Regular Paper

A Systems Approach to Managing Oil Transportation Risk in Prince William Sound

Jason R. W. Merrick,[1*] J. Rene van Dorp,[2] Jack Harrald,[2] Thomas Mazzuchi,[2] John E. Spahn,[2] and Martha Grabowski[3]

[1]*Virginia Commonwealth University*, 1015 *West Main Street, Richmond*, VA 23284

[2]*The George Washington University, Washington*, DC

[3]*Rennslaer Polytechnic Institute, Troy*, NY *and Le Moyne College, Syracuse*, NY

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ABSTRACT

The grounding of the Exxon Valdez caused public and government concern about the safety of oil transportation in the Prince William Sound, Alaska. As a result, a large number of proposals and recommendations were made to improve safety, but stakeholders could not achieve a consensus on their effectiveness at reducing risk. A steering committee representing all local stakeholders, including the Prince William Sound Shipping Companies, the Prince William Sound Regional Citizens Advisory Committee, the Alaska Department of Environmental Conservation, and the U.S. Coast Guard, was formed to address the issue of risk intervention effectiveness. The Steering Committee hired a team of consultants who were charged with assessing the current risk of accidents involving oil tankers operating in the Prince William Sound and evaluating measures aimed at reducing this risk. The team created a detailed model of the Prince William Sound oil transportation system, using system simulation, data analysis, and expert judgment, capable of answering the majority of the questions posed by the Steering Committee. The success of the project has been demonstrated by the acceptance of the major recommendations by all stakeholders and has, to date, resulted in multi-million dollar investments. © 2000 John Wiley & Sons, Inc. Syst Eng 3: 128–142, 2000

*Author to whom all correspondence should be addressed.

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1. INTRODUCTION

The grounding of the Exxon Valdez on Bligh Reef in 1989 led to the spilling of 11 million gallons of crude oil into the Prince William Sound (PWS), Alaska. Affected were 1,500 miles of shoreline with both immediate and lingering impacts on fish and wildlife resources and the lives of people in coastal communities. It has been estimated that the cleanup operations cost Exxon Corporation $2.2 billion (Exxon Corporation, 1999). The accident focused national attention on ways to reduce the risk of oil spills from tankers, culminating in the Oil Pollution Act of 1990 (US Federal Law, 1990). Regionally, the state of Alaska's oil pollution prevention and response statutes (State of Alaska, 1991) created a large body of prevention and response regulations, with specific escort vessel requirements included in the state of Alaska's oil discharge prevention and contingency plans (Alaska Department of Environmental Conservation, 1995).

Questions concerning the effectiveness and benefits of existing prevention regulations and concerns about many of the regulations still under consideration surfaced in the PWS community in early 1995, with particular attention focused on escort vessel operations and design. A joint industry/government/citizen study, the Disabled Tanker Towing Study (Glosten Associates, 1994) was funded to determine appropriate design specifications for such vessels to meet the state's requirements. Even with information learned from this study, the role of escorts and their purpose in the PWS oil transportation system were neither well defined nor accepted by all stakeholders. Answers to questions about the effectiveness, mission, performance, and operation of escort vessels needed to be clarified.

With the escort issue, and the lingering concerns of the PWS community about the benefits of other existing and proposed risk intervention measures, the PWS Shipping Companies proposed a risk assessment study to the Alaska Department of Environmental Conservation (ADEC), the U.S. Coast Guard (USCG), and the Regional Citizens' Advisory Council (RCAC). The RCAC and the PWS Shipping Companies agreed to fund the project, and the Coast Guard contributed funding for peer review to insure objectivity of the study. As a first step, a steering committee was formed representing all stakeholders to address these issues and concerns. Members of the Steering Committee included ship's captains, fishing industry experts, senior corporate managers, environmental regulators, the USCG Captain of the Port, experts in prevention systems, and community representation.

The Steering Committee recognized the need for a structured and rational method to evaluate the merits of risk intervention measures for improved allocation of resources and to avoid implementing measures that would adversely affect system risk. In addition, the Steering Committee also wanted the project to be used as a forum to build trust among stakeholders and to foster a better and more common understanding of risk and oil transportation for all interested parties. The Steering Committee engaged a consultant team from Det Norske Veritas, Rennslaer Polytechnic Institute and the George Washington University to assist them in their risk assessment effort.

The PWS study team took a systems approach to risk assessment and management by a detailed analysis of the sub-systems and their interactions and dependencies. This required combining Probabilistic Risk Assessment (PRA) techniques with the use of expert judgment elicitation methods and system simulation. This paper reviews the need for system simulation and expert judgment in a systems level approach to risk assessment and presents an overview of the techniques used. Readers interested in a complete, technical description are referred to the report of the Prince William Sound Steering Committee, 1996. A subset of the study's results are given that demonstrate the need for the systems approach with specific examples of risk intervention measures that, while successful at reducing the risk of targeted scenarios, increase the overall risk in the system.

The objectives and scope of the study are discussed in Section 2. An overview of the modeling approach used and the probability model developed for maritime risk is given in Section 3. In Section 4, the necessity of simulation for modeling the dynamic properties of maritime risk and the building of the system simulation is discussed. The use of expert judgment to extend the scope of available data and the expert judgment elicitation method is discussed in Section 5. Section 6 reviews the results of the analysis for a selected subset of risk interventions that demonstrate the need for a systems approach. Section 7 presents some conclusions from the study.

2. OBJECTIVES AND SCOPE OF THE PWS RISK ASSESSMENT

The involvement of all local stakeholders in the management of the project provided unique access to individuals and information in an attempt to ensure that all viewpoints were considered in construction of the objectives and scope. The study scope consisted of the risks of marine oil transportation from the Valdez Marine Terminal to 20 miles outside of Hinchinbrook Entrance (Fig. 1). Causal and contributory factors such

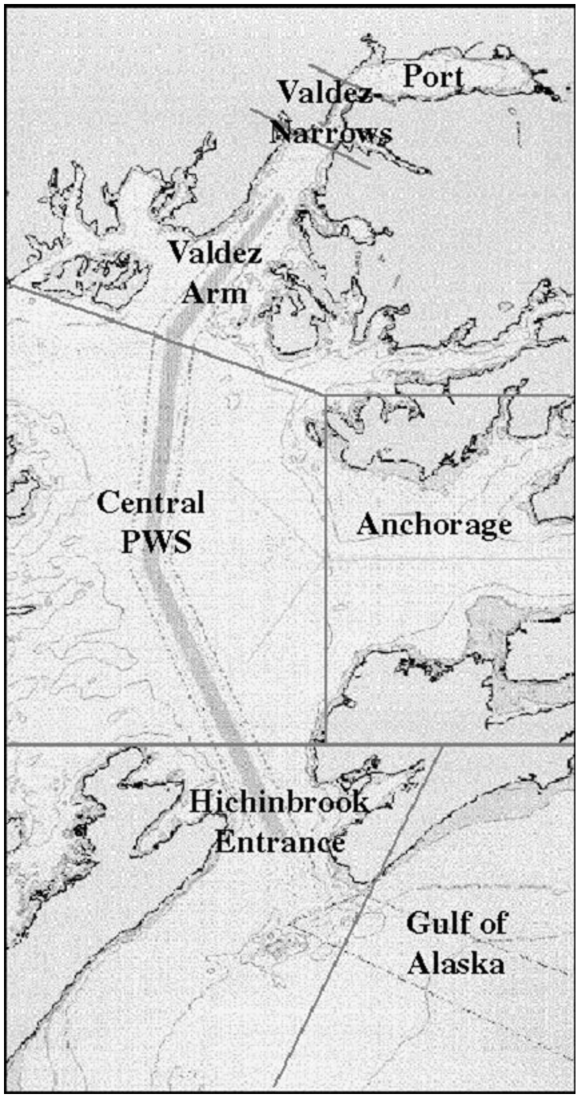


Figure 1. The Prince William Sound divided in to seven locations.

as marine traffic, weather, external environmental variables, human error, and mechanical failure were all to be addressed. In addition, the study was to include both technical and operational aspects of the tanker fleet, as well as regulatory requirements and operating company management. Excluded from the scope of the study were events that could occur within the terminal itself or events caused by certain low probability natural phenomena (e.g., a lightning strike or earthquake). Specifically, the Steering Committee established three primary objectives for the study:

- to identify and evaluate the risks of oil transportation in PWS,
- to identify, evaluate, and rank proposed risk intervention measures, and
- to develop a risk management plan and risk management tools hat could be used to support a risk management program.

To achieve the first objective, the risk associated with the accident types listed in Table I was to be considered. The measure of system risk requested by the Steering Committee was the average oil outflow per year in the PWS oil transportation system, a measure of both the probability and the severity of accidents. To understand the distribution of system risk, this measure was requested for each accident type in Table I and location in Figure 1. In addition, the Steering Committee wanted to know whether a high average oil outflow was due to high frequency/low consequence or low frequency/high consequence accidents.

In considering the second objective, it is important to note that some risk interventions attempt to reduce exposure to specific causal contributory factors that elevate system risk, while other risk interventions attempt to intervene in the sequence of events leading to an accident and its subsequent consequences. Thus, achieving the second objective required a detailed model of system risk that incorporates the effect of causal contributory factors, the frequencies of accidents, their precursors, and the severity of their consequences.

The third objective could be achieved only after the completion of the first two. This required the Steering Committee to be involved in a group decision process incorporating not only the information obtained in the consultant team's study but also cost, feasibility, and social acceptability information. This is a separate topic, outside the scope of this paper.

3. A PROBABILISTIC MODEL FOR SYSTEM RISK IN THE PRINCE WILLIAM SOUND

An accident is not a single event but the culmination of a series of cascading events (Garrick, 1984). The immediate precursor of the accident is termed a triggering incident. In this model, triggering incidents were further categorized as mechanical failures or human errors. The specific classifications of mechanical failures and human errors used in the study are listed in Tables II and III, respectively. Furthermore, accidents and triggering incidents occur within the context of a system state. In terms of accident risk, the system state is defined by combinations of organizational factors (OF) and situational factors (SF). The organizational and situational factors included in the model are listed in Table IV.

Figure 2 summarizes the accident probability model used in the study, including both the time sequence of

Table I. Accident Types

ACCIDENT TYPE	DESCRIPTION
Drift Grounding	The contact with the shore or bottom by a drifting vessel not under control due to a propulsion or steering failure.
Powered Grounding	The contact with the shore or bottom by an underway vessel under power due to navigational error or steering failure and lack of vigilance.
Collision	The colliding or striking of two underway vessels due to human error or mechanical failure and lack of vigilance (inter ship collision) or the striking of a floating object by an underway vessel (e.g. ice collision.)
Foundering	The sinking of a tanker due to water ingress or loss of stability.
Fire/Explosion	The occurrence of a fire in the machinery, hotel, navigational, or cargo space of a tanker or an explosion in the machinery or cargo spaces.
Structural Failure	A structural failure due to hull or frame cracking or erosion, serious enough to affect the structural integrity of the vessel.

Table II. Mechanical Failures

FAILURE CLASSIFICATION	DESCRIPTION
Vessel Propulsion Failure	A loss of the vessel's ability to propel itself through the water (.e.g. loss of boiler, turbine, Main diesel, loss of propeller, broken shaft
Vessel Steering Failure	Loss of the vessel's ability to control it's rudder (e.g. steering gear or steering motor failure, jammed or lost rudder)
Vessel Electrical Power Failure	The loss of ship's electrical power to all critical systems such as navigation and lighting
Vessel Structural Failure	The cracking of the vessel's hull while under way

Table III. Human Errors

HUMAN/ORGANIZATIONAL ERROR CLASSIFICATION	DESCRIPTION
Diminished ability	Physical, mental, motivational or emotional conditions that degrade performance
Hazardous shipboard environment	Poor ergonomic design, poor maintenance, or poor vessel housekeeping
Lack of knowledge, skills, or experience	Lack of general professional knowledge, ship specific knowledge, knowledge of role responsibility, or language skills
Poor management practices	Poor supervision, faulty management of resources, inadequate policies and procedures
Faulty perceptions or understanding	Inability to correctly perceive or understand external environment

Table IV. Organizational and Situational Factors

ORGANIZATIONAL FACTORS	SITUATIONAL FACTORS
Vessel size	Location
Vessel age	Traffic Proximity
Vessel material	Traffic type
Vessel hull type	Traffic direction
Officer type	Escort vessels
Officer years service on vessel	Wind speed
Officer years service in billet	Wind direction
% of officers sailing below license	Visibility
Bridge team stability	Ice conditions
Officer training (individual, team)	Current
Management type	Own vessel type
Flag (U.S. other)	

the accident event chain and the influence of organizational and situational factors on this chain. To simplify the probability model, it was assumed that organizational factors influence the occurrence of triggering incidents and that situational factors influence the occurrence of accidents, whereas both affect the consequences of an accident.

The accident probability model discussed herein was based on the notion of conditional probability. The levels of conditional probability reflected in Figure 2 are

- **P(OF,SF):** the probability that a particular set of organizational and situational factors occur in the system.
- **P(Incident| OF):** the probability that a triggering incident occurs given the organizational factors.
- **P(Accident| Incident, SF):** the probability that an accident occurs given that a triggering incident has occurred.
- **P(Consequences| Accident, OF, SF):** the probability of an oil spill of a particular level given that an accident has occurred.

The probability of an accident with given consequences occurring in the system follows by summing the product of the conditional probabilities over all accident types in Table I, all triggering incidents in Tables II and III, and all combinations of organizational and situational factors in Table IV.

To perform an assessment of the risk of an accident using this model, each term in the probability model needs to be estimated. In Section 4, the use of system simulation in assessing the exposure to combinations of organizational and situational factors, i.e., assessing **P(OF,SF)**, is discussed. The use of expert judgment is discussed in Section 5 to assess the effect of organizational and situational factors on the frequency of triggering incidents and accidents, i.e., **P(Incident|OF)** and **P(Accident|Incident,SF)**. The severity of the con-

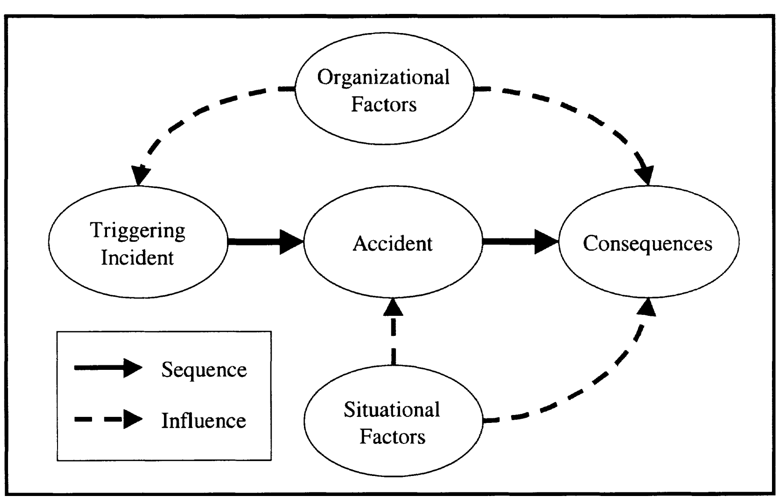


Figure 2. The accident probability model.

sequences, **P(Consequences|Accident,OF,SF)**, were estimated using an oil outflow model provided by DNV (Prince William Sound Steering Committee, 1996).

4. SYSTEM SIMULATION OF THE PRINCE WILLIAM SOUND OIL TRANSPORTATION SYSTEM

The frequency of occurrence of each system event defined by a combination of organizational and situational factors, specifically **P(OF,SF),** is determined using a systems simulation to count the annual numbers of each such event. In Section 4.1, the need for system simulation in estimating these frequencies is discussed; the specifics of building the PWS System Simulation are discussed in Section 4.2.

4.1 The Need for System Simulation in Assessing Risk in Prince William Sound

System risk is dynamic in nature, due to the dynamic variation of situational and organizational factors as different vessels pass through the system. Weather-based closure restrictions shut down transits through the Valdez Narrows and Hinchinbrook Entrance during periods of high winds and lead to periods of traffic congestion following prolonged closure. The specific closure conditions depend on the size of the tanker and whether the tanker is laden or unladen. A one-way zone in Valdez Narrows for deep-draft vessels further complicates the dynamic pattern in this area, increasing the frequency of vessel interactions on either side of the special navigation zone. Additionally, there is a limitation on dock space and the number of escort vessels, with escort vessel requirements based on the size of the tanker and the wind speed in Valdez Narrows.

The term **P(OF, SF)** is the probability of a system state defined by the 23 factors in Table IV. Although data is collected individually on specific vessel arrivals and environmental conditions, data on the combinations of these events is not collected. If vessel arrivals and environmental conditions were independent processes, then **P(OF,SF)** could be found by simple multiplication of marginal frequencies of each factor from Table IV. In fact, traffic rules in place lead to complex interdependencies between the vessel arrivals and movements and the environmental conditions. The complexity of the traffic rules described above and the manner in which data is gathered necessitates the use of systems simulation to estimate **P(OF,SF);** the simulation counts the frequency of system states **(OF, SF)** and estimates **P(OF,SF)** directly.

In addition to enabling the estimation of **P(OF,SF)** in the current system, the use of a systems simulation is important for system-wide evaluation of risk interventions. The closure restrictions in the Valdez Narrows migrate risk from this targeted area to the Port and Valdez Arm locations, in the form of increased traffic congestion. Similar to these closure restrictions already in place, proposed risk interventions may also have the potential to migrate risk. The system-wide effects of such risk interventions will result in a risk reduction only if the positive effect in the targeted area outweighs the adverse effects of risk migration in other areas. The use of a system simulation captures the complex dynamic nature of the PWS oil transportation system and allows for the system-wide evaluation of risk intervention measures.

4.2 Building a System Simulation of Prince William Sound

The first step in creating a simulation representative of the PWS oil transportation system was to collect data on the traffic movement and environmental conditions. Numerous data sources from the PWS community were used in the traffic model. The United States Coast Guard Vessel Traffic System (VTS) provided both paper logs of vessel transits by vessel types, date, and time, along with graphical printouts of the transit routes. Visual printouts of typical routes taken by the different vessels from VTS plots were entered into the simulation program as routes and all vessels were assigned to one of 125 different routes programmed into the simulation. The VTS data was the sole data source for the Barge, Cruise, and Tour vessel arrival models. The Ship Escort/Response Vessel System (SERVS) maintains logs for tanker escort transits that provide information on the total number of tanker transits per year. Fishing vessel information was provided through a survey format from the fishing industry. All Fishing vessels, including tenders and floating processors, were included in the survey. State Ferry traffic was modeled directly from published schedule information.

Using these data sources, traffic inter-arrival distributions were estimated for each of the traffic types, and a traffic arrival generator was created. The organizational factors were attributes of the tankers in the simulation and were obtained from a management survey of each company running tankers in the PWS and from physical descriptions of each of the tankers.

A weather model was created to simulate the change in wind and visibility and the presence of ice in the traffic lanes. The weather model used a Markov Chain approach with parameters estimated using data from meteorological observations taken periodically by SERVS' escort tugs and four moored weather buoys in

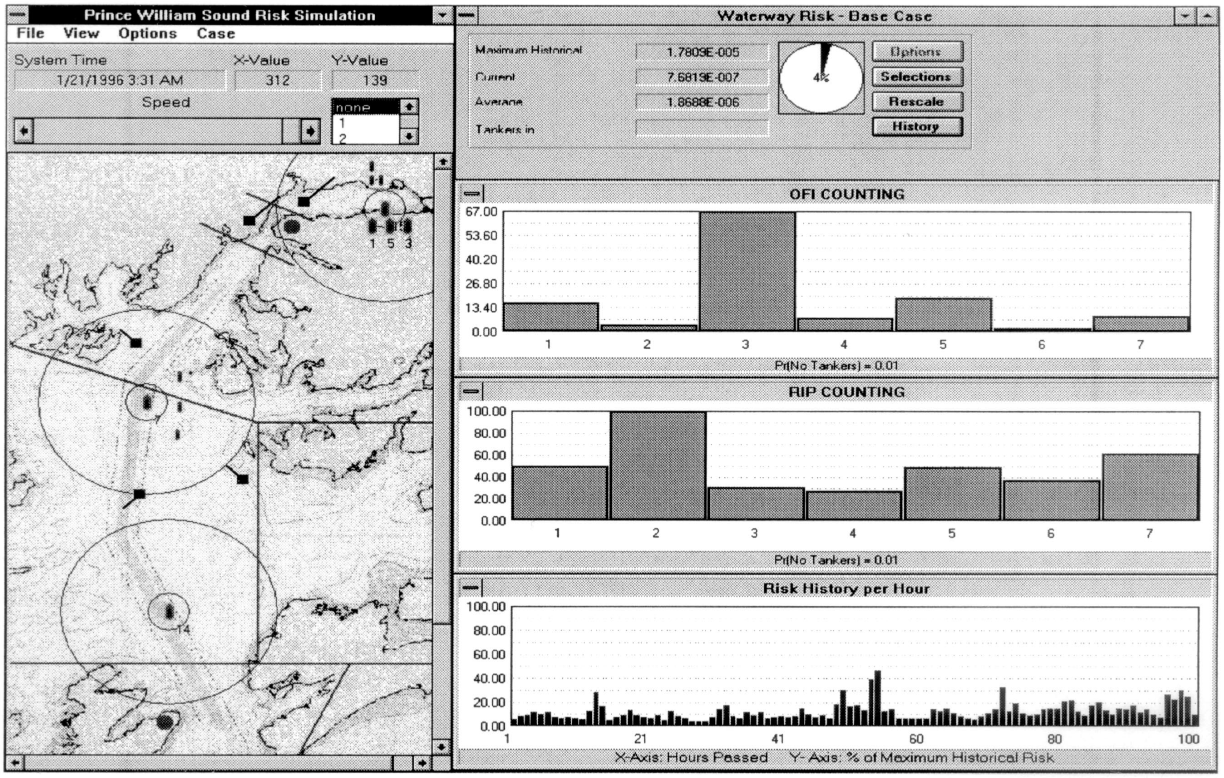


Figure 3. A visual representation of the PWS system

PWS maintained by the National Oceanographic and Atmospheric Administration.

Vessels transiting PWS between the Valdez Marine Terminal and Cape Hinchinbrook are required to participate in the USCG VTS and therefore, are, required to follow a set of defined traffic rules. Closure restrictions at Valdez Narrows and Hinchinbrook Entrance, one-way zone restrictions in Valdez Narrows, escort requirements for oil-laden tankers, dock availability, and anchorage rules were programmed into the simulation for accurate system representation. For verification of the simulation, summary statistics were recorded, for example counts of the number of trips to anchorage. VTS personnel verified the realism of the simulation through comparison of these summary statistics to actual observations. Simulated traffic behavior was also presented visually to VTS personnel (Fig. 3), who verified that observations from the simulation were in agreement with actual traffic patterns observed at the VTS center.

Within the simulation, the system state was calculated once every 5 minutes based upon traffic arrivals, environmental conditions, and the previous system state. The simulation was used to count the occurrence of combinations of organizational and situational factors. For each tanker in the system at any given time, a system event was counted that included the organizational and situational factors for that tanker. A system event was also counted for each vessel considered to be interacting with the tanker. The simulation was run for 25 years of simulation time and for each 5-minute period the system events that occurred were counted. Thus, the average yearly frequency of particular combinations of organizational and situational factors could be estimated using the simulation.

5. THE USE OF EXPERT JUDGMENT TO ASSESS SYSTEM RISK

The next step in the estimation of accident frequency was to estimate the two levels of conditional probability of triggering incidents and accidents. These are the conditional probability of a triggering incident occurring given the organizational factors of the vessels involved, **P(Incident|OF)**, and the conditional probability of an accident given that a triggering incident has occurred under a given set of situational factors, **P(Accident|Incident,SF)**. In Section 5.1, the need for expert judgment in the assessment of these probabilities is discussed, with the specific techniques used outlined in Section 5.2.

5.1 The Need for Expert Judgment

The preferred method for estimating the above probabilities is through the statistical analysis of accident data. However, the Steering Committee required that only PWS specific data should be used in the analysis. In the history of the PWS oil transportation system, there have been only two accidents involving oil tankers, the well-known Exxon Valdez grounding and the collision of the Overseas Ohio with ice. Clearly, this data is insufficient to estimate the effect of the factors in Table IV on accident and incident frequency. Thus analysis had to rely, at least in part, on expert judgment solicited from the PWS community.

Expert judgment elicitation is often crucial in performing risk analyses (Cooke, 1991; Moslesh et al, 1988) and has been used in areas as diverse as aerospace programs, military intelligence, nuclear engineering, evaluation of seismic risk, weather forecasting, economic and business forecasting, and policy analysis. The approach developed was built on the premise that the judgments of experts that have a deep understanding of the system would provide a basis for the assessment of risk, see the article by Paté-Cornell, 1996. It must be noted, however, that when applicable all available data was used in this approach.

5.2 The Expert Judgment Method

Experts may be classified in three categories (DeWispelare et al., 1995):

- **Normative experts** who have the analysis background to quantify the judgments of the substantive experts and combine their judgments.
- **Generalists** who have a thorough understanding of the project and play a role in defining the issues addressed and communicating with the experts
- **Substantive experts** who have the deep knowledge and experience of a system that allow them to provide information about the functioning of that system.

Certain members of the risk assessment team were normative experts, with knowledge of decision theory, probabilistic reasoning, and expert elicitation techniques. Other members were generalists with both maritime experience, knowledge of maritime risk issues, and systems engineering techniques.

The parameters of the model were based only on the responses of substantive experts. A total of 162 substantive experts with significant years of experience were drawn from the oil company fleets, the pilots association, the Ship Emergency Response Vessel System (SERVS), the local fishing industry, and the US Coast Guard. Only people with a deep and current knowledge of the situations being posed were given questionnaires specific to their area of expertise. For example, the experts answering the questionnaire on mechanical failures were primarily Chief Engineers working in the PWS tanker calling fleet. Stakeholders took the surveys to familiarize themselves with the expert elicitation process, but their responses were not used in the estimation of model parameters. A large number of experts answered each questionnaire to maximize the pool of available information (Clemen & Winkler, 1999).

The key to good expert judgment elicitation is to define both a methodology and an instrument that can be easily comprehended by the experts and yet is powerful enough to be useful in the analysis. As discussed by Cooke, 1991, indirect elicitation of probabilities is preferable to direct probability elicitation, especially when the experts are unfamiliar with probability assessments. The expert judgments in the PWS Risk Assessment were elicited indirectly using pairwise comparisons (Bradley and Terry, 1952) with an extended scale (Saaty, 1977). The pairwise comparisons presented to the experts were at a level of detail defined by the organizational and situational factors in Table IV. This level of detail was necessary for the questions to reflect actual situations observed by the experts.

Figure 4 is a pictorial representation of one of the pairwise comparisons in the questionnaires. In each situation in this comparison there is an inbound tanker greater than 150,000 DWT that has just had a propulsion failure in the Central Prince William Sound. It is within 2 to 10 miles of a tug with tow, in winds over 45 miles per hour blowing on shore (to the closest shore point) and with the visibility greater than half a mile. The situation on the left includes an iceberg in the traffic lanes and on the right the iceberg is omitted.

The question being asked of the expert is which of the two situations is more likely to result in a collision. In each question, only one attribute is changed to enable the experts to more easily compare the difference in relative likelihood of collision between the two situations. Figure 5 shows the format of the question in Figure 4 as it was presented to the experts. The questionnaire booklets contained 100–150 questions in the format of Figure 5. Note that all attributes for the situation on the left are completely defined. Only the attribute that has changed is shown for the situation on the right. If the attributes are left blank they are identical to the situation on the left.

If the expert feels the situation on the left (right) is much more likely to cause an accident he or she would circle a larger number (e.g., 7, 8, 9) on the left (right). Circling a 1 indicates indifference between the two situations. The scale was left to the judgment of the expert and later calibrated to the available data. The

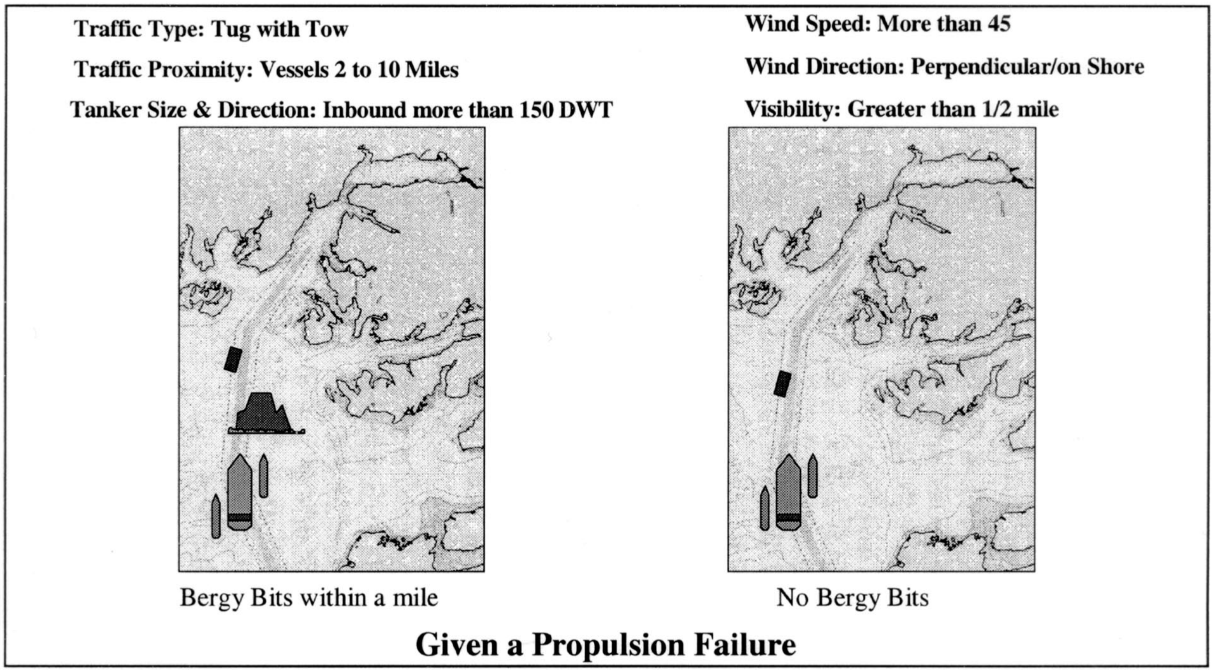


Figure 4. An example of a scenario pictured in the questionnaires.

magnitude of the number is related to the relative importance that a particular expert puts on the attribute that was changed. Thus only the relative magnitude of the probabilities of an event in different scenarios can be obtained from this expert judgment technique, requiring a baseline multiplicative constant to achieve absolute probabilities.

The questions in the books were randomized to reduce response bias and the results statistically tested to ensure meaningful responses. The results of each subgroup were plotted to show if significant differences in the judgments of experts were present in the responses. No substantial disagreement was observed between the different groups of substantive experts, which indicates absence of group-specific motivational biases (Cooke, 1991). At the end of each pairwise comparison questionnaire, a series of open-ended questions were asked concerning completeness and comfort level. Most experts responded favorably with respect to the completeness of the model and their comfort level with answering the pairwise comparison questions.

The aggregation of multiple experts' responses is a complex problem. Numerous techniques exist, including simple averaging techniques, such as the linear opinion pool and the logarithmic opinion pool (Clemen & Winkler, 1999), techniques for weighting the judgments of the experts (Cooke, 1991), and Bayesian techniques that require the decision maker to express judgments concerning the abilities of the experts (Clemen and Winkler, 1990; Mendel and Sheridan, 1989). However, the results from experimental comparisons do not show a clear advantage for the more complex techniques over simple averaging techniques (Clemen and Winkler, 1999). In this study, the experts are giving ratio estimates; thus a geometric average of the expert responses was taken (Moslesh and Aspostalakis, 1983) with equal weighting of each expert. The aggregated responses were used to estimate the parameters of the

Location	Central Sound	**LIKELIHOOD OF COLLISION**		Location
Traffic Proximity	Vessels 2 to 10 Miles	**9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9**		Traffic Proximity
Traffic Type	Tug with Tow			Traffic Type
Tanker Size & Direction	Inbound More Than 150DWT			Tanker Size & Direction
Escort Vessels	Two or more			Escort Vessels
Wind Speed	More Than 45			Wind Speed
Wind Direction	Perpendicular/On Shore			Wind Direction
Visibility	Greater Than 1/2 Mile			Visibility
Ice Conditions	Bergy Bits Within a Mile		No Bergy Bits in a Mile	Ice Conditions

Figure 5. The form of the actual questionnaires.

relative incident and accident probability models through a log-linear regression.

The relative incident probability model was calibrated to actual mechanical failure data and using the assumption that 80% of all accidents are caused by human error because there were no data to directly estimate this proportion for the PWS. This assumption is based on risk analysis studies from the United Sates Coast Guard (USCG, 1995) and was accepted by the Steering Committee.

6. RISK INTERVENTION MEASURES CAUSING RISK MIGRATION

For a complete discussion of results, the reader is referred to the study's final report (Prince William Sound Steering Committee, 1996). In this section, a discussion of the importance of considering system-wide risk is emphasized through selected analysis of those intervention measures that exhibited risk migration, specifically

- Weather closure restrictions.
- Tanker and fishing vessel coordination.
- Escort procedures.
- Ice transit restrictions.

A baseline simulation was created that represented the operation of the PWS oil transportation system in 1996. This base case was used as the basis for comparison of the effectiveness of all intervention measures.

As discussed in Section 3.1, weather-based closure restrictions were implemented to reduce the risk of drift and power groundings in the Valdez Narrows and Hinchinbrook Entrance, by not allowing transit through these locations in high wind speeds. A simulation run was performed without the closure restrictions to test their effect on system risk. Figure 6 shows that the closure restrictions were effective at reducing the risk of oil outflow in the targeted locations, but increased the risk in the Valdez Arm and Central PWS. The overall effect was a small reduction in the average oil outflow.

A further scenario was considered that tightened the closure restrictions at Hinchinbrook Entrance and Valdez Narrows by reducing the maximum wind speed in which transits were allowed. Tightened closure restrictions at Hinchinbrook Entrance were motivated by concerns about the escort capability for saving a tanker in adverse weather in this location. Tightened closure restrictions were motivated at Valdez Narrows due to limited maneuverability and response time concerns for a tanker in adverse weather conditions in this location. Figure 6 shows that the effect of this tightening is to increase risk in all locations apart from the Valdez Narrows, thus the migration of risk away from the targeted locations leads to an overall increase in risk.

Further analysis of the baseline scenario revealed an interesting result. Figure 7 shows the breakdown of collision frequency by the type of the other vessel. The highest collision frequency is with fishing vessels. Fishing vessels operate in large numbers during the summer months when the State of Alaska allows "fishing openers." This leads to a high number of interactions with tankers. Although the majority of the fishing vessels are not large enough to damage the hull of a tanker and cause an oil spill, these interactions were of concern to the Steering Committee in terms of overall safety. A scenario was created in the simulation that included rules to delay openers until a tanker had passed through the area or to delay a tanker until the end of an opener. Figure 7 shows that the collision frequency with fishing

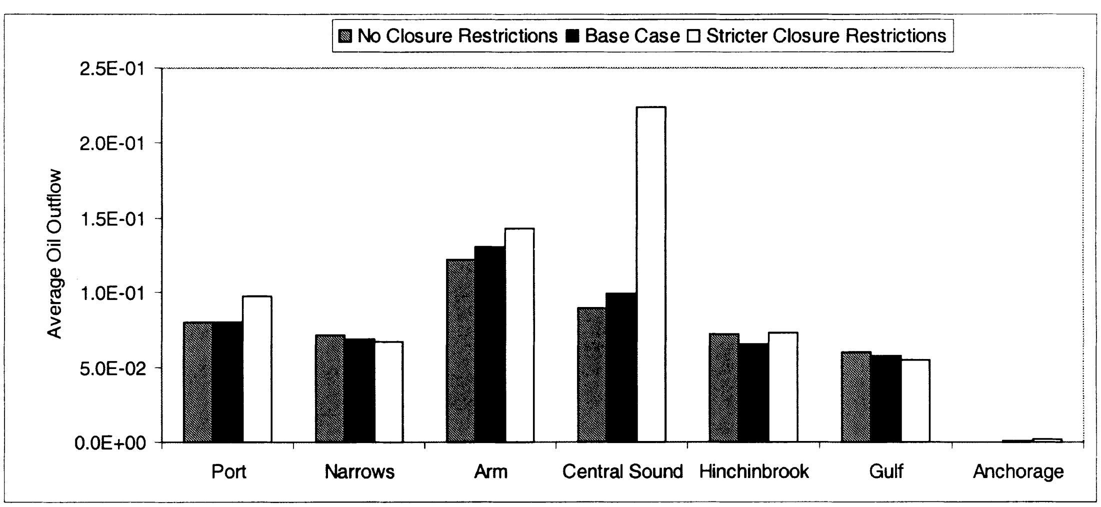


Figure 6. The migration of risk amongst locations due to closure restrictions.

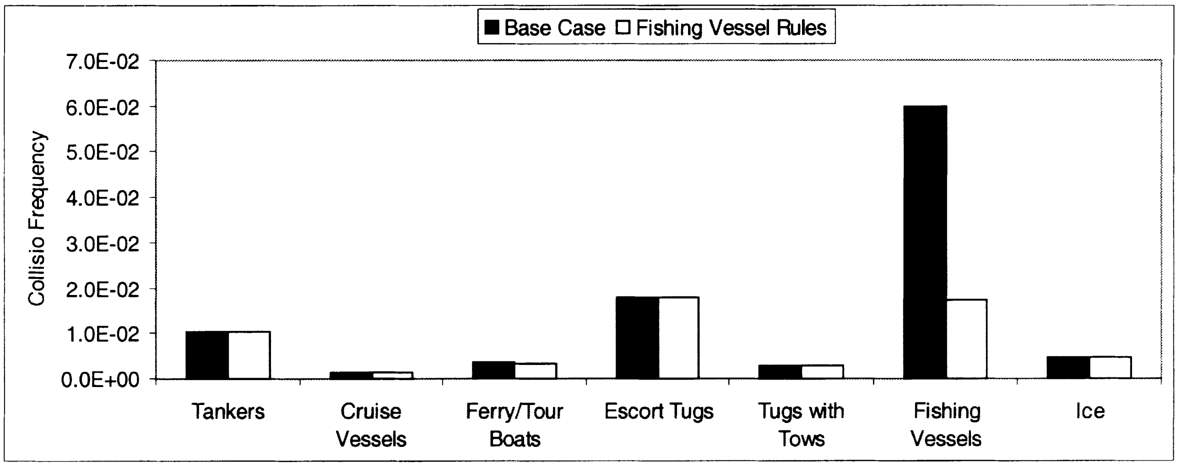


Figure 7. The migration of collision frequencies amongst vessel types due to fishing vessel rules.

vessels was significantly reduced by these rules, and there was no migration of risk to other vessel types or indeed to other accident types.

As mentioned previously, the Oil Pollution Act of 1990 and the State of Alaska's oil discharge prevention and contingency plans put in place specific escort vessel requirements. The purpose of an escort vessel is to stop a drift or powered grounding accident by attaching a line to a tanker in risk of grounding and pulling it away from shore. The escort system implemented included continuous escorting of all outbound, oil-laden tankers from the port to the Gulf of Alaska. Two or three escorts were used depending on the wind speeds in Valdez Narrows and the size of the tanker. The escort vessels returned to port following an escort assignment.

The escort system was removed from the baseline simulation, and the risk for a system with no escorts was compared to the system with the baseline escort scheme. Figure 8 shows that the escort system was successful in reducing the average oil outflow from drift and powered groundings, but it increased the average oil outflow from collisions as the escort vessels returning from an escort assignment interacted with the tankers in the system. In fact, Figure 7 shows that the second highest collision frequency in the base case is collisions with escort tugs, and a further analysis showed that escort tugs are the highest cause of oil outflow from collisions. Despite the migration of risk from grounding accidents to collisions, the overall effect of the escort system was estimated to be a 43% reduction in the average oil outflow.

However, the risk migration raised the question of whether the reduction in grounding accidents could be maintained, while minimizing the additional collision

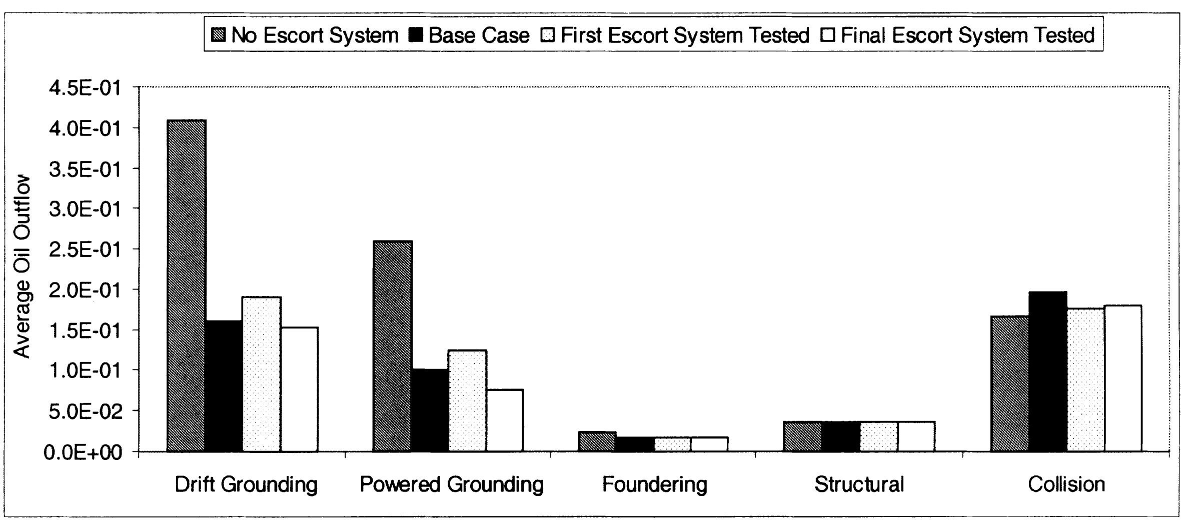


Figure 8. The migration of risk amongst accident types due to escort schemes.

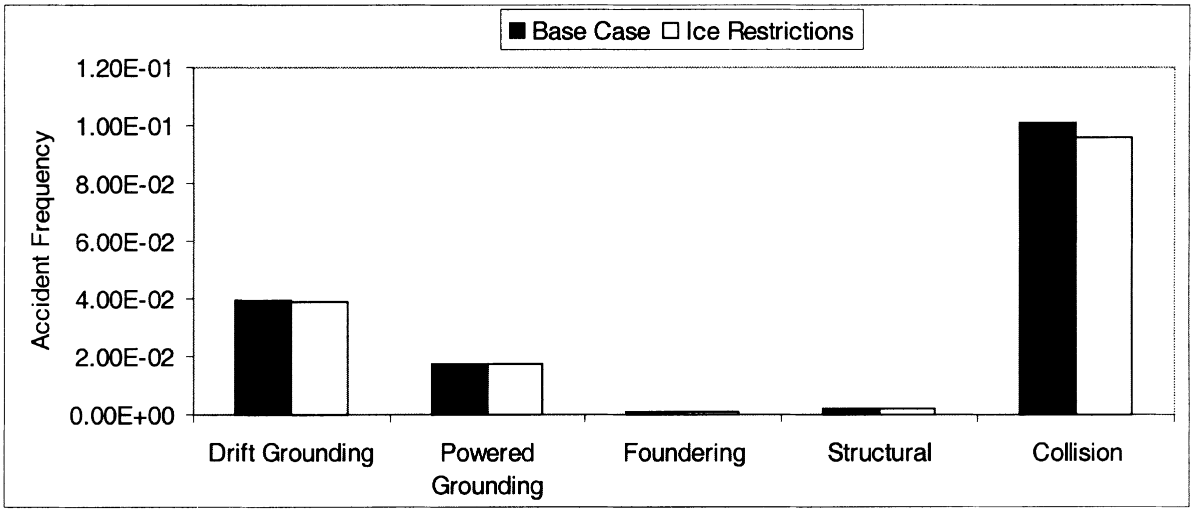


Figure 9. The migration of risk amongst accident types due to ice transit restrictions.

risk. The first escort scheme that was tested reduced the number of escorts from two or three to one or two, depending on the wind speed in Valdez Narrows. The idea behind this is to reduce the total number of escort transits and thus reduce interactions between tankers and escort vessels. Figure 8 shows that this system would reduce the average oil outflow from collisions, but migrates risk back to drift and powered grounding accidents. This is because the accident probability model indicated an increased probability of grounding with only one escort as opposed to two. Thus although these changes to the escort system achieved their goal of reducing collisions, the total average oil outflow was increased by 8%.

The final escort scheme tested used two escort tugs to escort outbound, oil-laden tankers from port through the Valdez Arm and Hinchinbrook Entrance, where the tanker is closest to shore, but used only one close escort and multiple pre-positioned, standby escorts through the Central PWS. Figure 8 shows that this escort scheme

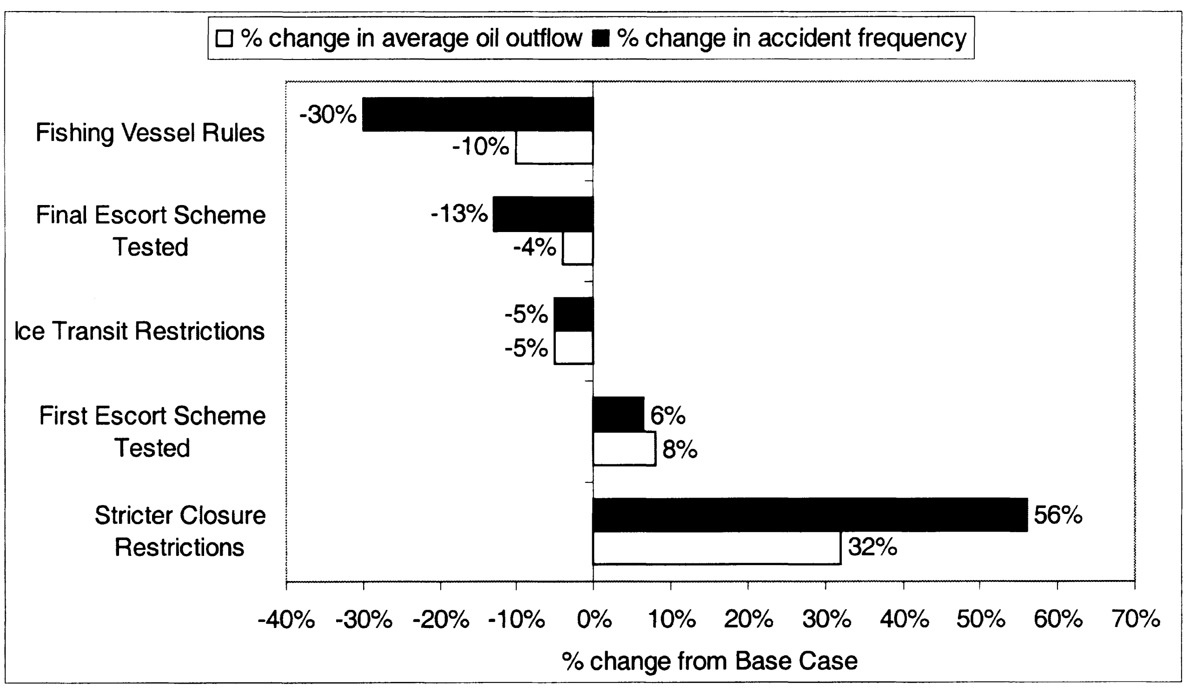


Figure 10. Estimated risk reduction for inbound tankers by intervention.

is as or more effective than the original escort scheme at reducing drift and powered grounding risk, but reduces the migration of risk to collisions, thus achieving the goal of reducing average oil outflow from collisions without migrating risk to other accident types.

In the two historical accidents involving oil tankers in Prince William Sound, the grounding of the Exxon Valdez was caused by errors in navigation while attempting to steer around icebergs in the traffic lanes, and the Overseas Ohio collided with ice. With these events in mind, the Steering Committee proposed transit restrictions that limited nighttime outbound transits while ice was present in the traffic lanes. This case was programmed into the simulation and compared with the base case. It should be noted that in the baseline simulation, one shipping company had already made a unilateral decision to implement these rules.

Figure 9 shows that the implementation of nighttime ice transit restrictions successfully reduces the total collision frequency, particularly with ice, while there is no migration of risk to other accident types. This can be partly explained by the scarcity of non-tanker related traffic during the periods of the year when ice can be present in the traffic lanes.

Figure 10 shows a tornado diagram for a summarized list of the risk interventions discussed thus far. Further major reductions indicated by the model were improving the human and organizational performance through the International Safety Management program (ISM) and introducing tankers with a second (redundant) propulsion system.

7. CONCLUSIONS

At the conclusion of the study, the contract team delivered a final report to the Steering Committee (Prince William Sound Steering Committee, 1996). This report included technical documentation of the methodology used in the study, the results of the modeling performed, and a set of recommendations based on these results. Following the project, the Steering Committee separated into risk management teams charged with implementing the recommendations in specific areas of operation. The level of implementation of the recommendations of a risk assessment project is one measure of its success. To date the following risk interventions discussed in this article have been implemented:

- The Coast Guard VTS manages interactions between fishing vessels and tankers.
- The improved escort scheme with standby escorts has been implemented.
- Nighttime transits are restricted when ice is observed in the traffic lanes.

The implementation of these risk interventions and the avoidance of targeted interventions that had negative system-wide effects demonstrate the necessity for a systems approach to managing risk. Other risk interventions implemented include improving the safety management systems of the shipping companies and the deployment of new, high-powered escort tugs, the Nanuq, the Tan'erliq, and the Gulf Service.

Despite the impact of the study, several limitations should be mentioned. The findings of a quantitative study must be interpreted with care as uncertainty is introduced at various level of the analysis (Paté-Cornell, 1996). Sources of this uncertainty include incomplete and/or inaccurate data, biased or uninformed expert judgment, modeling error, and computational error. Testing for the level of uncertainty in an analysis requires accounting for both parameter uncertainty and model uncertainty and their impact on the results and conclusions. Such an uncertainty analysis was not approved by the Steering Committee.

Although the use of proper procedures, such as rigorous data selection and cross validation, structured and proven elicitation methods for expert judgment, and use of accepted models, can reduce uncertainty and bias in an analysis, it can never be fully eliminated. The reader should recognize that the value of an analysis is not in the precision of the results *per se*, but rather in the understanding of the system through the identification of peaks, patterns, unusual circumstances, and trends in system risk and changes in system risk through risk migration.

A second major drawback in the study was the treatment of human error as a triggering incident. A full discussion of the model used is given in the article by Harrald et al., 1998. The classifications of human error used were taken from the UCSG's Prevention Through People study (USCG, 1995). However, the modeling effort was hampered by the current lack of understanding of the processes and factors that lead to human error and the lack of data on the occurrence of human errors in the maritime field. Some results were drawn from other fields, such as risk analysis in the nuclear power industry, but it is not self-evident that these are directly applicable to maritime risk.

Even with the limitations mentioned above, the risk assessment was capable of answering the majority of the questions posed by the stakeholders. The application of system simulation, data analysis, and expert judgment allowed a detailed model of system risk to be created. The stakeholders started the project with very different and often opposing points of view. The ability to systematically break down the complex decisions using an understandable framework lead to a better understanding of the problem. It is important to note that at the end of the project, the environmental and local interest groups joined with Oil Company executives to write press briefings and to discuss implementation issues.

REFERENCES

Alaska Department of Environmental Conservation. Division of spill preparedness and pipeline program: Plan approval letter, October 2, 1995.

R. Bradley and M. Terry. Rank analysis of incomplete block designs, Biometrica 39 (1952), 324–345.

R. Clemen and R. Winkler. Unanimity and compromise among probability forecasters, Management Science 36 (1990), 767–779.

R. Clemen and R. Winkler. Combining probability distributions from experts in risk analysis, Risk Analysis 19 (1999), 187–203.

R.M. Cooke. Experts in uncertainty: Expert opinion and subjective probability in science, Oxford University Press, UK, 1991.

A. DeWispelare, L. Herren, and R. Clemen. The use of probability elicitation in the high-level nuclear waste recognition program, International Journal of Forecasting 11 (1995), 5–24.

Exxon Corporation. Exxon statement: Valdez ten-year anniversary. Valdez Bulletin, 1999.

G.J. Garrick. Recent case studies and advancements in probabilistic risk assessment. Risk Analysis 4 (1984), 267–279.

Glosten Associates, Inc. Prince William Sound disabled tanker towing study and appendices A-H, 1994. Prepared for the Disabled Tanker Towing Study Group and prepared in collaboration with Maritime Simulation Center, the Netherlands.

J. Harrald, T. Mazzuchi, J. Merrick, R. van Dorp, and J. Spahn. Using system simulation to model the impact of human error in a maritime system. Safety Science, 30 (1998), 235–247.

M. Mendel and T. Sheridan. Filtering information from human experts. IEEE Transactions on Systems, Man and Cybernetics, 36 (1989), 6–16.

A. Moslesh, V. Bier, and G. Apostolakis. Critique of the current practice for the use of expert opinions in probabilistic risk assessment, Reliability Engineering and System Safety, 20 (1988), 63–85.

A. Moslesh and G. Apostolakis. Combining various types of data in combining failure rates, Transactions of the 1983 Winter Meeting of the American Nuclear Society, San Francisco, CA, 1983.

M.E. Paté-Cornell. Uncertainties in risk analysis: Six levels of treatment, Reliability Engineering and System Safety 54 (1996), 95–111.

Prince William Sound Steering Committee, Prince William Sound risk assessment study final report, 1996.

T.A. Saaty. Scaling method for priorities in hierarchical structures, Journal of Mathematical Psychology 15 (1997), 234–281.

State of Alaska. Oil and Hazardous Substances Pollution Control Regulations. 18 AAC 75, 1991.

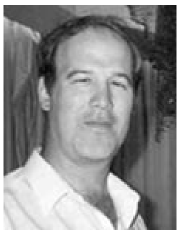
United States Coast Guard. Prevention through people. Washington DC, 1995.

United States Federal Law. The Oil Pollution Act of 1990. Public Law 101-380, enacted August 18, 1990.

Jason R. W. Merrick received his B.A. degree in mathematics and computation from Oxford University, England and his D.Sc. degree in operations research from The George Washington University, Washington DC. He is currently Assistant Professor of Operations Research and Statistics in the Department of Mathematical Sciences at Virginia Commonwealth University, Richmond VA. His research interests include probabilistic risk assessment, expert judgment elicitation, system simulation, and Bayesian statistics.

J. René van Dorp received his D.Sc. in operations research from The George Washington University. He is Assistant Professor in the Engineering Management and Systems Engineering Department at the George Washington University. His current topics of interest are risk management analysis for natural and technological disasters, maritime risk assessment, and project cost risk analysis. His main areas of interest are decision analysis, uncertainty analysis, reliability analysis, and probabilistic risk analysis.

John Harrald received his B.S. from the U.S. Coast Guard Academy, an M.S. from Massachusetts Institute of Technology, and an M.B.A. and Ph.D. from Rensselaer Polytechnic Institute, Troy, New York. He is Professor of Engineering Management in the School of Engineering and Applied Science at The George Washington University. His research interests include natural disaster vulnerability and mitigation, maritime safety and port risk analysis, response organizations and management systems, organizational learning, and the application of information technology to crisis and disaster management. He is the director of the Institute of Crisis, Disaster and Risk Management at The George Washington University. He is a founding member and director of The International Emergency Management Society (TIEMS). He is a board member of the Disaster Recovery Institute.



Thomas A. Mazzuchi received his M.Sc. and D.Sc. in operations research from The George Washington University. He is Acting Dean of the School of Engineering and Applied Sciences at The George Washington University and Professor of Engineering Management and Systems Engineering. He served for two and a half years as a research mathematician at the international operations and process research laboratory of the Royal Dutch Shell Company. Dr. Mazzuchi's research interests are Bayesian applications in reliability, risk analysis, and quality control problems. Current research interests include reliability growth assessment, software reliability modeling, design and inference in life testing, reliability estimation as a function of operating environment, maintenance inspection policies, and incorporation of expert judgment into reliability and risk analysis.

John Spahn received his B.S. in mechanical engineering from Bradley University, Peoria, IL, an M.S. in Operations Research from The George Washington University, and is currently seeking a D.Sc. from The George Washington University in operations research. He has worked six years as an Operations Engineer on the Maverick Missile Program for Hughes Aircraft in Tucson, Arizona, and has worked on several risk assessments and reliability projects as a research associate at The George Washington University.

Martha Grabowski received her B.S. from the United States Merchant Marine Academy, Kings Point, NY, and M.S., M.B.A., and Ph.D. degrees from Rensselaer Polytechnic Institute, Troy, NY. She is Professor of Management Information Systems in the Business Department at LeMoyne College in Syracuse, New York, and Research Associate Professor in the Department of Decision Sciences and Engineering Systems at Rensselaer Polytechnic Institute. Dr. Grabowski's research interests include the impact of embedded intelligent real-time systems and networks on systems and humans, human and organizational error in large scale systems, development and evaluation methods for real-time knowledge-based systems and networks, and methods for mitigating risk in safety-critical large scale systems. Dr. Grabowski serves as a member of the National Research Council's standing Committee on Human Factors and has served in the past as a member of the National Research Council's Marine Board and as a member of the U.S. Coast Guard's Navigation Safety Advisory Council.