressive collapse analysis of damaged hull sections, under vertical bending moments by use of the ALPS/ISUM computer code, was also described [30]. The procedure was applied to the grounding simulation of a double-hull tanker with a transverseless system [30]. Their conclusions can be summarized as follows:

- In grounding situations, the double bottom is more effective for reducing the raking damage than the single bottom. This is due to the increase of the equivalent plate thickness, which is one of the most significant contributing factors to cutting-damage resistance.
- The transverse bottom frames/floors and longitudinal bottom girders/stiffness contribute to the increase in grounding damage resistance.
- After the ship hull has suffered serous bottom damage as a result of grounding, the residual strength of the hull may decrease. In addition, the applied load may increase due to variations of tides and waves. Therefore, the possibility of hull girder breakage will be very high, particularly in a hogging condition.

Two models have been developed by Weirzbicki, Peer, and Rady to estimate the extent of bottom damage for longitudinally stiffened tankers involved in grounding accidents [31]. A more exact analytical model can predict the longitudinal and lateral extent of damage given the height of the obstacle, dimensions of the internal members of the hull girder, and global parameters of the ship such as mass, principal dimensions, and impacting velocity. A tearing model uses the concept of an equivalent thickness shell for a less exact representation of grounding [31]. It requires different input parameters, particularly the obstacle height-to-width ratio, and can only predict the longitudinal extent of damage. Four important failure modes have been identified in this study [31]:

- plastic stretching and rupture of hull plating
- bending and twisting of longitudinal stiffeners
- detachment of stiffeners from the bottom
- crushing of transverse web-frames and bulkheads.

This study concluded that grounding is a very complex problem. The most probable failure sequence, developed for a typical VLCC, however, provided information on how to avoid or reduce the occurrence of hull rupture. Excessively stiff transverse frames represent hard points that can start or help reinitiate hull rupture. A more uniform crushing strength provided by mixed framing, a boxed structure, or a double hull with a uniform crushable core would delay fracture initiation. It would also dissipate energy without hull rupture through friction and crushing of the bottom structure [31].

The ASCE Tank Committee on Modeling of Oil Spills of the Water Resources Engineering Division reviewed the state of the art of modeling oil spills and the components that form the models [32]. Their review addressed the following issues: needs and model uses, components forming a model, oil spill processes, real-time simulation experience, and demonstration of the state-of-the-art in simulation [32]. Both short- and long-term oil spill processes were identified. The physics of oil spill processes were described and the shortcomings of the present understanding were identified. Available oil spill models (state-of-the-art 2D and 3D) were also reviewed and were found to be useful in contingency planning and spill control during emergencies [32]. Three-dimensional models provide more detailed simulations, especially in the water column. This additional information is useful for environmental impact assessment and critical for predicting the behavior of rapidly dispersed oils or accidents that occur under water.

Two-dimensional models execute faster, although they lack some of the details provided by the 3D models [32]. The level of modeling activity is high, and available models present a very high-level implementation of the process algorithms. Also, significant activity is taking place in terms of integrating some of the high-tech features such as coupling of models to real-time data. While this is a step forward and improves the quality of simulations, this field needs further research into the physics of fundamental oil spill processes to achieve significant improvements in model quality [32].

The procedure of fatigue analysis, as part of the "Dynamic Load Approach (DLA)," was applied to a 280,000 dwt double-hull VLCC by Kawachi et al. [33]. This type of oil carrier is classed with DLA notation by the American Bureau of Shipping. A fatigue analysis of the 280,000 DWT double hull VLCC provided the following conclusions:

- The spectral fatigue analysis can give more reliable and precise results for fatigue life evaluation and predictions compared with conventional simplified methods.
- It is confirmed that the double-hull VLCC has sufficient fatigue strength after a soft toe is provided, or the configuration of the bracket toe is changed to a more softened shape at the connection between longitudinal and transverse primary members.

In the spectral fatigue analysis introduced in this paper [33], the procedure to obtain stress transfer functions (STF) was simplified; that is, stress analysis was performed on only a specified wave frequency and a stress transfer function was constructed following the shape of a vertical wave that induced a bending-moment response function. The study concluded that more precise results can be achieved if the dominant dynamic loads affecting fatigue strength, to be used in construction of a stress transfer function for each structural member, are identified [33].

A progressive collapse analysis was done by Kawachi et al. on the cross section of an existing double hull VLCC, applying a simple method of analysis, to assess the longitudinal strength of double-hull tankers [34]. The results of the analysis indicate that:

- Under the sagging condition, the ultimate longitudinal strength is attained soon after the deck collapses by buckling.
- Under the hogging condition, the initial collapse takes place at the deck by yielding. This is followed by buckling at the bottom plating and then at the inner plating, and the ultimate longitudinal strength is attained.

5.5 Safety Factors

The structural arrangement of the double-side and double-bottom tanks of double-hull tankers is usually cellular. Safe access to these spaces is essential to monitor ballast tanks, conduct surveys required by classification societies, and maintain ballast piping. In addition, access may be needed to rescue injured people from a double-bottom in the event of an accident. Some operators reported that access to double-hull spaces was very difficult, escape distances in an emergency situation were very long, and design complexity require ship personnel to have good knowledge of tank configuration before entering [3].

Proper ventilation of cellular double-hull spaces is another important factor to consider. Even after forced ventilation, these spaces might contain pockets lacking oxygen or, in case of oil leakage, pockets of flammable gases could cause fire and explosion.

The influence of corrosion damage on ultimate longitudinal strength was also examined, assuming a thickness reduction and failure of fillet weld. Some considerations were also made from a design aspect, including a comparison of collapse behavior between double- and single-hull tankers of the same size, and a safety assessment of a ship's hull by comparing the calculated ultimate strength with the design bending moment [34].

To quantify the regional economic impact of an environmental accident, an approach of coupling an environmental model to I-O analysis was carried out by Heen, Knut, and Andersen [35]. The model was implemented with data of a potential oil spill interacting with the salmon aquaculture industry in northern Norway. The production loss in salmon aquaculture and the regional income impact were computed and discussed.

A social planner's problem, using an optimal control theory to examine the relative cost effectiveness of double hulls and alternative pollution prevention technologies and the optimal installation strategy for such technologies, was developed by Jin et al. [36]. The model encompassed costs and benefits associated with shipping operations, damage to the marine environment, and investment in each technology [36]. A computer simulation of the model was used to evaluate investment strategies for two technological options: double hulls and electronic chart systems. Results indicate that electronic charts may be a far more cost-effective approach to marine pollution control [36].

Recently calculated rates were presented for tanker spills occurring during transport of Alaskan North Slope (ANS) crude oil after offloading from the Trans-Alaska Pipeline at Valdez [37]. These rates were used in environmental analyses of risks associated with the recently legislated exporting of ANS oil to the Far East. The use of spill statistics for such analyses was described, along with major assumptions and limitations of the methodology [37]. This study is part of the U.S. Minerals Management Service efforts in maintaining statistics on the frequency of offshore oil spills associated with platforms, pipelines, and tanker traffic [37]. This study showed that oil-spill occurrence rates have decreased slightly for U.S. offshore platforms, increased for U.S. offshore pipelines, and remained about the same for worldwide tankers (comparing rates calculated through 1992 to rates calculated through the mid-1980s) [37]

5.6 Modeling and Simulation of Tanker Accidents

The collision resistance of a 290,000-dwt double-hulled tanker designed by NKK was examined quantitatively using an analytical method developed by the same company [17]. The mid-ship section had a 3.74 m double-hull depth. A cement carrier with a displacement of 11,000 tons was chosen as the colliding ship [17]. Assumptions made for this test and the subsequent analysis are:

1. The stern of the striking ship is rigid.
2. One ship collides against the other ship at a right angle.
3. The behavior of structures is sufficiently slow to be treated statically.

The analysis demonstrated that the collision resistance of a double-hull tanker is much higher than that of a conventional single-hull tanker. The depth of the double hull contributed significantly to the energy absorption capacity of the ship's side structure before leaking oil [17].

In the case of an accident, fluid flow (oil and exchanged water) within a double-hull tanker is very difficult to understand and predict. Predominant factors include gravity forces, viscous and turbulent forces, complex geometries, free spaces between hulls, and instantaneous oil/water exchange that occurs immediately after the rupture. Other factors include the effects of a ship's forward speed, current, and tide or sea state. Researchers employ scale models and accident scenarios to understand these complex phenomena and predict the outflow of oil so that new designs may be used to incorporate more safety measures to avoid oil spills in real situations.

Karafiath and Bell [10] and Karafiath [11] conducted physical model scale oil outflow experiments on mid-deck and double-hull tanker configurations. The scale model used in this study had a 1/30 ratio of a 280,000 dwt VLCC. The results of their experiments indicated that in the event of both the inner and outer hulls rupturing, the double hull could retain a significant amount of its cargo. The results of this work also suggested that it may be possible to design the void structures between the inner and outer hulls such that the instantaneous oil loss due to grounding can be minimized.

To further understand the hydrodynamics of oil-water outflow from double-hull tankers as a result of an accident, numerical calculations were performed on two models by Chang and Lin [12]:

1. A 1/30-scale model of a 280,000-dwt VLCC was used that had ruptures in the inner and outer hulls created by a cylindrical obstacle. This scale model is similar to the one used in previous studies [10, 11]. It assumes a compartmentalized cargo tank and excess capacity in the double-hull spaces (U-tank).

2. A full scale, 40,000 dwt Advanced Double Hull (ADH) was ruptured by a 45° conical obstacle.

The purpose of the 1/30-scale model calculations was to assess how well the results would compare with experiments and to learn the physics of outflows from double hull tankers. The calculations performed on the ADH were to obtain results for an ADH design with an accident scenario that came close to those simulated in the experiments of previous studies [12].

The cylindrical obstacle created 20% damage to the tank width of the 1/30-scale model, while the 45° conical obstacle created a rupture in the inner hull of the full-scale model, which measured 3.6% of its width [12]. The two-dimensional oil outflows computed for both cases considered only instantaneous oil exchanges and did not consider additional complexities of forward speed, tide, or sea state. The flow of oil from the two case scenarios was found to be very different and highlights the various physical processes that occur in oil outflows from double-hull tankers [12]. For example:

- The geometry of the inner and outer ruptures was found to be very important. If the water and oil jets are coincident, the oil has a very good chance of remaining in the U-tank. If the jets are not coincident, the oil can flow unimpeded out of the ship. However, if the accident occurs in shallow waters, the oil may bounce off the bottom and enter the U-tank.
- Increasing the flow resistance of the U-tank longitudinal web frames increased the amount of oil retained in the U-tank. It forced the water layer in the U-tank to remain stationary beneath the inner hull rupture. When a vertical resonance was set up in the cargo tank, the frequency was found to be a function of the tank volume and the amplitude seemed to depend on the dynamics of the U-tank, and the size of the inner hull rupture.
- The first “suction” event that occurs due to the cargo tank resonance is important for drawing water into the cargo tank and U-tank. This water layer is important for reducing further ejection of oil. The volume of the cargo tank with respect to the U-tank is an important factor in the volume of oil that is retained.

- It is not possible to recommend an optimal interior geometry of the U-tank for oil retention. However, further calculations may clarify this issue.

The authors [12] considered very few variables in their calculation of the oil outflow and, therefore, further studies are needed to correctly simulate actual events. Factors such as the effect of forward speed, the modeling of interior geometry, the effect of cargo tank size, compartmentalization, and other rupture scenarios must be included in the modeling and simulation of actual events.

The International Maritime Organization (IMO) sponsored oil spill model tests at the David Taylor Model Basin at the Carderock Division, Naval Surface Warfare Center [13]. The tests were carried out to investigate the fluid dynamics of accidental oil spills due to grounding of Mid-Deck Tanker (MDT) designs and Double-Hull Tanker (DHT) designs. The model tests were performed in the Circulating Water Channel facility, a hydraulic analogue of a wind tunnel, capable of a variety of flow visualization and flow measurement experiments [13].

The models used in [13] represented a length of hull and a complete interior cargo tank and were built of clear Plexiglas to a scale of 1/36 for both the MDT and the DHT. Both models represented 280,000-ton ship designs. However, the MDT model represented a 39-meter long cargo tank design and the DHT represented a 50.7-meter long cargo tank design. Metal "bow" and "stern" fairings were used to guide the flow over the models [13].

Model tests at the David Taylor Model Basin provided accidental oil spillage data that was used in another study, sponsored by the U.S. Coast Guard, to assess the probabilistic oil outflow from MDT and DHT designs [13].

The summary of this assessment was that the MDT design would spill oil when its single skin was ruptured, but that it would spill less oil than a DHT design in a severe accident scenario that breaches the DHT double bottom. A reexamination of the limited DHT model test data suggested that with a careful arrangement of the double-hull voids the oil loss in a severe accident scenario might be mitigated [13]. The double-hull model testing work indicated a great sensitivity in the oil loss as a function of internal double-hull arrangement (J-tank versus U-tank) and of the assumed accident scenario.

The limited double-hull model test data indicated that the oil outflow from the double hull under extreme accident scenarios may be significantly reduced by careful attention to the internal subdivision and structural details of the double-hull spaces [13]. Additional research and development was recommended to identify the effect of various internal double hull design features on the oil outflow performance of double hull designs [13].

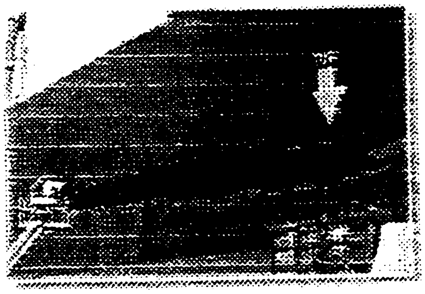
The study also recommended that further work should proceed to provide some design guidance with respect to the best arrangements of double hull tankers to minimize their oil loss in case of severe accident scenarios [13]. Such work would involve the testing of large size double hull models for which the internal structural details (longitudinal, transverse structures, lightening holes, bilge radius, tank corners, etc.) can be more meaningfully detailed. Rupture testing should be performed at real speed [13].

However, based on these studies, the Coast Guard concluded that at this time there are no alternative designs as effective as the double-hull tanker for prevention of oil outflow due to groundings, which is the most prevalent type of casualty in U.S. waters [13].

5.7 Double-Hull Tanker Safety: An Actual Test

The first test of double hull tankers came when a Conoco tanker was credited with preventing a major oil spill in southwest Louisiana because of its double-hulled design. The Conoco tanker named *The Guardian* sustained a 100-foot-by-4-foot gash during an October 31, 1997, collision with a tug-and-barge flotilla on the Calcasieu River near Lake Charles, Louisiana (see *Figure 8*). However, the 800-foot *Guardian* did not discharge any of its cargo of 550,000 barrels of crude oil, because of the ship's outer protective hull.

Coast Guard officials concluded that the collision would have created a major environmental incident had *The Guardian* not been a double-hulled vessel. Instead, the tanker safely discharged its cargo at Conoco's Clifton Ridge terminal and sailed to a Mobile, Alabama, facility for repairs. *The Guardian* resumed operations in November, 1997 [43].



A 100-foot-by-4-foot gash was sustained in the Guardian's outer hull

Figure 8. *The Guardian* Double-Hull Tanker Sustained a Major Gash to Its Outer Hull

5.8 Conclusions

The structural integrity of double-hull tankers, their safety, and possible prevention of oil spills have been the subject of many studies and programs. However, most of these studies have been done on laboratory models using 3-D models and computer simulations. Very few large double-hull tankers were built before the passage of OPA90 and, therefore, their track record had not been established and tested rigorously. It is evident from this literature review that research and development on double-hull technology is still in the learning stage. Issues such as oil outflow and ship stability characteristics remain of great concern. Intact stability, which has not been a major concern for single-hull tank operators, has become a concern in the operation of some double-hull tankers [3].

History suggests that industrial products such as moving equipment and automobiles take anywhere from 15 to 20 years of constant research and development before they can be introduced into the marketplace for public use. During this R&D period, design standards and industry guidelines are established, and all or most engineering and safety problems are solved. The double-hull technology is no exception. A new design, such as the double-hull in question, needs to take its course of R&D and rigorous testing before these new designs are fully ready for the marketplace.

OPA90 is an example of technology forcing by Congress—similar to the technology forcing that has marked other major environmental legislation in this country. Many studies by economists have concluded that technology forcing stifles the search for alternative, more cost-effective solutions. Fortunately, he regulatory authorities have resisted detailed specification of materials and design of DH ships. The results of this survey clearly indicate that the search for the optimal DH tanker is far from complete. In fact, if the authorities are concerned about minimizing the cost of OPA90 they should encourage further research and development in this area.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

The purposes of this chapter are to: (1) present estimates of the present value of net benefits, (2) examine the sensitivity of these estimates to different values for certain critical parameters, (3) offer a few policy options suggested by this study, and (4) suggest important items on the agenda for future research.

6.1 Present Value of Net Benefits

Based on the data presented in Chapters 3 and 4 for costs and benefits of double-hull tankers, a cost-benefit analysis may now be carried out for a 50-year time horizon. As a reminder, a 7% discount rate was used to calculate a present value for these streams of costs and benefits.

6.1.1 Benchmark Scenarios

6.1.1.1 Average Spill Case. Comparing the present value of total costs (as calculated in Chapter 3) and the present value of total benefits (as calculated in Chapter 4) for the average case and calculating the net present value, we find that the benefits of double-hulls are less than the costs. That is:

PVNB = PVB – PVC

PVNB = \$4.7 billion – \$5.3 billion = < 0.

6.1.1.2 Maximum Spill Case. Comparing the present value of total costs (as calculated in Chapter 3) and the present value of total benefits (as calculated in Chapter 4) for the maximum case and calculating the net present value, we find that the benefits are higher than the costs. That is:

PVNB = PVB – PBC

PVNB = $7.9 billion – $5.3 billion = > 0.

6.1.2 Alternative Scenarios

The benchmark scenarios are not the only possible outcomes. There are at least seven critical parameters, and different combinations of these parameters could yield different results. Thus, some sensitivity analysis is in order. The seven critical parameters are: spill size, annual increase in spill size, double-hull effectiveness, clean-up cost per ton, environmental damage per ton, real price of oil per ton, and discount rate. *Table 22* illustrates how different combinations of the first five parameters affect the PVNB. The real price of oil is assumed to be constant at $146.60 per ton and the discount rate remains at 7%.

TABLE 22. PRESENT VALUE OF NET BENEFITS
FOR ALTERNATIVE PARAMETER VALUES

Scenario	Spill Size		Annual Increase in Spill		Annual Decrease in Spill	Double-Hull Effectiveness		Clean-Up Cost Per Ton		Environmental Damage Per Ton		PVNB
	Avg	Max	3%	0%	3%	23%	30%	$4K	$25K	$15K	$30K	
1	x		x		x	x		x		x		< 0
2		x	x		x		x		x		x	> 0
3	x		x		x		x		x		x	< 0
4		x	x		x	x		x		x		< 0
5	x			x	x		x		x		x	< 0
6		x		x	x		x		x		x	< 0
7	x				x							< 0
8		x			x							< 0

6.1.2.1 Scenario 1 (Average Spill Case). As indicated above, with an average spill size, a 3% annual increase in volume spill, a 23% effectiveness of double-hull tankers in reducing spills, a lower-bound clean-up cost of $4,000, and lower-bound environmental damage of $15,000 per ton, the present value of net benefits is less than zero (PVNB <0)

6.1.2.2 Scenario 2 (Maximum Spill Case). Also as indicated above, with a maximum spill size, a 3% annual increase in spill volume, a 30% double-hull effectiveness, an upper-bound clean-up cost of $25,000 per ton, and an upper-bound environmental damage of $30,000 per ton, the present value of net benefits is greater than zero (PVNB >0).

6.1.2.3 Scenario 3. This scenario matches average spill size with maximum values for the other parameters. Given an average spill size, a 3% annual increase in spill volume, a 30% double-hull effectiveness, an upper-bound clean-up cost of $25,000, and an upper-bound environmental damage of $30,000 per ton; the present value of net bene-fits is less than zero (PVNB < 0).

6.1.2.4 Scenario 4. This scenario matches maximum spill size with average values for other parameters. Given a maximum spill size, a 3% annual increase in spill, a 23% double-hull effectiveness, a lower-bound clean-up cost of $4,000, and a lower-bound environmental damage of $15,000 per ton, the present value of net benefits is less than zero (PVNB < 0).

6.1.2.5 Scenario 5. This scenario matches average parameters with a 0% annual growth in spill size. Given an average spill size, with a 0% annual increase in spill, a 30% double-hull effectiveness, an upper-bound clean-up cost of $25,000, and environmental damage per ton of $30,000; the present value of net benefits is less than zero (PVNB < 0).

6.1.2.6 Scenario 6. This scenario matches maximum parameters with a 0% annual growth in spill size. Given a maximum spill size, with a 0% annual increase in spill, a 30% double-hull effectiveness, an upper-bound clean-up cost of $25,000, and a maximum environmental damage per ton of $30,000, the present value of net benefits is less than zero (PVNB < 0).

The results in the PVNB column strongly indicate that PVNB > 0 requires a maximum spill coupled with maximum values for other critical parameters, including a rate of increase in spill size greater than 2% per year. There is strong reason to believe that such a scenario is highly unlikely. First, this scenario probably requires at least one major spill every year of the 50-year horizon. Second, this scenario requires continuous growth in the average oil spill size. Both of these requirements seem unlikely and they are certainly inconsistent with the history of oil spills since the passage of OPA90. In fact, statistics covering the period, 1990-1995, show a decline in the quantity of oil spilled in U.S. waters and no spills greater than a million gallons. Indeed, there is a general perception within the maritime community that the quality of tankers operating in U.S. waters has improved greatly in recent years and that such improvement may have little to do with OPA 90. Among the possible explanations are: (1) increased awareness of the financial consequences of oil spills, spurred by costs and court awards associated with the *Exxon Valdez* accident; (2) actions by port states to ensure the safety of tankers using their ports; (3) increased efforts by classification societies to ensure that tankers meet or exceed existing requirements; and (4) improved audits and inspections by charterers and terminals.

Our calculations indicate, in fact, that the quantity of oil spilled has trended downward at an annual average rate of about 3% since 1980. Thus, we have also estimated two additional scenarios incorporating this assumption.

6.1.2.7 Scenario 7. This scenario matches average parameters with a 3% annual decrease in spill size. The present value of net benefits in this case is clearly less than zero (PVNB < 0).

6.1.2.8 Scenario 8. This scenario matches maximum parameters with a 3% annual decrease in spill size. The present value of net benefits in this case is also less than zero (PVNB < 0).

It is hard to escape the conclusion that OPA90 is a source of net social losses. In this respect, it is quite similar in kind to the technology forcing that has created net economic losses for so many other U.S. environmental regulations. Without a change in the law, it is unlikely that net losses can be avoided.

6.2 Policy Implications

One major source of net losses from OPA90 is its geographic scope. OPA90's double-hull requirement applies to all U.S. waters; i.e., double-hull vessels are required in all coastal areas, even in those that are not likely to be associated with significant risk of major spill or major environmental consequences. This makes about as much sense as it does to require catalytic converters on cars in both New York City and rural Oklahoma. Congress could probably reduce economic losses if it restricted the application of the double-hull requirement to areas that meet certain critical criteria of extreme environmental sensitivity or high likelihood of grounding. This may mean confining the double-hull requirement to shallow coastal waters—e.g., the Gulf of Mexico and Chesapeake Bay.

The results of Chapter 5 indicate that there is still much to be learned about the economics of double-hull design and that we have not yet exhausted the possibilities for finding lower-cost designs. Congress should avoid placing further restrictions on double-hull design or otherwise stifling the search for lower-cost design at this stage in the evolution of the concept. In fact, Congress should provide public support for research on double-hull design since more effective double-hull designs clearly have social benefits that exceed the extra profits or private benefits of more effective designs.

Finally, the last column of *Table 22* indicates economies of scale in double-hull tanker construction. If clean-up costs and environmental damages are an increasing function of tinker size, it may make economic sense to focus double-hull requirements on larger tankers only. The data for determining the merits of this option are not currently available, however.

6.3 Suggestions for Future Research

We have tried to cover the range of possible economic outcomes in the sensitivity analysis of this chapter, but there is clearly much work yet to be done in producing better estimates of each of the critical parameters of both costs and (especially) benefits. As always seems to be the case in environmental economics, much of this work would focus on producing better estimates of environmental damages, with greater attention to the costs associated with effects of oil spills on complex ecosystems and the destruction of option and amenity values.

We have also tried to produce useful forecasts of alternative scenarios, but they could, and should, be improved by constructing and applying forecasting models with stochastic properties in lieu of the naïve forecasting model of this study. It would be especially helpful to construct less deterministic scenarios of both volumes of oil likely to be spilled and the real future price of oil.

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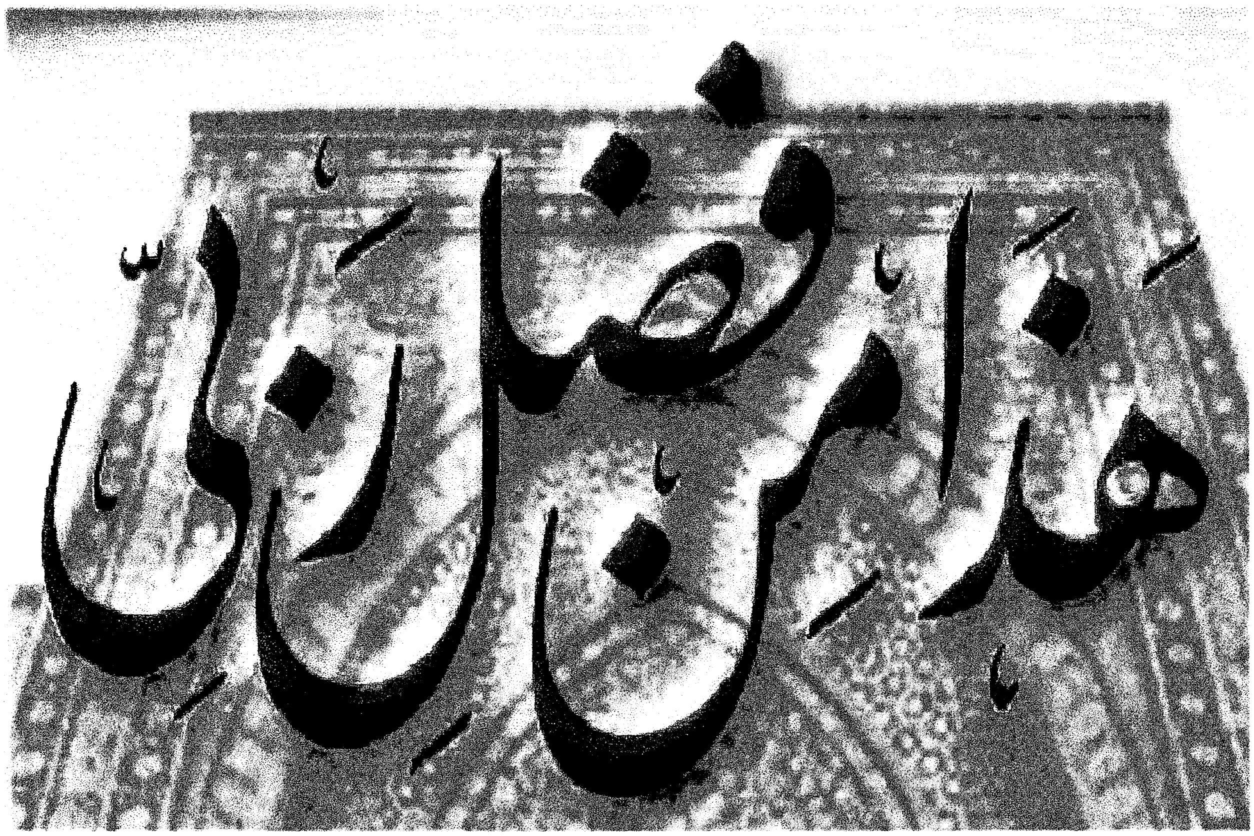

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