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The Prince William Sound Risk Assessment

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Abstract

After the grounding of the Exxon Valdez, and its subsequent oil spill, all parties with interests in Prince William Sound (PWS) were eager to prevent another major pollution event. While they implemented several measures to reduce the risk of an oil spill, the stakeholders disagreed about the effectiveness of these measures and the potential effectiveness of further proposed measures. They formed a steering committee to represent all the major stakeholders in the oil industry, in the government, in local industry and among the local citizens. The steering committee hired a consultant team, who created a detailed model of the PWS system, integrating system simulation, data analysis, and expert judgment. The model was capable of assessing the current risk of accidents involving oil tankers operating in the Prince William Sound and of evaluating measures aimed at reducing this risk. The risk model showed that actions taken prior to the study had reduced the risk of oil spill by 75 percent and identified measures estimated to reduce the accident frequency by an additional 68 percent, including improving the safety management systems of the oil companies and stationing an enhanced capability tug, called the Gulf Service, at Hinchinbrook Entrance. In all, various stakeholders made multi-million dollar investments to reduce the risk of further oil spills based on the results of the risk assessment.

(Decision analysis: risk. Industries: petroleum, transportation. Reliability: system safety)

On March 24, 1989, the Exxon Valdez ran aground on Bligh Reef, spilling an estimated 11 million gallons of crude oil into Prince William Sound, Alaska. The oil spill (Figure 1) spread rapidly, affecting more than 1,500 miles of shoreline. The spill had both immediate and lingering effects on fish and wildlife resources and on the lives of people in coastal communities. The cost to Exxon Corporation for clean up operations was estimated to be $2.2 billion (Harrald et al. 1990).

After the accident, all parties with interests in Prince William Sound (PWS) agreed to work to prevent such an event from happening again. They implemented several ideas for reducing the risk of an oil spill. They introduced weather-based closure restrictions that stopped all transits through Valdez Narrows and Hinchinbrook Entrance (Figure 2) during periods of high winds. The US Coast Guard designated Valdez Narrows a special navigation zone by restricting passage through the Narrows to one-way for deep-draft traffic, including oil tankers. The oil companies introduced escort tugs to accompany oil-laden tankers in their transit out of Prince William Sound. These tugs were to assist a tanker if they had propulsion or steering failures, attaching lines to the disabled tanker and holding it fast, thus preventing grounding accidents. The Oil Pollution Act (1990) stated that two escort tugs should accompany each oil-laden tanker; depending on the wind conditions and the size of the tanker, three tugs were sometimes used.

In early 1995, questions arose concerning the effectiveness and benefits of existing and proposed risk intervention measures. The PWS shipping companies (ARCO Marine Inc., BP Oil Shipping Company, USA, Chevron Shipping Company, SeaRiver Maritime Inc., and Tesoro Alaska Petroleum Company) concluded that they needed a comprehensive risk assessment to evaluate all proposals. They formed a steering committee along with the PWS Regional Citizens Advisory Committee (RCAC) [http://www.pwsrcac.org], the Alaska Department of Environmental Conservation (ADEC) [http://www.state.ak.us/dec/], and the US Coast Guard (USCG). The members consisted of presidents of oil shipping companies, local fisherman and environmentalists representing the RCAC, senior representatives of ADEC, and the USCG Captain of the Port for Valdez. Although the members of the group had different perspectives on the operation of the oil-transportation system, the committee captured the substantive expertise of the PWS oil transportation and eco system.

By forming the steering committee, the PWS community formalized its preference for a collaborative analysis approach rather than an adversarial one (Charnley 2000). Up to this point, the adversarial approach had prevailed in PWS risk and safety studies, pitting expert against expert. The adversarial approach often leads to a lack of trust in the decision-making process and subsequently may hamper the implementation of regulations and procedures aimed at reducing risk. Many see lack of trust as the major reason for the failure of sophisticated technological risk assessments to influence public policy in the nuclear power arena (Slovic 1993).

The steering committee decided to fund a risk assessment effort for the PWS oil transportation system and engaged a consultant team from George Washington University (GWU), Rennslaer Polytechnic Institute (RPI), and Det Norske Veritas (DNV). The committee stipulated the objectives of the risk assessment effort:

- to identify and evaluate the risks of oil transportation in PWS,
- to identify, evaluate, and rank proposed risk reduction measures, and

- to develop a risk management plan and risk management tools that can be used to support a risk management program.

This paper presents an overview of the modeling and analysis used in addressing the first two objectives, as well as a discussion of the effect of the analysis on the third objective and the implementation of the recommendations.

Risk Assessment and Management in Maritime Transportation

The National Research Council identified the assessment and management of risk in maritime transportation as an important problem domain (NRC 1986 1991 1994 2000). In earlier work, researchers concentrated on assessing the safety of individual vessels or marine structures, such as nuclear powered vessels (Pravda & Lightner 1966), vessels transporting liquefied natural gas (Stiehl 1977) and offshore oil and gas platforms (Paté-Cornell 1990). The USCG tried to prioritize federal spending to improve port infrastructures using a classical statistical analysis of nationwide accident data (USCG 1973; Maio et al. 1991). More recently, researchers have used probabilistic risk assessment (PRA) (US Nuclear Regulatory Commission 1975) in the maritime domain (Hara and Nakamura 1995; Roeleven et al. 1995; Kite-Powell 1996; Slob 1998; Fowler and Sorgard 2000; Trbojevic and Carr 2000; Wang 2000; Guedes Soares and Teixeira 2001) by examining risk in the context of maritime transportation systems (NRC 1999).

In a maritime transportation system (MTS), traffic patterns change over time in a complex manner. Researchers have used system simulation as a modeling tool to assess MTS service levels (Andrews et al. 1996), to perform logistical analysis (Golkar et al. 1998) and to facilitate the design of ports (Ryan 1998). The dynamic nature of traffic patterns and other situational variables, such as wind, visibility, and ice conditions, mean that risk levels change over time. The PWS risk assessment differs from previous maritime risk assessments in capturing the dynamic nature of risk by integrating system simulation (Banks et al. 2000) with available techniques in the field of probabilistic risk assessment (Bedford and Cooke 2001) and expert judgment elicitation (Cooke, 1991). The following sections discuss the definition of risk used in the PWS risk assessment, the system risk simulation model, the codification of expert judgment, the results of the risk assessment, the validity of the results, actions taken following the PWS risk assessment and finally the benefits of the risk assessment process followed.

Defining Risk

Lowrance (1976) defines risk as a measure of the probability and severity of the consequences of undesirable events. In the PWS risk assessment, we define the undesirable events to be accidents involving oil tankers, specifically the following:

- Collisions: An underway tanker colliding with or striking another underway vessel as a result of human error or mechanical failure and lack of vigilance (inter-vessel collision) or striking a floating object, for example ice.
- Drift Groundings: A drifting tanker out of control because of a propulsion or steering failure making contact with the shore or bottom.
- Powered Groundings: An underway tanker under power making contact with the shore or bottom because of navigational error or steering failure and lack of vigilance.
- Foundering: A tanker sinking because of water ingress or loss of stability.

- Fire/Explosion: A fire occurring in the machinery, hotel, navigational, or cargo space of a tanker or an explosion occurring in the machinery or cargo spaces.
- Structural Failure: The hull or frame cracking or eroding seriously enough to affect the structural integrity of the tanker.

The consequence of interest was oil outflow into Prince William Sound. The initial measure the Steering Committee wanted was the expected volume of oil outflow per year for each accident type and specified locations. However, after further discussion, it decided that any accident involving an oil tanker was an undesirable event, and thus the focus shifted to the expected number of accidents per year again broken down by accident type and location. We defined boundaries for seven locations to use in the study (Figure 2).

The basic technique used in the PWS risk assessment is PRA (Bedford and Cooke 2001). In performing a PRA, one identifies the series of events leading to an accident, estimates the probabilities of these events, and evaluates the consequences of the accident. Garrick (1984) notes that an accident is not a single event but the culmination of a series of events. A triggering incident is defined to be the immediate precursor of an accident. In the PWS risk assessment, we separated triggering incidents into mechanical failures and human errors. The mechanical failures considered to be triggering incidents were propulsion failures, steering failures, electrical power failures, and hull failures. The classifications of human errors used were diminished ability, hazardous shipboard environment, lack of knowledge, skills or experience, poor management practices and faulty perceptions or understanding. We based these on current US Coast Guard classifications.

We constructed an accident probability model using the relationships between the vessel's operating environment, triggering incidents and accidents (Roeleven et al., 1995). The combination of organizational and situational factors that describes the state of the system in which an accident may occur is termed an opportunity for incident (OFI). We based our accident model on the following conditional probabilities:

- P(OFI): the probability that a particular system state occurs,
- P(Incident| OFI): the probability that a triggering incident occurs in this system state,
- P(Accident| Incident, OFI): the probability that an accident occurs given that a triggering incident has occurred in this system state.

Once one has specified these probabilities, one can find the probability of an accident occurring in the system by summing the product of the conditional probabilities over all types of accidents and triggering incidents and all combinations of organizational and situational factors according to the law of total probability. Thus to perform an assessment of the risk of an accident using this model, one must determine an operational definition of an OFI and then estimate each of the terms in the probability model. Harrald et al. (1998) discuss the operational definition of an OFI in the PWS risk assessment.

The System Risk Simulation Model

The first term to estimate is the frequency of occurrence of each combination of organizational or situational factors, that is, each OFI. Although data is collected on vessel arrivals and environmental conditions, the combinations of these events are not. Traffic rules, such as a one-way zone, mean that the movements of vessels are dependent, while weather-based closure restrictions cause dependence between vessel movements and environmental conditions. A discrete-event simulation of the system captures the complex dynamic nature of the system and accurately models the interactions between the vessels and their environment.

We created the simulation model using operational data, such as vessel type and vessel movement data from the USCG vessel traffic service, tanker arrival and departure information from the ship escort/response vessel system (SERVS), and publicly available data, such as meteorological data from the National Oceanographic and Atmospheric Administration weather buoys. More difficult to obtain were data on open fishing times, locations, and durations, requiring local community surveys. Based on the data, we developed traffic arrival models and weather models. In addition, because all deep-draft vessels transiting PWS must participate in the USCG vessel traffic service and follow a defined set of traffic rules, such as weather-based closure restrictions, one-way zones, the tug escort scheme, and docking procedures, we programmed these rules into the simulation.

We used the simulation as an event counter, that is we used it to count the number of occurrences of individual OFIs throughout the PWS for a given time period. The simulation calculated the state of the system once every five minutes based upon the traffic arrivals, the weather, and the previous state of the system. We ran the simulation for 25-years of simulation time and, for each five-minute period, tabulated the OFIs that occurred and thus determined OFI frequencies (Merrick et al. 2000).

We estimated the two levels of conditional probability of triggering incidents and accidents. The preferred method for estimating these probabilities is through data. The steering committee required that we use only PWS specific data in the risk assessment, rather than worldwide accident data that might not be representative. Each of the PWS shipping companies supplied proprietary mechanical failure data. However, at the time we could obtain no reliable PWS human error data in the maritime domain and we could obtain very little from near miss reports (Harrald et al. 1998). Large databases of local accident data were not available for standard statistical analysis of the organizational and situational factors that could affect risk. Cooke (1991) cites the use of expert judgment in areas as diverse as aerospace programs, military intelligence, nuclear engineering and weather forecasting. We used expert judgment to assess relative conditional probabilities, and data to calibrate these relative probabilities.

Using the log-linear accident probability model (Roeleven 1995), we obtained relative conditional probabilities through a regression analysis of pairwise comparison surveys (Bradley and Terry 1952) constructed for the pilots, captains, and chief engineers with operational experience in the PWS. PWS oil shipping companies, SERVS and regional representatives on the PWS steering committee made these substantive experts available for elicitation sessions. An example of the type of questions posed is the following taken from the expert judgment questionnaire for collisions given that a propulsion failure has occurred (Table 1). In each situation there is an inbound tanker, greater than 150,000 DWT in size, which has just experienced a propulsion failure. It is within 2 to 10 miles of a tug with tow in winds over 45 MPH blowing on shore to the closest shore point with visibility greater than half a mile in the Central Prince William

Sound. The only difference between the two situations is that the first situation includes an ice flow in the traffic lane, while the second does not. We ask the expert to picture the two situations, to determine which situation is more likely to result in a collision and to indicate their sense of magnitude in the choice through a nine point scale, with one indicating equally likely (Saaty 1977).

For each question, we changed only one attribute so that the experts could estimate the difference in risk between the two situations. The experts could answer a book of 120 questions in one to one and a half hours. We put the questions in the books in random order and statistically tested the results to ensure nonrandom responses and to minimize response bias. All participants had very extensive knowledge, with at least 20 years of experience at sea. We treated the expert responses as ratios of the probabilities of an accident in each scenario. We estimated the parameters of the accident probability model using statistical regression and calibrated the model to available data. The *Prince William Sound Risk Assessment Final Report* contains specific details of the development of the simulation model, the design and analysis of the expert judgment questionnaires, and the integration of the simulation model and the accident probability model (PWS Steering Committee 1996).

The integrated system risk simulation model was capable of assessing the current risk of accidents involving oil tankers operating in PWS and of evaluating risk-intervention measures. We also implemented an oil outflow model, created by DNV, in the system risk simulation program. The program displayed risk in PWS dynamically (Figure 3) and we could interrogate it to determine the expected frequencies of accidents or the expected oil outflow per year broken down by accident type, location, and any of the organizational or situational factors.

Results of the Risk Assessment

The steering committee's first objective was to identify and evaluate the risks of oil transportation in PWS. We chose accident scenarios as the method of reporting, defining an accident scenario to be an accident type in a given location. We programmed the simulation to represent the shipping fleet, traffic rules and operating procedures in place in 1996, the year we performed the study. We ran the simulation program for 25 years (simulation time) and estimated the expected frequency of accidents. We broke the frequencies down by location and accident type to obtain the accident scenario results. As the primary interest was accident scenarios with the highest expected frequencies, we reported the results by sorting the accident scenarios from highest to lowest (Figure 4).

Before the risk assessment, people in PWS commonly believed that the most likely accident scenario was a drift or powered grounding in the Valdez Narrows or Hinchinbrook Entrance. However, we showed that the first seven accident scenarios accounted for 80 percent of the total expected frequency of accidents, with 60 percent coming from collisions in the port, in the Valdez Narrows and in the Valdez Arm. We performed a further analysis to find the primary cause of these accidents. We found that the primary risk was collisions with fishing vessels that operate in large numbers in these locations during fishing openers. Although they introduce a relatively high risk of collision, few fishing vessels are large enough to penetrate the hull of a tanker. Thus the expected oil outflow from these events was low. The perceived high-risk scenarios of drift or powered groundings contributed approximately 15 percent of the expected frequency of accidents.

Integrating the oil outflow model with the estimated frequencies of accident scenarios allowed us to estimate the expected volume of oil outflow as a measure of risk, again reported from highest to lowest (Figure 5). We discovered a surprising result using this metric. Potential collisions of outbound tankers with inbound SERVs' tugs (returning from escort duty) are a large contributor to the total expected oil outflow. Escort tugs leaving port with a tanker are intended to save the tanker in case of a propulsion or steering failure, but on their return from escort they introduce a risk of collision and can cause enough damage to tankers to spill oil. Less suprising, however, was the confirmation of the risk of drift or powered groundings in the Valdez Narrows or Hinchinbrook Entrance.

The steering committee's second objective was to identify, evaluate, and rank proposed risk intervention measures. We developed a set of risk-intervention measures for evaluation in consultation with the PWS steering committee. We classified risk-interventions in terms of their effect on modeling parameters and analyzed them accordingly. The modeling required was extensive, but because of the level of granularity incorporated in the system risk simulation model, we could change parameters of the accident probability model or simulation code to reflect the effects of risk-intervention measures. By stripping away previously implemented risk-intervention measures, we estimated the risk prior to the Exxon Valdez accident. Comparing this risk to the baseline case, representing the PWS system during the study period, we estimated that the accident frequency had been reduced 75 percent since the Exxon Valdez accident.

We identified further effective risk-intervention measures (Figure 6). Under the current system, interactions with fishing vessels and escort tugs were significant contributors to the overall risk. We developed rules to reduce the number of these interactions in cooperation with the Steering Committee and programmed them into the simulation. We demonstrated that modifying the escort scheme to reduce interactions with tankers and managing the interactions of fishing vessels and tankers lead to a major reduction in risk. The model also indicated that improving human and organizational performance through the International Safety Management (ISM) program would further reduce risk. We estimated the reduction in risk obtained by reducing the frequency of human errors in the accident probability model, with the reduction being estimated by personnel from DNV with experience in implementing the ISM program. We showed that some proposed risk-intervention measure increase risk, for example we showed that additional weather-based closure restrictions would increase traffic congestion.

Estimates of expected accident frequency and expected oil outflow by accident scenario are point estimates of risk. The preferred method for reporting accident risk would be a distribution that also represents the degree of uncertainty in the results (Paté-Cornell 1996). Although we proposed an uncertainty analysis to the steering committee, time and budgetary constraints did not allow it. This was a drawback in the study and additional research is needed to develop a technique to assess uncertainties in the system risk simulation model. The value of an analysis, however, is not only in the precision of the results, but in understanding system risk. Unlike risk assessments in more traditional areas, for example nuclear power, our focus was the dynamic risk behavior of the system. For risk management purposes it is valuable to identify the peaks, patterns, unusual circumstances, and trends in system risk and in changes in system risk made by implementation of risk-intervention measures.

Validity of the Results

In any study, it is important to validate the results. To assess the validity of our results, we need to validate both the simulation of the PWS system and the expert judgment based estimates of accident and incident probabilities. We used graphical comparison to the actual system and numerical comparison using summary statistics to validate the simulation part of the model. Specifically, USCG personnel from the Vessel Traffic Service (VTS) in PWS, who monitor traffic using screens resembling the graphical simulation output, verified the general behavior of traffic in the simulation regarding adherence to traffic rules, and patterns of vessel arrivals and departures. In addition, we compared summary statistics from the simulation, such as the average number of trips to the anchorage area as a result of weather-based closure conditions, the average number of tanker diversions due to ice in tanker lanes and the average number of closed waterways at separate locations due to weather restrictions, to those observed in the VTS system.

However, estimates of accident and incident probabilities based on expert judgments are more difficult to validate. While the use of proper procedures, such as structured and proven elicitation methods, can reduce uncertainty and bias in an analysis, they can never be eliminated. As one referee noted, our use of mariners with experience in PWS could introduce a group bias. For example, had the Exxon Valdez not run aground, the opinions of the experts might have been quite different. The bias the referee refers to is availability bias (Cooke 1991), that is, people make assessments in accordance with the ease with which they can retrieve similar events. In the case of the Exxon Valdez accident, the effect of the availability bias would be to increase perceived levels of accident risk. However, each question in the PWS questionnaires required the comparison of two carefully defined scenarios. One could argue that both scenarios would be affected by the availability bias in a similar manner. As a result, the effect of the availability bias would be reduced. The Exxon Valdez accident scenario (a powered grounding of a tanker in the Valdez Arm) received only a modest ranking of 10 out of 17 accident scenario's that contribute to approximately 95 percent of total accident risk (Figure 4).

Risk assessments typically deal with low probability, high consequence events, and thus statistical validation of their results is difficult even when using nationwide or global accident databases. Using nationwide or global accident data in localized risk assessments is also questionable in terms of validity, prompting the PWS steering committee to require our use of only PWS specific data. This requirement meant we could not validate our risk assessment in the traditional sense. In the case of the probability of triggering incidents, such as mechanical failures, where available data and expert judgments overlapped, we observed good correspondence. Such correspondence could add to the validity of the other expert based estimates, where such comparisons could not be made.

In the PWS risk assessment we followed a collaborative analysis approach (Charnley 2000). This included educating the steering committee in the language and modeling of risk. As we developed a common framework for analyzing risk, we discussed proposed risk-intervention measures at the level of their detailed effect on the whole system, rather than their gross effects on one part. We discussed the assumptions behind the model with the steering committee. The members of the steering committee were able to challenge the assumptions upon which they based their own opinions concerning the operation of the oil transportation system in PWS.

We presented all our results to the steering committee in monthly meetings. The members questioned various results and often required more detailed analysis to reach a deeper understanding. The simulation model allowed us to demonstrate many results graphically, giving the steering committee a better intuition and trust in their validity. Members challenged certain results and often identified problems with the analysis, such as incorrect implementation of vessel traffic rules in the simulation, which we corrected. The committee put no pressure on us to change results merely because members disagreed. In the end, the steering committee unanimously accepted the results we obtained with the system risk simulation model despite members' diverse perspectives at the onset of the study. Using the collaborative analysis approach, we built on the substantive knowledge represented in the steering committee and instilled trust in our results and recommendations, normally acquired through the use of classical statistical validation procedures.

Actions Taken

At the conclusion of the study, our 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 and recommendations based on these results. Following the risk assessment project, the steering committee split up into risk management teams charged with implementing the recommendations in specific areas.

One of the key questions the steering committee asked at the start of the study was whether the current escort system was capable of stopping drift groundings in the Valdez Narrows. The study showed that the current escort tugs were capable of saving a disabled tanker in the environmental conditions experienced in the Valdez Narrows. However, because of other considerations the PWS shipping companies decided to accept proposals for two tractor-tugs. The designers used our result extensively in the design process. Crowley Maritime Services have invested $30 million to build the tugs Nanuq (Figure 7) and Tan'erliq to fulfill the requirements developed.

To date the various organizations comprising the risk management teams have taken the following actions based on our results:

- The oil companies have introduced an enhanced capability tug called the Gulf Service (Figure 8) to escort oil laden tankers through Hinchinbrook Entrance, which is being replaced by new azimuthing stern-drive escort vessels designed for higher transit speed/open water assist scenarios that include the Hinchinbrook Entrance transit.
- We have completed a further project to find an improved escort scheme, which SERVS have adopted, minimizing interactions between oil tankers and escort tugs, while maintaining the ability to save disabled tankers.
- The Coast Guard VTS manage interactions between fishing vessels and tankers.
- SERVS has increased the minimum required bridge crew on board escort tugs from one to two to add additional error capture capability.

- The International Maritime Organization has approved a change to the tanker route through central PWS reducing the number of course changes required.
- The shipping companies have made long term plans for quality assurance and safety management programs.

The Benefits of the Risk Assessment Process

It is difficult to compare this project with other more traditional projects in operations research and management science, whose benefits are typically measured in terms of reduced operating costs or increased profits. The benefits of risk assessments are less tangible as the objective is to reduce the occurrence of future accidents. However, because clean-up operations for the Exxon Valdez accident cost over $2 billion, the benefits of preventing a single such accident would be of similar magnitude. We can only estimate the reduction in the frequency of accidents using our models and can only estimate the benefits of the study in terms of clean-up cost. Using our risk models, we estimated that accident frequency had been reduced by 75 percent since the Exxon Valdez accident. According to our risk models, the further reduction in accident frequency from all measures taken as a result of the Prince William Sound Risk assessment is 68 percent, with a 51 percent reduction in the expected oil outflow. This means that, since the Exxon Valdez accident, the accident frequency has been reduced by an estimated total of 92 percent. The costs of the risk assessment, roughly $2 million over a two-year period, pale in comparison to the potential clean-up costs for a single major oil spill resulting from a tanker accident. However, the benefits go beyond clean-up costs and include the protection of pristine environments, and the prevention of loss of life and injury to vessel crews. In addition, the shipping companies have used the results of the PWS model in making decisions to invest in multi-million dollar equipment.

While the stakeholders in PWS all recognized the need for a rational method to evaluate the merits of risk intervention measures, to improve the allocation of resources and to avoid implementing measures that would adversely affect system risk, they did not trust ach other at the beginning of the project. The steering committee wanted to use the project as a forum to build trust amongst stakeholders, to educate of all interested parties, and to provide a common understanding of oil transportation risk. The PWS risk assessment fostered a cooperative risk-management atmosphere involving all stakeholders.

At the end of the project, the stakeholders published the final report as their document, not just as a report from the consultant team. Members of the steering committee from environmental groups, the fishing industry and the oil companies wrote joint press briefings and formed risk-management teams to manage implementation of the model results. The unified acceptance and presentation of the results of the study by all stakeholders and the level of implementation of the results can be primarily considered a benefit of the collaborative analysis process. All stakeholders finished the project convinced that they had reduced risk of further multi-billion dollar accidents and, with the cooperation fostered by the collaborative analysis process, the stage has been set for further improvements in managing risk.

The success of the Prince William Sound risk assessment has not gone unnoticed and National Science Foundation has awarded other researchers funding (e.g. NSF SBR-9520194, NSF SBR-9710522) to study the risk-assessment process we followed. Our study is described as an example collaborative analysis by Busenberg (2000) and Charnley (2000). Busenberg (1999) commented as follows:

"All ten of the participants who were interviewed agreed that this process allowed the steering committee to gain a better understanding of the technical dimensions of maritime risk assessment … The results of the risk assessment were released in late 1996, and were unanimously accepted as valid by the RCAC, oil industry, and government agencies involved in this issue. The participating groups agreed that the study showed the need for an ocean rescue tug vessel in the Sound. In 1997, the oil industry responded by deploying a vessel of this class in the Sound."

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Table 1. We elicited expert judgments from the substantive experts using pairwise comparison questionnaires in which we defined a given scenario and varied only one attribute, in this example changing whether there is ice in the traffic lanes.

Figure 1. The stricken Exxon Valdez spilled oil in to Prince William Sound, Alaska affecting over 1,500 miles of shoreline.

Figure 2. We divided Prince William Sound into seven locations for reporting risk.

Figure 3. We created the system risk simulation program to perform the analysis and demonstrate the results to the steering committee. On the left is a display of the dynamic behavior of the Prince William Sound marine transportation system including traffic patterns and environmental conditions, such as wind speed and direction. On the right, the analysis shown is broken into seven locations (Figure 2), with estimates of the probability of an opportunity for an incident, the probability of an accident given such an opportunity and finally the dynamic variation in the expected frequency of accidents for the whole region.

Figure 4. We sorted the combinations of accident types and locations by their expected frequency (dark bars). The cumulative percentage of the total expected frequency up to each such combination (white bars) is indicated by the total height of each bar. For example, we found that the first seven accident scenarios account for 80 percent of the total expected frequency of accidents.

Figure 5. We sorted the combinations of accident types and locations by their expected oil outflow (dark bars). The cumulative percentage of the total expected oil outflow up to each such combination (white bars) is indicated by the total height of each bar. For example, we found that the first seven accident scenarios account for 55 percent of the total expected oil outflow.

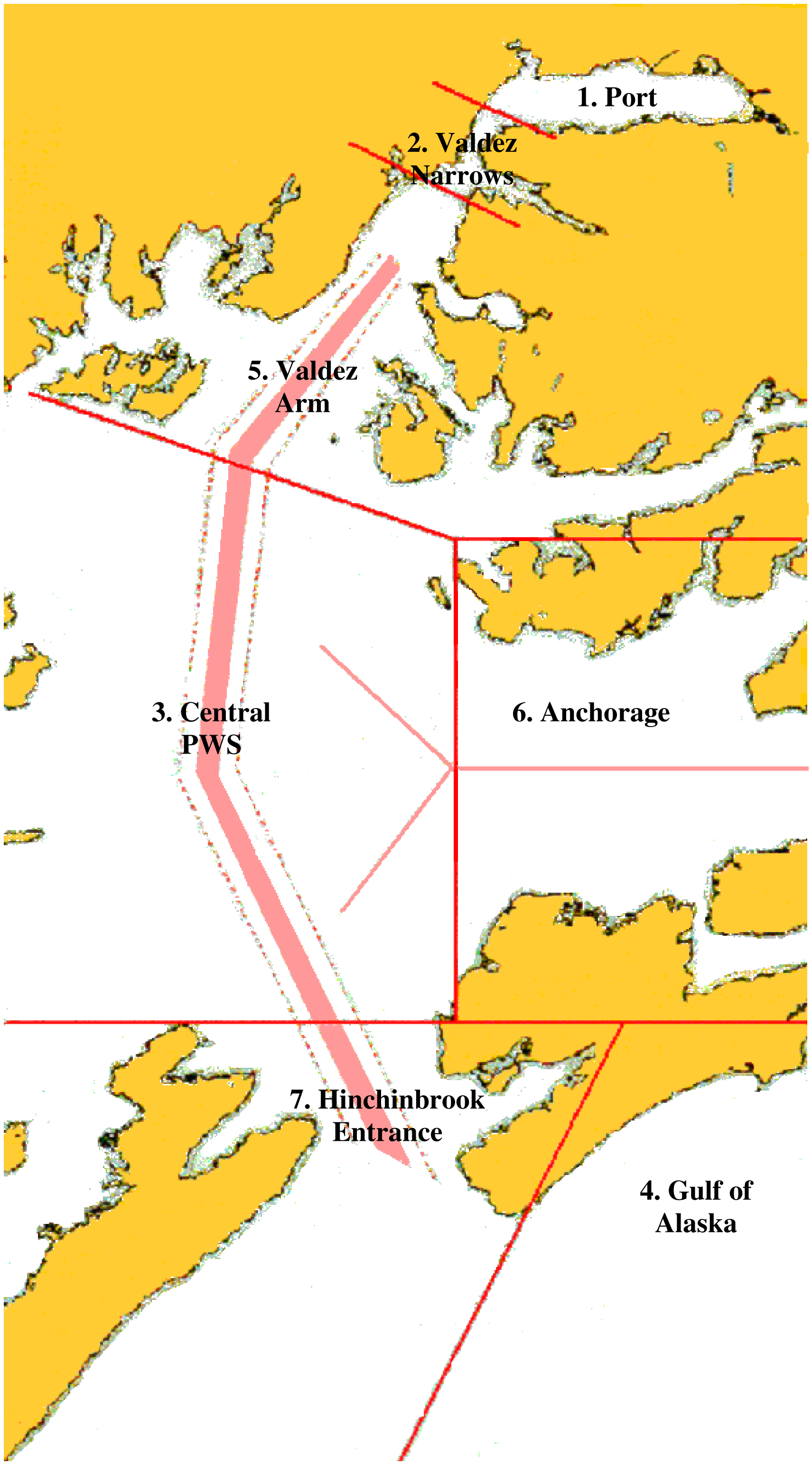
Figure 6. We tested proposed risk interventions in the system risk simulation and ranked them by percentage reduction from the study year in the expected frequency of accidents (black bars) and expected oil outflow (white bars) per year.

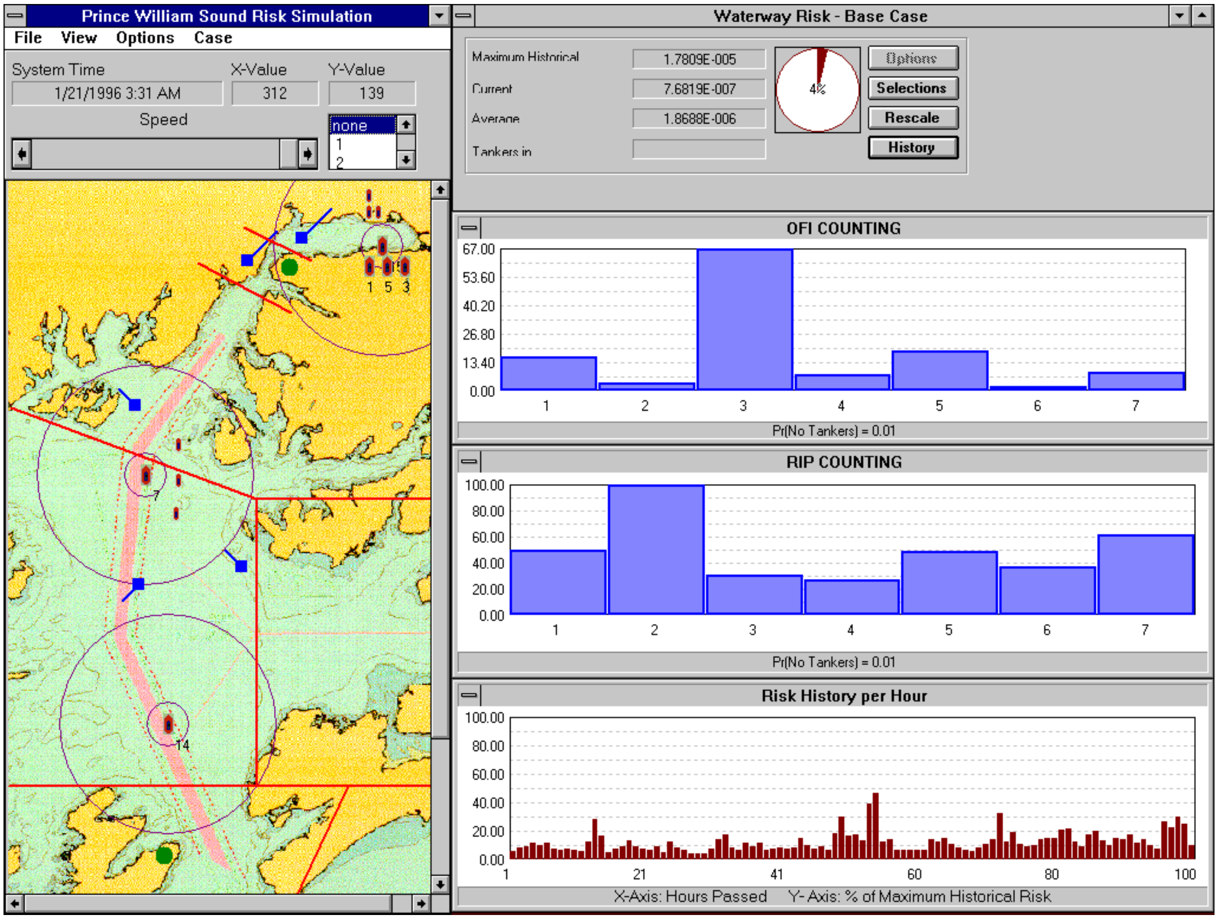
Figure 7. The 153-foot, 10,000 horsepower, state-of-the-art tractor-tug Nanuq has been put in service to escort tankers through Valdez Narrows.

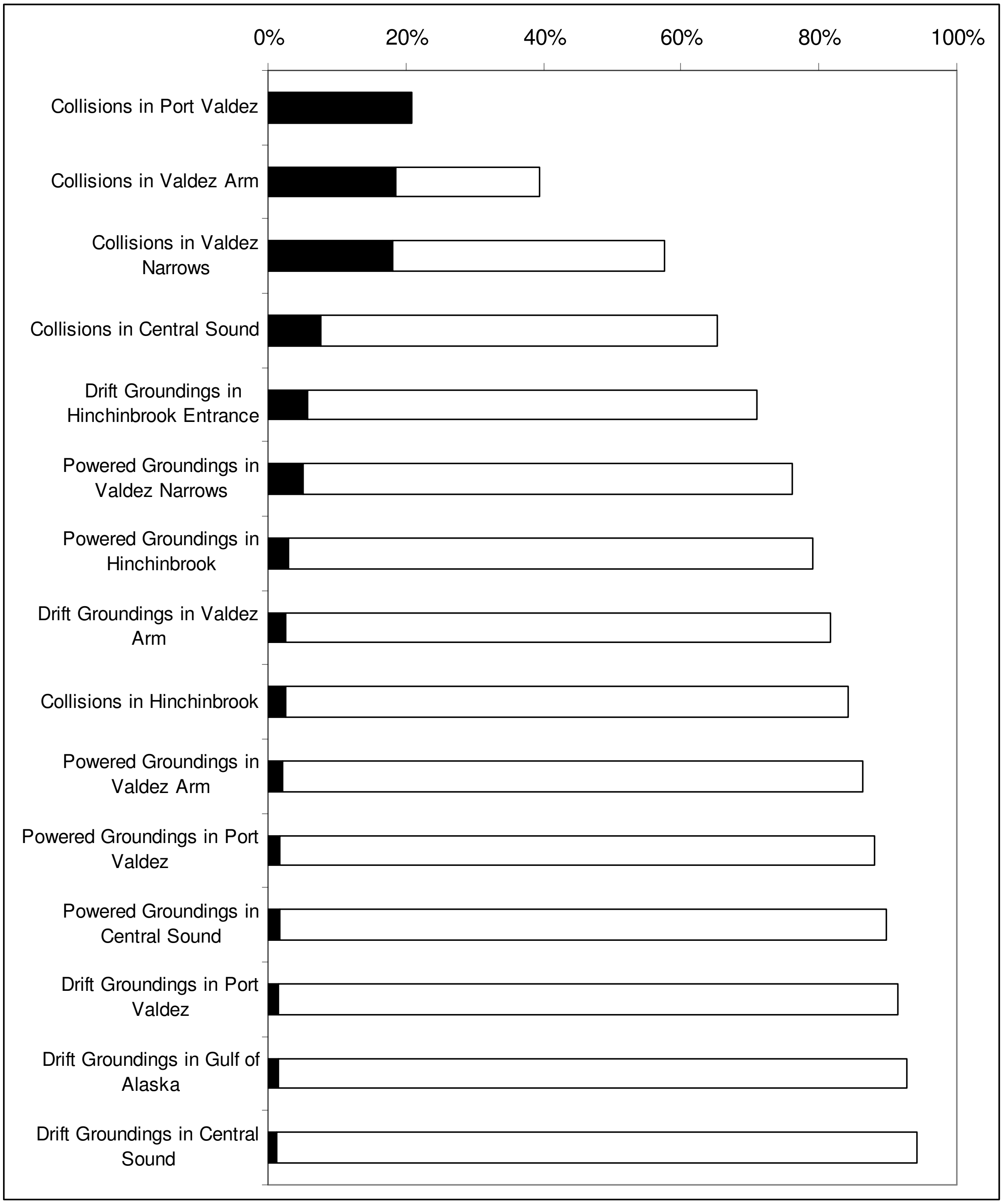
Figure 8. The enhanced capability tug Gulf Service has been stationed at Hinchinbrook Entrance to save disabled tankers even in extreme environmental conditions.

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


APR 13 '89


1. Port
2. Valdez
Narrows
5. Valdez
Arm
3. Central
PWS
6. Anchorage
7. Hinchinbrook
Entrance
4. Gulf of
Alaska


Prince William Sound Risk Simulation
File View Options Case
System Time
X-Value
Y-Value
1/21/1996 3:31 AM
312
139
Speed
none
1
2
Waterway Risk - Base Case
Maximum Historical
1.7809E-005
Current
7.6819E-007
Average
1.8688E-006
Tankers in
4%
Options
Selections
Rescale
History
OFI COUNTING
Pr(No Tankers) = 0.01
RIP COUNTING
Pr(No Tankers) = 0.01
Risk History per Hour
X-Axis: Hours Passed Y- Axis: % of Maximum Historical Risk


0%
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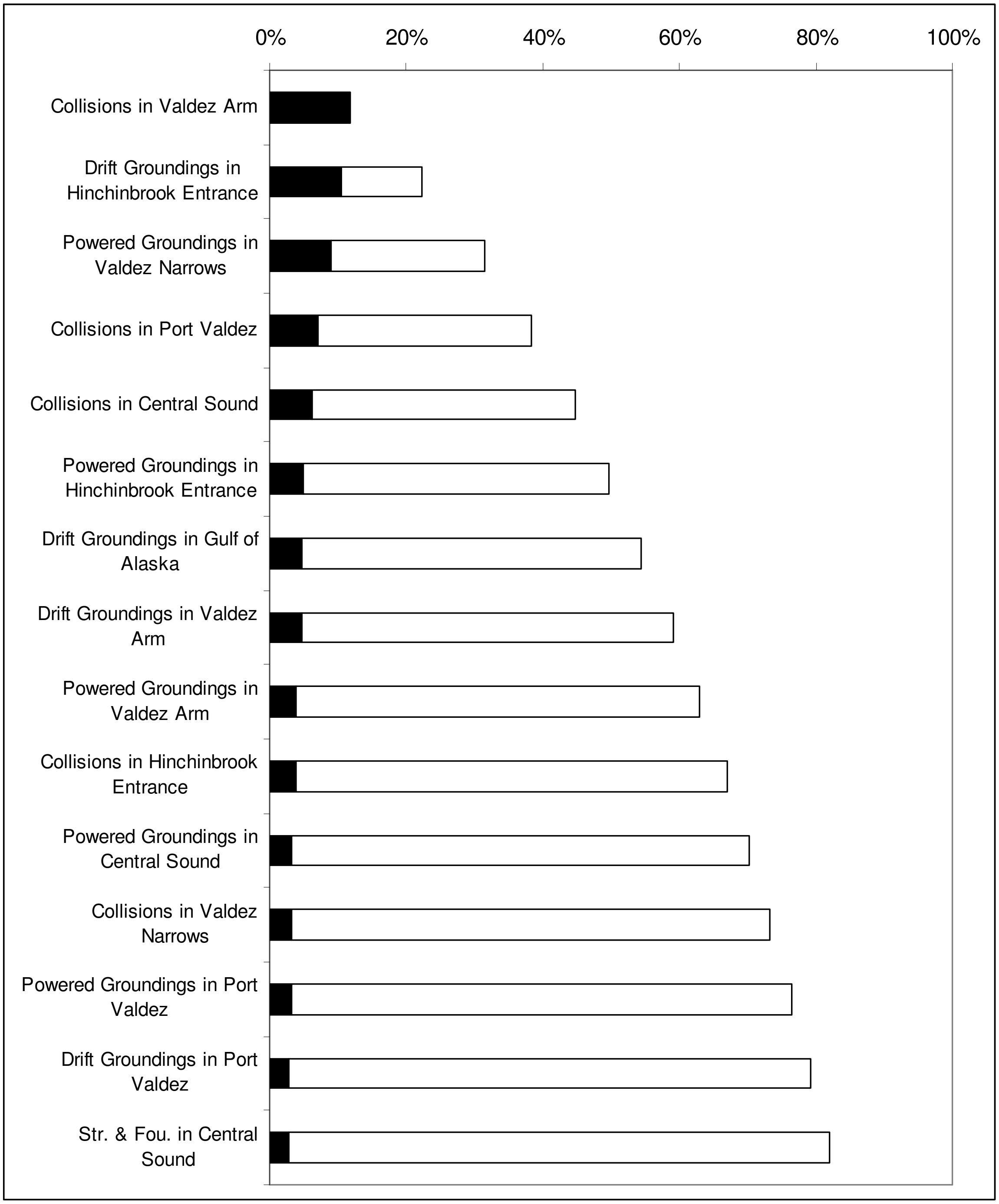
100%
Collisions in Port Valdez
Collisions in Valdez Arm
Collisions in Valdez Narrows
Collisions in Central Sound
Drift Groundings in Hinchinbrook Entrance
Powered Groundings in Valdez Narrows
Powered Groundings in Hinchinbrook
Drift Groundings in Valdez Arm
Collisions in Hinchinbrook
Powered Groundings in Valdez Arm
Powered Groundings in Port Valdez
Powered Groundings in Central Sound
Drift Groundings in Port Valdez
Drift Groundings in Gulf of Alaska
Drift Groundings in Central Sound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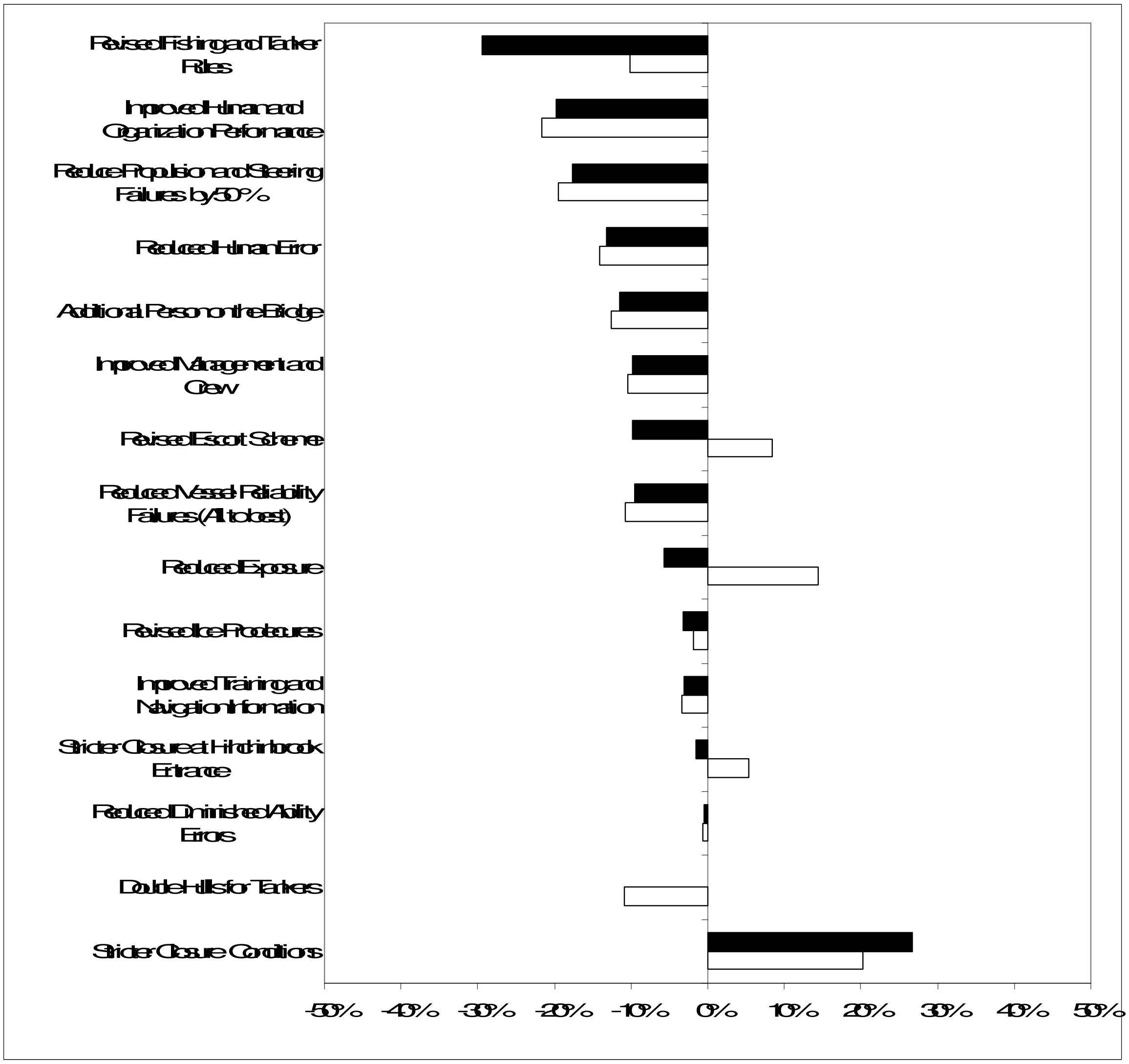
Collisions in Valdez Arm
Drift Groundings in Hinchinbrook Entrance
Powered Groundings in Valdez Narrows
Collisions in Port Valdez
Collisions in Central Sound
Powered Groundings in Hinchinbrook Entrance
Drift Groundings in Gulf of Alaska
Drift Groundings in Valdez Arm
Powered Groundings in Valdez Arm
Collisions in Hinchinbrook Entrance
Powered Groundings in Central Sound
Collisions in Valdez Narrows
Powered Groundings in Port Valdez
Drift Groundings in Port Valdez
Str. & Fou. in Central Sound


Revised Fishing and Tanker Rules
Improved Human and Organization Performance
Reduce Propulsion and Steering Failures by 50%
Reduced Human Error
Additional Person on the Bridge
Improved Management and Crew
Revised Escort Scheme
Reduced Vessel Reliability Failures (All to best)
Reduced Exposure
Revised Ice Procedures
Improved Training and Navigation Information
Stricter Closure at Hinchinbrook Entrance
Reduced Diminished Ability Errors
Double Hulls for Tankers
Stricter Closure Conditions
-50% -40% -30% -20% -10% 0% 10% 20% 30% 40% 50%


CROWLEY
NANUQ