

Tanker Environmental Risk - Putting the Pieces Together

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ABSTRACT

The tools necessary to quantify tanker risk, and to effectively make investment and regulatory decisions relative to tanker safety, are limited. In the absence of a complete quantitative understanding of tanker risk we see a number of knee-jerk reactions to public outcries over tanker safety. The complexity of the tanker/waterway system forces industry, government and academia to focus on manageable pieces of the total problem or, when a total system perspective is necessary, to take a top-down statistical approach. No one method of analysis, regulation, or piece of the system tells the whole story. This paper presents a total-system approach to tanker oil spill risk built from the bottom-up. A hybrid total-system model of tanker risk being developed at MIT is discussed. Students from a recent project course at MIT in tanker safety and invited guests contributed significantly to this development. Preliminary results, particularly for grounding accidents, are encouraging. A prioritized plan for further research is proposed based on these preliminary results and other insights derived from the work-in-progress.

BACKGROUND

Tankers support a major portion of world seaborne trade (Figure 1) and 40% of the world's energy demand. More than 99.99% of seaborne petroleum cargo is carried without incident. Due to the efforts of a large segment of the tanker industry, this record is improving. Despite this record, tankers spill an average of 100,000 tonnes of oil per year.

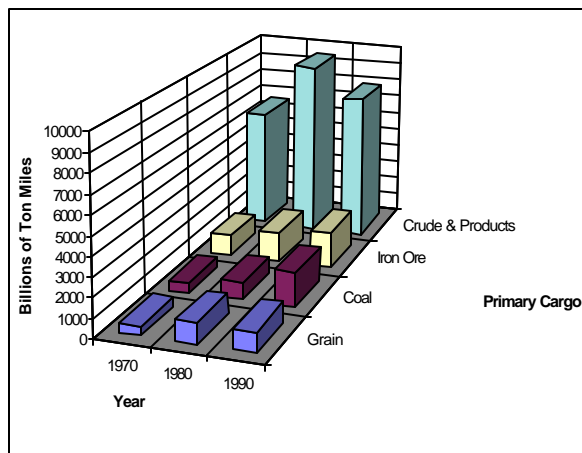


Figure 1. Seaborne Trade Primary Cargo [1]

As illustrated in Figure 2, tanker oil spill statistics represent a random process. They are influenced by many variables which are constantly changing, and whose relationship to

spill statistics is not well understood. Therefore, it is difficult to draw any cause and effect conclusions from statistics, which is necessary when implementing measures to reduce oil spills. Until there is a better understanding of accident mechanisms, any attempt to minimize accidents based on statistics alone is reactionary with questionable effectiveness.

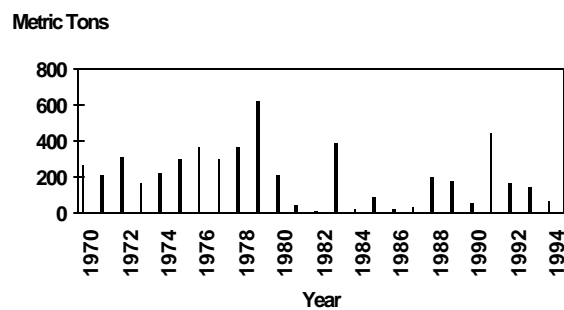


Figure 2. World Tanker Oil Spills [2]

Simply stated, risk is the product of the probability of an accident and the consequence of an accident. From Figure 2, the three worst years in recent history: 1979, 1983 and 1991, resulted primarily from three large spills (*Atlantic Empress*, *Castillo de Bellver* and *ABT Sumner*). Tanker oil spill risk is classified as low probability-high

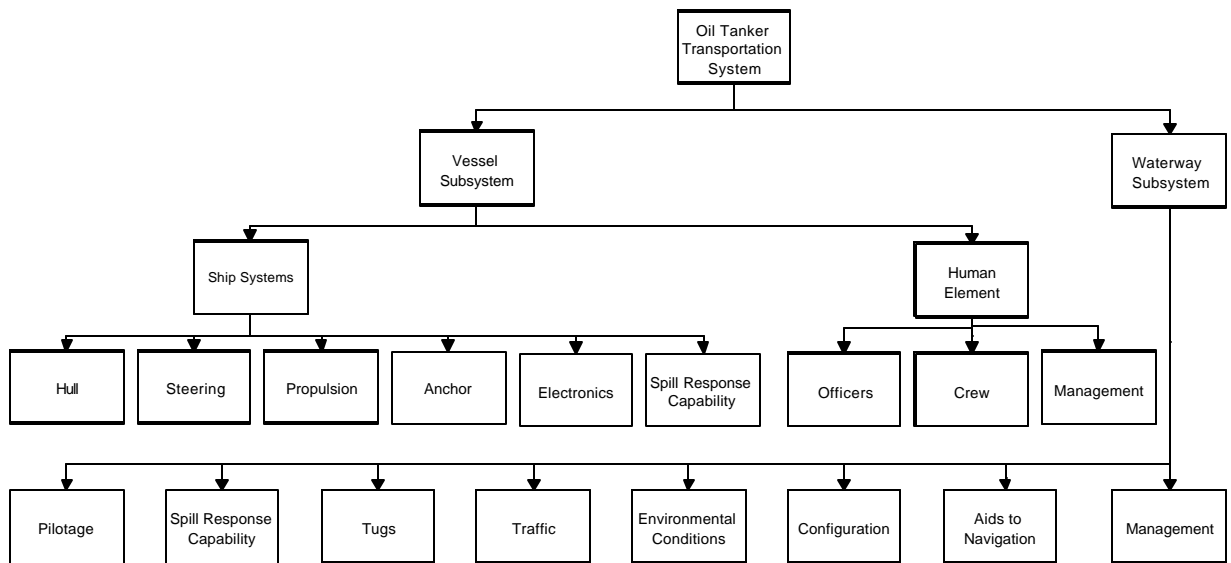


Figure 3. Oil Tanker Support System

consequence. The consequences of these spills were relatively minor compared to the large volume of oil spilled, and they received little public attention compared to the *Exxon Valdez* and the *Braer*. Consequence is dependent on location and the random nature of the ocean environment. The volume of oil spilled, although convenient, is not a valid consequence metric. The fate and effect of a spill is the best metric, but very difficult to quantify.

Given these difficulties with both the probability and consequence of tanker spills, can we say anything definitive? How do we quantify tanker risk so that we can make informed decisions regarding tanker safety? Top-down statistics provide only limited insight. We must work fundamentally from the bottom-up so that systematic causes and effects can be filtered from the apparent randomness and properly addressed. The probability of a spill and its consequence must both be considered.

The first obstacle encountered when approaching tanker risk from the bottom-up is the complexity of the tanker transportation system. Figure 3 provides some insight into the scope of this problem. The tanker cannot be analyzed in isolation from the waterway. Likewise, the waterway cannot be analyzed in isolation from the ship. Both the ship and waterway are complex systems involving physics and the human element. They are also extremely interdependent. A total-system approach must incorporate their inherent synergism.

There have been many methods of analysis and much regulation applied to pieces of the tanker risk problem. Methods of analysis include fault trees, influence diagrams, expert opinion, oil outflow calculations, collision and grounding models, structural damage models, human factors models and oil spill impact and cost models. Recent regulations include OPA-90, Standards of Training Certification and Watchkeeping (STCW), the International Safety Management (ISM) Code, and MARPOL Regulation 13F. Each of these brings something to bear on the total problem, but because of the complexity of the tanker/waterway system, no one method of analysis, regulation, or piece of the system tells the whole story. A total system approach is required to draw meaningful conclusions, make cost-effective investment decisions, and draft effective regulation.

TANKER SYSTEM MODEL

Overview

Different users require different perspectives on tanker risk.

Our tanker-transport system model analyzes a specific ship in a generic waterway, but it can be adapted to analyze a generic ship in a specific waterway or a specific ship in a specific waterway. This flexibility is necessary to allow the user to focus on ship design and regulation problems (specific ship/generic waterway), waterway design and

regulation problems (generic ship/specific waterway), or ship and waterway operations problems (specific ship/specific waterway).

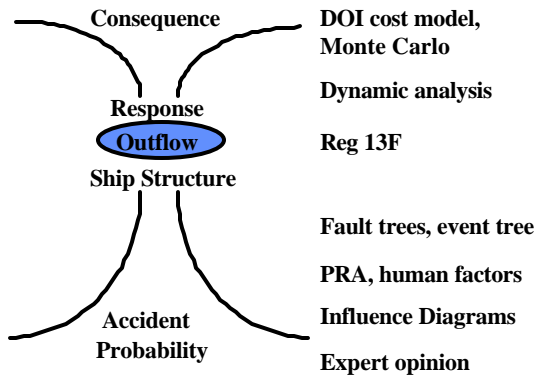


Figure 4. Tanker Risk Model Concept

The general structure of the model is illustrated in Figure 4. Accident probability is calculated using Probabilistic Risk Assessment (PRA) techniques including fault trees, event trees and human reliability analysis (HRA). Human failure events are quantified using basic Human Error Probabilities (HEP's) that are modified by a series of Performance-Shaping Factors (PSF's) [3]. Other probabilities are estimated using casualty statistics and expert opinion.

Once probabilities for the major oil spill events (grounding, collision, fire/explosion and global structural failure) are determined, probability of zero outflow and mean outflow are calculated using a simplified probabilistic method and a pdf for outflow is derived. Currently this method considers only ship principle characteristics and subdivision in estimating the extent of damage from collision or grounding. It requires the additional consideration of ship structural design to properly determine extent-of-damage probability density functions (pdf's).

Next, the immediate response to contain the spill is considered using a dynamic simulation model. Response is based on ship and waterway spill response assets. Probabilities are estimated using expert opinion. This calculation results in mean outflow after response.

Finally, spill consequence is calculated using a Monte Carlo simulation and a Department of the Interior (DOI) Type A Damage Assessment Model. The final risk metric for this calculation is in dollars (\$). The complete tanker risk calculation process is diagrammed in Figure 5.

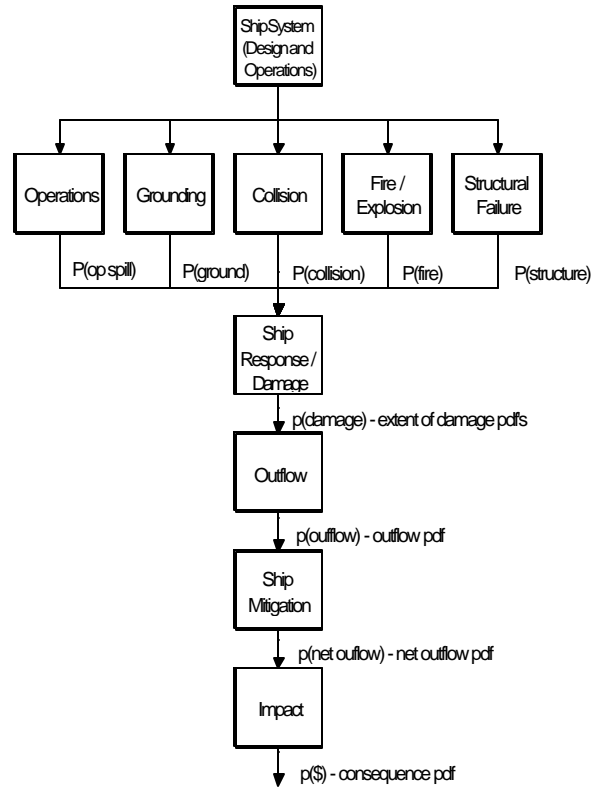


Figure 5. Tanker Risk Calculation

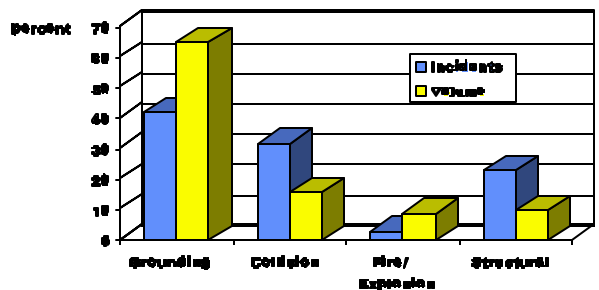


Figure 6. Major Tanker Oil Spill Causes [4]

Accident Probability

Four primary accidental oil spill causes are identified in Figure 6: grounding, collision, fire/explosion and structural failure. In our model each of these events is developed using PRA/fault tree analysis. Probabilistic risk assessment (PRA) provides a formal process of determining possible adverse occurrences, probabilities and expected costs for an undesirable event. Fault tree analysis is very effective in analyzing complex systems that have multiple failure modes

with physical and operational interactions, especially if the role of humans in the operation is a factor [5]. Fault tree analysis was developed for the aerospace industry for system safety analysis. Norman Rasmussen defined the essential tasks of a PRA in his safety study of the nuclear power industry [6]. Our model follows his example.

In constructing a fault tree, we start with a particular failure or undesired event and deductively work backwards to explore all the combinations of events that may lead to that failure. The reasoning used to build a fault tree for a system requires an understanding of the system and its intended use. At each reduction stage of the fault tree the causes for the undesirable top event must be determined in as broad of terms as possible. By being as general as possible at each reduction stage, it is more likely that all possible combinations of events may be taken into account.

Major disasters are rarely caused by any one factor. They arise from the unforeseeable concatenation of several diverse events, each one necessary but singly insufficient. Reason [7] has suggested a pathogen metaphor to emphasize the significance of causal factors present in the system before an accident sequence begins:

"All man-made systems contain potentially destructive agencies, like the pathogens within the human body. At any one time, each complex system will have within it a certain number of latent failures, whose effects are not immediately apparent but that can serve both to promote unsafe acts and to weaken its defense mechanisms. For the most part, they are tolerated, detected and corrected, or kept in check by protective measures (the auto-immune system). But every now and again, a set of external circumstances -- called here local triggers -- arises that combines with these resident pathogens in subtle and often unlikely ways to thwart the system's defenses and to bring about its catastrophic breakdown."

Like the etiology of multiple-cause illnesses due to resident pathogens, complex systems breakdown due to resident latent errors. The challenge for this framework is to show how latent and active failures combine to produce accidents and to indicate where and how more effective remedial measures might be applied.

When one considers all the things that must go wrong for an accident to occur, oil spills are truly remarkable events. Figure 7 illustrates the dynamics of an accident. Within the realm of accidents, system failures have their primary origins in the decisions of designers and high-level managers. At the ship level, the Master can exacerbate or mitigate the adverse effects of high level decisions, but the

Master can also introduce other pathogens into the system.

Each of the pathogens introduced into the system can play a significant role in both provoking and shaping a large set of individual errors. While very few individual errors result in actual damage or injury (giving a wrong rudder order in the open ocean has no effect on the safety of the ship), when errors occur in the presence of some hazard, then the potential for catastrophe is real. System defenses include redundancies, automatic safety devices, and alarms to warn operators of a hazardous situation. Since designers are unable to account for every possible situation, safety systems inherently have windows of opportunity for an accident trajectory to pass. Circumstantial factors can bias the system to align the mappings of the various failures, creating windows of opportunity through each layer of the system. Accidents occur when the mappings of system failures, human failures and individual errors all conform to allow the accident to breach each of the layers.

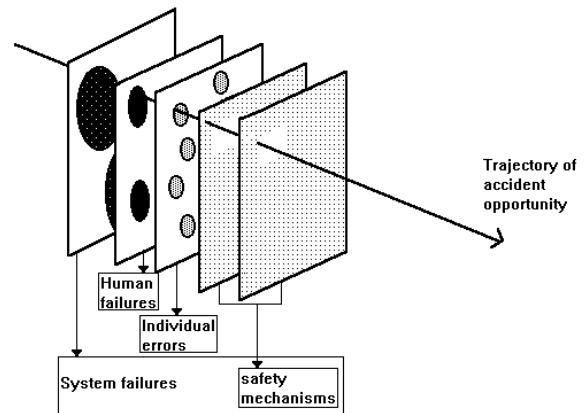


Figure 7. Dynamics of Accident Causation

Grounding Fault Tree

Figure 8 shows the top level of our very large oil spill accident fault tree.¹ Grounding fault tree examples sufficient to demonstrate the method are presented in the following paragraphs and in Figures 8 and 9. Grounding accidents include two broad categories:

1. Powered Grounding. The vessel is able to follow

¹ Fault tree logic incorporated in dynamic system model using modeling software (Vensim©).

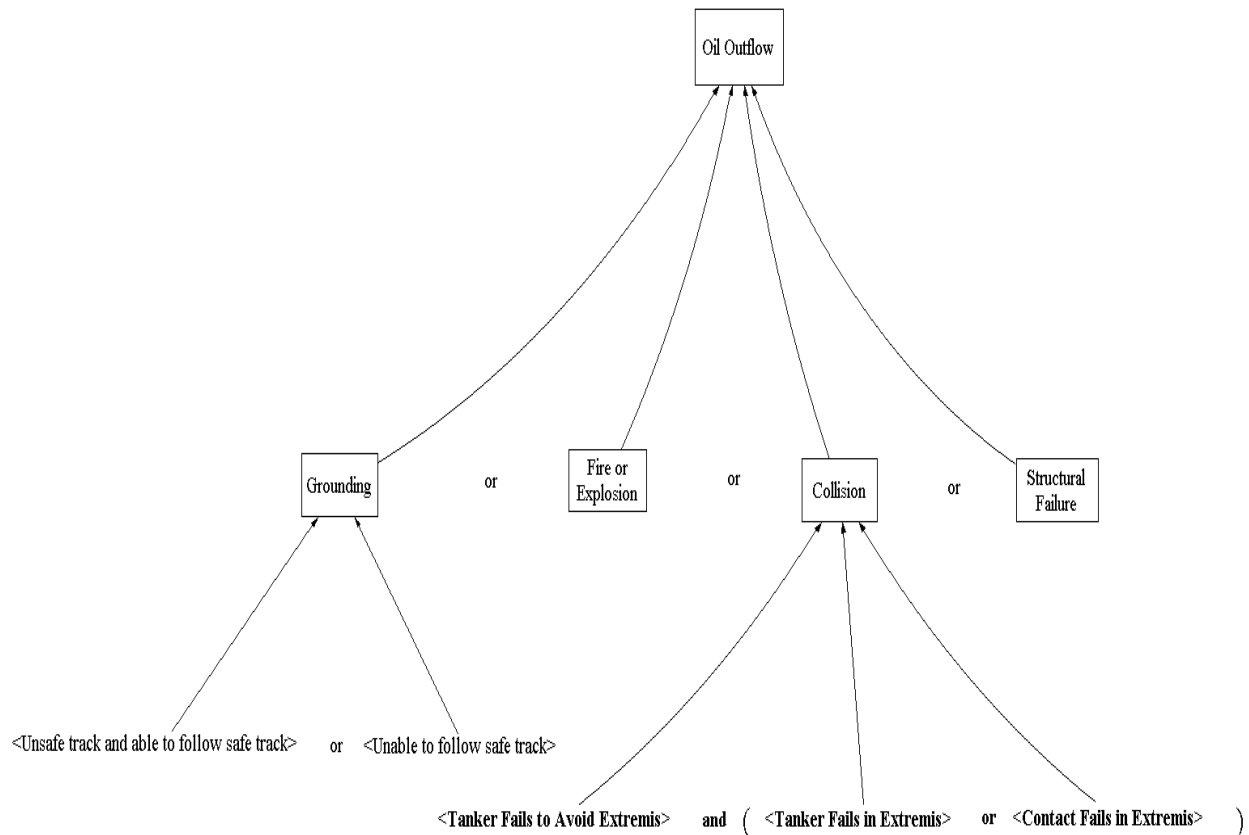


Figure 8. Top Level Oil Outflow Fault Tree

a safe track, however, it proceeds down an unsafe track due to planning or piloting failure.

2. Drift Grounding. The vessel is unable to follow a safe track because of mechanical failure, assistance failure and adverse environmental conditions.

The fundamental failures resulting in a powered grounding are in the processes of planning and piloting. Voyage planning and piloting are essential skills required of any mariner.

Piloting error is reflected in Figure 9 which shows the further development of the grounding fault tree in the specific event of a powered grounding where the actual course deviates from the desired track and is unsafe. The fault tree becomes increasingly specific at lower levels where basic probabilities can be assigned reflecting individual error or other system failure. Standard Human Error Probabilities (HEP's) are obtained from NUCREG/CR-1278, Handbook for Human Reliability Analysis [3]. Other probabilities are obtained from failure statistics, expert opinion and simulation studies. Event trees are used to further define tasks and

develop fault probabilities.

Taking a fix and detecting a difference error are essential tasks in the piloting process as shown in Figure 9. Taking a fix typically requires at least two radar ranges. This is done by selecting appropriate navigational aids, obtaining the ranges, and then plotting those ranges. The navigator must read the ranges off of the radar and plot them correctly on the chart. The result is the estimated ship's position at the time the ranges were taken. The ranges are presented in a digital format, hence, the applicable HEP is chosen from the table for "Probabilities of Errors of Commission in Reading Quantitative Information from Displays" [3]. The recording of the information obtained involves more than just writing down the information. Since some skill is required to plot ranges, the HEP for recording is taken from the table for "Probabilities of Error of Commission in Recording Readings" [3].

Once the fix is plotted, the navigator must assess if

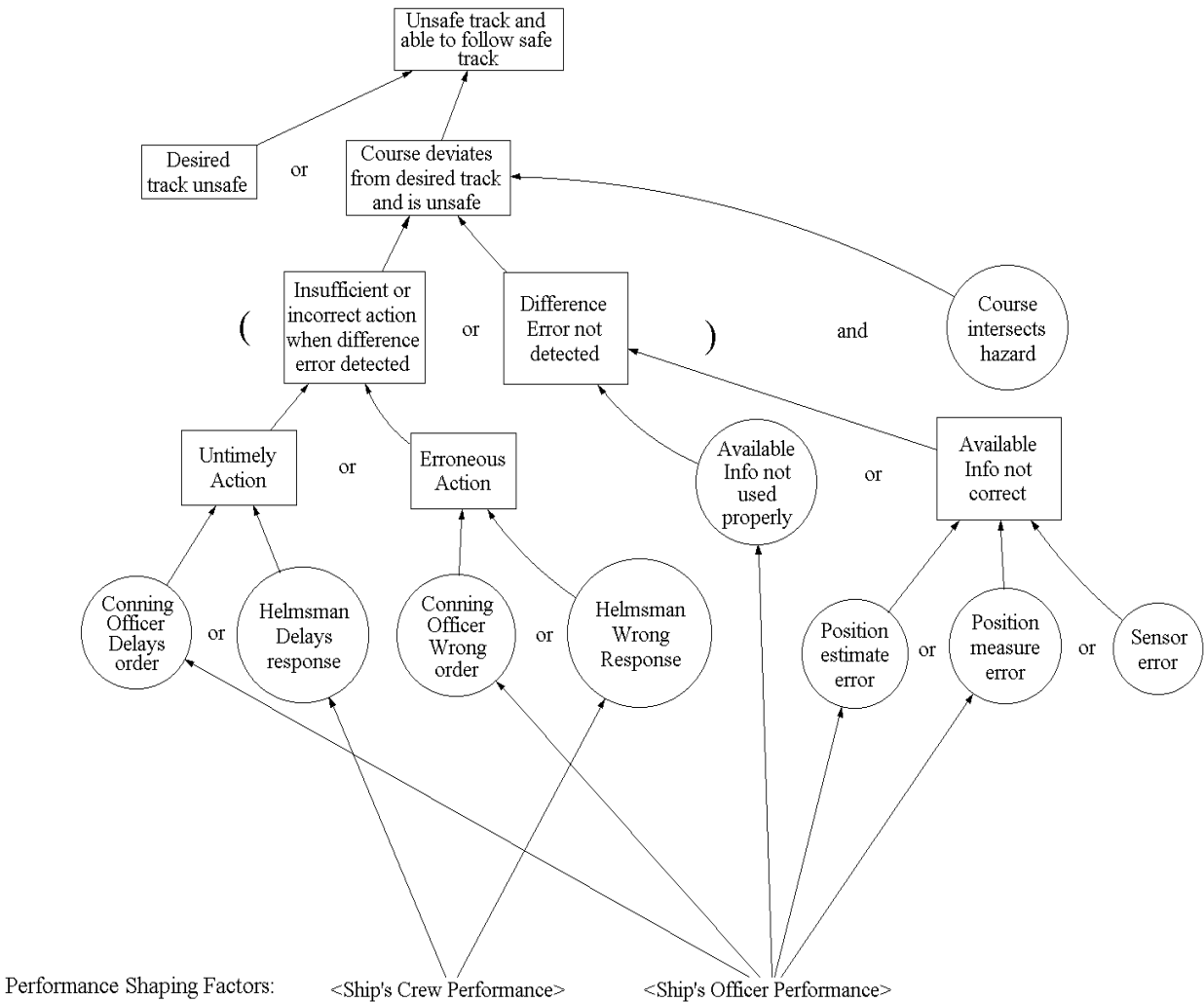


Figure 9. Powered Grounding Piloting Error Fault Tree

the course is following the desired track. This is analogous to a check-reading task where the navigator checks the plotted fix to ensure it is within tolerable limits of the desired track. Given that the error in the course is detected, the conning officer must ascertain the correct course change to order. This can be as simple as a rudder order. While there is no written procedure to follow, it is assumed that when a course deviation is detected, the procedure is to order a course change. The corresponding HEP is taken from the table for “Estimated Probabilities of Error When Using Written Procedures Correctly” [3].

When the order to change course is given, the helmsman must properly respond to the order. This involves turning the wheel while watching the rudder angle indicator and the gyro repeater until the ordered course is achieved.

The helmsman must immediately respond and the procedure requires some skill. The standard order to the helm includes both a rudder angle and a final course to steady on. The Table “Estimated Probabilities of Errors in Recalling Special Instruction Items Given Orally” from reference [3] is used for estimating this probability.

Once the helmsman responds to the order, the next event is to detect that the difference error is eliminated, which begins the sequence of events again.

The mate, Master and pilot play a verification role in this process. The analogous role in a nuclear power plant is that of either a second checker or an inspector.

As the ship deviates from its intended track it is

Table 1 - Performance Shaping Factors [3]

Procedures			Stressors		Internal
Situation Characteristics	Job and Task Instructions	Task and Equipment Characteristics	Psychological Stressors	Physiological Stressors	Organismic
Architectural Features	Required Procedures	Perceptual Requirements	Suddenness of onset	Duration of Stress	Training/Experience
Quality of Environment	Written or Oral Communications	Motor Requirements	Duration of Stress	Fatigue	Proficiency
Work Hours/Breaks	Cautions and Warnings	Control-Display Relationship	Task Speed	Pain or discomfort	Personality/Intelligence Variables
Availability/Adequacy of Equipment	Work Methods	Anticipatory Requirements	Task Load	Hunger or Thirst	Motivation/Attitude
Manning Parameters	Policies	Interpretation	High Jeopardy Risk	Temperature Extremes	Knowledge of Required Performance Standard
Organizational Structure		Decision-Making	Threats	G-force Extremes	Physical Condition
Actions by Supervisors		Complexity	Monotony	Atmospheric Pressure Extremes	Outside influences
Rewards, Recognition, Benefits		Narrowness of Task	Long, uneventful vigilance periods	Oxygen Insufficiency	Group Identification
		Frequency and Repetitiveness	Conflicts of Motives	Vibration	
		Task Criticality	Reinforcement absent or negative	Movement Constriction	
		Long and Short-Term Memory	Sensory Deprivations	Lack of Physical Exercise	
		Calculation Requirements	Distractions		
		Feedback	Inconsistent Cueing		

possible to recover. After each sequence of events in the piloting process there is some probability, given the ship fails to correct its course to the desired track, that the crew will recognize the error and implement correction in the next piloting sequence. Consideration of traffic density, navigational aids, the existence of a Vessel Traffic Service (VTS), the quality of the VTS, the geography of the surrounding land, and the contour of the waterway bottom can all influence the error detection factor and the piloting process. The nominal checking probability from reference [3] provides the basis for determining a value for the error detection factor. The lower limit is chosen as the error factor because of the many cues available to the mariner to recover.

In this manner HEP's and other error probabilities are built up for each terminal event in the fault tree. Below this level performance shaping factors (PSF's) for the specific ship and port are used to adjust HEP's.

It is essential that the proper PSF's be identified to determine the effect external influences have on the basic HEP's. Table 1 shows PSF's from NUREG1278 [3]. PSF's determine whether individual performance will be highly reliable, highly unreliable, or at some level in between. Using these generic PSF's as a starting point, specific ship and

waterway shaping factors are identified. Important ship PSF's are shown in Figure 10. Their parametric relationship to the fault tree HEP's is determined by simulation and expert opinion.

Architectural features and perceptual requirements are important PSF's determined by the bridge and equipment design of a ship. They can effect the performance of individuals either favorably or adversely.

In restricted waters important stressor PSF's include: suddenness of onset, duration of stress, long uneventful vigilance periods, distractions, fatigue, task load and inconsistent cueing. The mariner can spend days, or weeks in an open ocean transit where the risk of a grounding or collision are almost nonexistent and the margin for error is relatively large. Then there is a

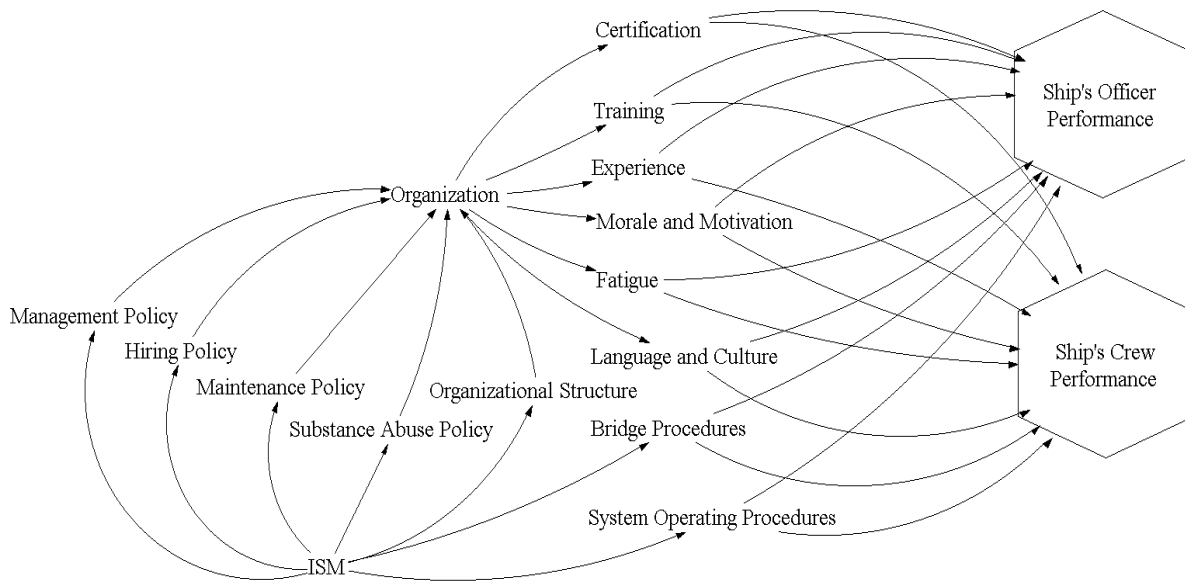


Figure 10. Ship Performance Shaping Factors

sudden transition to a restricted waterway where there can be a significant traffic density to avoid while contending with current and wind forces on the ship and maintaining a safe track through the use of navigational aids and radar fixes.

The scheduling of work hours and work breaks is unique in a sea duty environment. Watchstanding must be coupled with maintenance and repair activities. When loading and unloading cargo is coupled with scheduling pressures, time stress can occur. Individual performance is degraded when the body's circadian rhythms are disrupted. In addition to the stress that can be induced from long work hours, fatigue becomes a critical factor. Studies have shown that as fatigue increases, the detection of visual signals deteriorates and individuals exhibit more errors [3].

Internal PSF's are of vital importance to the safe operation of ships. Organizational structure (authority, responsibility, and communication) and corporate management have a major impact on these factors. Pressure to reduce cost and maintain schedule provides motivation to take greater risks and limit resources necessary for operators to function with a sufficient safety margin.

Administrative control, with regard to procedural compliance, is necessary to ensure a uniform minimum standard of operation. The perceived criticality of the task at hand determines how much attention an individual will devote to the task [3]. A conning officer's perception of importance will be directly influenced by the Master and the prevailing attitudes of the experienced personnel onboard.

Rewards, recognition and benefits provide incentive for

individuals to perform in accordance with the organization's goals. They effect individual decision criteria and how these criteria are used [3]. The bridge team structure effects the interaction of individuals that make up the team. By encouraging interaction, the principle of redundancy is employed. Additionally, once an error occurs, recovery action is more likely.

The pending revision to STCW and the new ISM Code are critical to the effective regulation, management, execution and monitoring of virtually all PSF's of concern to tanker safety as illustrated in Figure 10. STCW and ISM certification and inspection records can provide an up-to-date status of human factors onboard ship and in the ship's management. This data can be used to update the total-system risk status for a specific ship for use by management or regulatory authorities.

Oil Outflow

The International Maritime Organization (IMO) "Interim Guidelines for the Approval of Alternative Tanker Designs Under Regulation 13F of Annex 1 of MARPOL 73/78" provides a probabilistic methodology for estimating oil outflow. The method develops a pdf

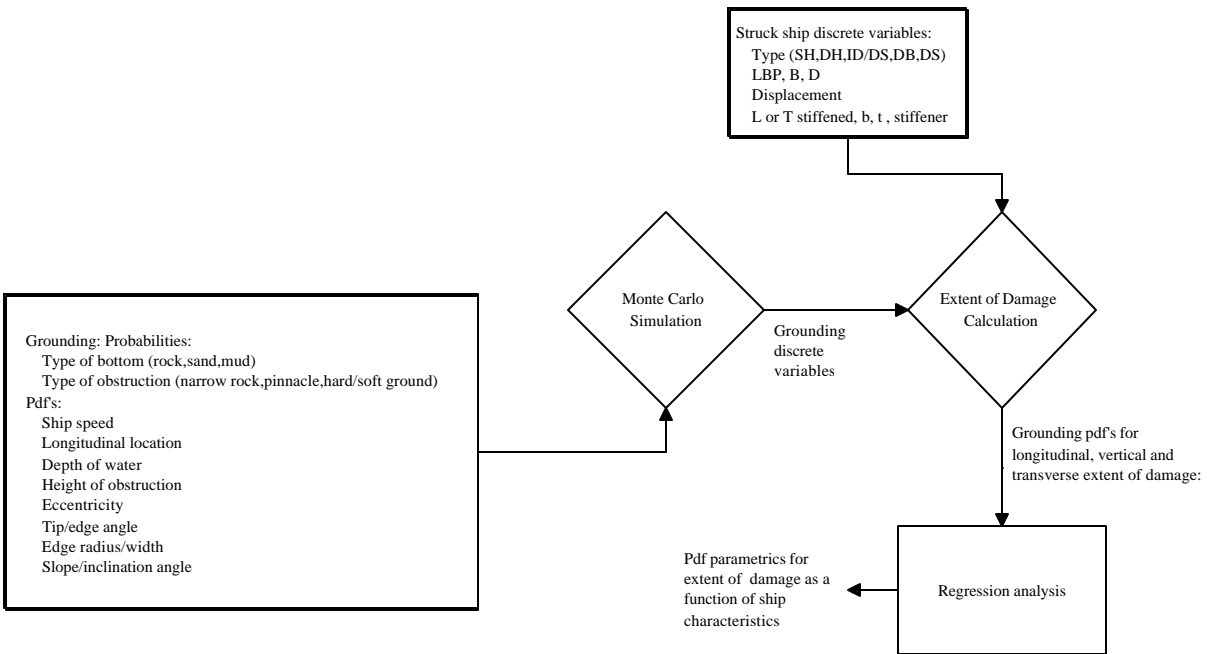


Figure 11. Develop pdfs for Extent of Damage in Grounding

for oil outflow and calculates the probability of zero outflow, mean outflow and extreme outflow for grounding and collision accidents using probability density functions (pdf's) for location and extent of damage. A simplified approach for applying this probabilistic method [9] is used in our tanker risk model.

Extent of Damage

One major shortcoming of the Regulation 13F methodology and our current model is that they do not consider the effect of structural design or crashworthiness on damage extent. The primary reason for this exclusion is that no definitive theory or data exists to define this relationship. The solution of this problem must consider the interaction between local structural damage and global ship motion. The variety of structural details and potential accident scenarios makes this difficult. A methodology which considers crashworthiness should be sensitive to at least the basic parameters defining unique structural designs while maintaining sufficient generality and simplicity to be applied by working engineers in a regulatory context for a ship in worldwide operation. It should not require detailed finite element analysis or be limited to a single accident scenario. The computational

model developed at MIT by Professor Tomasz Wierzbicki under the Joint MIT-Industry Project on Tanker Safety is ideally suited to such an application [10].

We propose to develop a set of parametric equations which define the pdf's for damage extent as a function of a simplified set of independent variables defining the ship and ship structural design. Initially this will be done for grounding accidents only. Figure 11 outlines our approach. A waterway grounding study determines probabilities for different types of bottom and obstructions, and pdf's for ship speed, depth of water and other bottom/obstruction characteristics. These are used in a Monte Carlo simulation to select discrete values for each of these variables. Using these values and a discrete set of parameters describing the ship and ship structural design, extent of damage is calculated. This process is repeated for the same ship characteristics until pdf's for extent of damage are developed. This process is then repeated for a series of ship parameters. The final pdf's are reduced to parametric form and regression analysis is applied to these parameters, relating them to the ship characteristics.

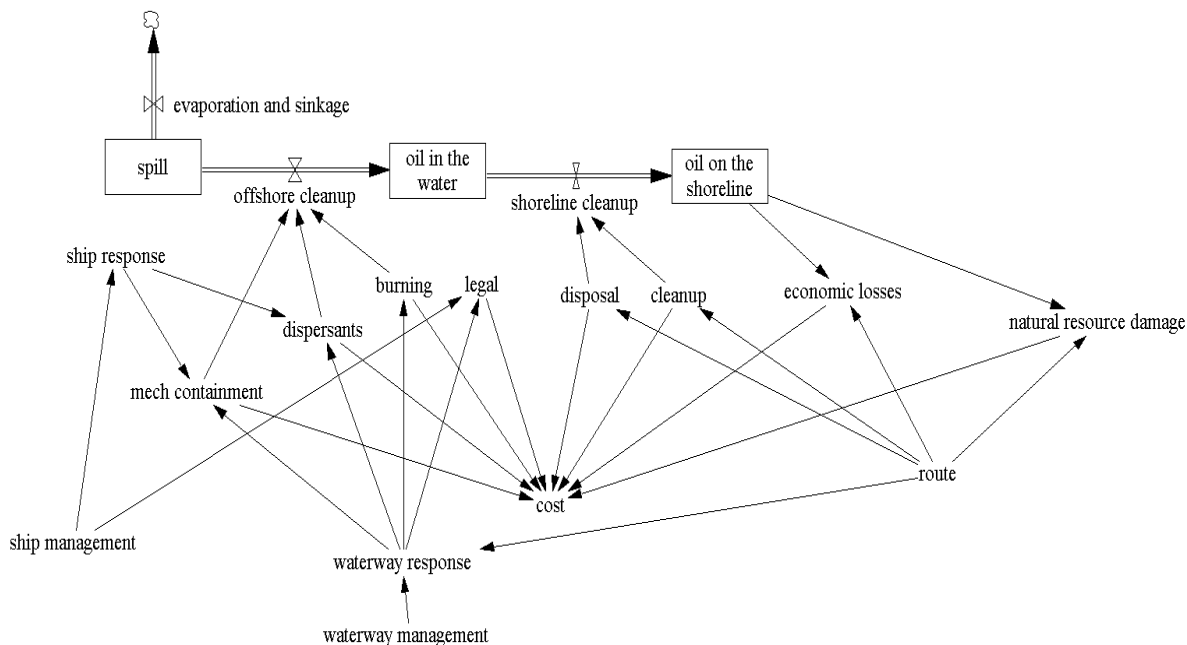


Figure 12. Spill Response

Spill Response

The options available for spill mitigation and cleanup include containment and elimination. Although the ship may have some onboard capability for containment, waterway assets, waterway management, and ship management are most important to the mitigation and cleanup function. Figure 12 illustrates our plan for a dynamic model of this process. Typically only 10-20% of the spilled oil is ever contained and recovered. The type and quantity of oil spilled, availability of personnel and equipment, environmental conditions and various human factors determine the effectiveness of the mitigation and cleanup effort. There is a room for great improvement in spill recovery and mitigation. Increasing recovery rates by 5-10% could significantly reduce spill consequences. Mitigation and cleanup should be actively investigated in the total system context.

Spill Consequence

As discussed previously, the volume of oil spilled is not a valid metric for measuring the consequence of a spill. The impact or fate and effect of a spill is the correct metric and

this is most conveniently quantified as a cost. There are five major categories of oil spill cost [11]: (1) commercial; (2) social and recreational; (3) ecological; (4) restoration; and (5) ship owners/cargo owners/insurance. Cost is extremely sensitive to the specific spill scenario. As a result, the use of an average spill unit cost is very controversial. Until a better approach is proposed, we will attempt to derive an average unit cost in the most rational way possible. Figure 13 illustrates our approach. It is similar to our damage extent model.

Probabilities and pdf's are developed to identify potential spill locations in various waterways along primary tanker routes. A Monte Carlo simulation chooses the spill location and scenario based on these probabilities. The most recent Department of the Interior (DOI) Type A Damage Assessment Model is used to estimate primary restoration costs and compensation costs for various spill volumes. Regression analysis is applied to these results to calculate cost pdf's as a function of type and quantity of oil spilled. Our initial plan is to evaluate this process for US ports only.

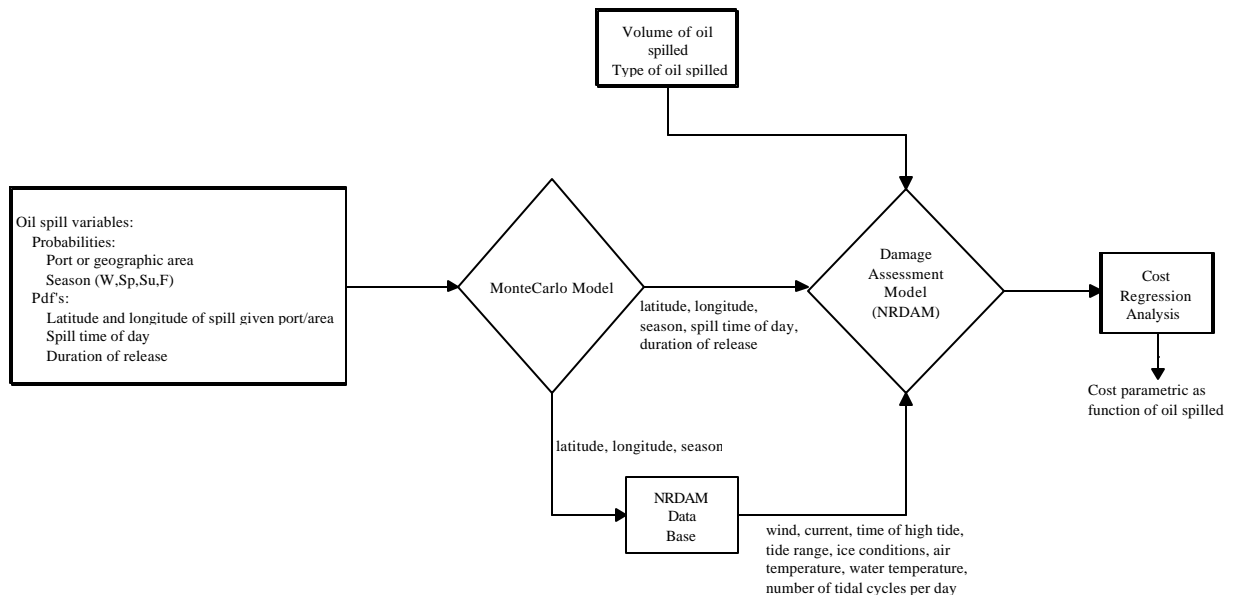


Figure 13. Consequence Model

RESULTS

Sensitivity analysis is used to assess the relative importance of the different failures effecting a powered grounding over their range of variation. Event trees are used to define tasks leading to terminal faults and to assess the change in task probabilities and resulting grounding probability over their full range of PSF values.

Table 3 provides sensitivity results for a planning fault (Desired Track Unsafe). From this table, the events that offer the largest potential for minimizing planning faults are: (1) Master's verification; (2) faulty waterway navigation information; (3) checking publications for changes in the waterway; and (4) properly determining the voyage waypoints. For voyage planning, it is essential to begin with the correct information by checking publications, incorporating the changes on the charts, and determining the correct waypoints, but the most important event is verification. While these factors offer the greatest potential for improvement over the range of uncertainty, they offer a greater potential for increasing the probability of failure if they are not performed correctly or at all. This emphasizes the importance of quality information, navigation fundamentals and the Master's role in verifying that the track is safe.

Table 4 provides sensitivity results for a piloting fault (Course Deviates from Desired Track and Is Unsafe). From this table, the events that offer the largest potential for

minimizing piloting faults are: (1) properly taking a fix; (2) detecting a difference error from the plotted fix and (3) the accuracy and reliability of the navigational equipment (a difference error is generated). Over the range of uncertainty, reliably detecting that a difference error exists between the actual and desired course offers the most potential to increase the probability of a piloting error. These are the most basic of piloting skills. They are fundamental to good seamanship. It is not surprising, but very significant, that basic skills of good seamanship are most critical to tanker safety.

CONCLUSIONS

A total-system tanker risk model offers the potential for identifying the most cost-effective alternatives for reducing tanker risk and provide a rational basis for tanker safety regulation. When probability, extent of damage and consequence/cost elements of the model are complete, diverse investment alternatives such as double hull, training, bridge automation and port facilities can be compared and the optimum investment plan determined.

In the course of model development, the human

Table 3 - Planning Failure Event Tree Sensitivity Analysis

Mean Probability for Implementing a Faulty Track	1.705E-4					
Probability that is Varied Over the Uncertainty Range	Probability of Implementing a Faulty Track at Low End of Uncertainty	Difference from Mean	Percent Difference	Probability of Implementing a Faulty Track at High End of Uncertainty	Difference from Mean	Percent Difference
check publications for changes	1.51E-04	-1.95E-05	-12%	2.40E-04	7.02E-05	41%
incorporate changes	1.65E-04	-4.52E-06	-3%	2.10E-04	4.02E-05	23%
determine waypoints	1.51E-04	-1.95E-05	-12%	2.40E-04	7.02E-05	41%
lay down track	1.70E-04	1.50E-07	negligible	1.73E-04	2.83E-06	1%
recognize faulty track	1.70E-04	5.00E-08	negligible	1.72E-04	1.84E-06	1%
Master verify plan	1.35E-04	-3.48E-05	-21%	3.62E-03	3.45E-03	2025%
faulty information	8.04E-05	-8.96E-05	-53%	1.07E-03	9.00E-04	528%

Table 4 - Piloting Failure Event Tree Sensitivity Analysis

Mean Probability for Piloting Error	2.95E-03					
Probability that is Varied Over the Uncertainty Range	Probability of Piloting Failure at Low End of Uncertainty	Difference from Mean	Percent Difference	Probability of Piloting Failure at High End of Uncertainty	Difference from Mean	Percent Difference
a difference error is generated	2.00E-03	-9.47E-04	-32%	3.00E-03	-4.97E-05	2%
fix is taken	2.45E-03	-4.99E-04	-17%	6.94E-03	3.99E-03	135%
fix is plotted	2.95E-03	-3.00E-07	negligible	2.95E-03	-2.00E-07	negligible
fix is verified	2.95E-03	-3.00E-07	negligible	2.95E-03	-2.00E-07	negligible
Master verifies fix	2.95E-03	-3.00E-07	negligible	2.95E-03	-2.00E-07	negligible
difference error is detected	2.45E-03	-4.99E-04	-17%	6.94E-03	3.99E-03	135%
correct course is ordered	2.95E-03	-4.00E-07	negligible	2.95E-03	-5.00E-07	negligible
course is verified	2.95E-03	-4.00E-07	negligible	2.95E-03	-1.00E-06	negligible
Master verifies course	2.95E-03	-4.00E-07	negligible	2.95E-03	-1.00E-06	negligible
helm responds correctly	2.95E-03	-4.00E-07	negligible	2.95E-03	-5.00E-07	negligible
helm response is verified	2.95E-03	-4.00E-07	negligible	2.95E-03	-1.00E-06	negligible
Master verifies helm response	2.95E-03	-4.00E-07	negligible	2.95E-03	-1.00E-06	negligible

element in maritime accidents is shown to be the major contributor to grounding accidents.

Based on our PRA and sensitivity analysis, avoiding failures resulting in powered grounding offers the greatest potential for risk reduction. Critical tasks include:

1. *Planning* - Check publications for changes,

Effective implementation of the STCW and the ISM Code addresses the most important factors (PSF's) impacting these critical tasks including: bridge procedures, training, experience, morale, motivation, fatigue, substance

determine waypoints properly, Master verify the plan.

2. *Planning Information* - must be accurate.
3. *Piloting* - Take fixes properly, recognize difference errors, provide accurate and reliable navigation equipment. abuse and maintenance.

Besides sound seamanship, technology may also have a place in reducing tanker risk. The potential for Electronic Chart Display and Information Systems (ECDIS) to reduce

planning errors is significant, if implemented properly and reliably.

One of the most noteworthy benefits of this work thus far is the perspective gained in the process of organizing and outlining a total-system approach to tanker risk. This perspective is a necessary first step to plan, prioritize and perform future research in specific tanker risk problem areas. It provides an essential understanding of the interdependence of all the pieces of this immensely complex and challenging system problem.

FUTURE WORK

1. Develop an extent of damage parametric model.
2. Develop a consequence/cost model.
3. Improve/develop PSF parametrics through simulation and expert opinion.
4. Complete the spill response dynamic model.
5. Improve the collision model.
6. Expand the model to consider specific port assessment.
7. Validate and apply.

REFERENCES

- [1] United Nations Conference on Trade and Development, *Review of Maritime Transport 1992*, United Nations, New York, 1993
- [2] The Institute of London Underwriters, *The Institute of London Underwriters 1992 Casualty Statistics*, 1992.
- [3] Swain, A.D., Guttman, H.E., *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*, NUREG/CR-1278, U.S. Nuclear Regulatory Commission, Washington D.C., 1983.
- [4] National Research Council, Committee on Tank Vessel Design, *Tanker Spills: Prevention by Design*, National Academy of Sciences, National Academy Press, Washington D.C., 1991.
- [5] Modarres M., *What Every Engineer Should Know About Reliability and Risk Analysis*, Marcel Dekker, Inc, New York, 1995.
- [6] WASH-1400 (NUREG 75/014), *Reactor Safety Study, An Assessment of Accidental Risks in US Commercial Nuclear Power Plants.*, October, 1975.
- [7] Reason J., *Human Error*, Cambridge University Press, Cambridge, 1990.
- [8] Bea R.G., *The Role of Human Error in Design, Construction, and Reliability of Marine Structures*, Ship Structures Committee, SSC-378, November, 1994.
- [9] Michel, K., Moore, C., Tagg, R., "A Simplified Methodology for Evaluating Alternative Tanker Configurations", Herbert Engineering Corp., San Francisco, 1995.
- [10] Little, P., Pippenger, D. and Simonsen, "Development of a Computational Model for Predicting Damage to Tankers", Joint SNAME/SNAJ Conference on Designs and Methodologies for Collision and Grounding Protection of Ships, San Francisco, 1996.
- [11] Astrup, O., Monnier, I., Sirkar, J. and Cojeen, P., "Framework for Evaluating Alternative Designs and Configurations for Tankers", 1995.
- [12] Amrozowicz, M.D., "The Need for a Probabilistic Risk Assessment of the Oil Tanker Industry and a Qualitative Assessment of Oil Tanker Groundings," Master of Engineering Thesis, Department of Ocean Engineering, Massachusetts Institute of Technology, January, 1996.
- [13] Amrozowicz, M.D., "The Quantitative Risk of Oil Tanker Groundings," Naval Engineer Thesis, Department of Ocean Engineering, Massachusetts Institute of Technology, January, 1996.