DEVELOPMENT, EVALUATION, AND IMPLEMENTATION OF SAFETY MEASURES TO PREVENT MARINE ACCIDENTS

by

Stephen Mark Shapiro

Report submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING

in

Systems Engineering

APPROVED: L. K. Harmon
L. K. Harmon, Chairman

Donald R Drew
D. R. Drew

Ben S. Blanchard
B. S. Blanchard

August, 1991

Blacksburg, Virginia

DEVELOPMENT, EVALUATION, AND IMPLEMENTATION OF SAFETY MEASURES TO PREVENT MARINE ACCIDENTS

by

Stephen Mark Shapiro

Committee Chairman: L. Kenneth Harmon, Jr.
Industrial and Systems Engineering

(ABSTRACT)

Methodologies to determine, evaluate, and implement prospective measures for preventing marine collisions and groundings are presented. The use of cost-benefit analysis to evaluate prospective safety measures is emphasized.

Prospective safety measures are represented as changes to variables that relate to the life-cycle of an oil tanker. Most of these variables, such as crew size and training, are associated with the operational phase. A systems engineering approach was used to develop a causal diagram which models the influence of these variables on a tanker's accident risk and profitability.

The practical application of cost-benefit analysis to evaluate prospective safety measures is examined. The benefit of a specific safety measure is presented as the reduction of accident risk derived by implementing that measure. Since human factors play a significant role in most marine collisions and groundings, a risk analysis of these accidents is largely a human reliability analysis. A human reliability analysis is a special case of risk

analysis, which emphasizes human factors.

The necessity of suitable data for conducting human reliability analyses of tanker navigation is discussed. Recommendations are offered to improve the quantity, quality, and availability of such data.

The current economic climate inhibits the implementation of safety measures in excess of established minimum requirements. Reforms of marine insurance practices to promote greater implementation of safety measures are presented. These reforms create financial incentives by firmly linking the cost of insurance to accident risk.

ACKNOWLEDGMENTS

I would like to thank the many people whose contributions have made a significant positive impact on my entire graduate program and, most particularly, on my project and report.

I especially want to thank the professors who have served as members of my advisory committee. Foremost is Professor Ken Harmon, who has been my advisor for this project and report. His optimistic encouragement and wise counsel throughout this process are greatly appreciated. Professor Ben Blanchard first introduced me to the Systems Engineering Program in 1988. That was on one of the many visits he routinely makes to Northern Virginia to advise students and prospective students. His efforts to closely coordinate the on and off-campus programs provide an essential foundation for the high quality of the off-campus programs. His guidance on my plan of study resulted in a very interesting and rewarding program. Professor Don Drew taught me (and all other systems engineering students) about the widespread applicability of systems engineering. His frequent visits to Northern Virginia to conduct pre-exam tutorial sessions are also greatly appreciated.

There are many others who have been very helpful to me. Mr. Daniel F. Sheehan, Associate Program Director of the Coast Guard's Office of Marine Safety, Security, and

Environmental Protection, Mr. Martin Bockenhauer, Senior Surveyor for Germanischer Lloyd, and Mr. William O. Gray, President of Skaarup Oil Corporation, generously took the time to review an earlier draft of this report and provide comments. My supervisor at Coast Guard Headquarters, Commander John G. Hersh, provided consistent encouragement as well as the work schedule flexibility that made it possible for me to complete this report. My parents, Lionel and Charlotte Shapiro, provided their love and strong moral support, as well as my undergraduate education. These have all been essential assets throughout my career (and in many other areas).

I must add a special note here in memory of my grandparents, Michael and Cecelia Shapiro. For many years, ever since I received my undergraduate degree in 1982, they both strongly advised me to continue my education and obtain a graduate degree. They were extremely proud when I entered the graduate school at Virginia Tech, and never failed to inquire about my progress, offer encouragement, or otherwise express their affection, love, and generosity. Although they are not here to see me complete my degree, they had no doubts that I would. Their strong guidance was among the most influential factors of my decision to return to school.

TABLE OF CONTENTS

I. Background of the Project

On March 24, 1989, the crude oil tanker EXXON VALDEZ grounded in Alaska's Prince William Sound. About 35,000 tons of oil escaped, creating a major environmental and economic disaster. At that time, the author was (and is) employed by the U.S. Coast Guard as a project manager for regulatory actions concerning tanker construction. It is an understatement to say that March 25 (and each day since) was rather hectic. Significant public attention was focused on the issues of tank vessel safety and pollution prevention. This attention provoked a considerable number of pointed questions from the press, Congress, and the general public.

Understandably, most questions were variations of "How did it happen?," "Whose fault was it?," and "How can future spills be prevented?" There was considerable pressure to deliver immediate authoritative answers, with the emphasis on <u>immediate</u>. Various new studies were quickly initiated, while records from past studies and spills were frantically combed (many by the author) for responsive information. The resemblance of all this activity to the aftermath of the last major U.S. spill (ARGO MERCHANT, off Nantucket in 1976) has been striking. Congress responded to the high level of public interest, as it did thirteen years earlier, and embarked on a year long process to draft the Oil Pollution Act of 1990 (OPA 90). That mammoth piece of legislation addressed many minute details of tanker construction, operation, maintenance, and liability (limits on liability for pollution incidents). Engineering considerations were not particularly relevant to the legislative process.

However, engineering considerations are directly related to these largely technical issues. The next two sections provide an overview of this project and report, which applies engineering principles to develop a technical process for determining actions to prevent pollution.

The opinions, conclusions, and recommendations that are presented by the author are his personal views, which should not be construed to represent official positions of the United States Coast Guard.

II. Operational Problem and Project Goal

The question of "How can future spills be prevented?" is a significant problem with many engineering implications. This report assumes that U.S. and international energy demands will require a constant level of oil tanker traffic into the foreseeable future. Therefore, accidental oil spillage can be reduced by decreasing the rate of accidents, given a constant level of traffic, and by decreasing the amount of spillage resulting from accidents that do occur. The latter was recently addressed by an ad-hoc Committee of the National Academy of Sciences that was sponsored by the Coast Guard (1). This project and report address the former problem of accident prevention. The report recommends three actions to reduce the long term risk of accidents. One action is to improve the current methods of accident data collection. Another is to perform cost-benefit evaluations of prospective safety measures, which will be facilitated by better accident data. The third recommendation is to modify the legal and economic climate in order to create incentives necessary to encourage implementation of specific measures.

A basic principle for developing solutions to the problem of preventing accidents is that taking action to promote safety should be financially advantageous. "An essential prerequisite of successful engineering application is economic feasibility." (2) Solutions that result in financial hardship are unlikely to be implemented. This is particularly true in the marine transportation industry, where some competitors will not exceed minimum requirements.

The goal of this project has been to determine the necessary sequence of analyses to perform a cost-benefit evaluation of prospective measures to reduce the accident risk faced by a tanker. Accidents addressed include collisions and groundings. These two types of incidents have caused 60% of accidental oil spillage (by volume) worldwide and 90% of such spillage into U.S. waters (3). It is important to emphasize that these percentages apply to past events. It is misleading to attribute these percentages to ongoing events in the present, since they refer to low probability/high consequence incidents. Each past incident has occurred within the context of a set of specific factors (i.e. new technology) that may change over time. If consideration is limited to a relatively short time frame, where few relevant factors may change, a single incident, such as the EXXON VALDEZ grounding, can significantly change the percentages of oil spillage attributed to specific types of incidents.

The original goal was to prescribe specific measures for reducing accident risk. It was not initially apparent that this was unrealistic within the context of a project and report. The most complex task in justifying specific measures is to quantify their anticipated benefits.

III. Chronology of the Project

The execution of this project has been analogous to chasing a moving target. The result of research has not generally been progress toward the goal, but to progress the goal further out! However, it is now apparent that this continuing refinement process itself was a significant and necessary objective towards solving the larger problem of preventing tanker accidents.

It is useful to summarize the stages, or iterations, of this process (Figure 1), which will be examined later in more detail. The first step was to develop a causal diagram of factors impacting the accident rate and of those impacting profits. Sufficient knowledge of the industry and of the life-cycle of a typical tanker within the industry were prerequisites to developing the causal diagram. Causal diagrams are sometimes used to develop systems dynamics models. These models can be simulated by the DYNAMO program or other similar program to show system response over time. It was anticipated that such analysis could be used to determine the impacts on accidents and profits from spending $1000 on crew training. In this case, the causal diagram provided some useful insights, including the fact that the levels of accidents and profits are not inherently time-dependent (Crew proficiency is not a function of time.). Tankers are not dynamic systems with respect to safety.

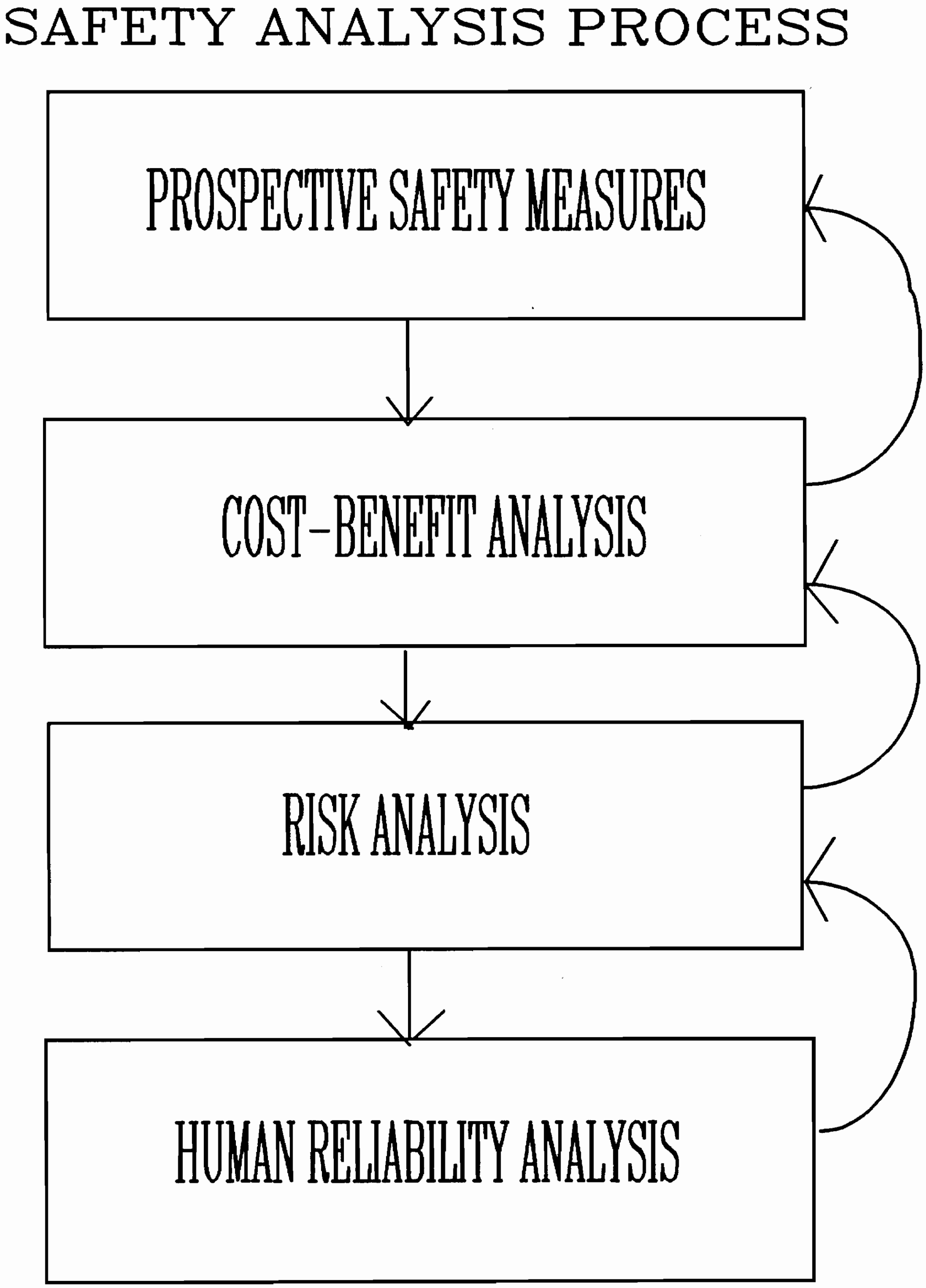


Figure 1. The Safety Analysis Process

The next methodology explored was a graphical cost-benefit analysis. This seemed quite straightforward. The costs and benefits of various prospective measures could be analyzed, and the most cost-effective measures chosen by a goal programming or other optimizing procedure. For example, the cost of training could be defined as $1000 per unit of training - a simple linear relationship. Unfortunately, determining the benefit, or resulting risk reduction, from a $1000 unit of training is neither straightforward nor simple, but absolutely essential for the cost-benefit analysis.

The emphasis of this project had evolved into a risk analysis project. The author discovered a range of risk analysis methods used to explore solutions to many similar problems. Fault-tree analysis seemed to be a particularly straightforward and promising method, just as cost-benefit analysis itself had seemed weeks earlier.

Risk analysis is particularly complicated for marine transportation accidents since 80% of such accidents are the result of human error (4). "It is a well established fact that most collisions are due to human failures, and it is widely accepted that human behavior cannot be described well by mathematical formulae (5)." Even though probabilities of human failure are more difficult to determine than probabilities of failure for many physical components, the field of human reliability analysis does provide means to evaluate events that depend on human behavior. Such analysis is central to determining the benefits of, for example, $1000 worth of crew training. Human reliability analysis is the final analysis element considered during this project, and it is the first element of cost-benefit evaluations of most accident reduction measures. The conclusion to this report contains recommendations on how results of such evaluations could be used to reduce the risk of tanker collisions and groundings.

IV. Overview of the Industry

Oil has been transported in tankers for over 100 years. Even though their basic design has changed little over time, the size of an average tanker has increased dramatically due to growing economies of scale. In 1947, the largest tankers carried 27,000 tons (capacity is the deadweight; hence deadweight tons or DWT). Relatively few tankers built today are so small. In 1981, a tanker was converted to 560,000 DWT (6)! Crude oil and refined petroleum products are transported within distinct trades. Crude oil is generally shipped across oceans from an exporting country to a refinery in or near an industrialized country. Generally tankers over 60,000 DWT serve this trade. Most tankers under 60,000 DWT carry refined products from a refinery to ports on the same or nearby continent for further shipment over land.

Tanker transportation is a huge industry. In 1984, nearly one billion tonnes of crude oil were shipped 4.5 trillion tonne-miles. Another 300 million tonnes of refined products were shipped 1.1 trillion tonne-miles (7). In 1990, the world tanker fleet numbered 2,645 vessels (over 10,000 DWT) with a combined capacity of 225 million DWT. Oil shippers can estimate to pay a ship owner $10,000/day to timecharter (for a specific time, usually years; charters can also be for a specific voyage) a 30,000 DWT tanker and around $20,000/day for a 250,000 DWT tanker (8). Actual costs may vary widely from these estimates. Fuel costs, paid by the timecharterer, are an additional $10,000/day for a 265,000 DWT tanker. Most other operating costs, paid by the owner, are about $8,000/day for a 265,000 DWT tanker (9),(10). Total shipping costs account for less than 5% of the price of oil delivered in the United States (11).

An oil shipper can own vessels outright or lease vessels under charter. Most large oil companies maintain shipping subsidiaries which own vessels. In recent years, the percentage of the world fleet owned by the large oil companies has decreased to one third. The remaining two thirds are owned by companies that do not own the cargo.

Tankers are not generally registered in the country of their owner. The country of registration, the flag state, is usually selected on the basis of cost. There are significant variations among countries on regulations that impact cost, particularly for crew requirements. A flag of convenience (FOC) is usually a third world nation which attracts vessels of foreign ownership with low taxes as well as laws and regulations which permit lower operating costs. One third of all tanker tonnage is registered in Liberia or Panama. U.S. law requires that U.S. flag ships be operated by predominantly American crews. In addition, vessels carrying oil between most U.S. ports (coastwise trade) must be U.S. flag and of U.S. construction. Therefore it is not surprising that virtually all U.S. flag tankers carry oil in domestic coastwise trade. Most of this trade is for product oil. However, most Alaskan crude oil is also shipped in U.S. flag tonnage since it cannot be exported. Few U.S. flag vessels can compete economically in foreign trade.

Most industrialized countries have government agencies which conduct or oversee inspections of tanker construction and maintenance. FOC's generally delegate this responsibility to a classification society. Classification societies are organizations that establish technical rules for vessel construction and maintenance. They employ field surveyors (inspectors) to enforce these rules. These societies were originally established to serve the risk assessment needs of the marine insurance industry. Approval by a classification society was, and is, a prerequisite for insurance (12). In modern times, fees for the initial classification of a new ship are generally paid by the shipyard. Fees for classification surveys performed after delivery are paid by vessel owners. In industrial countries, societies often complement similar functions performed by the government. Societies are based in one country; however, the largest societies perform operations worldwide. The majority of tankers registered in an industrialized country will be classed by the society headquartered in that country. Most U.S. flag tankers are classed by the American Bureau of Shipping. FOC's do not have established national societies. However, most tankers are registered in such countries. Societies from industrial countries compete for business among the FOC fleets.

Since tanker operations are almost, by definition, an international enterprise, the necessity for international cooperation in regulating the design, construction, operation, and maintenance of tankers has long been recognized. Most of these efforts are coordinated through the International Maritime Organization (IMO), which is part of the United Nations. Many significant international agreements to improve tanker safety have been achieved through IMO (13). There are ongoing efforts to review existing international standards in light of the EXXON VALDEZ grounding.

An international protocol to provide an international cleanup fund as well as to limit liability for pollution incidents at an insurable level was drafted at IMO in 1984. However, the U.S. Oil Pollution Act of 1990 (OPA 90) specifically retained the existing law permitting the states to impose unlimited liability for damages under state laws. This precludes U.S. ratification of the 1984 IMO protocol. Two similar international efforts failed to receive U.S. ratification due to Senate concerns that the limits were too low as well as reluctance to preempt state laws (14). Exxon has spent over $2 billion to cover unprecedented cleanup costs and damages related to the EXXON VALDEZ grounding.

The maximum available liability coverage is now about $1 billion. OPA 90 requires insurance or bonding to cover $1200/gross ton (volumetric, not DWT), or $125 million on an EXXON VALDEZ size vessel (210,000 DWT), on all tankers trading in the United States. Liability for cleanup costs under <u>federal</u> law is capped at that level. However, many state laws provide for unlimited liability for pollution incidents.

Most owners obtain liability insurance (or, Protection and Indemnity; P & I) by membership in a mutual P & I club (15). This coverage can be thought of as similar to the liability coverage on automobile policies. Individual rates for renewal policies are based on a vessel's size and the individual member's claim experience for claim's under $600,000, and on that club's experience for claims up to $1.2 million. Additional premiums are assessed on the various <u>clubs</u> within a reinsurance pool, based on club claim experience, to cover pooled costs of claims above $1.2 million from within the pool. These assessments are allocated among each club's individual members based on vessel size and (sometimes) base premium. Rates for new policies are functions of the flag state, classification society, and the owner's prior experience. Ninety percent of all tonnage (not just tankers) is covered by a P & I club. Some large oil companies with substantial assets may self-insure their vessels. Some small companies, with few assets to protect, may forego insurance beyond any amount needed to meet legal requirements.

Most owners obtain marine (or, hull) insurance (16), which can be thought of as similar to automobile coverage against collision and comprehensive damage. Factors influencing hull insurance rates for tankers include size, age, flag, and the claim experience of the operator. The owner's choice of classification society is not a factor.

V. Life Cycle of a Tanker

It is useful to examine the life cycle of a typical tanker (Figure 2). The life cycle of a tanker begins when the need for a specific vessel is realized and ends when that particular tanker is scrapped. Intermediate life cycle events include the design, construction, operation, and maintenance of the tanker (17). It is important to consider each of the later events during the design phase. However, this has not always been done for tankers.

Tankers routinely change ownership during their lifetimes, and owners are often not the operators. This diminishes incentives to consider the entire life cycle, and encourages maximizing short-term profits. When the life cycle is considered, consideration is often limited to impacts on short-term profits (18). Similar to other businesses, the intense nature of competition within the industry makes it difficult for a single owner to incur expenses beyond those of other owners. The industry standard for safety related expenses generally does not exceed the minimum safety requirements imposed by flag states, classification societies, and International Maritime Organization (IMO) conventions.

After the construction of a vessel has been justified on economic grounds, the design generally conforms to rules established by the classification societies, and follows on

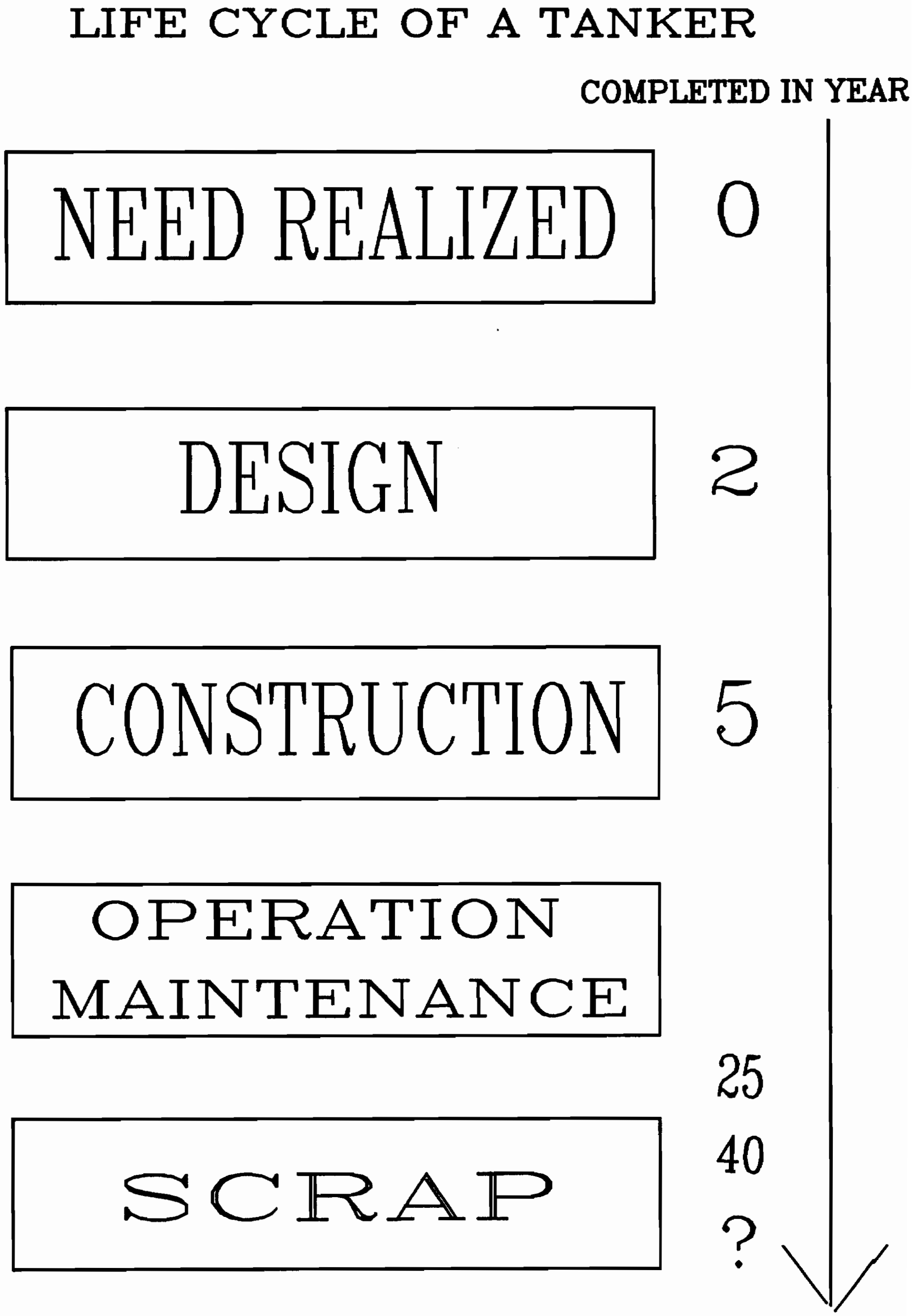


Figure 2. The Life Cycle of a Tanker

existing proven designs. Tankers are too expensive to build by trial and error. Industry is often unwilling to accept results of computer simulations in the absence of actual experience (19).

Shipbuilding is a design-build enterprise. Tankers are usually designed by the shipyard that will construct the vessel. Shipyards prepare preliminary designs and cost estimates for use in bidding on the detailed design-build package. Many decisions impacting safety are made at the preliminary design stage. There is an obvious incentive to keep bid prices low and to perform preliminary designs within short time frames. Only owners that intend to retain ownership of a tanker for many years are likely to specify safety features in excess of minimum requirements.

Construction takes place under the supervision of the classification society selected by the owner and, sometimes, under the additional supervision of the owner and/or the flag government. Quality assurance can be crucial for the successful operation of the vessel. Poor design details and workmanship can result in future structural failures and expensive repairs in later years (20).

The operational phase of a tanker's life cycle is the primary focus of accident prevention since groundings and collisions occur during this phase. Again, the industry's emphasis is often on minimizing short term costs. Crew and maintenance costs are among the most variable operational costs. Many operators frequently change crews, which precludes familiarity with the vessel and reduces the incentive and ability to provide extensive training. The ability of the crew to perform competently generally receives less oversight than a vessel's materiel condition. Maintenance is another important variable, which is often overlooked by less reputable charterers and owners who do not contemplate a long-term interest in their vessels. Proper maintenance is essential to avoid a premature end to the operational phase. "A 15-year-old Scotch whiskey gets better with age simply by sitting idle. A vessel doesn't..." (21) There is financial pressure on owners to minimize maintenance costs as well as to extend the life of existing tankers in order to minimize capital costs. The current trend is for tankers to remain in service until the cost of maintenance required to permit continued operation becomes prohibitive. Classification societies and, sometimes, the flag state conduct periodic surveys to determine specific maintenance required to permit continued operation (22). The rigor of these surveys and requirements is sometimes questionable (23). International treaties (i.e. IMO requirements) are primarily enforced by the individual flag states; some port states will also take enforcement action on visiting foreign ships. The International Maritime Organization does not perform independent surveys.

VI. Systems Model of Tanker Safety

This report examines a tanker as a system. Blanchard and Fabrycky (24) define a system as "a set of interrelated components working together toward some common objective." Therefore an important step of this project is to define the components, and their interrelationships, that form a tanker. The philosophy behind this process is that a "big picture" or "top-down" approach to examining systems affords the most complete means of understanding how a system operates and how changes to a component or an interrelationship can change the overall system. A simple example of this process is to see an exploded view of a simple machine of ten components. The diagram will show the components individually and also show how they fit and function together to constitute the whole machine. A tanker is not a simple machine; it has many more than ten parts. These parts include the crew as well as the physical components of the vessel. Therefore, a critical task in defining or modeling a tanker in terms of a system is to determine the appropriate level of detail.

Although an individual tanker is the primary unit of analysis, it must be recognized that a tanker operates as a subsystem within a larger marine transportation system. This is particularly relevant to collisions, which involve (at least) two vessels. Significant factors such as communication, navigation, weather, and financial matters are external to the tanker. Similarly, it will be necessary to analyze certain internal components as smaller subsystems. The results of subsystem analyses will need to be aggregated to determine their impact on the whole tanker.

Brown (25) offers a three level approach to systems engineering originally published by the American Society of Safety Engineers. The separate levels represent increasing degrees of detail. The purpose of the levels is to ensure a sufficient top level view of the problems and avoid premature consideration of fine details and exclusion of other potential solutions. The top level, Level I, involves the determination of objectives. In this project, accident (collision and grounding) prevention is the objective. In Level II, alternative subsystems, or solution methodologies, are considered. This report is now at Level II. A model of subsystems impacting tanker safety will be presented later in this section. Level III is the step where specific subsystems or solutions are evaluated in sufficient detail to permit selection and implementation of specific solutions. Methods to conduct the Level III evaluation of measures to prevent accidents will be addressed later in this report.

Several systems analyses of oil tankers have been performed in the past. In 1970 (following the TORREY CANYON accident), Stratton and Silver (26) presented a method of conducting an operational analysis of marine accidents and a statistical analysis of tankers accidents occurring in the previous decade. Four years later, Dunn and Tullier (27) adopted a systems approach in developing a program of research into marine accidents, with emphasis on collisions. Cheaney and Coyle (28) performed a similar study in 1976, with emphasis on fires and explosions. In 1977 (after ARGO MERCHANT), a four year research project to investigate the causes of collisions and groundings was launched by the Norwegian classification society, Det norske Veritas (29). That project resulted in a detailed statistical analysis of collisions and groundings (30). Particular emphasis was on determining the frequency of specific causal factors during accidents. The many variables affecting ship safety, and the resulting difficulty in conducting a systems engineering analysis, was recently discussed by Beetham (31).

The appropriate role of statistics in conducting a systems analysis is often difficult to determine. Collisions and groundings can be considered low-probability/high consequence incidents. Therefore, the utility of statistics as a primary means to analyze tanker casualties is often overestimated. There is a tendency to make excessive use of narrow details concerning past casualties, while ignoring the broad factors that affect the potential for future casualties. Statistics are more appropriate as a means to verify an analysis.

Drew and Hsieh (32) offer a causal approach to systems analysis. Causal diagrams are symbolic models of systems that show cause and effect relationships between components. Drew (33) provides the sequence for developing a causal diagram. This includes identifying key variables, identifying relationships between variables, and determining the polarity of those relationships. Causal diagrams are primarily offered as a means to develop mathematical equations for performing dynamic simulations of systems. However, causal diagrams can also be useful tools for analyzing systems composed of variables that are not necessarily functions of time.

Figure (3) is a diagram of factors influencing accident (collision and grounding) risk and short term profits. This diagram was developed through an iterative process that began with writing a list of factors impacting safety. Almost immediately, there was an additional emphasis on factors impacting costs as well as safety. These are further shown in Figure (4). In retrospect, the early mingling of safety and profit concerns may not have been beneficial. It is possible that this caused factors impacting safety, but not necessarily costs, to be unintentionally omitted from consideration. It soon became necessary to create a composite variable (P), which represented variables requiring specific payments for maintenance, training, labor, equipment, etc. This composite variable, which was later split into short (PS) and long (PL) term payments on items affecting the risk of accidents (AR), is one of the most significant variables. The immediate impact of such payments on profit is relatively clear and simple to determine. Their impact on accident risk is much more complex.

It seems reasonable to expect owners to make such expenditures only on measures that will cost-effectively reduce risk (or that will reduce the public perception of risk). Therefore, it would be useful for the industry to have some means of estimating the risk reduction that could be attributed to specific payments as well as the impact of accident risk on costs. Owners make some payments, such as for insurance, based on concerns of liability or potential liability. Classification society rules and government regulations make operation of the vessel contingent on certain payments (to implement minimum safety requirements).

It will be useful to determine whether the larger system in which individual tankers operate is currently structured to maintain appropriate levels of safety and profitability. This raises the question of feedback. It is noteworthy (and troubling) that the model in Figure 3 does not contain any feedback loops. It is troubling because a system that is self-regulating can be expected to have a negative feedback loop acting as the regulator (34).

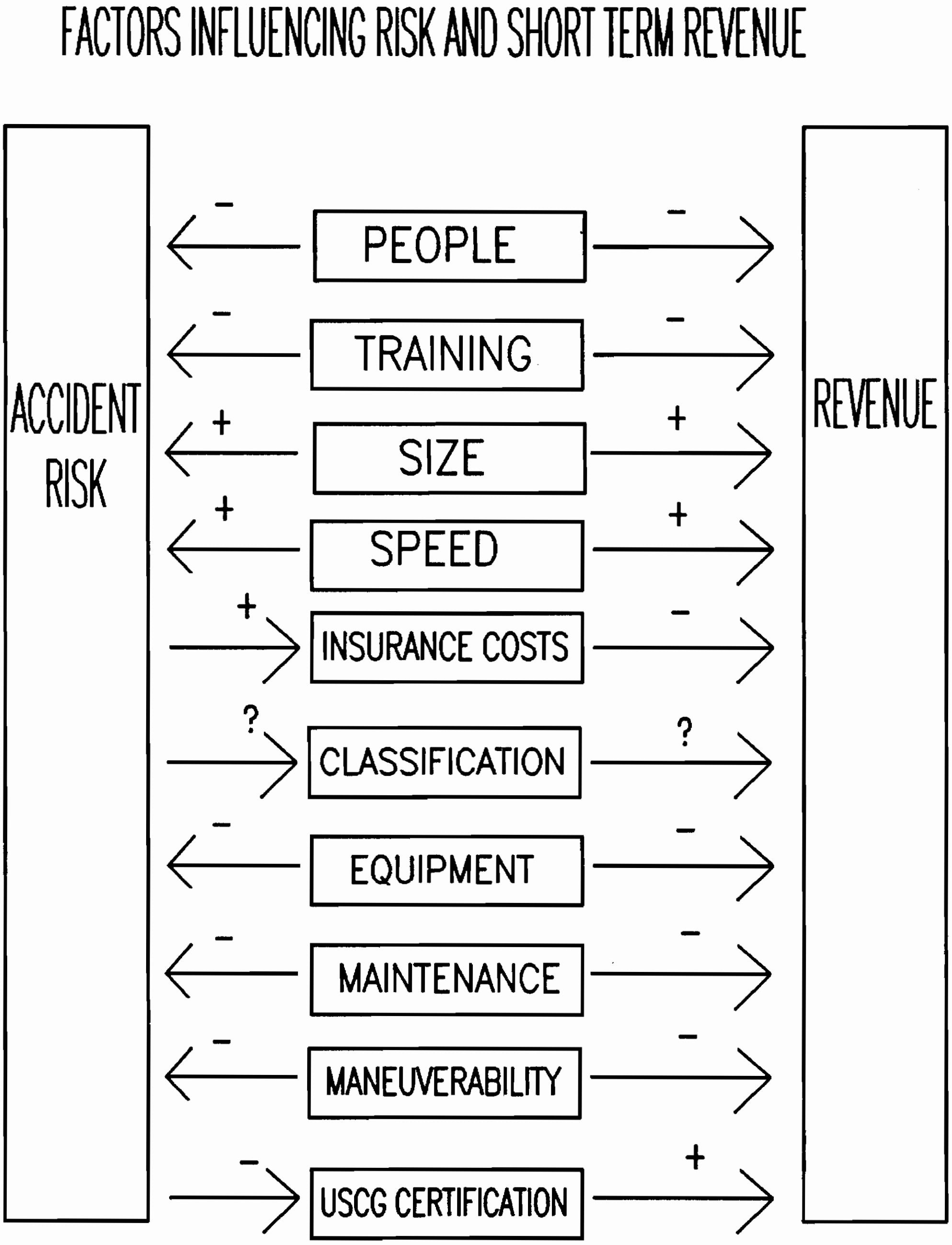
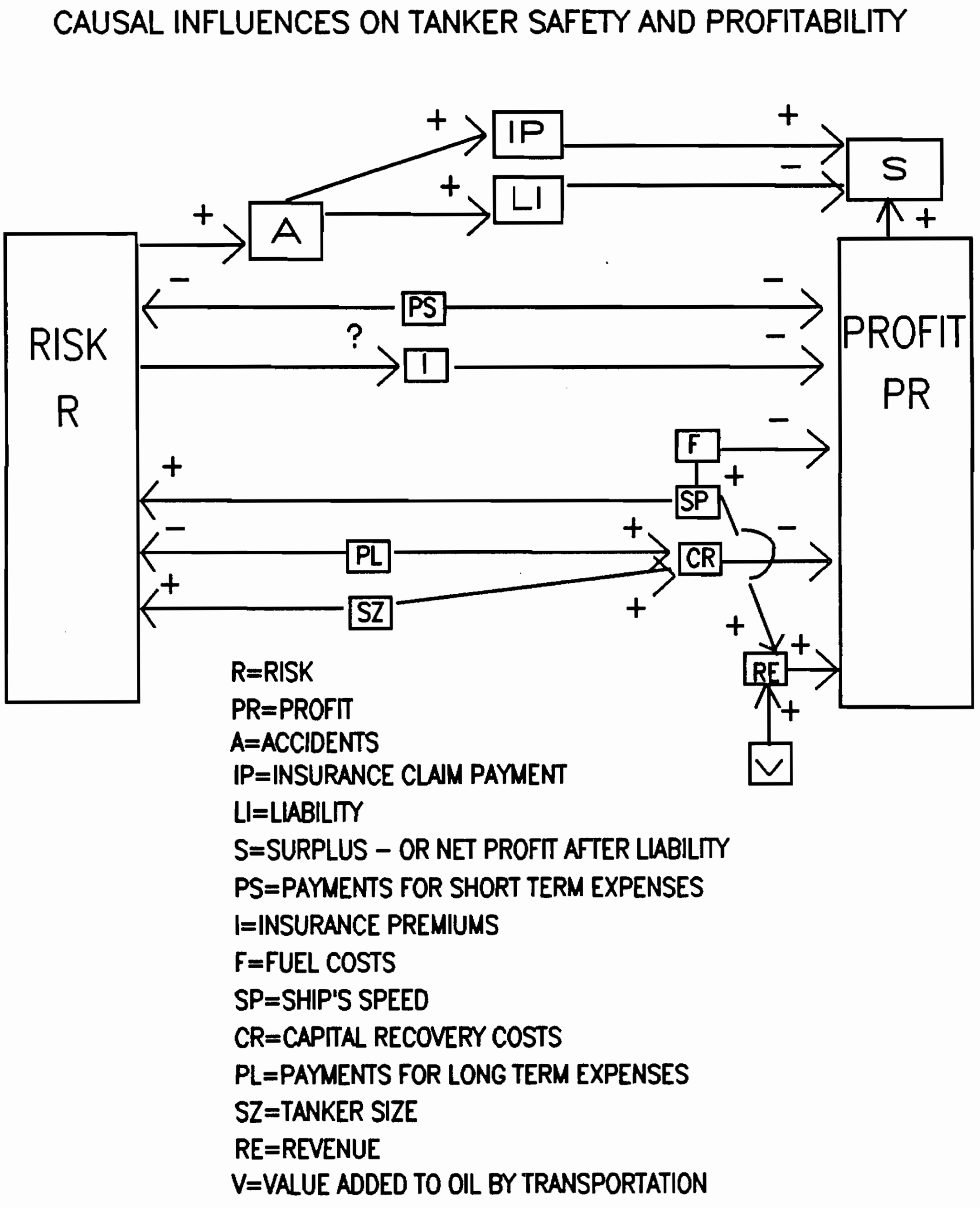


Figure 3. Causal Factors Influencing Risk and Revenue



R=RISK
PR=PROFIT
A=ACCIDENTS
IP=INSURANCE CLAIM PAYMENT
LI=LIABILITY
S=SURPLUS – OR NET PROFIT AFTER LIABILITY
PS=PAYMENTS FOR SHORT TERM EXPENSES
I=INSURANCE PREMIUMS
F=FUEL COSTS
SP=SHIP'S SPEED
CR=CAPITAL RECOVERY COSTS
PL=PAYMENTS FOR LONG TERM EXPENSES
SZ=TANKER SIZE
RE=REVENUE
V=VALUE ADDED TO OIL BY TRANSPORTATION

Figure 4. Causal Influences on Tanker Safety and Profits

Therefore, lack of feedback could suggest that the current system is not self-regulating. However, the specific payments noted in the preceding paragraph for insurance and for safety related items required by rules and regulations would be expected to have a regulating effect that would be reflected by the presence of negative feedback in Figure 3.

Figure 5 provides a possible answer which draws on the reasonable premise that these variables are not functions of time. Figure 5 is an enlarged section of Figure 3, which helps focus on the impacts on (PS). The output from (PS) does not feed directly back into (PS). However, the first-order derivatives of outputs of (PS), (PR-profit) and (LI-liability) (e.g. change in profit or liability as a function of additional payments on safety related items) do feed back into (PS). This aspect of the model is reinforced by the cost-benefit analysis in the next section. It is likely that these first order derivatives are functions of (PS), which would provide the elusive feedback.

Now that a sensible model has been developed, it must be analyzed. Cost-benefit analysis is presented in the following section as an appropriate method of evaluation.

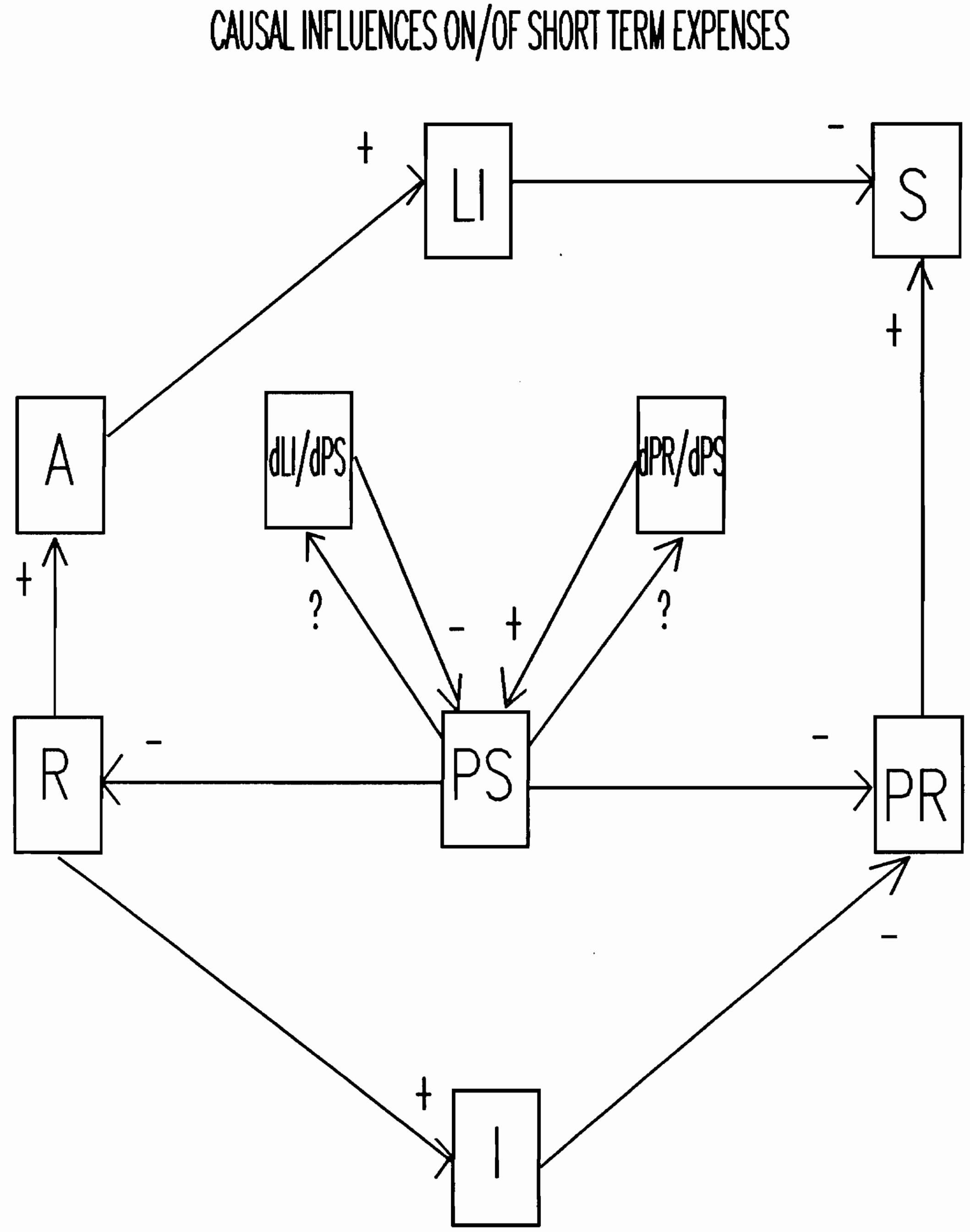


Figure 5. Causal Influence of and Feedback to Expenses

VII. Cost-Benefit Analysis of Safety Measures

Figure 3 suggests that there is very limited dependence between the variables affecting risk and profit. Therefore it should be appropriate to examine the effect of changing a single variable on risk and profit, while assuming that the effect of all other variables will remain constant. This section discusses cost-benefit analysis as a method to determine the impact of changing individual variables on risk and profit.

Moghissi (35) states that "the application of cost-benefit analysis is by far the most important objective part of risk management. It provides a decision maker...with an objective tool to evaluate the cost of various options and the benefits that may be derived from them." Goss (36) discusses cost-benefit analysis as an approach to determine appropriate safety measures for merchant ships. Figure 6 (37) shows how such analyses could be used to determine an optimal level of safety. Two curves are plotted to show the costs and resulting benefits of safety measures. The optimal level of safety is implemented where the vertical distance between the curves is greatest. At this point, the slopes of the two curves are equal. In economic terms, the marginal (derivative of the) benefit curve intersects the marginal cost curve at this point (Figure 7 (38)); returns on any further expenditures would not cover their costs.

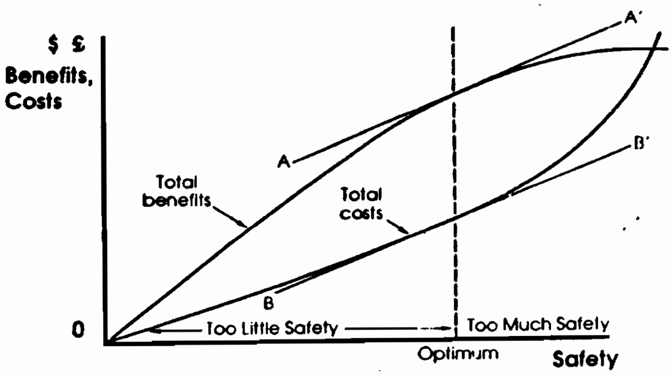


Fig. 4—The optimum level of safety

Figure 6. (Reference 37)

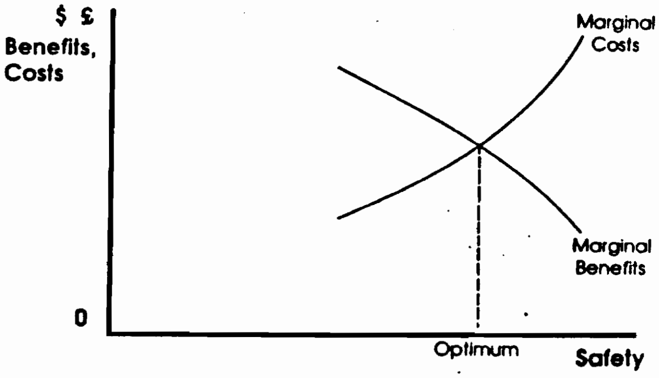


Fig. 5—The optimum level of safety

Figure 7. (Reference 38)

Professor Goss notes that "this presentation is both simple and well known to the point of being obvious; and I would not do it if these fundamental ideas were not ignored by all those responsible for formulating maritime safety rules." These points may be well known to those with economics or management backgrounds. However, since the technical community is less familiar with them, Dr. Goss' presentation within an engineering forum is extremely valuable.

The procedure to quantify these curves and determine actual optimal points is specifically left aside. The difficulty in quantifying these curves in a defensible manner is a key reason for the infrequent use of cost-benefit analysis in developing safety requirements. Executive branch agencies of the U.S. government are required to consider costs and benefits of prospective requirements (39). However, the best available estimates of costs and benefits are often too rough to support detailed analysis.

A comparison of Figures 5, 6, and 7 is extremely interesting. Figure 6 is a graphical presentation of the symbolic model in Figure 5. The cost and benefit curves in Figure 6 represent (PRofit) and (Risk) in Figure 5. The marginal cost and benefit curves in Figure 7 represent the (dPR/dPaymentS) and (dLIability/dPS) terms that influence (PS) in Figure 5. This result serves to validate the model in Figure 5. The (Surplus) term in Figure 5 will be maximized at the optimum point in Figures 6 and 7.

Brown (40) offers a similar graphical presentation of a cost-benefit analysis of safety measures, shown in Figure 8 (41). This particular example is from the timber industry, but the approach is generally applicable to most industries. The "cost" curve represents costs of accidents (on the horizontal axis) as a function of days lost. "C" is the cost of one lost day; it represents more than just dollar costs. Related costs that may be very difficult to quantify (e.g. human costs of injuries) must be considered. The determination of "C" is a key segment of the decision-making process and is often likely to be controversial since it may largely represent subjective judgment. Moghissi notes that "in practice, it is difficult...because one faces the extremely difficult issue of comparing economic costs with human life." (42) Assigning economic costs to resulting environmental damage causes additional difficulties when assessing the total cost of marine accidents. The "return" curve represents the reduction of accidents (on the vertical axis) in terms of days lost as a function of expenditures on safety measures. In this example, the expenditures are a composite of many safety measures implemented to optimal degrees. These expenditures are in terms of (the cost of) days lost. The vertical difference between these curves represents net profit (in terms of reduced days lost) due to

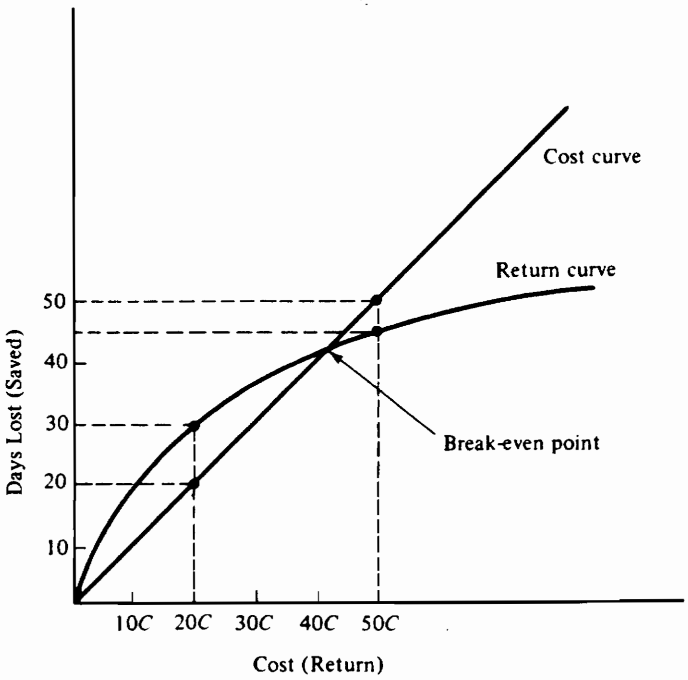


Figure 10.3. Superimposed cost and return curves

Figure 8. (Reference 41)

these safety measures. Expenditures on safety measures beyond the "break-even" point result in less profit than with no safety measures.

Figure 9 is the author's modification of Figure 8. It superimposes the cost/return curve ("benefit" curve) discussed by Brown (43), which represents the benefit of safety measures (in terms of reduced days lost) on top of a line representing the cost of safety measures (in terms of dollars) ("cost" curve) as a function of dollars. Another horizontal scale is added to translate dollars invested into the specific measures paid for by those dollars. Another vertical scale is added to translate the benefits into dollar values. This requires a determination of "C." Even though the "benefit" curve and scale are fixed, this new "value" scale can be amended to reflect different opinions of "C." This permits the "costs" and "benefits" to be measured and compared along the same scale. However, the "cost" curve must be re-drawn to maintain a slope = 1 for each value of "C." This will change the optimal and break-even points as functions of "C," as shown in Figure 10.

It is important to separate the technical and social issues addressed in these models. The shape of the "benefit" curve and its interpretation along the "benefit" scale is (only) a technical determination. Society (only) will determine "C." The interpretation of benefits along the "value" scale represents the specific value society

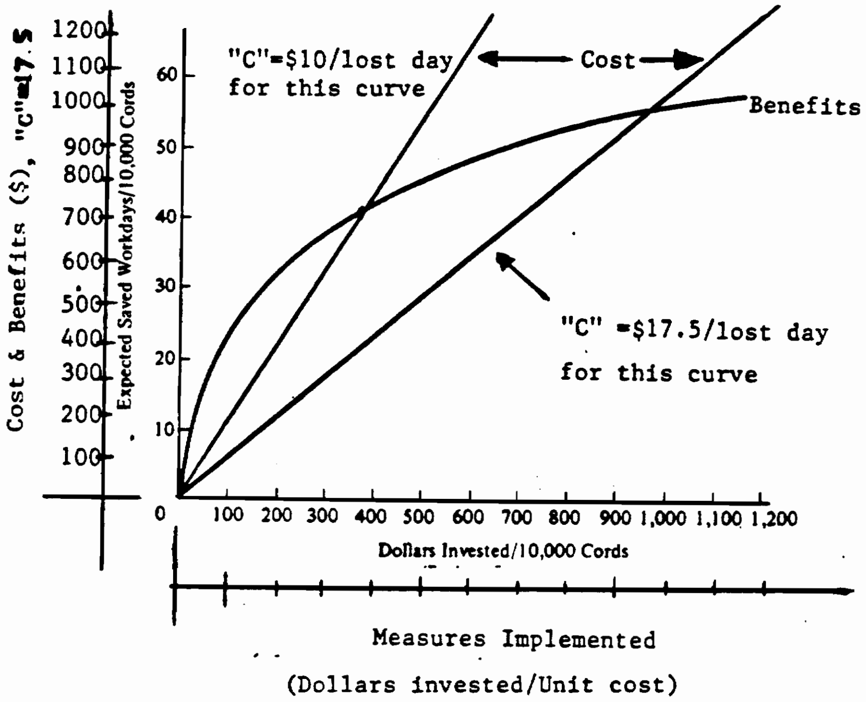


Figure 9. Costs and Benefits of Safety Measures

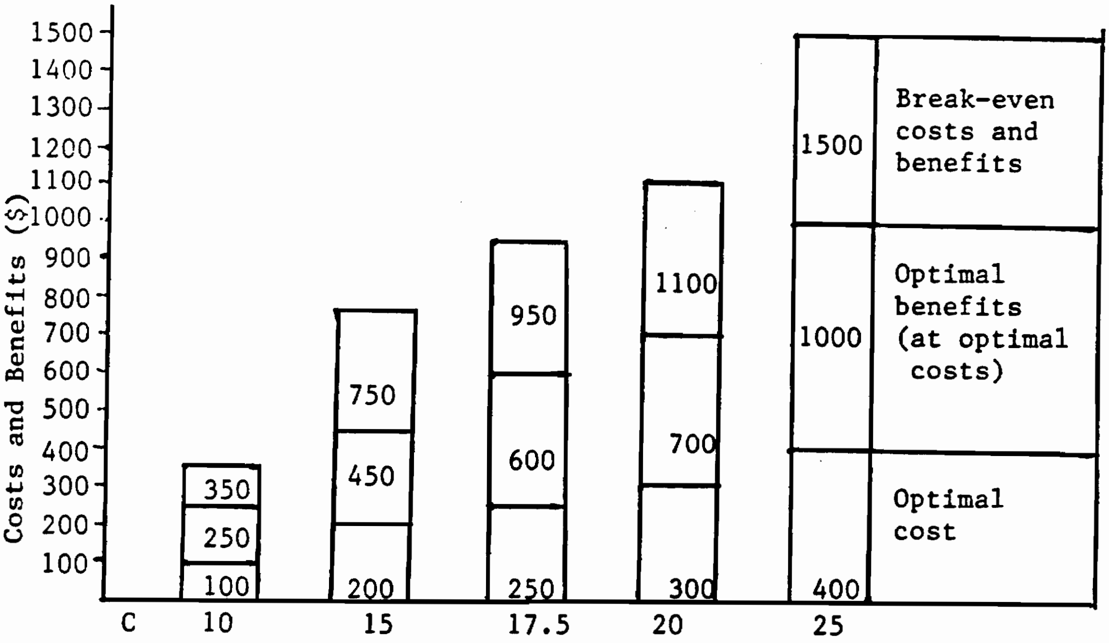


Figure 10. Costs and Benefits as Functions of "C"

places on specific technical benefits.

Giziakis (44) offered an earlier (possibly the first) paper comparing the costs and benefits of safety measures for ships, shown in Figure 11 (45). He then went forward to quantify the cost of accidents (or, the value of reduced accidents) in monetary terms. A similar study of the cost of accidents was performed by the U.K. Department of Industry in 1976 and recently discussed by Maybourn (46). It appears that accident cost statistics are not compiled too frequently, at least not for public review. This information provides the "C" variable offered by Brown as discussed above. It could be used to develop a (monetary) benefit value scale (Figure 9) for reducing tanker accidents. However, the scales are useless unless actual curves can be developed. Canada and Sullivan (47) note that "it is clearly a waste of time and effort to construct a model that cannot be run because the data to drive it are unobtainable." However, such efforts can be worthwhile, even if requisite data is not available, as a means to determine what data is needed to achieve useful or necessary results.

Data to facilitate the construction of actual "cost" and "benefit" curves in Figure 9 is the key to practical application of cost-benefit analysis. Data on cost should be readily available. It should be relatively easy to obtain cost estimates of specific safety measures, even

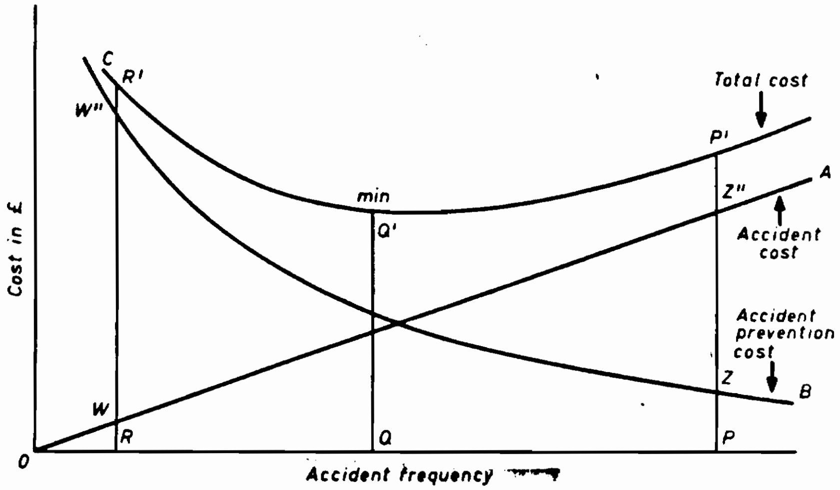


Fig. 1. Cost of accidents and cost of prevention

Figure 11. (Reference 45)

though it can be difficult to obtain estimates that will be universally accepted. For example, the cost of an additional watchstander on the navigating bridge can be obtained from data on wage rates. Drawing the "cost" curve is a simple matter once the "value" scale is established since it is a line with slope = 1.

Drawing the "benefit" curve is relatively difficult. This requires determinations of "benefits" such as the reduction of accident risk, if any, due to the presence of the additional watchstander. These determinations require risk analyses of various versions of the system (i.e. with and without the additional watchstander). The necessary steps to derive this curve and to perform a cost-benefit analysis of prospective measures are presented in the Conclusions and Recommendations.

VIII. Risk Analysis to Support the Cost-Benefit Analysis

As was noted in the previous section, an understanding of the relationship between implementation of a safety measure and the resulting reduction of accident risk is necessary for performing a cost-benefit analysis of such measures. This would define accident risk as a function of safety measures. Risk, as used here, refers to the probability of an accident. There is no attempt to define the consequences of such accidents at this stage. Consequences are considered in determining the value of preventing accidents, as discussed in the previous section. A plot of this risk or probability function would yield the "benefit" curve in Figure 9. The various points along this curve must be determined by risk analysis.

The concept of using probability to evaluate safety measures is relatively new, particularly in the marine industry. Traditionally, standards for specific measures were set by deterministic methods. These are based largely on historic precedence of what is generally known to be safe. Meyer (48) notes that the degree of risk inherent to a system conforming to deterministic standards is unknown. Therefore the benefits (accident prevention) of deterministic standards are difficult to quantify.

Cox and Slater (49) and Cuming and Jensen (50) present typical diagrams of the risk analysis process, shown in

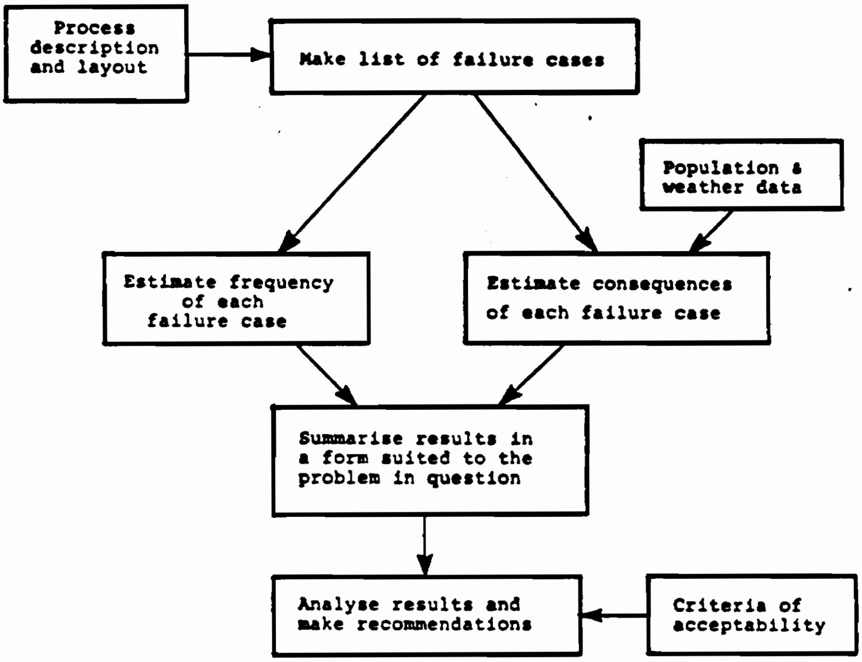


Fig. 3. Overall flow diagram of risk analysis.

Figure 12. (Reference 51)

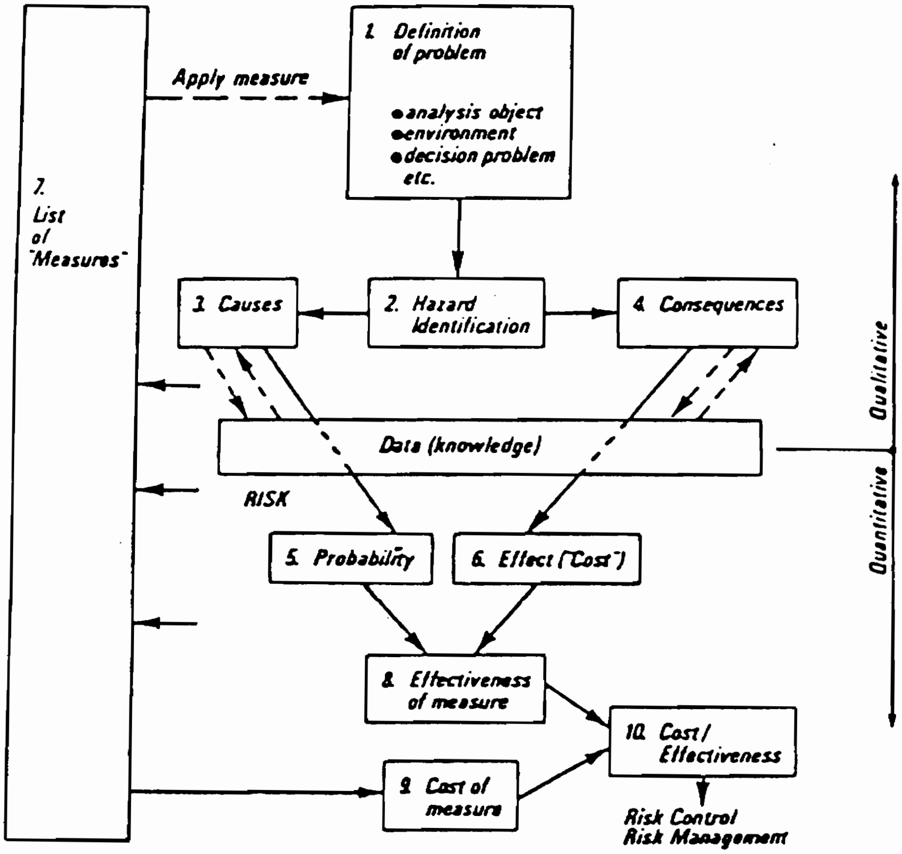


Fig. 1. Typical risk analysis framework

Figure 13. (Reference 52)

Figures 12 (51) and 13 (52). Much of the process took place back in Section VI, when the systems model of tanker safety was developed, and in Section VII, when cost-benefit analysis was discussed. The current task is to estimate the frequency (probability) of failure, or accident, for each case or set of conditions. Each set of conditions refers to varying degrees of a specific safety measure, with other variables held fixed. The level of detail in the overall analysis is now at Level III of the systems engineering process discussed by Brown, which was noted in Section VI. This corresponds to the "Detailed Design" stage of hazard analysis depicted by Cox and Slater in Figure 14 (53).

There are several methods in the literature for determining the probability of specific accidents. There seems to be particular controversy over the appropriate degree of subjectivity or objectivity to be used in such analysis. This is especially true for analyzing the likelihood of low-probability/high-consequence (LP/HC) accidents, for which little useful data may be available.

One group advocates the use of Bayesian statistics. This is an approach to aggregate different sources of information by weighting the different sources according to the analyst's judgment as to the appropriate relative weight for each source. Most of the literature on Bayesian methods involves extreme examples of LP/HC accidents, such as dam failures and nuclear power plant catastrophes. Data for

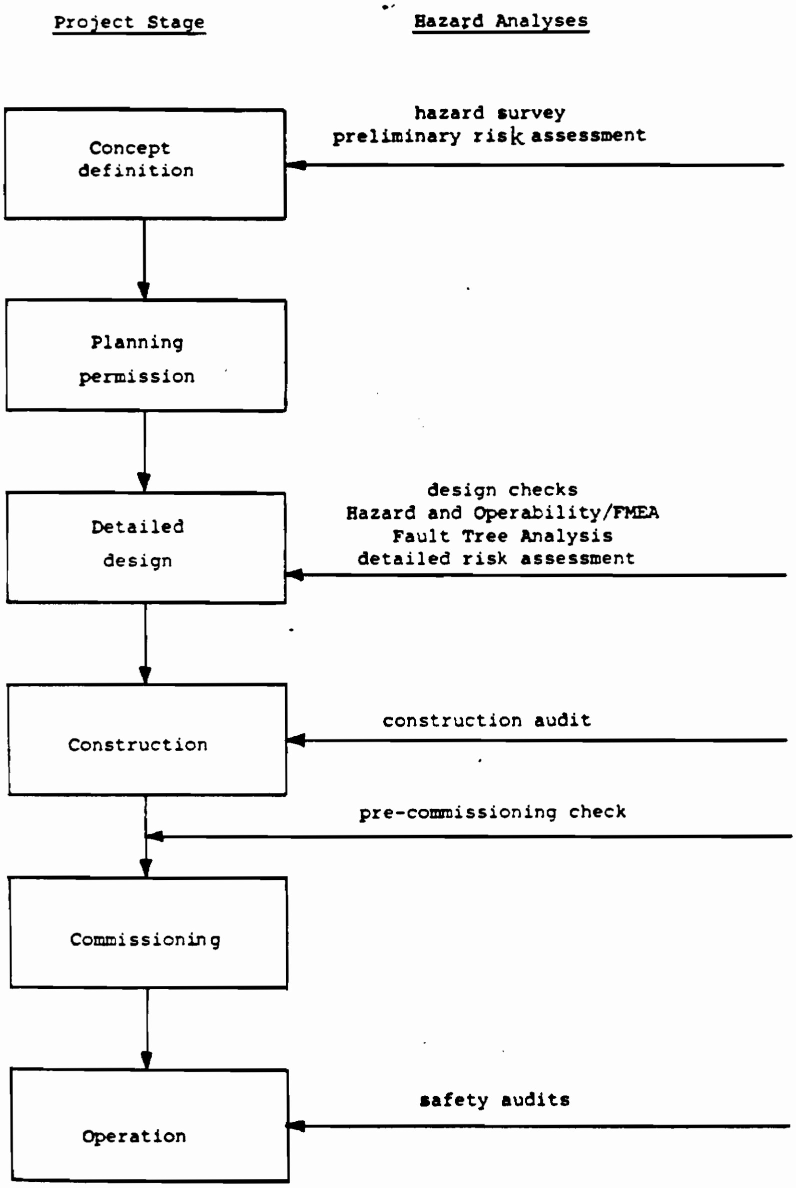


Fig. 2. Hazard analyses during the development of a project.

Figure 14. (Reference 53)

for estimating the probability of these incidents is exceedingly rare. Therefore, the aggregation of all available information, including expert opinion, is viewed as necessary. Mosleh and Apostalakis (54) have offered a Bayesian model for aggregating expert opinion to derive the probability of LP/HC incidents. Martz and Bryson (55) have presented a Bayesian procedure for estimating the probability of dam failures by aggregating diverse sources of information including event and fault tree analysis, historic data, expert opinion, time without failure, and failure rates for similar types of accidents. The author is aware of two marine accident studies (discussed later) that have incorporated Bayesian analysis.

The other type of analysis is classical, or non-Bayesian. Classical analysis incorporates objective quantitative methods to evaluate probability. Fault and event trees are prominently featured. Vohra (56) offers a classical analysis of nuclear power plant accidents. Most of the (relatively few) existing marine accident analyses have incorporated classical analysis.

An excellent comparison of Bayesian and classical methods has been presented by Singpurwalla (57) and Abramson (58). In general, the author suggests a classical approach for evaluating tanker accidents. It does not seem appropriate to determine the probability of accidents based solely on the weighted opinion of experts. This would be counter to the systems engineering philosophy and model that have been presented in earlier sections. Similarly, it does not appear that a weighted aggregation of different sources is an optimal procedure. For example, there should be a close relationship between results obtained by simulating a model, such as an event and fault tree, and actual historic data. If historic data does not validate the model, the model should be examined to determine the cause of the discrepancy. Merely weighting two different types of data (simulation and historic) without further investigations does not seem appropriate. Using the actual length of time (or number of voyages) without accident to determine probability is an extreme example of the previous point. This is particularly true for LP/HC incidents. Unfortunately, it is very common in the tanker industry to dismiss prospective safety measures as unwarranted, based solely on the absence of actual accidents. It is likely that an <u>actual</u> LP/HC accident will <u>not</u> occur within a particular short time frame. However, it is possible that the <u>probability</u> of that accident could still be cost-effectively reduced by implementing specific measures.

This a timely point to address the appropriate use of empirical data, which is a related issue involving risk analysis. Ballestero et. al. (59) discuss the use (by others) of "methods which have nothing to do with the physical processes which could cause the storm" before presenting their analysis of floods, which "disaggregates data into subsets which are characterized by the physical process causing the extreme event." Vohra (60) cautions that "given a set of data points....it is not sufficient to fit a straight line and use the best fit slope as there is no a priori reason for assuming a linear relationship." Brown (61), while explaining empirical and a priori methods of probability prediction, notes the limitations of basing estimates of the probability of future accidents on empirical data.

The use of empirical vs. a priori approaches has been discussed with specific reference to tanker accidents. A paper by Fujii (62) is based entirely on empirical data. It derives relationships to define the probability of collision by comparing accident rates from before and after specific measures (a vessel traffic system) are implemented. It would be preferable to derive relationships using an a priori approach. However, the difficulties and uncertainties inherent in an a priori analysis can be considerable indeed. Kwik (63) discusses the drawbacks of strictly empirical approaches and presents a mathematical (a priori) model of ship collisions. Spouge (64) advocates the use of empirical data to predict tanker accident probabilities, since "theoretical analysis....is much more speculative (than empirical data), and cannot be certain of covering all the possible routes to failure."

This debate has the appearance of a "chicken or the egg first" question. Systems engineering suggests that predictions should be based on an a priori analysis of the system. However, this raises the issue of how to determine a feasible basis for an a priori analysis. Sometimes a straightforward theory can be applied. Sometimes empirical data of sufficient quantity and quality can be relied upon to predict future events, particularly if the states (conditions) of all relevant variables (of the prior events) are known and are valid with respect those future events. Sometimes expert judgment may be the only available basis. However, the underlying bases for such judgments should be closely examined.

Zalosh (65) has presented an interesting example of a risk analysis of industrial fire hazards. He discusses an event tree developed by Holmes (Figure 15)(66), which considers the potential outcomes of a presumed specific fire. These outcomes represent varying extents of damage. The fire must proceed through a different barrier to arrive at each increasing extent of damage. Only a few of the potential paths, with relatively small probabilities, result in the most extreme damage. In this example, developing the event tree was much simpler than assigning probabilities to the branches. Developing the causal relationships, or fault tree, describing a spreading fire seems relatively straightforward. The probability of passage through each

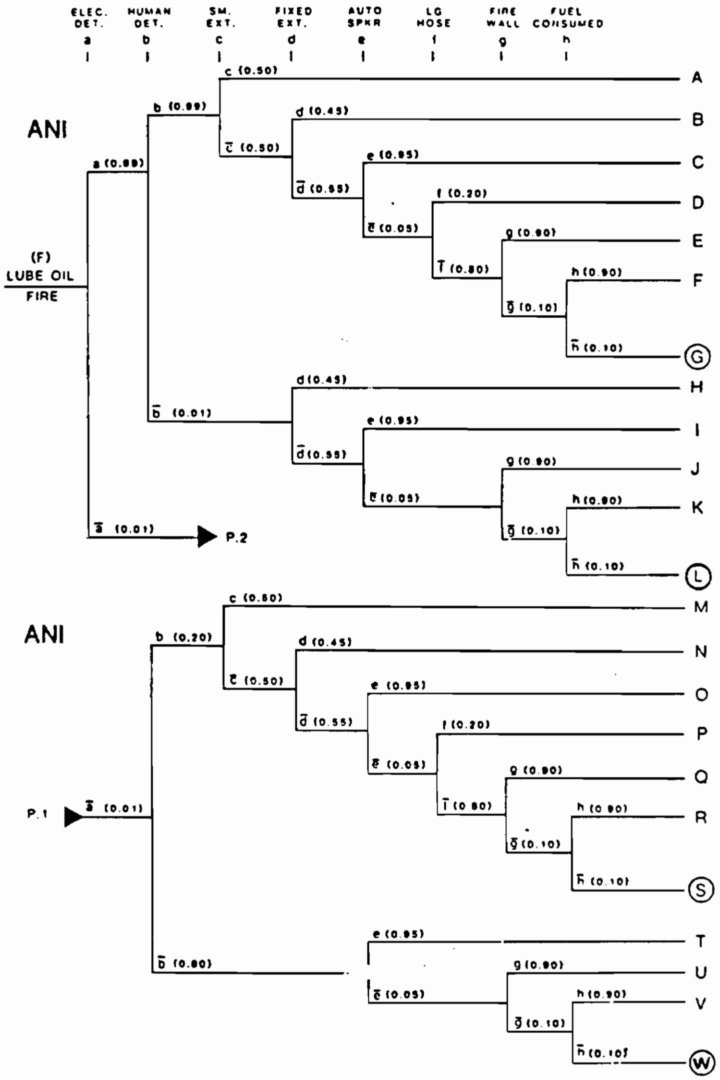


Fig. 5 Event Tree for Turbine Lube Oil Fire
Holmes (Reference 16)

Figure 15. (Reference 66)

specific barrier was taken from available published data. A relatively large data bank exists for estimating the probability of events in building fires. The relatively large number of buildings compared to ships or nuclear power plants facilitates the accumulation of usable data. However, available data must be evaluated for applicability to the specific situation under study. In this case, a strictly a priori determination of the probability of the branches would have been very difficult. For example, using physics and thermodynamics to estimate the probability of automatic sprinklers extinguishing a fire would be difficult, and the many variables and assumptions required for such an analysis would preclude a high degree of confidence in the result. This echoes the opinion of Spouge (67), which was noted earlier. Therefore, data reflecting a <u>large number of incidents</u> can sometimes be used with greater confidence than a priori estimates, particularly if the states of relevant variables (e.g. room size, sprinkler size, water pressure, etc.) from the past cases used to generate the data and from the case under evaluation are known.

The paths to tanker collisions and groundings, and their probabilities, are much more difficult to establish. Unlike building fires, the number of marine accidents is relatively small, and efforts to extract useful data have been meager. The author is aware of two past risk analyses of marine accidents incorporating fault trees.

One was completed by Dunn and Tullier for the U.S. Coast Guard in 1974 (68). That study introduced SALT trees (Safety Analysis Logic Tree). These are basically fault trees, with an emphasis on expanding the examination beyond events that are considered "faults." A SALT analysis was performed on a single hypothetical collision in great detail. The SALT tree fills twelve pages. There was no attempt to assign probabilities to any of these events. Two less detailed evaluations within that same study did quantify accident probabilities. In one evaluation, a panel of experts was asked whether specific measures would have prevented specific accidents. In the other, the frequencies of generic accident causes were established for specific sets of 219 rammings (collisions with fixed objects) and groundings.

The other study was performed from 1978-1981 by a team from the Norwegian classification society, Det norske Veritas (DnV) (69). This study produced a similar fault tree analysis of a specific grounding scenario (7 pages). Also, this study did not determine probabilities for the tree events either. However, this study did produce a detailed statistical analysis of 3,599 accidents, of which 2742 (76%) were collisions or groundings (70). This analysis included lists of potential safety measures for preventing those accidents.

There is a close correlation between the results of the statistical analyses performed during these two studies. However, there is no straightforward process to translate these statistics of top level events into probability estimates of the lower level events or factors that lead up to them. In the building fire analysis described above, the lower level events were discrete events that lent themselves to individual (independent) analysis or experimentation. Therefore, the solution lies in determining how to analyze individual events leading up to marine accidents as separate, independent events.

It is useful to consider a less detailed fault tree based on the general causes of marine collisions and groundings discussed in the above studies. This is shown in Figure 16. The top level event, "accident," could be split into its components of collisions and groundings, since the likeliest root causes for each are slightly different. However, they are combined here for simplicity. The author has chosen three broad causes of accidents: material failures that impact propulsion or steering, severe weather, and navigation errors. Not all accidents can be neatly categorized, even among these three broad categories. For instance, suppose a tanker near the coast suffers mechanical damage that degrades, but does not totally incapacitate the steering system. The vessel slowly heads for a safe port to make repairs. While enroute, the tanker encounters a

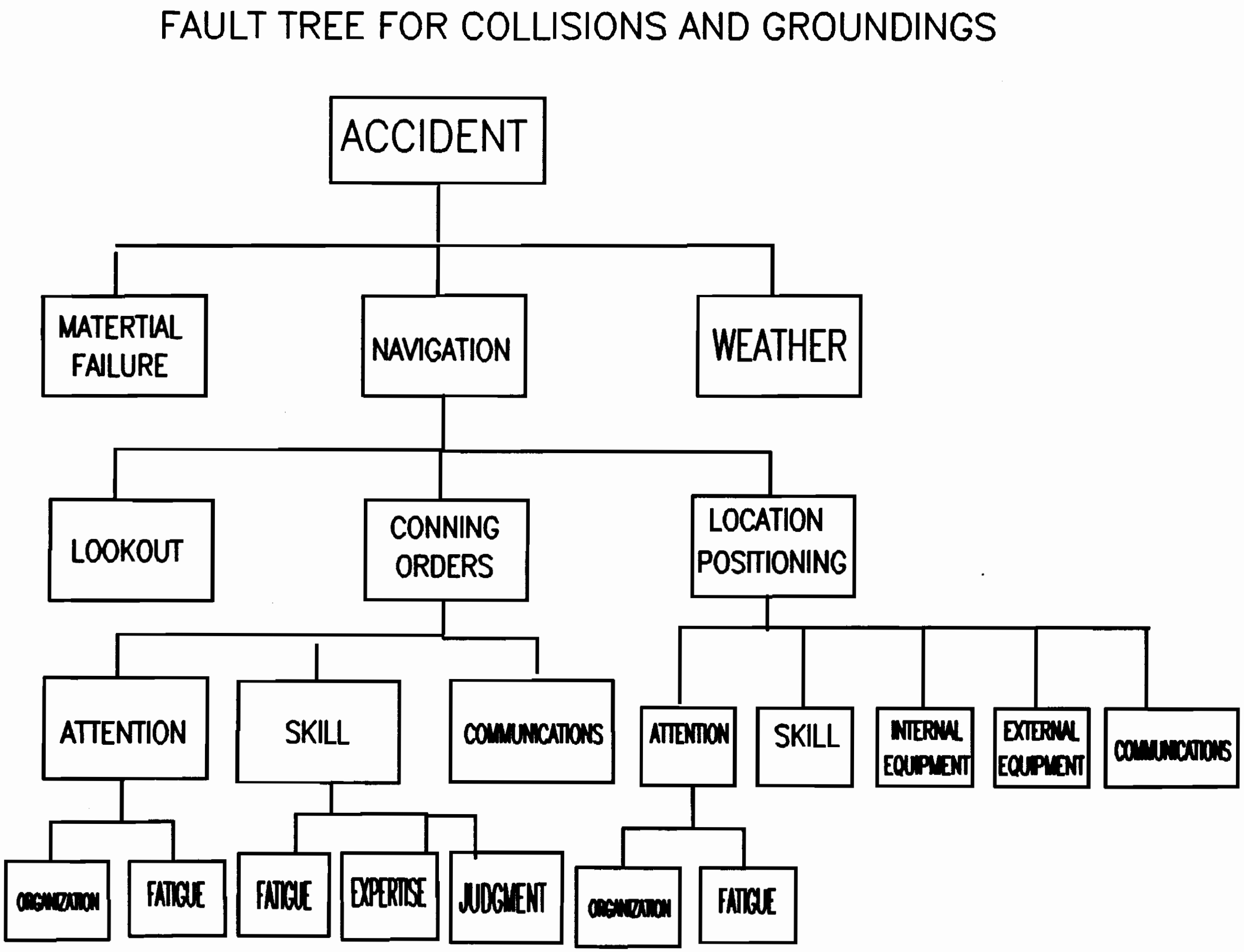


Figure 16. Fault Tree for Collisions and Groundings

hurricane, which throws the vessel upon a reef. This grounding could be attributed to both weather and material failure. Further details could even attribute the grounding partly to navigation error. Pate-Cornell has presented a method that could be adapted to allow experts to apportion the "blame" for a specific casualty to more than one cause (71). Since most accidents are primarily due to navigation errors, causes of material failure and weather will not be considered further.

Navigation errors can result from three broad sources. Navigation, as used here, refers to actions of the navigating watch to control the course and speed of the tanker. The conning officer (or officer of the deck) is the focal point of this activity. Data concerning a tanker's position, course, and speed relative to land (positioning) and data on the position, course, and speed of other vessels (lookout) must be provided to the conning officer. Various combinations of watchstanders (crew) and equipment (e.g. radar) will be available to perform these functions. On large military vessels, there may be over a dozen watchstanders on the bridge. On a few of the most modern tankers, there may be only one watchstander, assisted by highly automated equipment. The conning officer must digest this information and determine the appropriate actions (Figure 17). The quality of this determination is a function of the positioning and lookout information as well

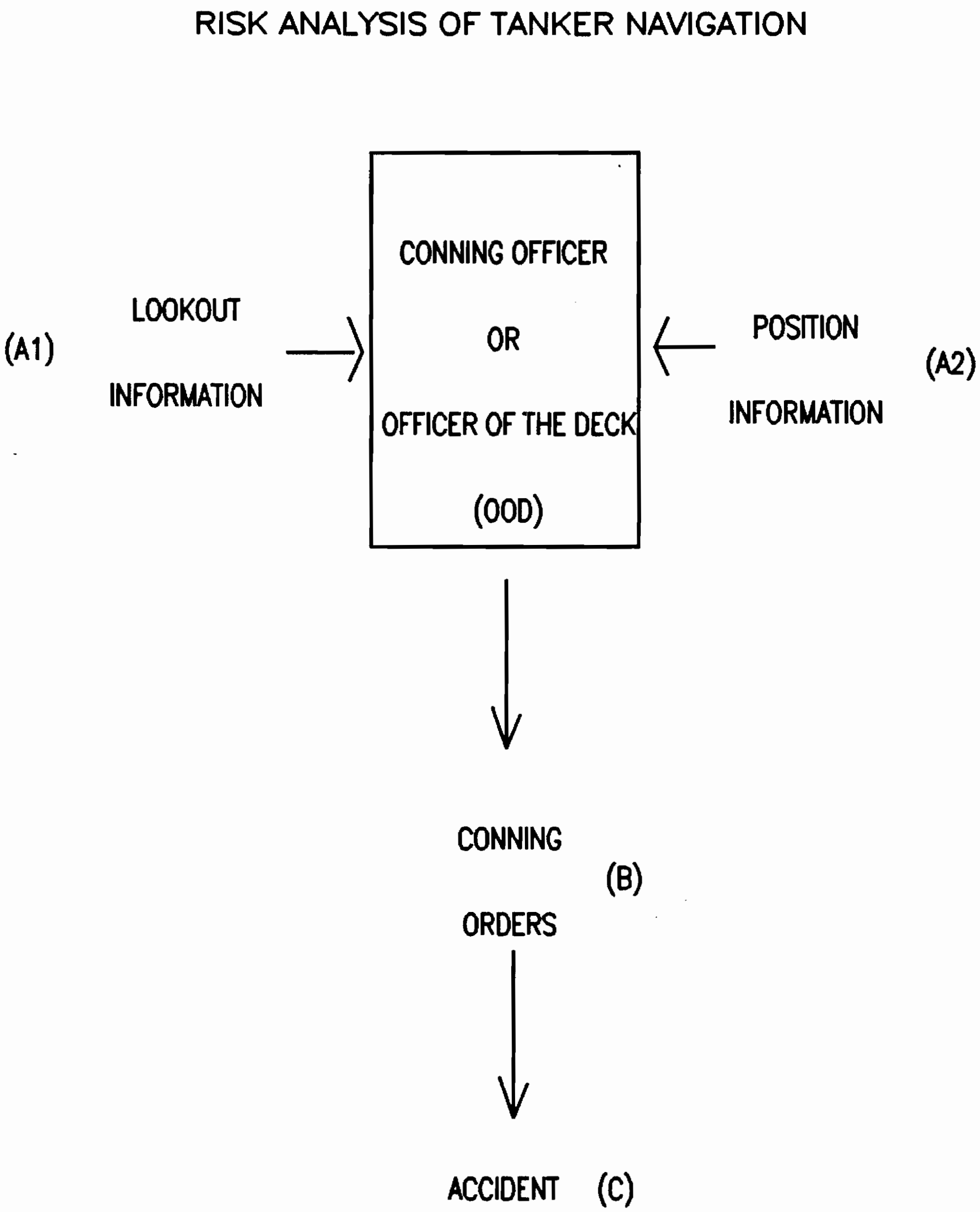


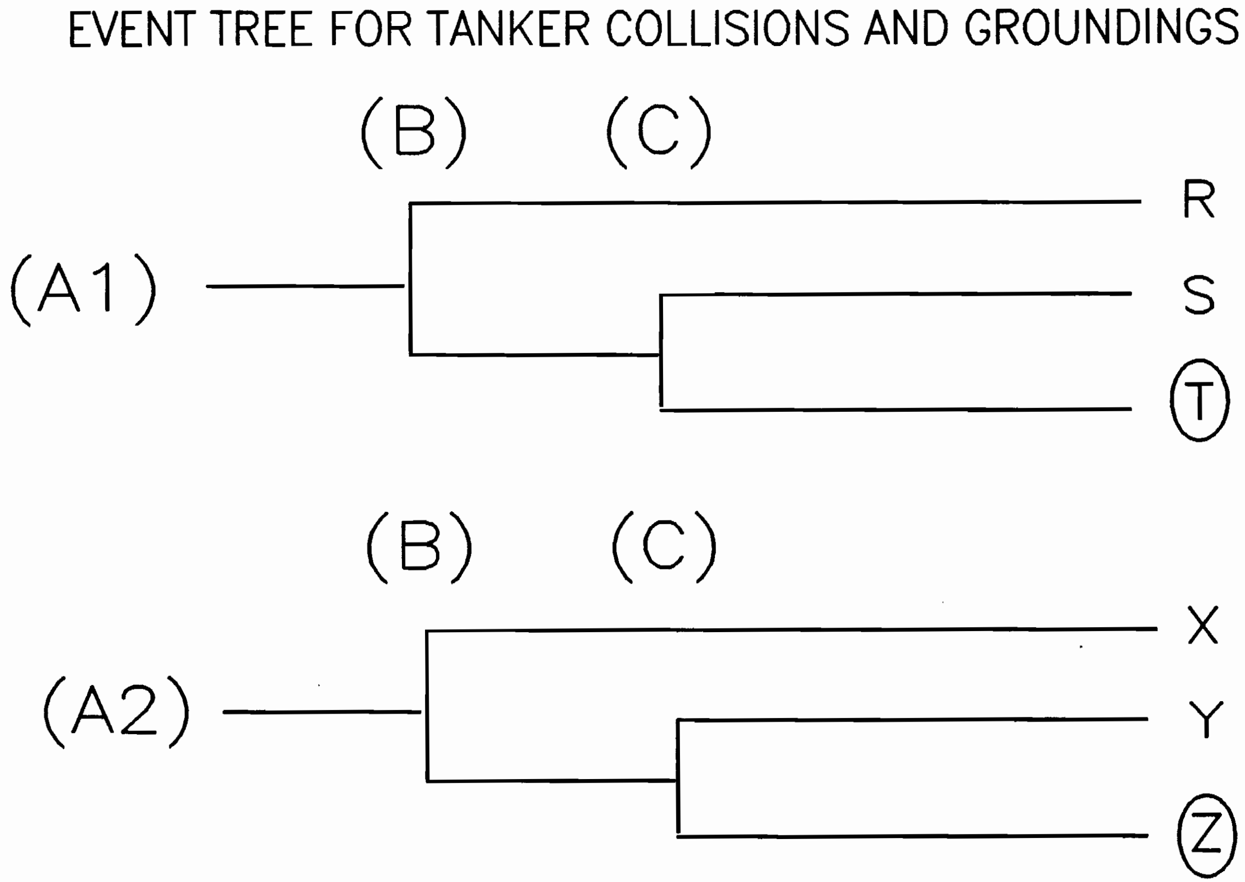
Figure 17. Risk Analysis of Tanker Navigation

as the alertness and skill of the conning officer. Orders for specific actions must often be transmitted to another watchstander for execution.

Assigning probabilities of success or failure to these events is a difficult problem. The probability of a tanker becoming involved in a collision, ramming, or grounding during a year from 1980-1989 was 7.6 X 10E-3 (72). If eighty percent of accidents are due to navigation error, then the probability of accident due to navigation error would be 6.1 X 10E-3. This presumes that the statistics of prior accidents precisely relfect future risk. However, this number does not provide the probability of a navigation error resulting in an accident. That probability would be heavily dependent on the definition of "error."

It is useful to compare an event tree for marine accidents (Figure 18) based on Figure 17, with the event tree presented by Zalosh for the turbine lube oil fire previously discussed (Figure 15). If the probability of an accident due to navigation error is 6.1 X 10E-3, then [A1+A2] X B X C = 6.1 X 10E-3. Factors such as attention, skill, external equipment (e.g. buoys), and internal equipment (e.g. radar) are not events, but they may have a significant impact on the probability of correct positioning (A2), which is an event.

If the effect of upgrading radar equipment is being evaluated, it is necessary to derive (A2) as a function of



(A1+A2) X (B) X (C) = (T) + (Z) = 6.1 X 10E−3

Figure 18. Event Tree for Tanker Collisions and Groundings

internal equipment, assuming other variables are held constant. It would be reasonable to assume that (A2) should decrease. However, it has been shown that the introduction of radar did not decrease the overall accident rate (73)! While it is likely that (A2) did actually decrease, there was an apparent offsetting increase in (B). The probable cause of the increase is over-reliance on the radar (inattention) and/or increased risk-taking (judgment) of actions that would not be considered without radar. Similarly, actions that decrease the overall probability of one type of accident (collision) may increase the probability of another (grounding) (74). Figures 17 and 18 ignore the additional accident-producing errors that initiate at (B).

It is becoming clear that establishing probabilities of events relating to marine accidents is a complex problem. When compared to events related to building fires, there are many more (undetermined and unfixed) variables that affect probability. In addition, these events and factors involve human reliability. It is much easier to establish the effect of insulation on fire resistance than to establish the effect of radar on a conning officer's judgment. Determining the probability of success or failure of events with a significant human component is discussed in the next section.

IX. Human Reliability Analysis to Support the Risk Analysis

People are a significant system component of an operating tanker. Since accidents are attributed to "human error" more often than to any other cause, it is necessary to understand the reliability of the human component in order to evaluate and improve the reliability of the entire system.

Figure 19 represents the phases of a human reliability analysis (75). Key tasks are identifying the potential human errors and determining their probabilities. It is necessary to identify relevant tasks (events) that must be performed by the human before they can be evaluated for potential errors that could prevent successful performance. The two risk analyses for marine accidents discussed in the last section each performed a highly detailed qualitative analysis of hypothetical accidents. Standard hypothetical accidents would have to be established for evaluating potential error reduction from prospective safety measures. The level of detail must be commensurate with the capability and necessity for evaluating the details. It may be possible to stop breaking down the tasks after a point where the results from further analysis would have little impact on the overall results. For example, to evaluate the impact of improved positioning due to upgrading the radar, it may not be necessary or practical to investigate every potential

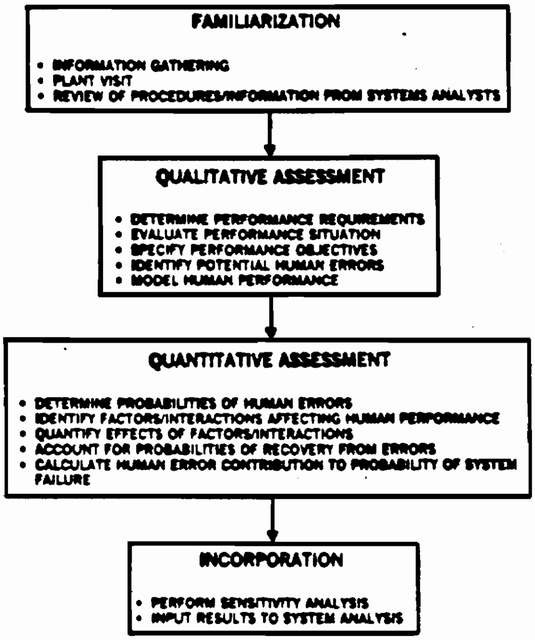


Fig. 1. Four phases of Human Reliability Analysis.

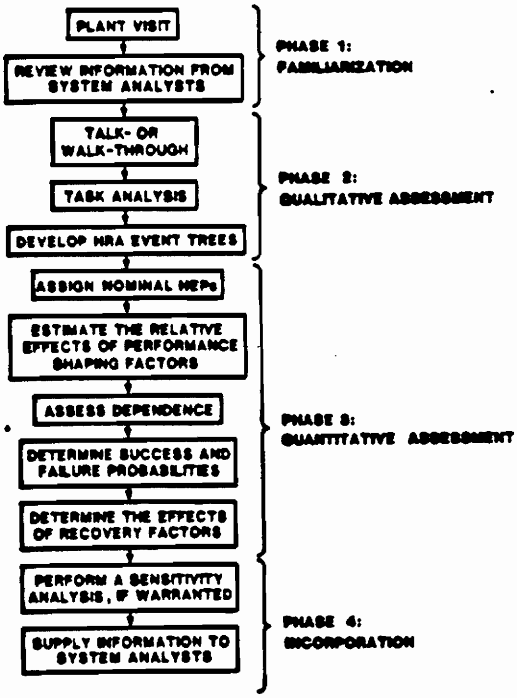


Fig. 3. Outline of a THERP procedure for HRA.

Figure 19. (References 75 and 80)

task associated with use of the radar. If the upgrade permits more distant coverage, the evaluation should examine errors likely to be affected by that feature. However, the degree to which coverage distance should be considered when establishing benchmark probabilities of accident (from all causes) must be carefully considered. Statistics of past cases where this may have been a factor could be helpful. However, just using expert opinion may be equally valid.

After qualitative analysis has established specific events for further study, the probability of their successful completion (as a function of variable conditions) must be established. This quantitative analysis can be difficult to perform. Bell notes that probability estimates can be based on data stores, expert prediction, or extrapolation of data from similar events (76). Hall addresses the problem of making valid use of available data as well as considerations for collecting data with regard for its use in estimating probabilities of error (77).

"Error" must be defined before it can be quantified. The number of actual errors can be divided by the total opportunity for error to derive the human error rate. This data can be taken from actuarial sources, developed by simulation, or estimated by experts. Hall splits errors into three broad categories: cognitive (judgement), procedural (management), and multiple (many procedural errors). Cognitive errors are the most significant error type for the nuclear industry. Redundancy mitigates the impact of procedural errors. The least amount of data is available on cognitive errors. According to Hall, the only sources for cognitive error data are expert opinion and advanced simulation (78). However, the author is not convinced that actuarial data could not be evaluated for information on cognitive error.

Dhillon discusses several procedures to evaluate human reliability (79). The Technique for Human Error Prediction (THERP), which is among the most widely known, is shown in Figures 19 and 20 (80)(81). However, THERP appears to be just another variation of risk analysis as previously discussed. Step 3 in the THERP process is the most important and least accomplished task. Dhillon notes that error rates can be estimated from experimental or other empirical data. The difficulties with such data have been previously addressed. Pontecorvo's method, also shown in Figure 20 (82), is similar to THERP. Dhillon does concede that "there is a lack of data in human reliability work in comparison to the availability of techniques and methods for predicting human reliability" (based on that lacking data) (83). Possible sources of data include expert opinion, laboratory simulation, and actuarial records. Various data banks from all three sources have been established.

Chapannis and Johnson have presented the concept of "error-provocative" situations (84). This concept

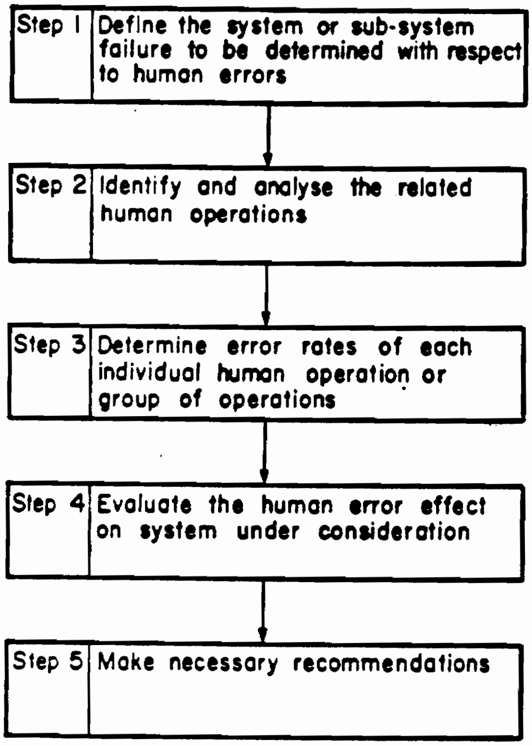


Figure 5.1. Steps associated with THERP.

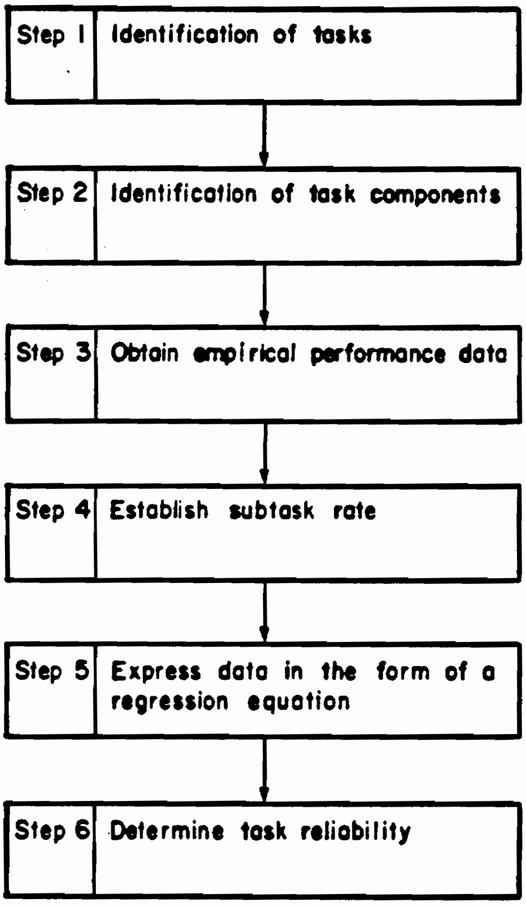


Figure 5.4. Steps of Pontecorvo's approach.

Figure 20. (References 81 and 82)

recognizes that the probability of error is a function of the factors (or the state of variables) relevant to a given situation. It also recognizes that all errors do not result in accidents. Therefore, situations where errors, but not necessarily accidents, have occurred, may be analyzed for useful data. The amount of potential data can be greatly increased by considering errors, or "near-misses" in addition to actual accidents. This concept is incorporated in fault tree analysis, where errors are considered as faults which may or may not result in an accident. However, the expansion of data collection efforts to include errors and near-misses could provide a valuable source of new data for performing fault tree analyses. Data collection from marine accidents has been generally limited to actual accidents.

Availability of appropriate data is the most missing link to permit widespread application of human reliability analysis. Expanding the data pool to include errors as described above is part of the solution to this problem. In addition to expanding the data pool, improvements in the extraction of data from the pool is necessary. Swain has presented procedures and forms for collecting and recording data, shown in Figures 21 and 22 (85). A primary step is to identify and analyze "performance shaping factors" (PSF) which modify or influence task performance (86). This step is performed as part of any human (or other) reliability

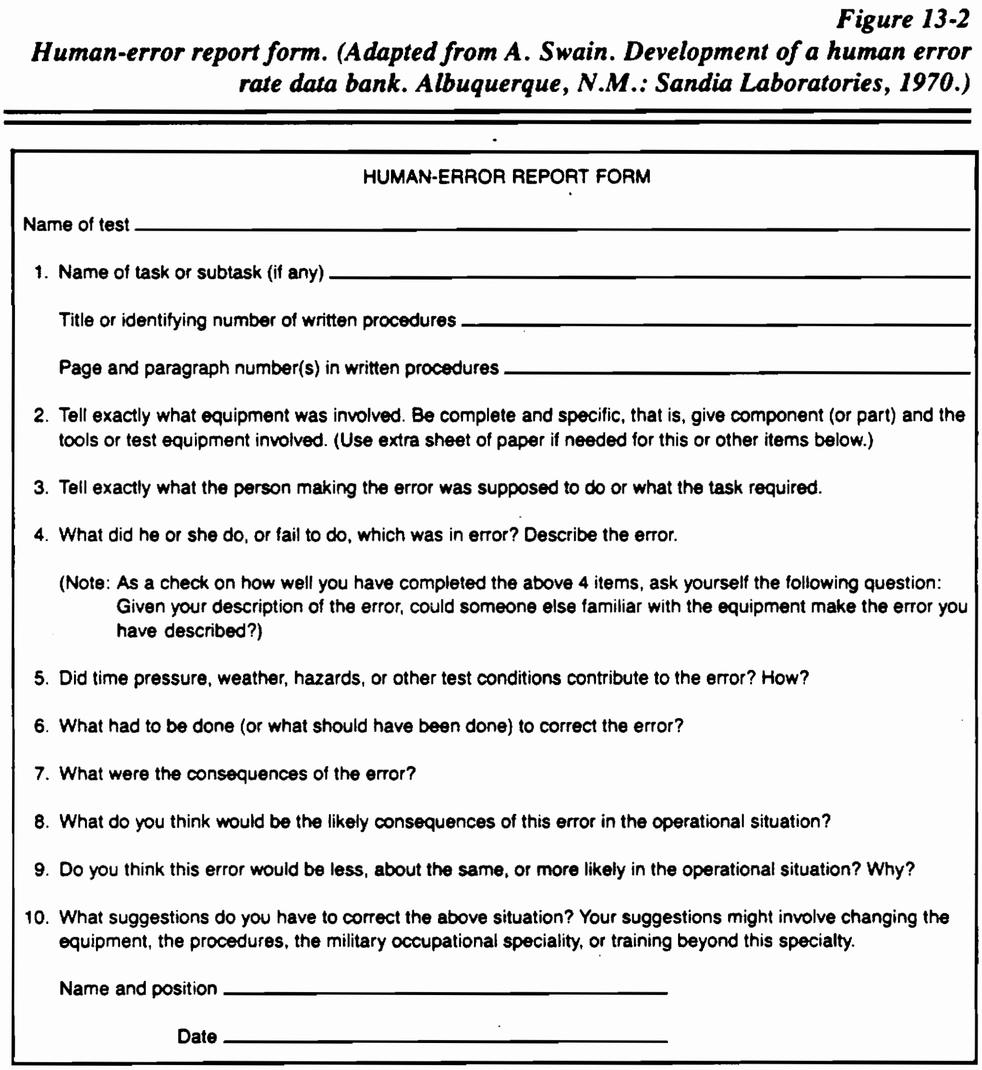


Figure 13-2

Human-error report form. (Adapted from A. Swain. Development of a human error rate data bank. Albuquerque, N.M.: Sandia Laboratories, 1970.)

HUMAN-ERROR REPORT FORM

Name of test ________________________________

1. Name of task or subtask (if any) ________________________________

   Title or identifying number of written procedures ________________________________

   Page and paragraph number(s) in written procedures ________________________________

2. Tell exactly what equipment was involved. Be complete and specific, that is, give component (or part) and the tools or test equipment involved. (Use extra sheet of paper if needed for this or other items below.)

3. Tell exactly what the person making the error was supposed to do or what the task required.

4. What did he or she do, or fail to do, which was in error? Describe the error.

   (Note: As a check on how well you have completed the above 4 items, ask yourself the following question: Given your description of the error, could someone else familiar with the equipment make the error you have described?)

5. Did time pressure, weather, hazards, or other test conditions contribute to the error? How?

6. What had to be done (or what should have been done) to correct the error?

7. What were the consequences of the error?

8. What do you think would be the likely consequences of this error in the operational situation?

9. Do you think this error would be less, about the same, or more likely in the operational situation? Why?

10. What suggestions do you have to correct the above situation? Your suggestions might involve changing the equipment, the procedures, the military occupational speciality, or training beyond this specialty.

    Name and position ________________________

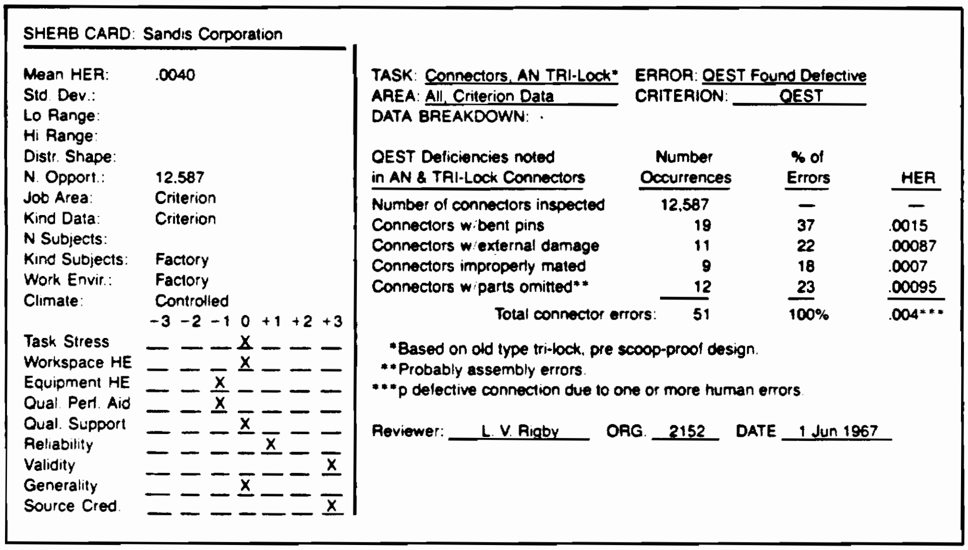
    Date ________________________

Figure 21. (Reference 85)

Figure 13-3

The SHERB card: (A) front; (B) back. (From A. Swain. Development of a human error rate data bank. Albuquerque, N.M.: Sandia Laboratories, 1970.)

A The front side of a typical SHERB card.



SHERB CARD: Sandıs Corporation

Mean HER: .0040
Std Dev.:
Lo Range:
Hi Range:
Distr. Shape:
N. Opport.: 12.587
Job Area: Criterion
Kind Data: Criterion
N Subjects:
Kind Subjects: Factory
Work Envir.: Factory
Climate: Controlled

	−3	−2	−1	0	+1	+2	+3
Task Stress				X			
Workspace HE				X			
Equipment HE			X				
Qual. Perf. Aid			X				
Qual. Support				X			
Reliability					X		
Validity							X
Generality				X			
Source Cred.							X

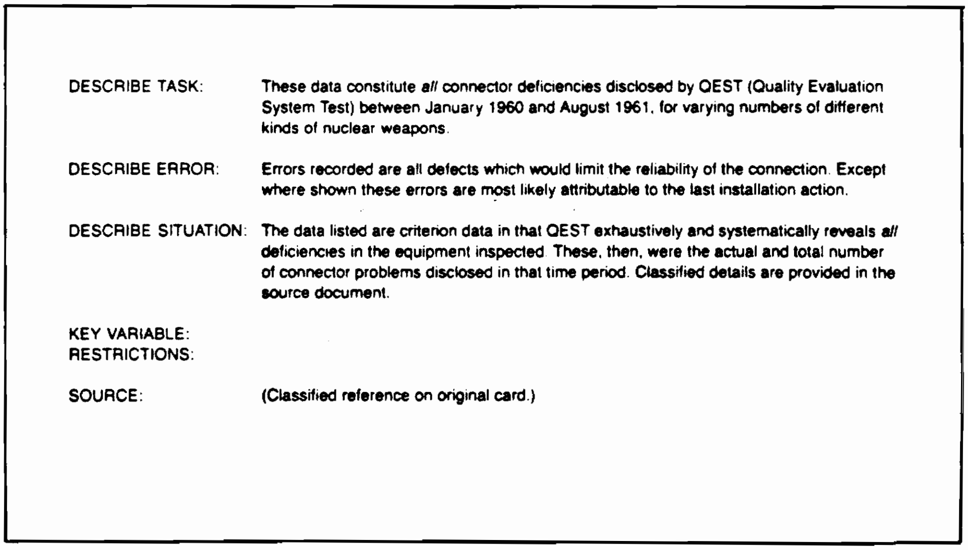
TASK: Connectors, AN TRI-Lock* ERROR: QEST Found Defective
AREA: All, Criterion Data CRITERION: QEST
DATA BREAKDOWN: ·

QEST Deficiencies noted in AN & TRI-Lock Connectors	Number Occurrences	% of Errors	HER
Number of connectors inspected	12,587	—	—
Connectors w/bent pins	19	37	.0015
Connectors w/external damage	11	22	.00087
Connectors improperly mated	9	18	.0007
Connectors w/parts omitted**	12	23	.00095
Total connector errors:	51	100%	.004***

*Based on old type tri-lock, pre scoop-proof design.
**Probably assembly errors.
***p defective connection due to one or more human errors.

Reviewer: L. V. Rigby ORG. 2152 DATE 1 Jun 1967

B The back side of a typical SHERB card



DESCRIBE TASK:	These data constitute *all* connector deficiencies disclosed by QEST (Quality Evaluation System Test) between January 1960 and August 1961, for varying numbers of different kinds of nuclear weapons.
DESCRIBE ERROR:	Errors recorded are all defects which would limit the reliability of the connection. Except where shown these errors are most likely attributable to the last installation action.
DESCRIBE SITUATION:	The data listed are criterion data in that QEST exhaustively and systematically reveals *all* deficiencies in the equipment inspected. These, then, were the actual and total number of connector problems disclosed in that time period. Classified details are provided in the source document.
KEY VARIABLE:	
RESTRICTIONS:	
SOURCE:	(Classified reference on original card.)

Figure 22. (Reference 85)

analysis, even though different labels (rather than PSF) may be used (87). PSF's include all the factors shown in Figure 16 that influence the probability of specific errors. For example, Swain has estimated that experience (skill) can decrease the probability of error when performing certain operations by half. The qualitative relationship between experience and human reliability is intuitive. However, quantifying such relationships can be difficult without valid supporting evidence (88).

The author is aware of two human reliability studies of marine collisions, which have been previously discussed. Brok and van der Vet focus on the performance of Collision Avoidance Maneuvers (CAM) as a means to assess the probability of collisions (89). They have used a Bayesian approach to aggregate expert opinions of the influence of relevant factors (PSF's again) on collision probability. This method estimates the number of CAMs necessary for a specific voyage as well as the probability for successful completion of each CAM. Brok and van der Vet then compare results from this method with probabilities based on actuarial data (collisions/total transits) for the Scheldt River. They note that data for similar waters can be adapted with caution. Plots of their results for several factors are shown in Figure 23 (90). This process can overcome some of the difficulties in using methods based solely on limited empirical data. Kwik has presented a very

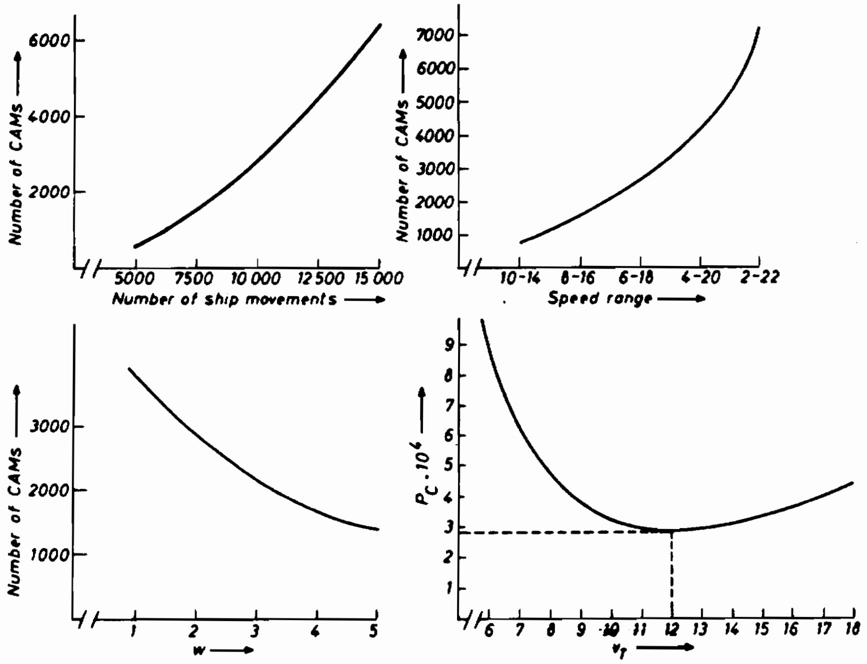


Figure 23. Collision Avoidance Maneuvers (Reference 90)

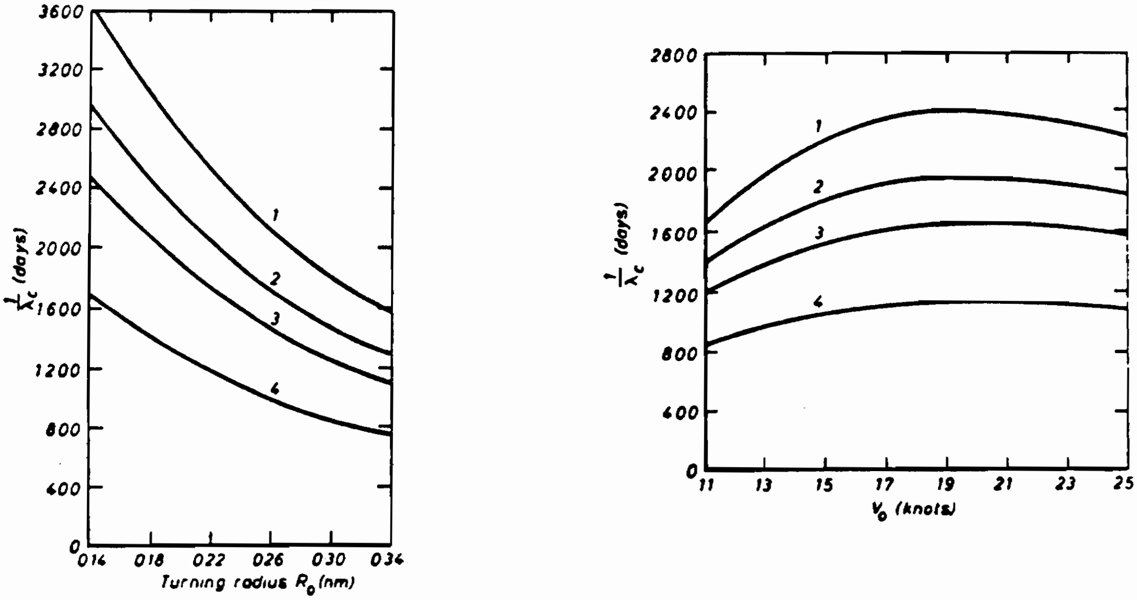


Figure 24. Collision Probability (Reference 92)

similar method to estimate collision probability in the Dover Strait as a function of PSF's, based on empirical data (91). Plots of his results are shown in Figure 24 (92). Both sets of results show that there are optimal speeds for transiting specific areas to minimize the probability of collision. It would be interesting to compare results from these methods for the same waters.

Now that the current state of human reliability analysis, risk analysis, and cost-benefit analysis have been examined with respect to marine accidents, their future application to preventing tanker collisions and groundings are addressed in the final two sections.

X. Observations of Industry Experts

The need for action to prevent tanker accidents is not new. This problem has been recognized and potential solutions have been debated for decades. The observations of contemporary industry experts provide excellent insights on actions with significant potential to reduce accident risk as well as on certain factors that are impeding such progress. The most important areas discussed for future action are improvements in casualty data extraction and analysis, the role of human factors, and economic incentives for safety.

Brace has noted that aircraft casualties are investigated by technical experts with an emphasis on collecting data for improving safety, whereas marine casualties are investigated with an emphasis on liability (93). He also noted that marine casualty statistics that do exist are not readily available in a format which supports research. Meek et al. have also noted that the air transportation industry has had more success in developing effective safety measures based on accident research (94). Harrold discusses the current environment in which marine casualty investigations occur (95). He cites the need for casualty data to be freely available and notes that the Institute of Marine Engineers maintains a library of casualty data. Recently, the International Maritime

Organization (IMO) encouraged member states to compile and share casualty data (96). However, the current international consensus does not go beyond encouragement.

It is only in recent times that the significant role of human factors in marine transportation has become widely recognized. Petersen attributes the first text on accident prevention which emphasizes human factors to H. W. Heinrich in 1931 (97)! The date "1931" is repeated twelve times in the first chapter of Petersen's book. This is a strong reminder to the reader that the role of humans in causing accidents, and the role of management to prevent them, are certainly not new concepts. Unfortunately, the marine industry has been slow to recognize and act on this. Brace concluded in 1980 that there was an urgent need to revise ship operating procedures (98). The International Maritime Organization issued recommended guidelines on management for the safe operation of ships and for pollution prevention in 1989, fifty-eight years after the first edition of Heinrich's book (99)! Spruyt expects that these guidelines "are a start to what will be a continuing and relentless pressure to bring all ship operators up to the standards of the leaders." (100) The Norwegian classification society, Det norske Veritas, has established classification rules for ship management and operation in response to the IMO guidelines (101). These rules adapt existing international ISO-9000 standards for use by the marine industry. These ongoing activities are an encouraging sign of progress.

The advisability and practicality of providing financial encouragement for safe practices are controversial topics that are now receiving considerable attention. Nunn suggests that "insurers must find ways to give greater reward to the top flight owner." (102) He recommends insurance discounts based on the quality of ship management. Maughan recommends against a rating scheme to compare fleets, citing the lack of a capable authority to perform the ratings and the difficulties such ratings would pose for the industry. "Would anyone contemplate allowing the operation of jumbo jets full of holiday makers being operated by 'one-star' (five-star being best) airlines?" (103) Hopefully not. However, many tankers are indeed operated by 'one-star' owners, while others are of much higher caliber. Pretending that 'one-star' operations do not exist does not serve to improve them. Scutts notes that "the only commitment we (insurers) expected of them (ship owners) was to comply - as we assume they did with statutory regulations - and to be classed. Possibly for far too long we have expected too much of the Classification Societies who, just like marine underwriters, are subject to commercial pressures." (104) Cowley recounts a continuing debate over the relationship between insurance and safety, noting that accident rates are decreasing while average single accident costs are rising (becoming even more LP/HC incidents)(105). Cheek recalled a 1981 study that determined "the previous known incident (when a British captain delayed sailing due to unseaworthiness) was in 1876!" (106) Kelly questions whether it is "really in the public good that a shipowner that runs a tight ship be faced in the event of an accident with multi-million dollar penalties, the inability to limit his liability, and possibly a jail sentence to boot?" (107) Meek et al. note that none of the principal members of the marine industry - owner, operator, shipper, insurer, or classification society - have a strong incentive to promote safety (108). They conclude that the marine insurance industry could play a greater role. Meek and Fulford repeat these same points (109). They further conclude that "in the end therefore, it must be outside interests i.e. the general public who bring pressure to bear for greater safety and who decide, not necessarily in a particularly logical or rational way, whether ships are safe enough." Maybourn notes that there have been suggestions for "a relationship (between insurance rates and) with quality as well as with performance, but it is difficult to see how the necessary data bases could be provided and maintained. It seems that not only does insurance allow the unfortunate to be supported by the fortunate, but also allows the bad to be supported by the good." (110) He also recalls suggestions that "a good safety record should be self-financing; the cost of accidents should exceed the cost of preventing them."

XI. Conclusions and Recommendations

The public is requiring an improvement in the overall level of safety of oil tankers. It is important that safety measures to reduce risks of collisions and groundings be developed with due consideration for technical and economic feasibility. Three subject areas in which advancements would lead to substantial improvements in tanker safety are casualty data collection, evaluation of prospective measures, and implementation of justified measures. Current procedures for casualty investigation must be overhauled to facilitate the extraction and availability of useful data. Next, this data must be applied to perform cost-benefit evaluations of prospective safety measures. Lastly, the legal and economic environment must be revised to encourage the implementation of justifiable measures by ensuring their cost-effectiveness in specific applications.

The primary obstacle to performing meaningful cost-benefit evaluations is the lack of data to support human reliability analyses of tanker collisions and groundings. New initiatives to actively support the collection and availability of marine casualty data are essential. It is possible to improve the quantity and quality of available data on marine casualties; however, this will require a concerted international effort.

The focus of marine casualty investigations must be changed to emphasize data that is useful for analyzing casualties for the purpose of preventing recurrences. The role of human factors is essential to this analysis. Standardized forms will assist shipboard personnel to determine which data will be most useful and obtain it. The scope of analyzed incidents must be broadened beyond those resulting in actual injuries or substantial property damage. There should be "near-miss" standards that would trigger the recording of data if a vessel comes within a specific distance (or similar standard) of a collision or grounding. Additionally, data should be recorded when an officer or crew member believes that a specific situation posed a significant accident risk. There must be no legal or financial disincentive to recording and providing such data. Various forms of legal immunity and/or anonymity could be necessary. Fines for noncompliance would be impractical to enforce; detection of "near-misses" by an enforcement agency would be difficult or impossible (and certainly not cost-effective). The aggregation of data should be standardized. Universally implemented standardized forms (as described above) and a worldwide central data collection point would be very helpful. The International Maritime Organization (IMO) is the logical conduit for developing and implementing universal forms as well as for receiving and maintaining data. Access to such an IMO data bank should be widely available through member states, professional engineering societies, and classification societies.

Advances in the evaluation of prospective measures can improve tanker safety by focusing limited resources on the measures that provide the greatest accident risk reduction. These could include specific measures (such as a number of watchstanders or limits to working hours) to implement general guidelines for ship management that have been recently proposed. If the costs and benefits of alternative measures could be quantified, it would be possible to select an optimal set of cost-effective measures. It is not currently possible to perform a cost-benefit analysis that can support this optimization. It is generally possible to estimate the costs of prospective measures that have been developed to the point of technical feasibility. The inability to estimate the benefits (risk reduction) due to implementation of prospective measures precludes precise cost-benefit analyses of such measures.

It should be possible to perform precise cost-benefit analyses in the future. The first step is to build the necessary marine casualty data bases outlined above. As this is accomplished, the specific tasks or operations needed for successful navigation (such as the Collision Avoidance Maneuvers previously discussed) should be defined. Fault trees could be used to accomplish this. With the updated data bases, the human reliability of these specific tasks can be evaluated using THERP, Pontecorvo's approach, or similar procedure. Once a base line task reliability (or error rate) is established, it should be recalculated for variations of the conditions associated with the base line case. These variations reflect the implementation of specific prospective measures.

In addition to investigating measures that primarily impact human reliability, measures to improve equipment reliability should also be similarly examined. Once sufficient information has been developed on the impact of prospective measures on equipment and human reliability, their overall impact on the risk of collision and grounding should be established. These risk analyses can be accomplished by forming event trees using the previously developed fault trees and reliability information. This will also be an iterative process to determine the overall impact of various measures, implemented to varying degrees.

Once the above impacts have been evaluated, prospective measures can be optimized in order of greatest risk reduction per unit cost. At this point, curves of costs and resulting benefits can be plotted. However, the benefits will be in raw units (such as accidents prevented). A value judgment (Figures 9 and 10) is needed to translate these benefits into monetary values. This will permit comparison of associated costs and benefits using consistent units.

Developing a list of specific, effective safety measures is insufficient to ensure their implementation. Owners (and other responsible parties) must be ensured financial rewards for reducing risk; safety measures must be conspicuously cost-effective. Insurance is a logical vehicle for accomplishing this. Liability for accidents should have a legal limit - albeit a high one to ensure that damaged persons are likely to be appropriately compensated and that appropriate efforts are undertaken to restore the environment. The limit must be sufficiently high to permit governments, especially ours, to ratify it. The limit must be ironclad - without loopholes permitting local governments to exceed it. Once a limit has been established, insurance to cover the entire limit should be required. Since insurance represents a relatively small percentage of overall costs, the amount of available cover is probably underestimated (though P & I clubs may need restructuring).

The rates for this insurance cover must be strongly based on risk. National or international commissions (of industry, government, or both) could be developed to set guidelines for determining premiums. Guidelines based on the model shown in Figure 25 could be used to ensure financial advantage for risk reduction measures. The most essential attribute of an effective plan is firm linkage between accident risk and insurance cost. Despite valid claims that it will be very difficult to defend specific rates based on the relationship between specific safety measures and their impact on risk, rates based on the status quo are less defensible. The terms in Figure 25 relate to those in Figure 16. (Revenue) represents the immediate impact on gross profits from implementing a safety measure (PS). This is a downward sloping line, with a slope corresponding to the price of implementation. If there is no relationship between risk and insurance premiums (In), there is an economic incentive to provide the least possible degree of safety. Net profit, the vertical difference between (Revenue) and (In), is maximized at the vertical axis, where no resources are expended for safety. (PSo) represents the minimum implementation that may be required by a flag state, port state, or classification society. There may be no economic incentive to exceed it. If premiums are related to risks, (In) is replaced by (Risk). There is an economic incentive to implement to the point where the difference between (Revenue) and (Risk) is maximized (PSn). If the public demands a greater reduction of risk, rates could be artificially tweaked (I) to maximize net profit at a greater degree of implementation (PSg). Figure 26 compares net profit <u>as</u> a function of risk, with net profit <u>not</u> as a function of risk. Since marine accidents are relatively low-probability events, it will be much more appropriate to base premiums primarily on overall evaluations of risk, rather than just on accident history.

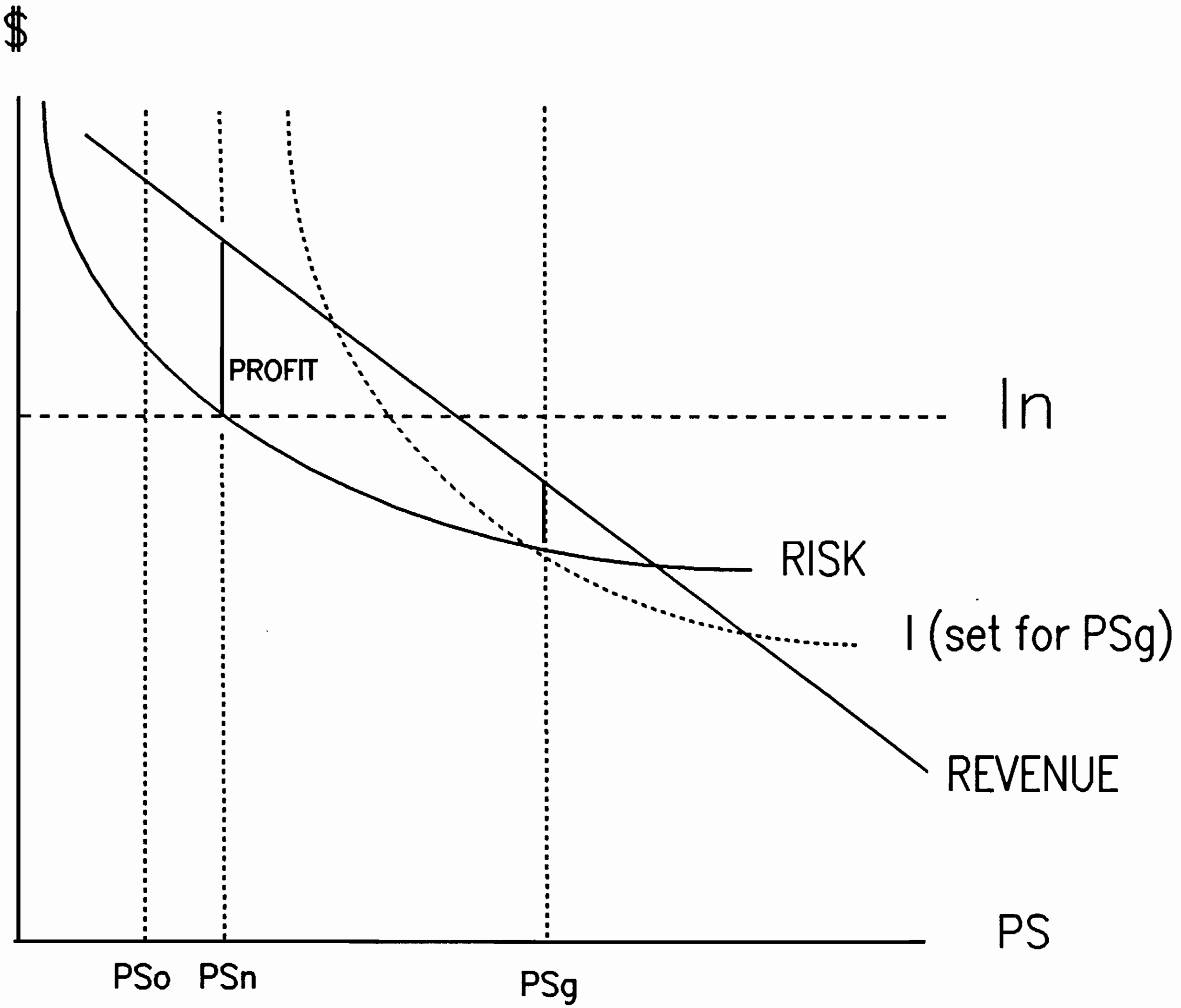


Figure 25. Adjusting Insurance Cost as a Function of Risk

These evaluations must consider the crew as an integral component of the tanker system.

Classification societies, or similar organizations, will be needed to provide meaningful information to insurers on the condition of tankers (and of their crews). Such information should be publicly available. Class does not now provide sufficient information. Vessels (and crews) should be classed or rated according to risk. The role of classification societies should be expanded to verify the condition of vessels between current surveys. The advent of third party pre-charter surveyors, who perform optional supplementary surveys for prospective charterers, shows a need for more frequent and insightful surveys than are currently provided by classification societies. It is simpler for only one organization, such as the relevant classification society, to be responsible for assessing a vessel's condition. Of course, the owner must bear responsibility for maintaining a vessel's condition. Insurance rates based on reliable assessments of risk will encourage owners to fulfill this responsibility.

Related to this proposed expansion of the role of classification societies is a need to sever financial ties between owners and classification societies. The current arrangement, whereby owners pay classification societies to inspect and approve their tankers, has few tolerated parallels. If information obtained by a classification

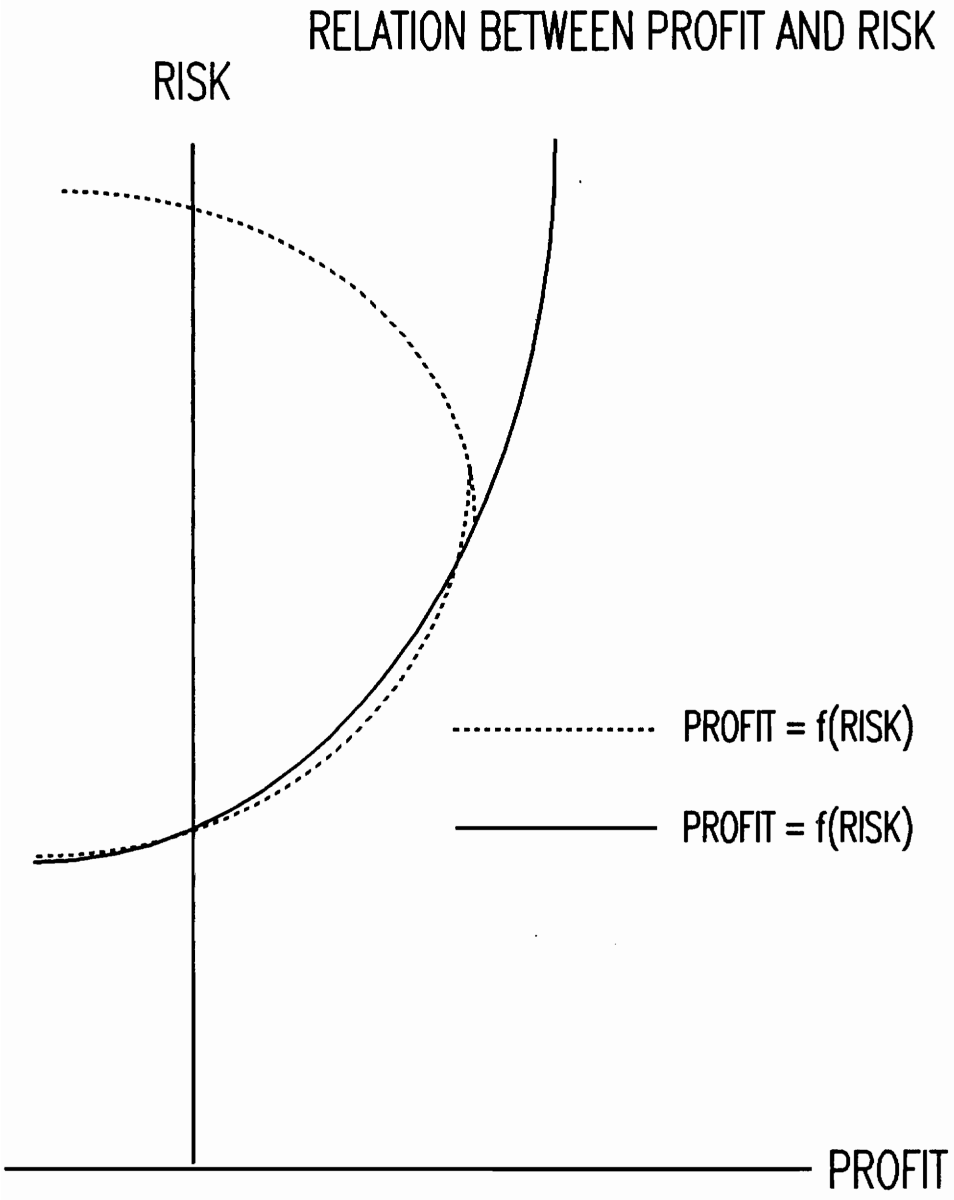


Figure 26. Relationships Between Profits and Risk

society is primarily for the use of an insurer, charterer, or government, that user should pay for the information. An insurer can, in turn, recoup classification fees through premiums. Classification fees should be a legitimate cost of operating an insurance business or club, for which sufficient reliable information should be expected.

Obviously, a tremendous amount of technical capability and political fortitude will be needed to accomplish this. Laws on marine insurance and liability would have to undergo radical revision. An unprecedented degree of international cooperation would be essential. However, it is indeed possible to make concrete progress in this direction, even though an ideal system for creating appropriate incentives may be impossible to define, let alone achieve. This report has outlined some steps in the areas of cost-benefit analysis, risk analysis, and human reliability analysis that could permit progress to begin.

XII. Glossary

Accident	Unintended incident that results in damage or injury to persons, property, or the environment.
Casualty	same as Accident (used interchangeably).
Classification Society	Non-profit organization which develops and maintains standards for ship construction and maintenance, and that certifies (classes) vessels meeting those standards.
Collision	Vessel makes physical contact with another vessel.
Conning officer	Directs the speed and heading (direction) of a ship.
Cost-benefit analysis	Evaluation and comparison of the costs to implement or execute an action and of the benefits derived from the action. These are often difficult to quantify, especially in consistent units.
Crude oil	Oil that is taken directly from below the ground and which has not been refined. It is composed of many different types (fractions) of hydrocarbons as well as impurities.
Deadweight tonnage (DWT)	Cargo carriage capacity of a vessel, usually in metric tons.
Error	A significant deviation from a previously established, required, or expected standard of performance that results in (or raises the probability of) unwanted or undesirable delay, difficulty, problem, trouble, incident, malfunction, or failure (or accident). (111)
Event tree	Graphic representation of potential sequences of events that depicts the probability of occurrence of each

	event (or probability of a specific outcome of an event) associated with each potential sequence. An accident may be the final event or outcome of one or more potential sequences.
Failure Mode and Effects Analysis (FMEA)	An equipment (not human) oriented analysis of the ways in which equipment can fail, and the effects of such failures on other system elements. The analysis determines components likely to fail, probable modes of failure, causes of failure, effects and criticality of failure, probability of failure, and actions to prevent or correct failures. (112)
Fault tree	Symbolic representation of events or occurrences (faults) that lead to an accident.
Flag of Convenience (FOC)	A country in which a vessel is registered in order to avoid taxes and/or regulations.
Grounding	Vessel makes physical contact with the bottom of the ocean, lake, bay, or river it is transiting
Human reliability	The probability that humans will accomplish a job or task successfully at any required stage in system operation within a specified time limit (if time is specified). (113)
International Maritime Organization (IMO)	United Nations agency which develops international treaties regulating the construction and operation of ships.
Navigation	Coordination of a vessel's movement during a voyage.
Positioning	Determining the location of an object with respect to the earth's surface (e.g. latitude and longitude; or, a specific distance and direction from a fixed point).
Product oil	Individual products that have been refined from crude oil. These include any petroleum based liquid

	substance, except for crude oil and petrochemicals. However, the distinction between oil products and petrochemicals is not always clear.
Risk	Probability of an incident or occurrence that generally has undesirable consequences.
Safety	Mitigation of accident risk.
Steering system	System to control the rudder, which controls the heading or direction of a vessel's movement.
Timecharter	Lease of the transportation services of a vessel for a specific time. "Bareboat" charters include only the vessel itself; other necessary expenses are not included.
Tonne	Metric ton, or 2205 pounds. It is commonly used in international treaties.
Vessel Traffic System (VTS)	A navigation system which monitors the movement of vessels within a specific area that may have designated rules such as traffic lanes and speed limits.
Watchstander	Member of a team assigned to perform ship navigation or engineering duties during a specific time period.

XIII. Literature Cited

(1) Committee on Tank Vessel Design, Tanker Spills: Prevention by Design, National Academy Press, 1991

(2) B. S. Blanchard and W. J. Fabrycky, Systems Engineering and Analysis, Prentice Hall, 1981

(3) Committee on Tank Vessel Design, ibid., Figs. 1-10 and 1-11

(4) C. Perrow, Normal Accidents, Basic Books, Inc., 1984, p. 174

(5) J. F. C. Brok and R. P. van der Vet, "The Analysis and Processing of Marine Collision Data," Journal of Navigation, Royal Institute of Navigation, Vol. 37, No. 1, Jan. 1984

(6) A. Marks, Elements of Oil Tanker Transportation, PennWell Publishing, 1982, Chapter 1.

(7) I. L. Buxton, Engineering Economics and Ship Design, Third ed., British Maritime Technology, Ltd., 1987, p. 13-14

(8) Shipping Statistics and Economics, No. 234, April 1990, Drewry Shipping Consultants, Ltd., (England), page 1

(9) A. J. Klingel, notes on Cost Assumptions-New Tank Vessels, U.S. Coast Guard Headquarters, May 1990.

(10) I. L. Buxton, ibid., p. 27

(11) B. Wilhelmsen, "U.S. Tanker Legislation - An Industry Reaction," International Association of Independent Tanker Owners, presented at the Marine Log Symposium on Tanker Legislation, Washington, D.C., October 1990

(12) D. Arnott, Classification of Ships, American Bureau of Shipping, 1944

(13) J. Cowley, "The International Maritime Organisation and National Administrations," Transactions of the Institute of Marine Engineers (England), Vol. 101, Part 3, 1989

(14) C. E. Russell, "Liability and Damage Compensation for Tanker Oil Spills," Conference on Oil Tanker Transportation (November 1978), U.S. Department of Transportation and the University of South Carolina, Report No. PS-80600 DOT, 1979

(15) P. G. F. Leader, "Protection and Indemnity Insurance," Maritime Policy and Management (Wales), Vol. 12, No. 1, Jan-Mar 1985

(16) N. C. Proctor, "Marine Insurance," Maritime Policy and Management (Wales), Vol. 12, No. 1, Jan-Mar 1985

(17) B. S. Blanchard and W. J. Fabrycky, ibid., p. 19

(18) M. Meek and K. G. Fulford, "The Ship: Design, Construction, and Initial Certification," Conference on Safety at Sea and in the Air, The Royal Aeronautical Society, November 1990

(19) Committee on Tank Vessel Design, ibid., p. 5

(20) J. G. Beaumont, "Ship Construction and Safety (with particular reference to oil tankers)," Transactions of the Institute of Marine Engineers (England), Vol. 102, Part 5, 1990

(21) W. Kramer, American Institute of Marine Underwriters, Nor-Shipping Conference, 1989, reported by R. Mottley, "Underwriters Bemoan Shipping Trends," Marine Log, August 1989.

(22) D. G. Redpath, "Marine Surveys and Surveyors Today," Transactions of the North East Coast Institution of Engineers and Shipbuilders (England), Vol. 104, No. 2, Mar 1988

(23) W. J. Warren, "Who the Hell Cares About Ship Safety," American Shipper, January 1991

(24) B. S. Blanchard and W. J. Fabrycky, ibid., p. 4

(25) D. B. Brown, Systems Analysis and Design for Safety, Prentice-Hall, 1976, Section 1.2

(26) A. Stratton and W. E. Silver, "Operational Research and Cost Benefit Analysis on Navigation, With Particular Reference to Marine Accidents," Journal of the Institute of Navigation, Vol. 23, No. 3, July 1970

(27) W. A. Dunn and P. M. Tullier, Spill Risk Analysis Program Phase II - Methodology Development and Demonstration, Operations Research, Inc., Department of Transportation Report No. CG-D-15-75, Aug 1974

(28) E. S. Cheaney and A. J. Coyle, System Safety Analysis of a Commercial Vessel, Battelle Columbus Laboratories, Department of Transportation Report No. CG-D-39-77, Nov 1977

(29) K. H. Drager et al, "DnV to Investigate Collisions and Groundings," Safety at Sea, International Trade Publications, Ltd. (England), No. 112, Jul 1978

(30) K. H. Drager et al, "Cause Relationships of Collisions and Groundings - Conclusions of Statistical Analysis," Norwegian Maritime Research, Vol. 9, No. 3, Aug 1981.

(31) E. H. Beetham, "Safety in Operations - The Seafarer's View," Conference on Safety at Sea and in the Air, ibid.

(32) D. R. Drew and C. H. Hsieh, A Systems View of Development, Cheng Yang Publishing Co. (Taipei, ROC), 1984

(33) D. R. Drew, System Dynamics: Modeling and Applications, Department of Civil Engineering, Virginia Polytechnic Institute and State University

(34) D. R. Drew, ibid., Section 3.4

(35) A. A. Moghissi, "Risk Analysis: The Process and Its Application," Engineering Applications of Risk Analysis, The American Society of Mechanical Engineers, 1988, p. 4

(36) R. Goss, "Rational Approaches to Maritime Safety," Transactions of the North East Coast Institution of Engineers and Shipbuilders (England), Vol. 105, No. 3, Jun 1989

(37) R. Goss, ibid., Figure 4

(38) R. Goss, ibid., Figure 5

(39) U.S. Executive Order 12291

(40) D. B. Brown, ibid., Ch. 10

(41) D. B. Brown, ibid., Figure 10.3

(42) A. A. Moghissi, ibid.

(43) D. B. Brown, ibid., Figure 10.1

(44) K. Giziakis, "Economic Aspects of Marine Navigational Casualties," Journal of Navigation, Royal Institute of Navigation, Vol. 35, NO. 3, Sep 1982

(45) K. Giziakis, ibid., Figure 1.

(46) R. Maybourn, "The Broad Operational Scene and Its Management: Shipping," Conference on Safety at Sea and in the Air, ibid.

(47) J. R. Canada and W. G. Sullivan, Economic and Multiattribute Evaluation of Advanced Manufacturing Systems, Prentice-Hall, 1989, p. 386

(48) T. A. Meyer, "Risk Based Decision Making with Potential Application to Public Works Improvements," Engineering Applications of Risk Analysis, ibid.

(49) R. A. Cox and D. H. Slater, "Risk Assessment of Chemical Plants in Europe," Low-Probability/High Consequence Risk Analysis, Plenum Press, 1984

(50) J. A. Cumming and T. K. Jenssen, "Risk Analysis of Shipping and Offshore Structures," Journal of Navigation, Royal Institute of Navigation, Vol. 37, No. 1, Jan. 1984

(51) R. A. Cox and D. H. Slater, ibid., Figure 3.

(52) J. A. Cumming and T. K. Jenssen, ibid., Figure 1

(53) R. A. Cox and D. H. Slater, ibid., Figure 2.

(54) A. Mosleh and G. Apostalakis, "Models for the Use of Expert Opinion," Low-Probability/High-Consequence Risk Analysis, ibid.

(55) H. F. Martz and M. C. Bryson, "Predicting Low-Probability/High-Consequence Events," Low-Probability/High-Consequence Risk Analysis, ibid.

(56) K. G. Vohra, "Statistical Methods of Risk Assessment for Energy Technology," Low-Probability/High-Consequence Risk Analysis, ibid.

(57) N. D. Singpurwalla, Introduction to Section 3 - Part I, Low-Probability/High-Consequence Risk Analysis, ibid.

(58) L. G. Abramson, Introduction to Section 3 - Part II, Low-Probability/High-Consequence Risk Analysis, ibid.

(59) T. B. Ballestero et. al., "Flood Prediction with Causal Analysis," Low-Probability/High-Consequence Risk Analysis, ibid.

(60) K. G. Vohra, ibid.

(61) D. B. Brown, ibid., Section 4.2

(62) Y. Fujii, "Recent Trends in Traffic Accidents in Japanese Waters," Journal of Navigation, Royal Institute of Navigation, Vol. 35, No. 1, Jan 1982

(63) K. H. Kwik, "Collision Rate as a Danger Criteria for Marine Traffic," Journal of Navigation, Royal Institute of Navigation, Vol. 39, No. 2, May 1986

(64) J. R. Spouge, "The Use of Risk Assessment for Ships Carrying Hazardous Cargo in Port Areas," Conference on Safety at Sea and in the Air, ibid.

(65) R. G. Zalosh, "Applications of Engineering Risk Analysis for Industrial Fire and Explosion Protection," Engineering Applications of Risk Analysis, ibid.

(66) W. Holmes, referenced in R. G. Zalosh, ibid., Fig. 5

(67) J. R. Spouge, ibid.

(68) W. A. Dunn and P. M. Tullier, ibid.

(69) K. H. Drager, et al, "Study of Relationships Between Different Causes of Collisions and Groundings," Third International Symposium on Marine Traffic Service, Liverpool, 1978. Veritas (Det norske Veritas) Report No. 78-081

(70) K. H. Drager et al, "Cause Relationships of Collisions and Groundings - Conclusions of Statistical Analysis," Norwegian Maritime Research, Vol. 9, No. 3, Aug 1981.

(71) M. E, Pate-Cornell, "Opinions and Preferences in Decision Problems," Low-Probability/High-Consequence Risk Analysis, ibid.

(72)D. S. Aldwinckle, "Ship Casualties and Some Loss Control Indicators for Safety Management," Conference on Safety at Sea and in the Air, ibid., Table 3

(73) C. Perrow, ibid., p. 203

(74) A. N. Cockcroft commenting on K. H. Kwik, ibid., p. 298

(75) B. J. Bell, "Human Reliability Analysis: A Case Study," Low-Probability/High-Consequence Risk Analysis, ibid., Figure 1

(76) B. J. Bell, ibid.

(77) R. E. Hall, "Quantification of Human Performance Through the Use of Nuclear Power Plant Experience," Low-Probability/High-Consequence Risk Analysis, ibid.

(78) R. E. Hall, ibid.

(79) B. S. Dhillon, Human Reliability with Human Factors, Pergamon Press, 1986

(80) B. J. Bell, ibid., Figure 3

(81) B. S. Dhillon, ibid., Figure 5.1

(82) B. S. Dhillon, ibid., Figure 5.4

(83) B. S. Dhillon, ibid., page 166

(84) A. Chapannis and W. G. Johnson, quoted in D. Petersen, Human-Error Reduction and Safety Management, Aloray, Inc., 1984

(85) A. D. Swain, quoted in D. Petersen, ibid., Figures 13-2 and 13-3

(86) A. D. Swain, quoted in D. Petersen, ibid., page 174

(87) D. Meister, "Alternate Approaches to Human Reliability Analysis," Low-Probability/High-Consequence Risk Analysis, ibid., page 325

(88) D. Meister, ibid., page 327

(89) J. F. C. Brok and R. P. van der Vet, ibid.

(90) J. F. C. Brok and R. P. van der Vet, ibid., Figures 3-6

(91) K. H. Kwik, ibid.

(92) K. H. Kwik, ibid., Figures 2 and 3

(93) J. Brace, "The Application of Civil Aviation Operational Techniques to Merchant Ship Operations," Journal of Navigation, Royal Institute of Navigation, Vol. 33, No. 2, May 1980

(94) M. Meek et al., "A Shipbuilder's View of Safety," Maritime Policy and Management, Vol. 12, No. 4, Oct-Dec 1985

(95) A. F. Harrold, "The Investigation of Marine Casualties," Transactions of the Institute of Marine Engineers (England), Vol. 100, Part 3, 1988

(96) International Maritime Organization Resolution A.637(16), adopted 19 October 1989

(97) D. Petersen, ibid., Chapter 1

(98) J. Brace, ibid.

(99) International Maritime Organization Resolution A.647(16), adopted 19 October 1989

(100) J. Spruyt, "Marine Insurance and the Ship Manager," remarks to the 1990 annual conference of the International Union of Marine Insurance in London, reported in *Seaways*, The Nautical Institute, November, 1990.

(101) "DnV to Class Management," *Safety at Sea*, June 1990

(102) A. S. Nunn, "Marine Insurance Now and in the Future," *Transactions of the Institute of Marine Engineers*, Vol. 101, pages 97-111

(103) M. J. H. Maughan, "Chairman of the Joint Hull Committee Answers the Questions," remarks to the 1990 annual conference of the International Union of Marine Insurance in London, reported in *Seaways*, The Nautical Institute, November, 1990.

(104) T. Scutts, commenting on A. S. Nunn, ibid.

(105) J. Cowley, commenting on A. S. Nunn, ibid.

(106) P. M. Cheek, commenting on A. S. Nunn, ibid.

(107) J. Kelly, "Future of Shipping - How it May Affect Insurers," remarks to the 1990 annual conference of the International Union of Marine Insurance in London, reported in *Seaways*, The Nautical Institute, November, 1990.

(108) M. Meek et al., ibid.

(109) M. Meek and K. G. Fulford, ibid.

(110) R. Maybourn, ibid.

(111) G. Peters, quoted in D. Petersen, ibid., p. 44

(112) B. S. Blanchard and W. J. Fabrycky, ibid., p. 353

(113) B. S. Dhillon, ibid., p. 3

XIV. Vita

Stephen Mark Shapiro was born in Baltimore, Maryland on October 24, 1960. He attended Tufts University in Medford, Massachusetts, where he earned the Bachelor of Science in Mechanical Engineering degree in 1982.

After graduation, he joined the federal civil service, preparing shipboard machinery specifications for the U.S. Coast Guard Headquarters' Naval Engineering Division.

In 1984, he left Headquarters to attend the USCG Officer Candidate School, where he was commissioned as an Ensign on May 4, 1984. After OCS, he was assigned to the Cutter ESCAPE, homeported in Charleston, South Carolina, as a shipboard engineering trainee. Upon leaving ESCAPE in 1986, he was reassigned to the USCG Marine Safety Center in Washington, where he reviewed merchant vessel construction plans for compliance with applicable safety requirements.

In 1988, he transferred from active duty back into the civil service. He returned to USCG Headquarters, where he develops construction requirements for tank vessels.

Steve Shapiro is a registered professional engineer and a third assistant engineer of motor vessels. He holds a commission as a Lieutenant in the USCG Reserve. He is a member of the American Society of Naval Engineers and the American Society of Mechanical Engineers.

Stephen M. Shapiro