Event Tree Analysis of Lock Closure Risks

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Abstract: The use of event trees and subjective probabilities in risk analysis is illustrated via a case study: the estimation of the probability of closure of Poe Lock on St. Marys River (Sault Ste. Marie, Mich.) because of vessel accidents and other nonstructural failures. The risk of closure is needed to determine the benefits of building a second Poe-class lock at that location. An event tree structures the risk analysis. Probabilities associated with the branches of the tree were developed from a combination of historical data and subjective probabilities. The latter were obtained in workshops with navigation experts. This paper summarizes the risk analysis, and discusses the difficulties associated with obtaining the necessary probabilities. It was found that a 30-day closure could occur about once every 50 years. The results are most sensitive to assumptions concerning how often ships hit lock gates.

INTRODUCTION

The 1996 destruction of a shopping center in New Orleans by an out of control freighter has focused public attention on the reliability of our waterway transport system. This paper summarizes a risk analysis of Poe Lock (on St. Marys River) Sault Ste. Marie, Mich. In particular, the study estimates the probability of a vessel or bridge accident causing an extended closure of this important component of the Great Lakes navigation system. These estimates are to be used to determine the benefits of building a second Poe-class lock at that location. The purpose of a second lock is to prevent disruption of navigation should one lock close.

Poe Lock is the largest of the four locks that comprise the Soo Locks system. The others are the Sabin, MacArthur, and Davis locks. The Soo Locks are located between lakes Superior and Huron, on St. Marys River (Fig. 1). Poe Lock is the only one of the four capable of accommodating the 1,000 ft (305 m) cargo carriers that sail the Great Lakes. When Poe Lock is closed, the vessels cannot pass between Lake Superior and the other lakes. Economic consequences of an extended outage of Poe Lock would be severe, because the Great Lakes steel industry depends on iron ore from Lake Superior. For example, a 30-day outage would cost $18,000,000 in terms of higher transport expenses and revenue losses (USACE 1986).

Structural failures or vessel accidents could close Poe Lock for 30 days or longer. The U.S. Army Corps of Engineers (USACE or Corps) has studied this possibility, its economic impact, and the need for a backup lock for larger ships. In 1986, the Corps recommended construction of a new Poe-class lock on the site of the present Sabin and Davis locks (Fig. 1). Its construction cost of $227,000,000 would have to be justified by the reduced risks of navigation disruption.

In 1994, the Corps undertook risk analyses to review that recommendation. As part of the investigation, they sponsored this paper's study of the probability of extended closures of Poe Lock due to vessel or railroad accidents. A parallel study investigated the probability of extended closures due to structural failures of the lock system itself (USACE 1994). The results of these studies are input to a comparison of the expense of a new lock with the cost of closure of Poe Lock.

Event trees and subjective probabilities were used in the Poe Lock nonstructural risk analysis. The purpose of this paper is to use that analysis to illustrate the practical difficulties of using these two methods. The techniques employed in the study are reviewed in the next section. An overview of the case study then follows, emphasizing the obstacles encountered in applying the methods. Probabilities of lock closures of various durations are summarized along with their sensitivity to assumptions. The paper closes with conclusions about the usefulness of subjective probabilities.

METHODS

Event Trees

Event trees represent sequences of events that could lead to a system failure—here, an extended closure of Poe Lock. Such trees are used to calculate the probability of system failures of various severities. Probabilities are associated with each event, conditioned on what previous events have happened. The overall chance of system failure is computed from the individual event probabilities.

Event trees were first developed for identifying significant sequences associated with nuclear power plant accidents (U.S. Nuclear 1975). They have been applied to other risk problems since then, but the few water applications have focused on dam safety and hydroelectric generator reliability (Obradovich, unpublished report, 1993; Salmon et al. 1997).

Event trees are a chronological approach. They describe failure mechanisms by starting with initiating events or antecedent conditions and then moving forward in time, showing possible subsequent events that could cause system failure. In

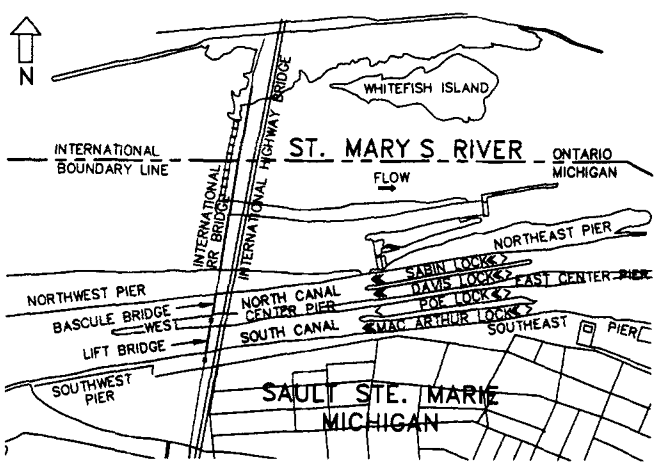

FIG. 1. Soo Locks System (US) [Source: USACE (1986)]

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building a tree, the analyst asks "What could happen next?" The overall probability of system failure is the sum of the probabilities of all event sequences that conclude with a failure. Each sequence's probability is the product of the conditional probabilities of the events defining the sequence.

For logical convenience, the elements of an event tree can be classified as follows:

- Antecedent conditions describe states of the system (e.g., weather, type of vessel entering the lock) that affect the probability of various events. These conditions could instead be treated as initiating events. However, the logic of event trees is easier to explain if antecedent conditions, which are associated with a period of time and precede an accident sequence, are separated from events that occur at points in time.
- Initiating events (such as an equipment failure) begin a sequence of events that could lead to system failure.
- Intermediate events logically follow the initiating event but by themselves do not represent system failures.
- Recovery actions represent responses that attempt to prevent or mitigate the damage from a failure.
- Terminal events represent various modes and severities of system failure.

Event trees can be contrasted to fault trees (Henley and Kumamoto 1991; Modarres 1993). Fault trees start with the last event (system failure) and move backwards in time. For each event, it asks "What could have been the cause?" A combination of event and fault trees is often used; event trees help identify major failure mechanisms, while fault trees can describe the likelihood of particular events on the event tree.

An important decision in an event tree analysis concerns level of detail: what events to include and how finely to divide them. Ideally, event trees show all possible combinations of events. This comprehensiveness may uncover failure sequences that the analyst might otherwise have overlooked. Unfortunately, listing all combinations leads to an unmanageably large tree if there are many possible events. Further, numerous implausible or bizarre sequences divert attention from truly significant sequences. Therefore, an event tree of a complex system must be "pruned" to a manageable size.

But branch elimination poses dangers. Fischhoff et al. (1978) show that people examining a tree do not fully appreciate how much has been omitted from it, resulting in a downward bias in the calculated probability of system failure. Branch pruning should be judicious, so that low probability branches with disastrous consequences are not eliminated.

Subjective Probabilities

Probabilities must be associated with the event tree's branches to compute the overall probability of system failure. There are four general ways to estimate probabilities of events (Watson and Buede 1987; Morgan and Henrion 1990):

1. Analysis of historical frequencies
2. The principle of equal likelihood—events that do not differ in important ways should be equally likely
3. Subjective probability—a measure of an individual's degree of belief concerning the likelihood of an event
4. Models—used to deduce probabilities of events that are the outcome of complex processes; the inputs to the calculation are usually probabilities of basic events derived by the other three methods

The historical frequency approach is the most desirable way to quantify branch probabilities, but the necessary data are often lacking. In that case, unless models are available, analysts must elicit subjective probabilities from experts.

Compared to frequency-based probability, the concept of subjective probability has found acceptance only recently. Yet some subjectivity is present in most risk analyses, because there is nearly always some subjective element in applying any of the preceding four methods. An example is flood frequency analysis, which involves the subjective assumption of climate stationarity. A recent trend in risk analysis has been to make such subjective judgments explicit to ease review by others (Otway and von Winterfeldt 1992).

Subjective probability assessment is complex and needs to be undertaken carefully (Otway and von Winterfeldt 1992; Haimes et al. 1994). Otherwise, the assessed probabilities may be biased or fail to reflect the expert's best judgment. One reason subjective assessment is difficult is that individuals are generally uncomfortable with probabilities. Protocols to overcome this discomfort are recommended in the literature. Spetzler and Staël von Holstein (1975) present a popular five-phase protocol: motivation (establishment of rapport and exploration of possible motivational biases); structuring of the uncertain quantity; training to avoid cognitive biases; the actual quantification of probabilities; and verification of consistency.

Even experts in probability theory have difficulty avoiding biases in probability estimation. Some predictable biases result from shortcuts, or "heuristics" (Tversky and Kahneman 1974). As an example of a bias, people estimate a higher than appropriate frequency for events that are glamorous or well publicized even if they occur rarely. This bias results from the available heuristic, where bigger probabilities are ascribed to more easily recalled events.

Another important bias is overconfidence, thinking that you know more than you actually do. For example, assume someone is asked to estimate "almanac" variables, such as populations of cities. For each estimate, the person is to state his or her 90% confidence interval $[X_{05}, X_{95}]$ (meaning the person is 90% sure that the answer is between X_{05} and X_{95}). On average, one would hope that this person would give intervals embracing the true value 90% of the time. Yet experiments have shown that people are wrong more than half the time—even in matters that they are experts in. The overconfidence bias apparently stems from the anchor and adjust heuristic, in which a respondent chooses an initial value (anchor) for a variable and then adjusts it up and down to define an interval (Tversky and Kahneman 1974). The bias results because people tend to adjust too little.

Several methods attempt to overcome biases and improve the quality of subjective probabilities. For instance, the following methods were used to assess the risk of lung injury from ozone exposure (Winkler et al. 1995): (1) reviewing common biases and heuristics; (2) requesting extreme values in tails of the distribution first to avoid anchoring on middle values; and (3) urging experts to recall relevant studies to counter the tendency to overweigh the most recent information encountered. Unfortunately, these methods are unlikely to be completely effective (Büyükkurt and Büyükkurt 1991; Wright et al. 1994). Nonetheless, some of these techniques were employed in the Poe Lock study. The subjects were sensitized to the dangers of heuristics by demonstrations that they too are subject to biases such as overconfidence. They were also reminded of those biases during the assessments.

Subjective estimates of probabilities of rare events are particularly unreliable. Selvidge (1975) developed a three-step procedure for encoding such probabilities, which is used in this paper: decomposing the event; expressing uncertainty in relative terms (e.g., the change of event A is less than that of B); and using events of known probability as a reference for these relative comparisons.

J. Water Resour. Plann. Manage. 1997.123:169-178.

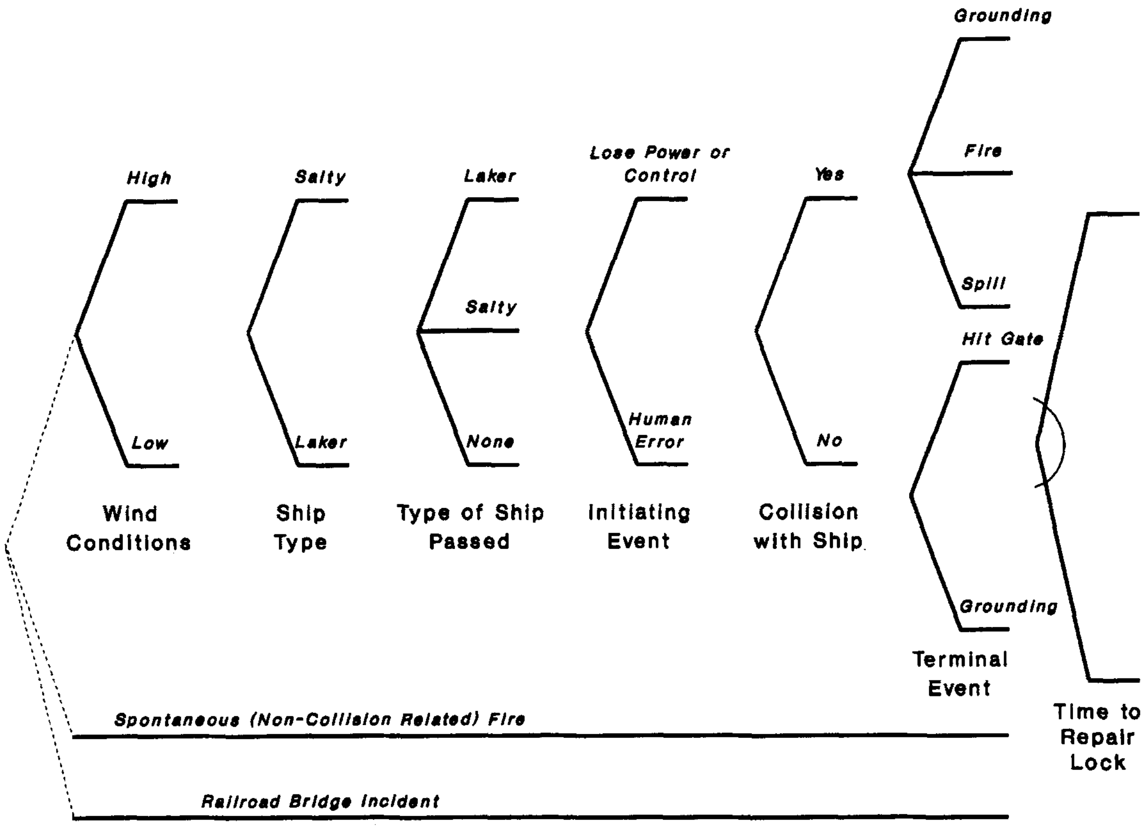

FIG. 2. Schematic Event Tree for Poe Lock Risk Analysis

Another challenge is eliciting probabilities from groups of experts. A method should be used that promotes effective group interaction. In the Poe Lock study, the nominal group technique (NGT) (Delbecq et al. 1975) was used to structure two probability-elicitation workshops. NGT allows groups to interact directly in a controlled environment, preventing dominance by aggressive members. The following are the steps taken in an NGT meeting:

1. Silent generation of ideas in writing.
2. Recording of each idea on a flip chart.
3. Round-robin discussion of recorded ideas for clarification and evaluation. Each person speaks in turn for a short period of time.
4. Individual voting to identify high-priority ideas, with the group decision being derived through rank ordering or averaging.
5. Round-robin discussion of voting results. A second vote can then take place, allowing participants to change their minds.

An important task in group elicitations is the combining of the participants' opinions. A simple and common technique is averaging (Cooke 1991). More sophisticated aggregation techniques exist, such as a Bayesian analysis that optimally weights the experts' opinions according to their level of expertise (Cooke 1991; Morris 1977).

APPLICATION

The Poe Lock system risk analysis is summarized in this section. Once the structure of the event tree is presented, the estimation of the event probabilities, the computation of the overall risk, and a sensitivity analysis are discussed. The section closes with the study findings. The practical compromises necessary to implement the methods are emphasized.

Structuring the Analysis

Fig. 2 presents a schematic event tree used to estimate the probability of vessel or railroad-related incidents that could close Poe Lock. [Beim and Hobbs (1994) present the complete tree, which, because it has 138 terminal nodes, is too lengthy to show here.] Except for the railroad bridge branch, the tree represents the risk faced by a single vessel traversing the locks. To obtain the total annual risk, the risk per vessel is multiplied by the annual vessel passages. Railroad bridge risks are expressed directly as events per year.

The tree was structured and pruned using information from a one-day workshop held at the offices of the Lake Carriers Association, in Cleveland, Ohio. Six of the 11 workshop attendees were shipmasters of "lakers," or ships that sail the Great Lakes only. Others include Corps researchers and representatives of shippers.

Using NGT, the participants developed long lists of events of each type. After consolidation of similar events followed by voting, the lists included:

- Antecedent conditions: conditions that could influence the risk associated with a ship passage, such as wind, ship type, and presence of another ship.
- Initiating events: events that could start a sequence of events leading to lock failure, such as loss of power or control by the ship, and human error.
- Intermediate events: events that can follow an initiating event but precede a terminal event, such as collision (contact between two vessels), and allision (contact between a vessel and a fixed object).
- Terminal events: these events, which result in lock closure, are grouped as follows:
  Collision-or allision-initiated events: blocking the canal or the lock because of vessel grounding; spill of oil or chemicals; fire on a vessel due to collision/allision; and a vessel hitting a gate.

Spontaneous fire on a vessel.

Railroad bridge collapse or failure to elevate, thus blocking the channel.

These events define the structure of the tree (Fig. 2). To simplify the presentation, all three classes of terminal events are shown on one tree. Following each terminal event in Fig. 2 is a probability distribution for the resulting duration of closure. Recovery actions are implicitly considered in each duration distribution.

A lesson from the workshop is that experts who are close to day-to-day operations can compile long lists of events. But the great majority of the events listed have probabilities that are either negligible or impossible to estimate. For instance, much time was spent refining causes of the initiating events —"human error" and "mechanical/electrical failure." However, because of the absence of data and because shipmasters could not define probabilities for each category, this effort was largely wasted. In the end, only one general category, human error, was used in the tree. Although ideas should not be discouraged in a NGT process, the experts should have been asked to focus on the most likely events for which either data exist or they would be willing to state probabilities.

Probability-Assessment Methodology

Once the tree's structure was developed, the next step of the risk analysis was to estimate branch probabilities. Event probabilities were determined from historical frequencies and by eliciting information from two groups of experts: shipmasters experienced in sailing the Great Lakes and traversing the Soo Locks (participants in the first workshop), and operators of the Soo Locks (attenders of a second workshop). Once all probabilities were developed, the probability of each sequence of events that could cause extended closure of Poe Lock was estimated. However, the Corps is interested in more than the frequency of failure. Frequencies of more severe closures are also needed, since costs are nonlinearly related to closure duration. Therefore, the Soo Locks operators specified probability distributions for closure time. This permitted computation of probabilities of closures of various severities, from five to 240 days.

Event probabilities were assessed by the following general procedures:

1. Historical frequency analysis alone. Where frequency data existed for the Soo Locks or for similar structures on the St. Lawrence Seaway or Panama Canal, they were used in preference to subjective assessments. Historical information was the primary basis for assessing the total probabilities of the terminal events of groundings, gate impacts, ship fires, and railroad bridge incidents. Frequency data were also available for high winds. Traffic information was used to compute the probabilities of encountering another vessel in the lock area, and to assess the chance of a given ship being a "laker" or a "salty." (A laker is a ship that sails the Great Lakes only; a salty also sails the oceans.)
2. Subjective probabilities alone. Subjective probability assessments from the two workshops were applied to those events for which workshop attenders made assessments, and for which no relevant historical data existed. Events for which this approach was used included the distribution of lock closure times and the probability of chemical/petroleum spills.
3. Disaggregation of historical frequencies using subjective relative frequencies. Subjective assessments of the ratios of frequencies of different events were used to disaggregate the total probability of terminal events (assessed from historical frequencies) into probabilities of particular sequences of events leading to those terminal events. This approach was used when overall subjective probabilities of events were unavailable, but relative frequencies were known. For instance, lock gate impacts can occur as a result of mechanical failure or human error on either lakers or salties. Shipmasters subjectively assessed the relative frequency of some of these events; this information permits disaggregation of the total chance of a gate allision into probabilities of gate hits by various causes.
4. Bayesian combination of subjective probabilities and historical frequencies. This is another useful approach when both historical frequency data and subjective probabilities are available. There have been no gate allisions severe enough to destroy a gate in the Great Lakes. But this does not mean that the chance of such an occurrence is zero, since most experts believe such events are plausible. Bayesian analysis is used to combine subjective beliefs and data regarding less severe gate hits to estimate a posterior probability of severe gate allisions (Appendix I).

In general, it was found that although subjective probability assessments and historical data were often complementary, subjective probabilities could not be used to fill all the gaps that remained after studying historical frequencies. The same conditions that made frequency analysis challenging (absence of events in the historical record, poor record keeping) also made it difficult for experts to imagine such events and state likelihoods. Protocols recommended in the literature described earlier (Spetzler and Staël von Holstein 1975) were used to overcome this difficulty, with limited success. For certain rare yet potentially severe events with no precedent (vessel fire and explosion within a lock), vessel and lock operators were understandably reluctant to voice any estimates. In these cases, as documented in the following section, assumptions had to be made.

Because of the lack of empirical or expert basis for some assumptions, the results of this study are uncertain. However, when combined with thorough sensitivity analyses to show the effect of uncertain assumptions, such a quantitative approach is still useful for (1) showing the order of magnitude of the uncertainties; (2) documenting the implication of alternative assumptions; and (3) discovering where better data would improve the overall risk estimates.

In subsequent subsections, examples of the assumptions and calculations undergirding each part of the Poe-event tree illustrate the methods used. Emphasis is placed on practical obstacles encountered (and only partially overcome) during probability estimation. First, calculations for the antecedent conditions are presented. Probabilities for initiating events are then addressed. Probabilities of collisions, allisions, and terminal events are then reviewed, leading to the probability distributions for lock closure times.

Antecedent Conditions

The first branches of the tree depict antecedent conditions (Fig. 2). As mentioned, the first workshop identified three significant antecedent conditions: wind, vessel type, and presence of another cargo vessel. The probabilities of each antecedent condition were determined from available meteorological and traffic data. For the first condition, wind rose data indicate that, on average, a ship has a 0.26% chance of encountering winds of 25 mph (40 kph) during the navigation season.

Concerning the second characteristic, the vessel characteristic that most influences accident probabilities, according to the shipmasters, is it being a laker or a salty. Shipmasters as-

J. Water Resour. Plann. Manage. 1997.123:169-178.

sumed that lakers are safer because they have more experience sailing the Great Lakes. Vessel transit data show that the change of a cargo ship being a laker is 91.6%. The third antecedent condition is whether another cargo vessel is passing the other way while engineering or exiting the lock. The following probabilities were computed using traffic data and length of time required to pass through the Soo Locks, assuming Poisson arrivals:

- Probability of passing a salty = 0.010
- Probability of passing a laker = 0.106

Initiating Events for Collision- and Allision-Caused Failures

The shipmasters identified the most important initiating events that could lead to an accident as losing power or control and human error. The probability of losing power/control during a passage was based on Welland Canal data and equals 2×10^{-4}/lock passage. The amount of time during which a vessel may encounter another vessel is approximately 20 min, out of a 90-min passage. Thus, the probability of losing power while passing another ship is two-ninths of that value, or 4.4×10^{-5}.

The shipmasters could not quantify the chance of a human error being made during a passage through the locks. For instance, they could not meaningfully respond to questions such as: "Please state your 90% confidence interval for the probability of human error (within the vessel) that could lead to a sill or gate allision, given: high winds; that the ship is a laker; and that there are no other ships in the channel." The difficulty stemmed from their lack of experience with accidents, compounded by discomfort with the concept of probability, especially involving low-frequency/high-consequence events. A final possible factor is motivational bias, in particular a possible (and unconscious) reluctance to admit the possibility of error on their part. If time had allowed, further training before the actual probability assessment might have lessened these difficulties.

Fortunately, there are some data on the relative frequencies of engine malfunction versus human errors as causes of allisions [e.g., Argiroff (1995), Schulze et al. (1982)]. These data indicate that the frequency of allisions caused by human error is roughly 3.5 times the frequency of loss of power/control. In contrast, the shipmasters believed that human error was much less likely to cause vessel collisions than mechanical/electrical failure, perhaps indicating the presence of motivational bias.

Nevertheless, some meaningful subjective inputs could still be obtained using the Selvidge (1975) ranking technique. That method involves comparing the relative probabilities of two events. For example, both the probability of losing power/control and the probability of human error were perceived by the shipmasters as being higher for salties than for lakers. As a base case, this opinion was interpreted as meaning that a salty's probabilities are twice as high as a laker's.

Intermediate Events: Collision Probabilities

Probabilities of a collision with another vessel were obtained from shipmaster responses. The situation of a collision resulting from a loss of power/control under normal wind conditions was quantified with two variations: (1) loss of power by a laker, and collision with a salty; and (2) loss of power by a salty, and collision with a laker. Using Selvidge's ranking technique, the participants addressed other situations qualitatively, such as collisions under high wind conditions and collision resulting from human error. For example, they assessed the probability of losing power under high winds as slightly higher than under normal winds.

The probability of a collision between two lakers, given that one lost power/control under normal wind conditions, was assumed to be 0.1 based on qualitative responses from workshop participants. Consistent with this assumption and on the relative increase in risk assessed by the participants, the probability of the foregoing situation when two salties were involved was assumed to be 0.7. These probabilities were increased by 0.1 in the case of high winds. These assumptions illustrate the amount of interpretation required by the analyst to translate subjective assessments by experts into the event tree inputs. The potential for analyst bias is obvious. Through sensitivity analysis, the importance of these assumptions was checked.

Terminal Events

Terminal events that can lead to extended lock closures include: grounding, fire, chemical spill, hitting of lock gate, and a railroad bridge incident. To calculate the probability of these events, their conditional probabilities, given antecedent conditions and initiating and intermediate events, had to be assessed. The annual frequency of each terminal event was then calculated as the probability of each per passage times the number of passages.

For grounding, the first terminal event, shipmasters at the first workshop assessed the probability of a grounding following a laker/salty collision as 0.0076. Since nearly all groundings are cleared within hours, the final probability of grounding was multiplied by 0.01 to obtain the probability of a severe grounding, which is defined as the terminal event.

The conditional probability of a fire, given that a collision occurred, was subjectively assessed as being 0.01. A probability of 0.05 for an oil or chemical spill, given a collision, was developed by Schulze et al. (1992) for St. Marys River. That report gives an estimate of 0.11 for the chance of a spill conditioned on a grounding occurring.

Since the workshop experts could not assess subjective probabilities of gate allisions, it was fortunate that historical frequencies of such events could be estimated. Recorded gate incidents in the Soo Locks, Welland Canal, and Panama Canal were summed up, and the total was divided by the number of lock passages in these locations. The resulting observed frequency was 2.4×10^{-5} per passage. However, this probability is lower than the historical value for just the Soo Locks, 9.6×10^{-5} per passage. The latter value was used in the base case, with the former applied as a sensitivity analysis.

Not all gate impacts cause damage severe enough to close a lock for a significant time. For instance, out of eight reported vessel/gate allisions in the Soo Locks, none shut the locks for more than a day. However, this does not mean that the chance of an extended outage is zero; indeed, a severe scenario where a runaway ship destroys a gate and releases Lake Superior is plausible. Bayesian analysis was used to combine the prior belief that severe gate impacts are possible with the observation that none of the gate allisions were so severe. Applying that method to the observation that there have been no severe gate hits out of eight allisions yields 0.074 for the conditional probability of a gate impact being severe. Appendix I summarizes the mechanics of the Bayesian analysis.

The last terminal event considered is the railroad bridge across the Poe entrance channel sticking in the lowered position or, worse yet, collapsing into the canal. The bridge has stuck once in the last 50 years, but was cleared relatively quickly. As a base case, it was assumed that such an incident lasting more than five days occurs no more than once a century, and so an annual probability of 0.01 was adopted for this terminal event. It was also assumed, despite the age of the structure, that this probability has not significantly worsened in recent years.

Final Failure Frequencies

Except for the railroad bridge branch, multiplying the probabilities along the branches of the event tree yields the probability per ship passage of a given terminal incident. For example, using the foregoing assumptions, the following equation gives the unconditional probability of a fire occurring after a collision between a laker and a salty, when the fire is caused by the salty losing power/control under high winds:

$$P(A \cap B \cap C \cap D) = P(D|A \cap B \cap C)P(C|A \cap B)P(B|A)P(A) = 1.06 \times 10^{-11}/\text{passage} \quad (1)$$

where event A = high winds; B = loss of control of a salty; C = collision with a laker; and D = fire. The necessary probabilities are calculated as follows:

$P(D|A \cap B \cap C) = P(\text{fire}|\text{collision}) = 0.01$
$P(C|A \cap B) = P(\text{collision}|\text{salty loses control while passing laker, high winds}) \times P(\text{pass by laker}) = 0.52 \times 0.106$
$P(B|A) = P(\text{loss of power/control}|\text{salty and high winds}) \times P(\text{salty}) = 8.8 \times 10^{-5} \times 0.084$
$P(A) = P(\text{high winds}) = 0.0026$

The final probability of a fire occurring during any passage by a given ship is obtained by cumulating the probabilities of all possible branches leading to a fire. Then the annual frequency of this terminal event can be obtained by multiplying the final probability by the annual ship traffic.

When calculated for all types of terminal events, the final probabilities per passage shown in Table 1, column 2, are obtained. Table 1 also shows the historical frequencies of each accident type (column 3). The probabilities per passage in Table 1 were then multiplied by the conditional probability of an event being severe enough to cause a lock closure (Table 2, column 3) and by the forecast number of passages. The calculation accounted for the fact that only Poe Lock passages cause gate impacts and fires within the lock, while both MacArthur and Poe Lock transits contribute to other system failures. Double counting of collisions was also eliminated (as a single collision involves the passage of two ships). This calculation yields the expected annual frequencies of lock closures shown in column 4 of Table 2.

TABLE 1. Comparison of Final Probabilities and Observed Frequencies of Terminal Events[a]

Terminal event (1)	Calculated probability (per passage) (2)	Observed frequency (per passage) (3)
Grounding	1.2×10^{-5}	1.2×10^{-5}
Fire within lock	3.6×10^{-6}	Total = 3.7×10^{-6}
Fire in canal	0.1×10^{-6}	
Gate impact	9.6×10^{-5}	9.6×10^{-5}
Spill	4.5×10^{-7}	4.8×10^{-6}

[a]Before downward adjustment using the conditional probability of severe event.

TABLE 2. Final Annual Frequencies of Terminal Events

Terminal event (1)	Calculated probability (per passage) (2)	P(severe event|event) (3)	Calculated annual frequency of severe event (4)
Grounding	1.2×10^{-5}	0.01	6.0×10^{-4}
Fire	3.7×10^{-6}	1	8.4×10^{-3}
Gate impact	9.6×10^{-5}	0.074	1.6×10^{-2}
Spill	4.5×10^{-7}	1	2.3×10^{-3}
Railroad	0.02[a]	0.5	0.01

[a]Annual probability.

Severity of Failures: Conditional Probability Distributions of Lock Closure Times

Once a serious accident happens, it does not automatically cause an extended lock closure. For each type of severe accident, there is a distribution of lock closure times. As there have been few such accidents at the Soo Locks, it is not possible to assess empirical distributions. In the absence of actual data, these distributions would be best obtained by a detailed analysis of possible severities of accidents, the sequence of activities needed to place the lock back in service, and the uncertainties associated with each. Such analyses were not possible in this study. Instead, probability distributions of lock closure times for each accident type were obtained from subjective assessments in a second workshop.

The second workshop was held at the offices of the U.S. Army Corps of Engineers in Sault Ste. Marie, Mich. Most attendees were Corps employees who operated the locks. The workshop agenda included a morning session during which accidents and responses needed to restore service were discussed, and an afternoon session where probability distributions for restoration times were assessed.

The NGT technique structured both sessions. For instance, the NGT was used in the afternoon to obtain responses to questions of the form: "Given terminal event X, please supply the 90% confidence interval for the length of time until restoration of service, taking into consideration activities and complications. Also supply the mean and maximum possible length of time (if everything goes wrong)."

It is important to obtain probability distributions of length of outage because the costs associated with a lock closure increase nonlinearly with duration (USACE 1986). Each person gave four responses in the following format:

- Lower bound of the confidence interval—denoted 5%—meaning that one is 95% sure that the restoration of service will take at least that amount of time.
- Upper bound of the confidence interval—denoted 95%—meaning that one is 95% sure that the restoration of service will take less than that amount of time.
- Mean time—expected time to restoration of service.
- Maximum time—worst case time to restore service.

Fig. 3 portrays the concepts of the 5%, mean, 95%, and maximum times. Participants were familiarized with the overconfidence bias prior to this assessment.

The answers were compiled and their mean and range shown to the participants. Continuing with the NGT, the group then discussed the results and revised their answers before the

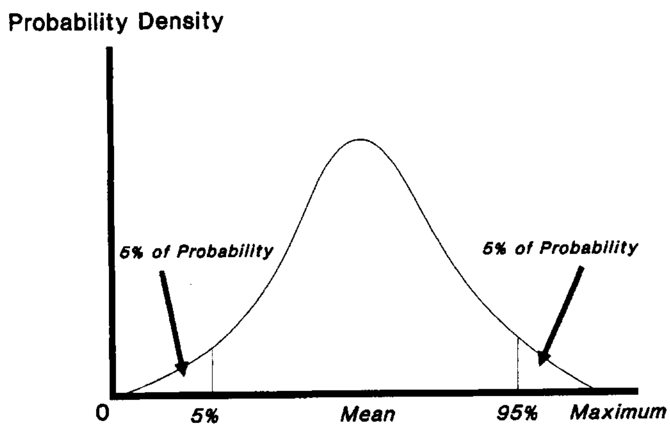

FIG. 3. Confidence Intervals for Time to Restore Lock Service

J. Water Resour. Plann. Manage. 1997.123:169-178.

final compilation. The final results were usually similar to the initial responses. Table 3 contains the average of the responses given for all categories of accidents. The experts' answers were averaged to obtain the group results, since there was no reason to give any one participant a higher weight.

To estimate the chance that a lock closure would exceed a given length of time (e.g., 30 days), five beta probability distributions were fit to the distribution data provided by the group (Table 3). The density $f(t)$ of a variable t that follows a Beta distribution is defined as follows:

TABLE 3. Average Times to Put Lock Back in Service—Final Compilation

Terminal event (1)	5% (days) (2)	Mean (days) (3)	95% (days) (4)	Maximum (days) (5)
Grounding[a]	17	42	80	114
Fire	25	108	203	330
Gate damage[b]	11	62	190	327
Spill	4	12	22	35
Railroad	6	23	54	82

[a]Given that the grounding is a severe one.
[b]Given that the gate damage will take five or more days to repair.

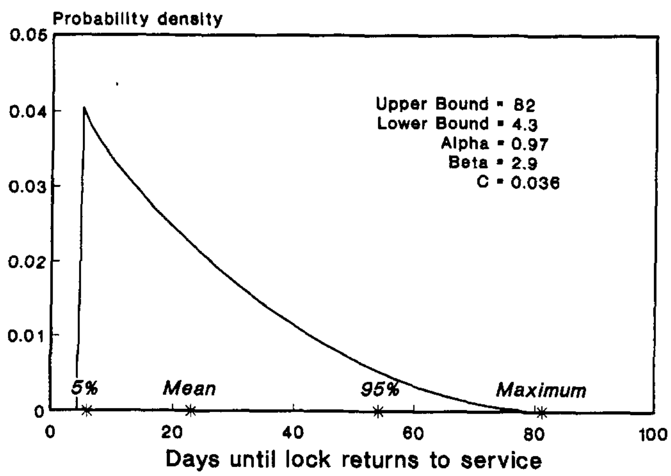

FIG. 4. Probability Distribution of Repair Times, Railroad Bridge Failure

TABLE 4. Probability of Time to Repair Exceeding *t*, Given Closure Has Occurred

Time to repair t (days) (1)	5 (2)	10 (3)	14 (4)	30 (5)	60 (6)	120 (7)	180 (8)	240 (9)
Railroad	0.986	0.804	0.678	0.307	0.025	0	0	0
Grounding	1	1	0.999	0.667	0.189	0.016	0	0
Fire	0.993	0.986	0.979	0.933	0.779	0.577	0.103	0.011
Severe gate damage	1	0.967	0.86	0.6	0.37	0.156	0.057	0.014
Spill	0.914	0.622	0.358	0.005	0	0	0	0

$$f(t) = C\left[\frac{(t-L)}{(U-L)}\right]^{\alpha-1}\left[\frac{(U-t)}{(U-L)}\right]^{\beta-1} \quad \text{for } L \le t \le U \qquad (2)$$

where the five parameters of the distribution are: L = lower bound (lowest possible value) for t; U = upper bound for t; α, β = exponents; and C = scaling parameter, chosen so that the integral of $f(t)$ between L and U equals 1. Beta distributions are used because (1) they are flexible (they can represent any degree of skewness); and (2) they are confined within a finite domain defined by L and U. Fig. 4 exemplifies the results for railroad bridge failure.

The probability that the time to repair exceeds t days is shown for each terminal event in Table 4. For example, given that a severe gate allision occurred, there is an 86% probability that repairs will take 14 days or longer and a 37% chance that 60 or more days are required. The latter figure is calculated as the integral of the repair time distribution from 60 to 325 days, the maximum possible repair time.

Final Risk Characterization: Yearly Probabilities of Times to Repair

The object of this study was to develop probabilities that a vessel- or bridge-related accident would close Poe Lock for an extended period of time. The Corps is particularly interested in periods of a week or more. Table 5 summarizes the results, expressed in terms of annual probabilities of lock closures equaling or exceeding various lengths of time. For instance, in a given year, there is a 0.0094 probability of a gate damage incident that closes the lock for 30 days or more (i.e., a one in 106 year event). Assuming that lock closures due to different events are probabilistically independent (e.g., a spill does not affect the chance of a railroad bridge incident in that same year), the total probability of an extended closure can be approximated as follows:

$$P(\text{closure} \ge t \text{ days}) = 1 - [1 - P(\text{closure} \ge t \text{ days due to railroad})]x \ldots x[1 - P(\text{closure} \ge t \text{ days due to spill})] \qquad (3)$$

For instance, the overall probability in a given year of a closure of 30 days or more is

$$P(\text{closure} \ge 30 \text{ days}) = 1 - (1 - 0.0031)(1 - 0.0004) \cdot (1 - 0.0078)(1 - 0.0094)(1 - 0.000001) = 0.021 \qquad (4)$$

a one in 48 year event. A severe closure (240 days) has a recurrence interval of 3,200 years.

Fig. 5 illustrates the contribution of each accident type to the probability of exceeding various times to repair. Gate accidents make up about 50% of lock closures of any duration. For repair times of 30 days or less, both railroad accidents and fires are particularly relevant. In particular, for the 14-day event, half the risk arises from gate impacts, while railroad and fire events account for most of the rest. Because the chance of a 60-day closure due to a railroad accident is minimal, such accidents are unimportant for longer times to repair,

TABLE 5. Yearly Exceedence Probabilities of Times to Repair

Time to repair (days) (1)	5 (2)	10 (3)	14 (4)	30 (5)	60 (6)	120 (7)	180 (8)	240 (9)
Railroad	9.9×10^{-3}	8.0×10^{-3}	6.8×10^{-3}	3.1×10^{-3}	2.5×10^{-4}	0	0	0
Grounding	6.0×10^{-4}	6.0×10^{-4}	6.0×10^{-4}	4.0×10^{-4}	1.1×10^{-4}	9.6×10^{-6}	0	0
Fire	8.4×10^{-3}	8.3×10^{-3}	8.2×10^{-3}	7.8×10^{-3}	6.6×10^{-3}	4.9×10^{-3}	8.7×10^{-4}	9.3×10^{-5}
Gate damage	1.6×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	9.4×10^{-3}	5.8×10^{-3}	2.4×10^{-3}	8.9×10^{-4}	2.2×10^{-4}
Spill	2.1×10^{-3}	1.4×10^{-3}	8.1×10^{-3}	1.0×10^{-6}	0	0	0	0
[Total]	3.7×10^{-2}	3.3×10^{-2}	3.0×10^{-2}	2.1×10^{-2}	1.3×10^{-2}	7.3×10^{-3}	1.8×10^{-3}	3.1×10^{-4}

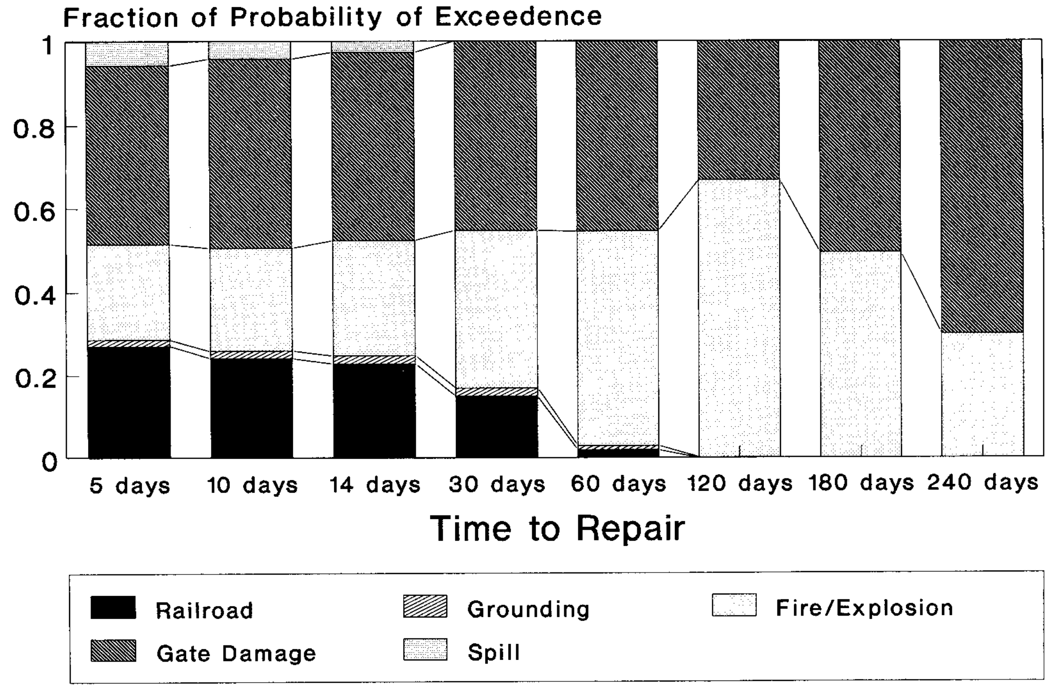

FIG. 5. Relative Contribution of Different Causes of Lock Closure to Closure Probabilities

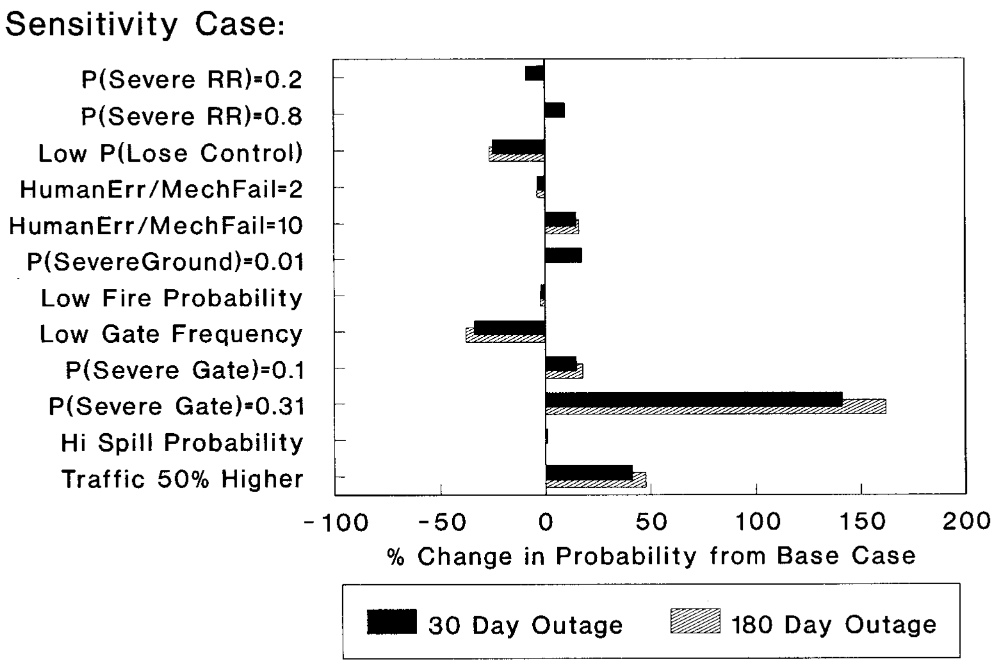

FIG. 6. Sensitivity of Closure Probabilities to Selected Assumptions

while fires gain importance. Fires cause longer outages because electrical and mechanical equipment of the lock may be damaged and require replacement.

The foregoing results imply that assumptions concerning gate accidents, fires, and railroad bridge incidents would most affect the results. However, the results are based on many assumptions that can be justifiably questioned. In the next section, the importance of these assumptions is tested.

Sensitivity Analysis

The effects of some alternative assumptions on the conclusions are summarized in Fig. 6. It shows the percentage change in the base probabilities of having an outage exceed 30 days and 180 days (0.021/year and 0.0018/year, respectively, Table 5) resulting from given changes in assumptions. For example, a 100% increase for the 30-day probability means that it increases to 0.042/year. The changes in assumptions considered in Fig. 6 are as follows:

- Lower and higher probabilities for railroad accidents
- Lower probability of losing power/control
- Lower and higher values of the ratio (chance of human error)/(chance of mechanical failure)
- Higher probability of a severe grounding
- Lower probability of a fire
- Lower frequency of gate allisions
- Higher chances of a gate impact being severe enough to cause an extended lock closure
- Higher probability of a chemical spill
- Traffic 50% higher

Each assumption was tested one at a time. In addition, combinations of alternative assumptions were tested; this is desirable if assumptions interact in a multiplicative rather than additive manner.

The case of gate allisions is an example of the type of analysis performed. It was noted earlier that the historical frequency of these incidents in the Soo Locks area is higher than that of other lock systems. The higher frequency was used in the base case for the computation of probabilities of lengthy lock closures. If the lower frequency recorded for the Soo Locks, Welland Canal, and Panama Canal (2.4×10^{-5}/passage) is used instead, considerably smaller risks result. This corresponds to the bar labeled "Low Gate Frequency" in Fig. 6. For example, a closure of five days would have a yearly probability of 2.5×10^{-2} with the lower frequency, and 3.7×10^{-2} with the higher one.

Fig. 6 shows that the results are most sensitive to assumptions concerning gate accidents. The effect of the assessed probability of a vessel losing power or control comes second in importance, with all other variables having much less influence on the final results.

Some combinations of alternative assumptions were tested. For instance, the two sets of assumptions that have the greatest upward impact on the risks are "P(Severe Gate Hit) = 0.31" and "Traffic 50% Higher," which increase the probabilities by approximately 150 and 50% respectively. If both assumptions are made simultaneously, the increase in risk is much greater than 150% + 50% = 200%. This is because the "P(Severe Gate Hit)" increases the probability per vessel of an outage by 150%, which when multiplied by a 50% higher annual traffic rate yields a total risk that is 275% higher [$= (2.5 \times 1.5 - 1) \times 100\%$]. However, given that (1) traffic has stagnated for the past two decades, and (2) plastics and aluminum increasingly substitute for steel made from iron ore shipped through the lakes, this combination of assumptions seems unlikely.

Because of the relative importance of gate allisions, two additional analyses should be undertaken. One is to obtain more extensive records on such incidents at Soo Locks, St. Lawrence Seaway, and Panama Canal. Second, a detailed examination of the activities required to repair or replace lock gates under various scenarios is needed to refine the probability distribution of the resulting lock closure times.

CONCLUSIONS

In this study, event trees and subjective probabilities were used to estimate the frequency of extended closures of Poe Lock due to vessel and railroad accidents. An event tree was used to model possible paths that lead to closure of Poe Lock, and effectively portrayed how a complex system such as this can fail. The application shows the importance of both subjective and frequency-based probabilities. Historical data were insufficient, resulting in the need for subjective probabilities. Conversely, difficulties in the process of eliciting subjective probabilities made the use of all historical data available critical to the completion of the study. The difficulties the experts faced included lack of familiarity with probability concepts, uneasiness in dealing with rare events, and biases in the assessment of probabilities. Time constraints compounded these difficulties; the length of the probability assessment workshops was insufficient to overcome these obstacles in spite of attempts to avoid biases using some of the approaches suggested in the literature.

Despite the concerns raised throughout this paper, the use of subjective probabilities is not only recommended, but inevitable. The analyst should follow protocols such as those of Spetzler and Staël von Holstein (1975) or Morgan and Henrion (1990) in order to minimize the pitfalls of subjective elicitation. However, biases will be lessened, not eliminated by such procedures. Sensitivity analysis is necessary to assess the robustness of the conclusions and to pinpoint assumptions that particularly influence the results and thus deserve more study. This study showed that the chance of an extended lock closure was not greatly affected by most of the variables tested in the sensitivity analysis.

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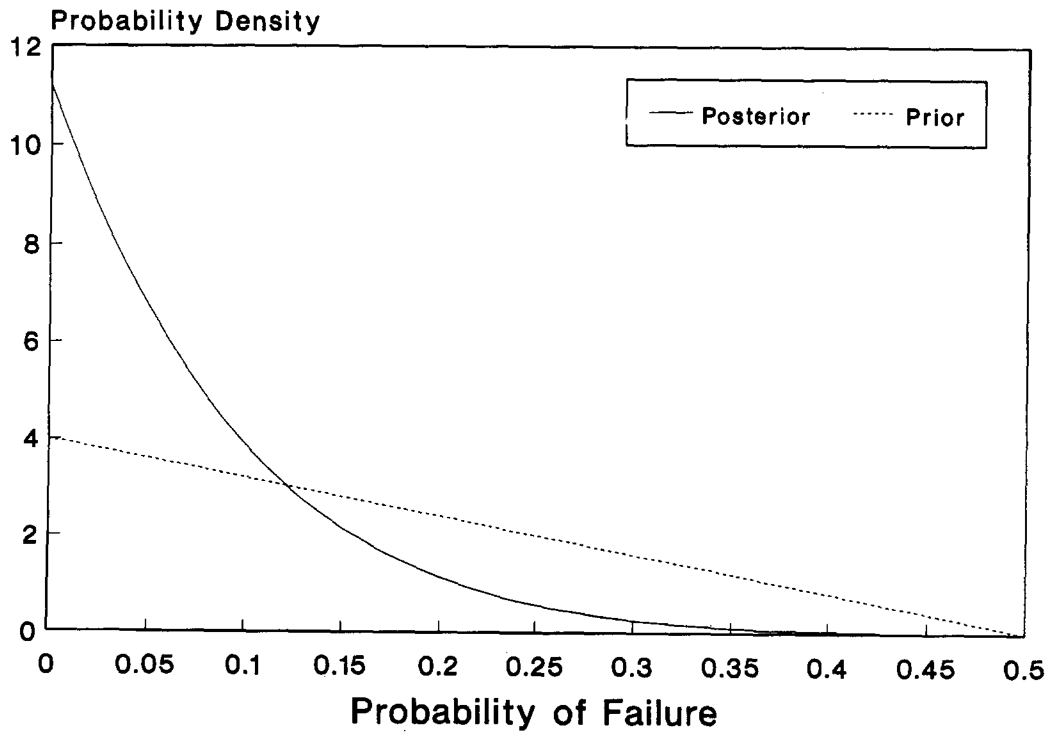

FIG. 7. Prior and Posterior Distributions of P_f, Triangular Prior

APPENDIX I. BAYESIAN ANALYSIS OF GATE ALLISION FREQUENCIES

Bayesian analysis was applied to combine the prior belief that severe gate impacts are possible with the fact that none of the observed incidents were severe. The mathematics of the analysis are summarized here. Let $P(P_f)$ be the prior distribution representing beliefs about the true conditional probability P_f of a severe gate incident, given that a gate has been hit. Let z represent the historical data obtained on accidents. Bayes' law says that the posterior probability combining those beliefs and information is

$$P(P_f|z) = \frac{P(z|P_f)P(P_f)}{P(z)} \tag{5}$$

where $P(z|P_f)$ = conditional probability of observing the historical samples given P_f; and $P(z)$ = marginal distribution of the historical sample [equal to $\int P(z|P_f)P(P_f)\,dP_f$]. Assuming a binomial distribution for the occurrence of severe gate hits (given the total number of hits), the likelihood of zero out of eight gate hits being severe has a probability of $(1 - P_f)^8$.

If there was no prior information about the conditional probability of severe gate hits, then one could use a flat or noninformative prior $P(P_f) = 1$ for $0 \le P_f \le 1$. Using (5), this would result in a posterior distribution $P(P_f|z) = 9(1 - P_f)^8$. The conditional expected value using this distribution $E(P_f|z) = \int P_f P(P_f/z)\,dP_f) = 0.1$ could be adopted as a "best guess" of P_f. However, since severe gate hits are rare in locks in the United States, a prior that says that low values of P_f are more likely would seem more appropriate. Fig. 7 shows the result of using a triangular prior to represent this belief. The observation that there have been no severe gate hits out of eight allisions shifts the distribution leftward, yielding a conditional expectation of 0.074 for P_f, the value used in the event tree.

APPENDIX II. REFERENCES

Argiroff, C. (1985). "An analysis of the West Center Pier at the Soo Locks, Sault Ste. Marie, Michigan." *Rep.*, U.S. Army Corps of Engrs. (USACE), Washington, D.C.

Beim, G. K., and Hobbs, B. F. (1994). "Poe Lock system risk analysis." *Rep. Prepared for U.S. Army Corps of Engrs. (USACE)*, Inst. for Water Resour., Elyria, Ohio.

Büyükkurt, B., and Büyükkurt, M. (1991). "An experimental study of the effectiveness of three debiasing techniques." *Decision Sci.*, 22, 60–73.

Cooke, R. (1991). *Experts in uncertainty—opinion and subjective probability in science.* Oxford University Press, New York, N.Y.

Delbecq, A., Van de Ven, A., and Gustafson, D. (1975). *Group techniques for program planning—a guide to nominal group and delphi processes.* Scott Foresman and Co., Glenview, Ill.

Fischhoff, B., Slovic, P., and Lichtenstein, S. (1978). "Fault trees: sensitivity of estimated failure probabilities to problem representation." *J. Experimental Psychology: Human Perception and Perf.*, 4(2), 330–344.

Haimes, Y. Y., Barry, T., and Lambert, J. (eds.) (1994). "When and how can you specify a probability distribution when you don't know much?" *Risk Anal.*, 14(5), 661–706.

Henley, E., and Kumamoto, J. (1991). *Probabilistic risk assessment.* IEEE Press, New York, N.Y.

Modarres, M. (1993). *What every engineer should know about reliability and risk analysis.* Marcel Dekker, Inc., New York, N.Y.

Morgan, M. G., and Henrion, M. (1990). *Uncertainty.* Cambridge University Press, New York, N.Y.

Morris, P. A. (1977). "Combining expert judgments: a Bayesian approach." *Mgmt. Sci.*, 23(6), 679–693.

Otway, H., and von Winterfeldt, D. (1992). "Expert judgment in risk analysis and management: process, context, and pitfalls." *Risk Anal.*, 12(1), 83–93.

Salmon, G., Cattanach, D., and Hartford, D. (1997). "Risk management at Wahleach Dam." *Civ. Engrg.*, ASCE, 67(2), 39–41.

Schulze, R. H., Wohl, G., and Wallendorf, L. (1982). "Probability of hazardous substance spills on St. Mary's River." *Rep. No. 795C, Prepared for Dept. of Army Corps of Engrs. Envir. Anal. Branch*, Arctec, Inc.

Selvidge, J. (1975). "A three step procedure for assigning probabilities to rare events." *Utility, Probability and Human Decision Making*, D. Wendt and C. Vlek, eds., Reidel, Dordrecht, The Netherlands, 199–216.

Spetzler, C. S., and Staël von Holstein, C. (1975). "Probability encoding in decision analysis." *Mgmt. Sci.*, 22(11), 340–358.

Tversky, A., and Kahneman, D. (1974). "Judgment under uncertainty: heuristics and biases." *Sci.*, 185(9), 1124–1131.

U.S. Army Corps of Engineers (USACE). (1986). "Great Lakes connecting channels and harbors." *Final Interim Feasibility Rep. and Envir. Impact Statement, R-3/86*, Detroit, Mich.

U.S. Army Corps of Engineers (USACE). (1994). "Structural reliability review." *Rep., Poe Lock, St. Mary's River Canal, Sault Ste. Marie, Michigan*, Detroit, Mich.

U.S. Nuclear Regulatory Commission. (1975). "Reactor safety study." *Rep. WASH-1400*, Washington, D.C.

Watson, S. R., and Buede, D. M. (1987). *Decision synthesis: the principles and practice of decision analysis.* Cambridge University Press, New York, N.Y.

Winkler, R. L., Wallsten, T. S., Whitfield, R., Richmond, H. M., Hayes, S., and Rosenbaum, A. S. (1995). "An assessment of the risk of chronic lung injury attributable to long-term ozone exposure." *Operations Res.*, 43(1), 19–28.

Wright, G., Rowe, G., Bolger, F., and Gammack, J. (1994). "Coherence, calibration, and expertise in judgmental probability forecasting." *Organizational behavior and human decision processes*, 57(1), 1–25.

APPENDIX III. NOTATION

The following symbols are used in this paper:

- A = event of high wind;
- B = event of salty losing power or control;
- C = event of collision with laker, scaling parameter in the beta distribution;
- D = event of fire;
- L = lower bound for t in the beta distribution;
- P_f = probability of severe gate impact, given gate allision;
- t = time until lock repair;
- U = upper bound for t in the beta distribution;
- z = sample information; and
- α, β = beta distribution exponents.