# Prince William Sound Risk Assessment
## System Risk Analysis by Simulation and Expert Judgment

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The use of dynamic simulation as a risk modeling tool was a unique aspect of the Prince William Sound (PWS) risk assessment. The simulation technique enhanced the estimation of risk due to situational interactions (such as adverse weather, traffic) and allowed the systemwide impact of dynamic interventions such as closure restrictions and escort requirements to be measured. The PWS risk assessment project was a joint project of Det Norske Veritas, Rensselaer Polytechnic Institute, and The George Washington University (GWU). The project was directed by a steering committee composed of the PWS shipping companies (ARCO, Sea River, British Petroleum, Chevron, and Tesoro), the PWS Regional Citizens Advisory Committee, the Alaska Department of Environmental Conservation (ADEC), and the U.S. Coast Guard (USCG). The involvement of all TAPS shippers, the Regional Citizens Advisory Council, Alyeska, the Coast Guard, and the ADEC in management of the project provided the study team with unique access to individuals and information and ensured that all viewpoints were considered in the analysis.

The risk of an accident is defined as the product of the probability of occurrence of the accident and the consequences of that accident. An accident is an event that has adverse consequences (injury, loss of life, economic loss, environmental damage). Seven accident types were considered in the PWS risk assessment: collision, powered grounding, drift grounding, foundering, structural failure, allision (i.e., a ship running into a stationary ship), and fire or explosion. An incident is an error such as a wrong course change or a failure such as a loss of propulsion that creates an unsafe condition that may result in an accident. The USCG uses the term vessel casualty to describe both incidents and accidents. The PWS risk assessment differentiates between triggering events (incidents) and events with direct adverse consequences (accidents).

The study scope addressed the risks of marine oil transportation from the Valdez Marine Terminal to 20 mi (32.2 km) outside of Hinchinbrook Entrance. It examined causal and contributory factors such as marine traffic, weather, external environmental variables, human error, and mechanical failure. The study included technical and operational aspects of the tanker fleet, regulatory requirements, and operating company management. Excluded from the scope of the study were events that could occur within the terminal itself or events that could be caused by certain extremely low probability natural phenomena (lightning strike, earthquake). The project approach integrated a system-oriented simulation-based methodology with more traditional statistical and event-oriented probabilistic methods. Historical data analysis and structured expert judgment were used to support each element of the modeling process.

## Risk Assessment Framework

The first objective of the risk assessment was to quantify the probability of the following accident types:

- Collisions: colliding or striking of two under way vessels because of human error or mechanical failure and lack of vigilance (intership collision) or the striking of a floating object by an under way vessel (ice collision);

- Drift grounding: contact with the shore or bottom by a drifting vessel not under control because of a propulsion or steering failure;
- Powered groundings: contact with the shore or bottom by an under way vessel under power because of navigational error or steering failure and lack of vigilance;
- Foundering: sinking of a tanker because of water ingress or loss of stability;
- Fire or explosion: occurrence of a fire in the machinery, hotel, navigational, or cargo space of a tanker or an explosion in the machinery or cargo spaces; and
- Structural failure: failure due to hull or frame cracking or erosion and serious enough to affect the structural integrity of the vessel.

The second objective was to identify, evaluate, and rank proposed risk reduction measures; thus, a single statistical estimate of the current probability of an accident was not sufficient. A comprehensive probabilistic model was developed that allowed such risk interventions to be evaluated. The model had to incorporate the effect of the major contributors to risk.

The probability of an accident depends on the organizational and vessel attributes of a tanker and the situational or waterway attributes that describe its environment. Vessel characteristics, such as size, age, material and hull type, and crew characteristics, such as years of service, training and bridge team stability, were considered, whereas situational factors included location and type of nearby vessels, wind speed and direction, visibility, and ice.

Accidents involving oil tankers are rare events. However, low-probability, high-consequence events lead to difficulties in the risk assessment process. Because such accidents occur infrequently, large accident databases are not available for a standard statistical analysis of the causal effect of each risk factor. Garrick (1984) notes that an accident is the culmination of a series of events and not a single event. Figure 1 shows the causal chain for the occurrence of a maritime accident.

The assessment framework differentiates between the triggering events (incident) and causal events (either basic or immediate causes). Triggering events were separated into mechanical failures (called vessel reliability failures) and human errors (called vessel operational errors). The mechanical failures considered to be triggering events were propulsion failures, steering failures, electrical power failures, and hull failures. The concept of classifying human errors is more complex. Harrald et al. (1998) discuss the full treatment of human error in the PWS risk assessment. The basic 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.

As mentioned previously, the probability of an accident involving a particular vessel depends on vessel attributes and waterway attributes that describe its situation. A set of vessel and waterway attributes defines an opportunity for incident (OFI). The accident model used was based on the notion of conditional probability. The levels of conditional probability in the accident model were as follows:

- *P*(OFI): the probability that a particular set of vessel and waterway attributes occur in the system,
- *P*(incident/OFI): the probability that a triggering incident occurs given the opportunity, and
- *P*(accident/incident, waterway): the probability that an accident occurs given that a triggering incident has occurred.

Figure 2 shows how this approach is applied to drift grounding accidents caused by propulsion failures. First, a tanker, with given vessel attributes, is in the system for 5 min. There is a certain probability that the tanker will

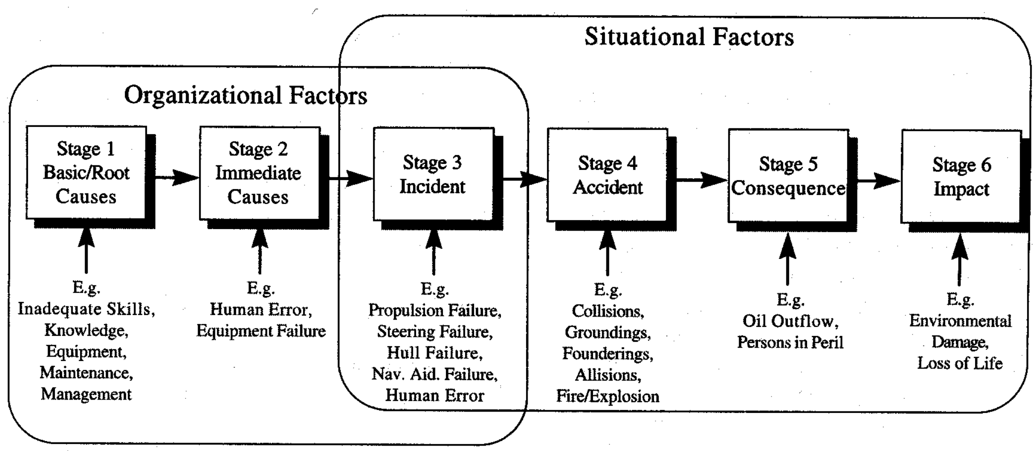


**FIGURE 1 Accident event chain.**

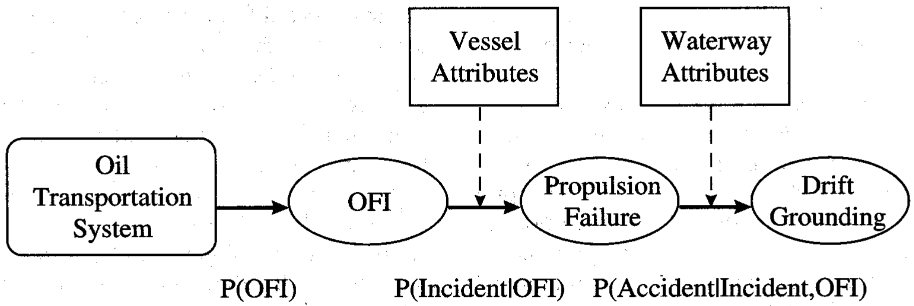


**FIGURE 2 Accident probability model for drift grounding accident.**

experience a propulsion failure. Once the propulsion failure has occurred, there is a certain probability that the tanker cannot be saved and cannot perform a self-repair and so it runs aground. This probability depends, for example, on the waterway attributes of the OFI, wind speed, and current.

The probability of an accident can be found by summing the product of the conditional probabilities over all types of accidents and triggering incidents and all combinations of vessel and waterway attributes. Thus, to perform an assessment of the risk of an accident with this model, one must estimate each of the terms in the probability model.

## Dynamic Nature of Risk in an Oil Transportation System

The system risk simulation approach relies on the premise that risk is a dynamic property of the system. Harrald et al. (1992) discussed the need for dynamic modeling in the assessment of risk in the maritime area. The system risk at any given time is the risk of all vessels in the system. As vessels pass through the system, the waterway and organizational characteristics of the vessels (the OFIs) in the system change with time and thus the risk changes.

To calculate the system risk, one must first estimate the frequency of occurrence of each combination of waterway and vessel characteristics. Although data are collected on vessel arrivals and environmental conditions, combinations of these events are not. Use of a discrete-event simulation of the system captures the complex dynamic nature of the system and accurately models the interactions between the vessel and waterway attributes. The first step in creating a realistic simulation of the PWS oil transportation system was to collect data on the traffic movement and weather conditions. The simulation was used as an event counter. The simulation sampled traffic arrivals once every 5 min of simulation time, and the weather was sampled once an hour. The state of the system in the simulation was calculated once every 5 min based on traffic arrivals, the weather, and the previous state of the system. The simulation was run for 25 years of simulation time.

## Need for Expert Judgment in Maritime Risk Assessment

The next step in risk estimation 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 that a set of vessel attributes has occurred and the conditional probability of an accident given that a triggering incident has occurred, with a defined set of waterway attributes. The preferred method for estimating these probabilities is with data. In the PWS risk assessment, there were insufficient data to estimate the probabilities as the number of explanatory variables that described each vessel were required to be reasonably large.

Cooke (1991) cited the use of expert judgment 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 need for expert judgment in performing risk analysis was discussed by Paté-Cornell (1996), whereas Harrald et al. (1992) proposed the use of expert judgment in the analysis of risk in ports and waterways.

Expert judgment was used in the PWS risk assessment to assess the relative probabilities of incidents for different sets of vessel attributes and the relative probabilities of accidents for different sets of waterway attributes, whereas data were used to calibrate these relative probabilities. This approach relies on the premise that the judgments of the experts who have a deep understanding of the system provide a more accurate basis for calculating risk than do the sparse, and possibly unreliable, data. It must be noted, however, that all available, reliable data were used to estimate the conditional probabilities. Figure 3 shows the format of one of the primary questionnaires, and two similar scenarios are described.

In each situation there is an inbound tanker, greater than 150,000 deadweight tons (DWT) in size, that has just experienced a propulsion failure. It is within 2 to 10 mi (3.2 to 16 km) of a tug with tow in winds over 45 mph (72 km/h) blowing on shore to the closest shore point, with visibility greater than half a mile (0.8 km) in the central PWS. The only difference between the two situations is that the situation on the left includes an iceberg, and that on the right has no iceberg. The expert is asked to determine which is more likely to result in a collision. In each question, to enable the experts to estimate the difference in relative risk between the two situations, only one attribute is changed. The experts found these questions possible to answer and could answer a book of 120 questions in a 1- to 1.5-h session. To minimize response bias, the questions in the books were asked in random order. The parameters of the probability model were estimated by statistical regression.

## Results of Risk Assessment

The first objective of the risk assessment was to identify and evaluate the risks of oil transportation in PWS. An accident scenario was defined to be an accident type in a given location. Before the risk assessment, there was a common belief that the most likely accident scenario was a drift or powered grounding in the Valdez Narrows or Hinchinbrook Entrance. Figure 4 presents a ranking of the expected frequency of the accident scenarios as a percentage of the total expected number of accidents.

Figure 4 indicates that the first seven accident scenarios account for 80 percent of the total expected number of accidents, with 60 percent coming from collisions in the port, Valdez Narrows, and Valdez Arm locations. A further analysis was performed to find the primary cause of the accidents. It was found that the primary risk was collisions with fishing vessels, which operate in large numbers in these locations. Although this introduces a relatively high risk of a collision, very few of the fishing vessels are large enough to penetrate the hull of a tanker. Thus, the expected oil outflow from these events was relatively low. The perceived high-risk scenarios of drift or powered groundings contributed about 15 percent of the expected frequency of accidents.

The risk models also estimated the expected volume of oil outflow as a measure of risk. A surprising result was discovered with this metric. Collisions with Sentinel Emergency Response Vessels (SERV) tugs were a large contributor to the total expected oil outflow. The tugs are intended to save disabled tankers, but they introduce a risk of collision and can cause enough damage to tankers to spill oil. It was found that the frequency of interactions with tugs returning from an assignment led to this high risk. Less surprising, however, was confirmation of the risk of drift or powered groundings in the Valdez Narrows or Hinchinbrook Entrance.

The second objective of the risk assessment was to identify, evaluate, and rank proposed risk reduction measures. Extensive modeling was required, but, because of the level of granularity incorporated in the model, pa-

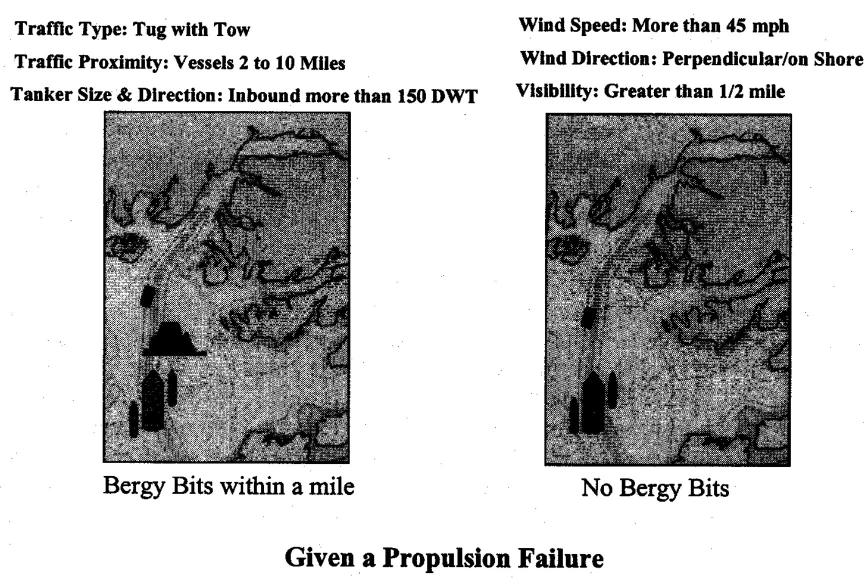


**FIGURE 3** Example of a scenario pictured in the questionnaires.

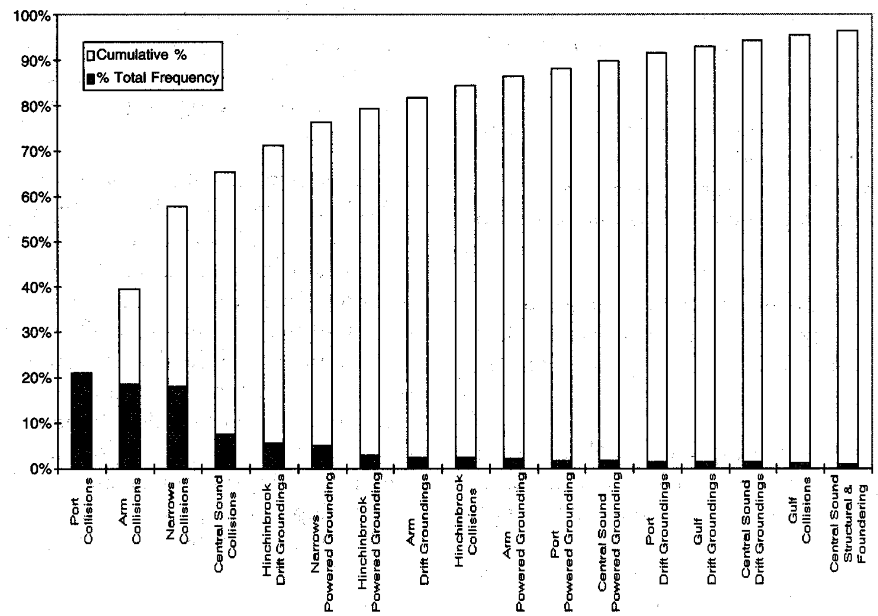


**FIGURE 4 Ranking of accident scenarios by expected number of accidents.**

rameters could be changed to reflect the effects of risk reduction measures. By stripping away previously implemented risk reduction measures, an estimate of the risk before the *Exxon Valdez* accident was calculated. When this was compared with the baseline case, representing the PWS system during the study period, the risk models indicated a 75 percent reduction in risk since the *Exxon Valdez* accident.

The analysis demonstrated that a major reduction in risk can be realized by modifying the escort scheme to reduce interactions with tankers and by managing the interactions of fishing vessels and tankers. The model also enabled estimation of the risk reduction resulting from improvement of human and organizational performance through the International Safety Management program.

## Study Recommendations

At the conclusion of the study, the contract team delivered a final report to the steering committee. 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. After the risk assessment project, the steering committee separated into risk management teams charged with implementing the recommendations in specific areas of operation. To date, the risk management teams have taken the following actions:

- To avoid collisions with fishing vessels, the Coast Guard Vessel Traffic Service manages interactions between fishing vessels and tankers.
- To avoid collisions with SERVs, a further analysis was completed to find an improved escort scheme. This analysis is described below.
- To avoid drift groundings in Hinchinbrook Entrance, an enhanced capability tug called the Gulf Service is now used to escort oil-laden tankers through the entrance.
- On board the escort tugs, the required bridge crew has increased from one to two to add additional error capture capability.
- The shipping companies have made long-term plans for quality assurance and safety management programs.

## Analysis of Alternative Escort Schemes

The PWS risk assessment determined that, under certain conditions, the escort vessels would not be able to "save" a disabled tanker at Hinchinbrook Entrance. An enhanced capability tug was stationed at Port Etches on Hinchinbrook Island to guard against this possibility. The presence of a tug at Hinchinbrook led to the question of whether an escort made up of one continuous escort, a second close escorting tug through the Valdez Narrow, Valdez Arm, and Hinchinbrook Entrance and standby escorts covering the transit through the central PWS would provide a more effective escorting scheme.

This escorting scheme is presented in Figure 5. The objectives of the analysis of this scheme performed by GWU were as follows:

- To verify that the proposed escort system was an improvement from the baseline, and
- To serve as a new baseline for future risk reduction measures assuming the implementation of the proposed escort scheme.

The analysis used to answer the following questions needed to verify the proposed escort scheme is described in detail in a 1999 Oil Spill Conference paper (Harrald et al., 1999):

- What is the effect on the expected number of drift groundings of having a single close escort and a standby escort through the central PWS for outbound laden tankers?
- What is the expected number of drift groundings for inbound tankers under the proposed escort scheme?
- What is the change in collisions from the revised base case provided by the proposed escort scheme?

The system simulation was used to determine the "save" effectiveness of the standby escorts. Thus, a drifting tanker simulation was used to count drift times for hundreds of drift scenarios. Figure 6 presents one such scenario. Two counts were kept in the simulation: the time until the standby escort reaches the drifting tanker and the time until the drifting tanker runs aground, assuming no assistance from the escorts.

Figure 7 presents the distribution of times sampled between the occurrence of the propulsion or steering failure and the standby escort reaching the disabled tanker.

The response times are almost always less than 1.5 h. In Figure 8, the distribution of times sampled between

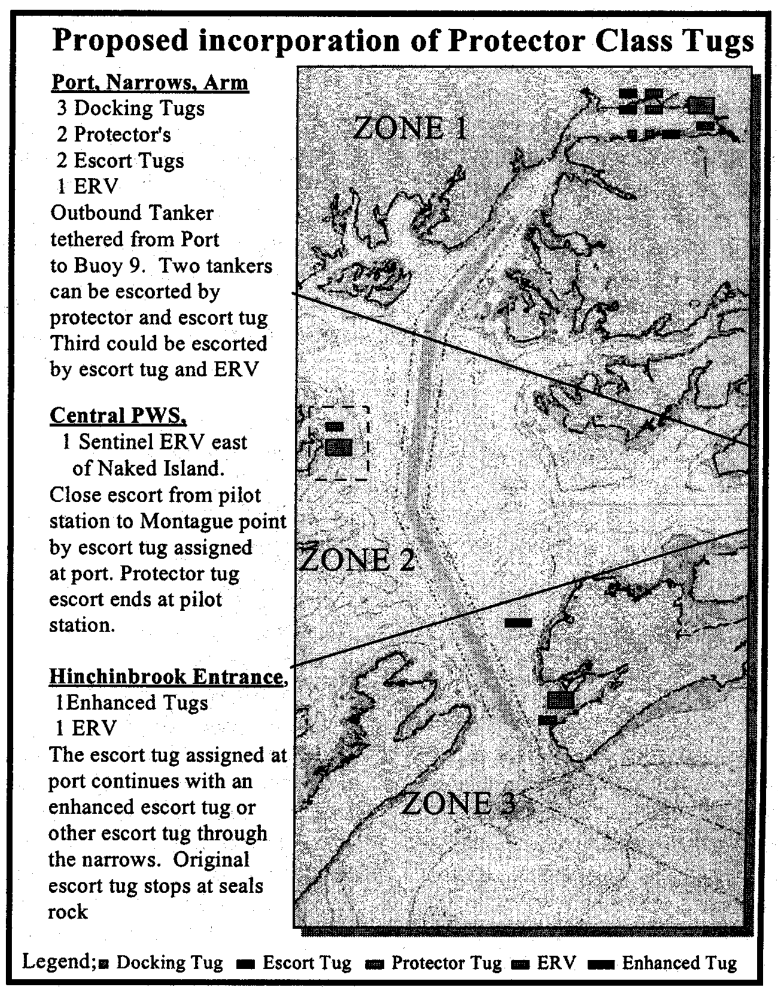


**FIGURE 5 Proposed escort scheme (ERV = emergency response vessel).**

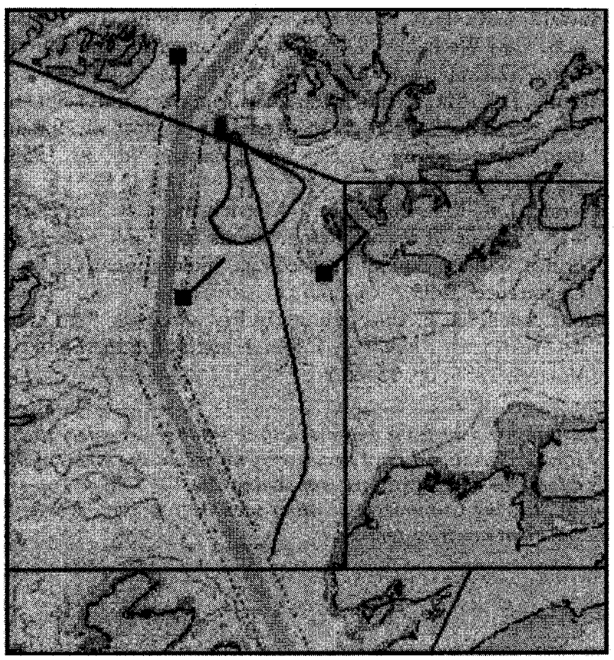

FIGURE 6 Long drift time scenario.

the occurrence of the propulsion or steering failure and the disabled tanker running aground (assuming that no assistance was given by the escorts) is presented; 15 percent of the drift times are >12 h and thus are not shown.

The time of interest is the difference between these two times; this represents the time that the standby escort has before the disabled tanker runs aground. This is the time available to assist the close escort in making a save. Even assuming that the tanker is not being slowed at all by the single close escort, the second escort will be with the drifting tanker for at least 1 h 96 percent of the time. In almost all situations sampled, the second escort will reach the disabled tanker with much longer than an hour to assist in the save.

To summarize the effect of the proposed escort scheme:

- The long-term average of the total number of accidents for outbound tankers is the same as the revised base case and may be better if the new escort vessels are shown to give better save capability; and
- The long-term average of the total number of accidents for inbound tankers is reduced by at least 18 percent.

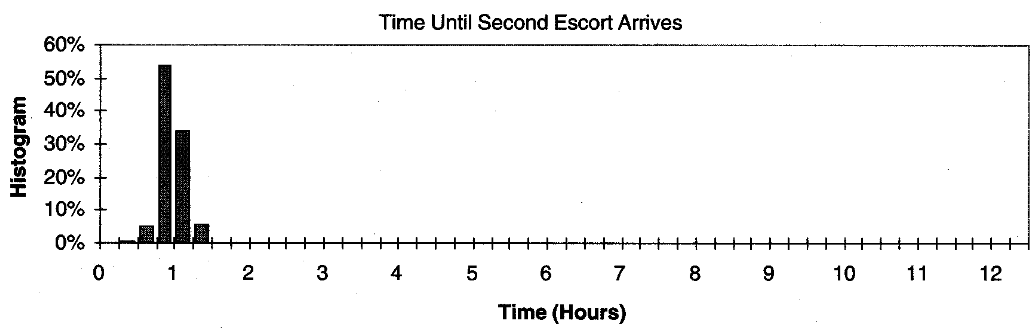


FIGURE 7 Distribution of times the standby escort took to reach the drifting tanker.

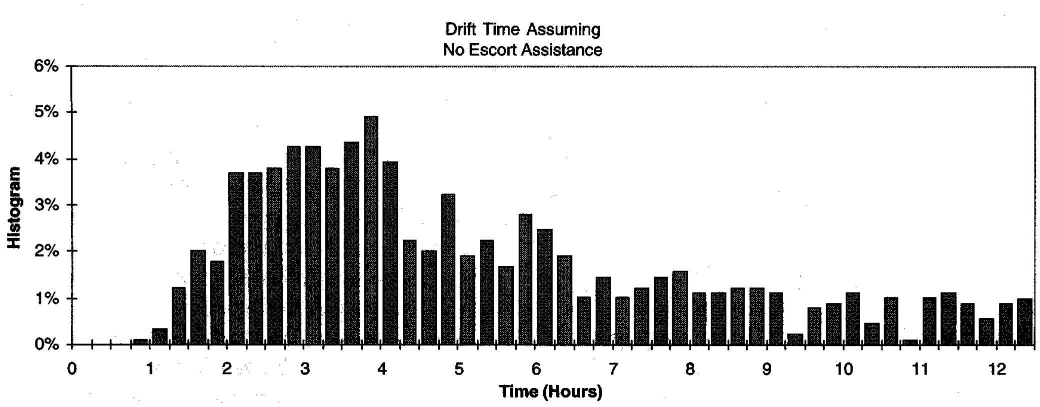


FIGURE 8 Distribution of times between the failure event and the tanker running aground (15 percent of the sampled drift times were >12 h).

The reduction will be significantly larger if simulations of inbound tanker drift paths can verify the degree of coverage given to inbound tankers in areas other than central PWS. The reduction justified thus far in the total number of accidents is 13 percent, and the reduction in the total oil outflow is 4 percent.

The recommendations of the basic study and the additional analysis have been implemented by the sponsor, enhancing the level of safety in PWS.

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