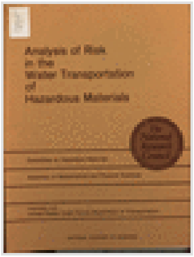

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ANALYSIS OF RISK IN THE WATER TRANSPORTATION OF HAZARDOUS MATERIALS

A Report of the
Risk Analysis and Hazard Evaluation Panel
of the
Committee on Hazardous Materials
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D. C.
1976

NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

This report was prepared by the Risk Analysis and Hazard Evaluation Panel of the Committee on Hazardous Materials, Office of Chemistry and Chemical Technology, Assembly of Mathematical and Physical Sciences in response to a request from the U. S. Coast Guard for an assessment of the utility and feasibility of risk analysis as a set of techniques for assisting management decisions regarding the regulation of water transportation of bulk hazardous materials.

The Panel surveyed a number of risk analysis studies, selected barge transportation on inland waterways for special study, and selected a probabilistic model of risk. In the course of the Panel's ongoing review of risk analyses, it became apparent that to develop a completely general risk model would require an impractical amount of time and resources. The Panel concluded that the greatest utility of the methodology, and perhaps the only practical one, lies in answering specific questions with output of a specific pre-determined nature. The Committee cautions the reader that the report should not be considered as a definitive study of risk analysis and its techniques or applications but as an assessment of the utility of risk analysis as an aid in decision-making for transport of hazardous materials.

The Committee is grateful for the useful suggestions and criticisms to the report provided by Dr. Peter Nichols, The Johns Hopkins University Applied Physics Laboratory; Mr. John Simmons, Science Applications, Inc., McLean, Virginia; and Dr. Malcolm Taylor, Ballistics Research Laboratories, Aberdeen Proving Ground.

Robert B. Beckmann
Chairman
Committee on Hazardous Materials

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I. INTRODUCTION

A. HISTORICAL BACKGROUND

The Committee on Hazardous Materials was formed in 1964 by the National Academy of Sciences at the request of the U. S. Coast Guard (USCG). Composed of representatives of U. S. Government agencies, universities, and private industry, the Committee provides continuing assistance on technical problems and questions related to the shipping of hazardous materials in bulk by water. The Committee performs its functions largely through the activities of ad hoc panels whose members are also chosen from government, industry, and academic sources.

One of the earlier efforts, an attempt to develop methods for establishing limits on the size of shipment of dangerous cargoes, was assigned to a Panel on Cargo Size Limitations. To form a basis for comparing the levels of danger associated with various quantities of transported materials the idea of relative hazard was developed.(1) For any system, depending on the cargo, the container, and the shipment mode, a hazard value was defined to be:

$$H = \frac{P_a D}{F_p}$$

where P_a = the probability of an accident

D = the extend of the expected damage resulting from the accident if allowed to proceed unchecked

F_p = the factor by which actions taken subsequent to the accident reduce damage or loss

The relative hazard of one system with respect to another was then defined to be the ratio of their hazard values:

$$H_r = \frac{H_2}{H_1}$$

Therefore an existing system with an acceptable hazard value provides a basis of comparison for a proposed new system.

However, acknowledged difficulties exist both in defining these terms with precision and in obtaining data to evaluate them. Each factor in the hazard value equation is in reality a function. The probability of occurrence of an accident, P_a, is a function of the type of accident--collision, explosion, fire, or spills of various types, for example. The appropriate units selected to express expected damage, D, are dependent upon the type of damage--destruction of property, injury to persons, or disruption to river traffic, for example; furthermore the extent of the damaged area may be different for each. The effect of actions taken subsequent to an accident to reduce damage or loss is especially difficult to quantify; the factor F_p is a function of not only the type of damage and the type of action taken but also of the extent of expected damage. Finally, the relative hazard, H_r, is dependent on the comparability of the factors H_1 and H_2 with respect to these considerations. The Panel on Cargo Size Limitations recognized these and other difficulties in its analysis of hazards. However the Committee on Hazardous Materials felt that this type of approach had potential value in assessing accidental losses and their associated probabilities.

Consequently, the Committee expanded the risk analysis investigation, with the following objectives:

1. Extend and quantify the risk analysis concepts developed by the Cargo Size Limitations Panel.
2. Recommend methods of implementing the risk analysis concept advocated by the National Transportation Safety Board.(2)

The Panel on Risk Analysis and Hazard Evaluation, formally organized January 4, 1972 under the chairmanship of Dr. Benjamin L. Harris, Technical Director, Edgewood Arsenal, Aberdeen Proving Ground, Maryland, agreed to concern itself with developing quantitative evaluation procedures for risk and hazard in water transport of various materials, to include the provision of a rationale and data necessary for decision-making. The Panel has accomplished the following:

1. A survey of a number of completed or continuing risk analysis studies from various sources, including,among others, U. S. Coast Guard, Department of Transportation Office of Hazardous Materials, Atomic Energy Commission, universities, and private consultants.
2. The selection of barge transportation of bulk hazardous materials on inland waterways for special study.
3. The selection of a probabilistic model of risk composed of four factors.

In late 1973, the Panel proposed a contract for adaptation of a risk analysis network model previously used for etiological agent transport and later modified for radiological agent transport.(3) While this action was being included in the budget to be presented to the Coast Guard, the R&D Division of that Agency proceeded on the basis of conclusions apparent at that time to generate a long-range multifaceted risk analysis study program. The Panel then turned attention to generation of input data to be utilized in the probabilistic model mentioned above, since such data would be needed whatever model was chosen for a given study.

In January 1974, as a result of communications between Dr. Harris and Mr. W. E. McConnaughey, Senior Technical Advisor, Cargo and Hazardous Materials Division, USCG, a general task statement and revised task objectives were developed for the Panel.

At a Workshop Conference held by the Committee at the U. S. Coast Guard Academy, New London, Connecticut, 10-12 June 1974, the Panel adopted the following formal task statement:

> "Provide the Coast Guard with an assessment of the utility and feasibility of risk analysis as a set of techniques for assisting management decisions regarding the regulation of water transportation of specific bulk hazardous materials. This includes determination of the necessity and availability of input parameters and development of an effective and realistic expression of risk."

Interim reports from the Panel members were incorporated into a conference workbook and distributed prior to the meetings and became the basis for the Panel's efforts to develop a progress report. Panel members and other invited participants considered damage estimation and data evaluation, identified a number of known risk analysis studies, and developed a detailed format for review and evaluation of existing risk models for relevance to USCG problems.

This report is based upon (1) the interim reports in the workbook, (2) the work done at the Conference, (3) evaluations of risk models subsequently submitted by conferees and others, and (4) additional reports prepared by the Panel members.

The report addresses the utility of risk analysis as an aid in decision-making for the transport of hazardous materials and should not be considered as a definitive study of risk analysis and its techniques or applications.

B. DEFINITIONS

The terms risk, hazard, loss, and risk analysis are sources of confusion because they have different meanings to different people. Risk and hazard are sometimes used interchangeably in technical writing as well as in general conversation. Hazard is used to mean a condition of threat or danger, a dangerous substance or procedure, an exposure to loss or injury, a chance of loss, or anything exposed to loss. Risk is used to mean a hazard, a probability of loss or damage, an amount of possible loss, or the act of exposure to loss. These lists, which are not exhaustive, illustrate the necessity of carefully defining terms to avoid confusion.

The Panel on Risk Analysis and Hazard Evaluation has used the definitions of risk and hazard agreed to at the initial meeting. The following definitions will apply in this report.

1. Loss:

Harm or privation resulting from an unwanted event or events.

2. Hazard:

A real or potential condition, characteristic, or set of circumstances which can cause injury or death, or damage to or loss of property or equipment or cause an event which leads to those losses.(2)

3. Risk:

The probability that hazards in a system will cause events to occur which will result in some loss.(2)

4. Hazardous Material:

A substance or material in a quantity and form which may pose an unreasonable risk to health and safety or property when transported in commerce.(4)

REFERENCES

1. Report, Factors Involved in Cargo Size Limitations, NAS Committee on Hazardous Materials, Washington, DC, July 29, 1970.
2. Report, Risk Concepts in Dangerous Goods Transportation Regulations, National Transportation Safety Board, NTSB-STS-71-1, January 27, 1971.
3. Report, A Risk Model for the Transport of Hazardous Materials, prepared for Department of the Army, Fort Detrick, Maryland by Holmes and Narver, Inc., Contract No. DAAA13-68-C-0190, August 1969.
4. Public Law 93-633, Transportation Safety Act of 1974 (H.R. 15223), Title I - Hazardous Materials.

II. RISK ANALYSIS

A. GENERAL CONSIDERATIONS

Risk analysis is a systematic effort to quantify uncertainties associated with undesirable events. The expression of uncertainty should provide a basis for choosing between alternatives; e.g., between systems, activities, procedures, or equipment. In the absence of reliable numerical data quantitative statements may be impossible; it may then be necessary to characterize an option qualitatively as high, medium, or low risk. For most purposes, however, it is desirable to obtain an expression which associates numerical values with uncertain events, thereby providing a more precise basis of comparison between options.

In the course of the Panel's ongoing review of risk analysis and of the related discipline, systems analysis, it became apparent that to develop a completely general risk model would require an impractical amount of time and resources. The U. S. Coast Guard's separate parallel effort to develop a broad outline of such a general model confirmed this conclusion. It appears then that the greatest utility of the methodology, and perhaps the only practical one, lies in answering specific questions with output of a specific predetermined nature. Even when the Panel limited its concern to barge traffic on inland waterways it appeared that a great effort would be required unless (1) the scope of the questions posed were limited and (2) restrictions on input and output parameters were imposed.

There is no standard model or format for a risk analysis; the specific techniques employed are suggested by the magnitude of the system being investigated, the results desired, and the availability of data. Certain techniques of risk analysis appear to be applicable to the decision-making process in the transportation of hazardous materials by water. The movement of cargo vessels on waterways suggests the applicability of network analysis. Arcs in a network might represent activities, such as the transit of a vessel between points, the use of a procedure to avoid an accident, or the loading and unloading of cargo. Network nodes might represent events, such as the start or completion of activities or decision points; i.e., events of uncertain outcome, such as the success or failure of an activity.

Numerical data can be assigned to the arcs and nodes, depending on the type of information required by the analyst. Costs, completion times, and the probabilities of successful completion of activities can be assigned to the representative arcs. The probabilities corresponding to the alternative outcomes of events can be assigned to the appropriate nodes. In this way a network representation of the transportation system can be developed. The uncertainties of cost and scheduling can be accommodated by the use of probability distributions instead of point estimates for these parameters.

Computer simulation programs exist for evaluating the network model by selecting activities according to the probabilities assigned to the alternative outcomes and by sampling values from the distributions for the parameters. This process can be repeated as many as 1000 times; the resulting overall costs, times, and probabilities of successful completion are compiled for each iteration. The resulting "statistics" are printed as nomograms which provide the probabilities for alternative outcomes and the approximate probability distributions for time and cost.

Sophisticated versions of this type of simulation program currently in use by Department of the Army (1,2,3,4) give useful approximations of very complex systems. Modifications which may be necessary to apply them to the problems of the transportation of hazardous materials offer no apparent difficulty. The practical difficulties attending the acquisition of reliable input data are common to most risk studies. As discussed in Part B of this section, accident, casualty, and damage records maintained by private firms and government agencies are frequently incomplete and fragmented and seldom provide all the information required. Subjective estimates by experienced persons familiar with systems are often used to supplement recorded data. Estimates by more than one expert are sometimes reconciled and refined by the use of averaging procedures or the Delphi Technique.(5,6)

Results of risk analyses on more than one alternative can be used as the input for a decision risk analysis. A variety of mathematical techniques including those and based on probability theory enable the analyst to compare options on the basis of many parameters, such as completion time, cost, reliability, and other attributes.(7) There is in addition a growing literature available on decision-making procedures.(8,9)

Another approach to the assessment of risk in the transportation of hazardous materials by water is presented in Section II.B., below.

B. THE RISK EQUATION

Identification of the variables is the necessary first step in assessing uncertainty. The number, variety, and relationships between variables and the type and availability of data directly affect the procedures available to the analyst. The Panel considered a variety of approaches to the development of an effective and realistic expression of risk. After considering the general types of information available, the Panel agreed on an expression of the risk of damage or other deleterious effects in the transportation of hazardous materials by barge tows on inland rivers based upon conditional probabilities, as follows:

$$P(ERIH) = P(H)\cdot P(I|H)\cdot P(R|IH)\cdot P(E|RIH)$$

Where:

H = the event that a shipment (i.e., at least one barge in a tow) contains a hazardous material

I = the event that a shipment is involved in an incident (see definition in Section II.B.2)

R = the event that a release of hazardous material occurs in a shipment which contains a hazardous material

E = the event that deleterious effects occur (e.g., casualties, property damage)

IH = the joint occurrence of events I and H in a shipment

RIH = the joint occurrence of events R, I, and H in a shipment

ERIH = the joint occurrence of events E, R, I and H in a shipment

A theoretical example which illustrates these concepts is included in Appendix A of this report.

Since the usefulness of this equation is dependent upon acquiring certain input information, the Panel formed separate working groups to obtain available input data for each probability factor in the expression and to suggest methods of supplying or estimating missing data. The information obtained is discussed in the following sections of this report; the numerical data collected is included in Appendix B.

1. P(H): Probability that a Given Shipment Contains a Hazardous Material

Since existing statistical information to permit the evaluation of the factor P(H) was unavailable, the Panel requested the U. S. Army Corps of Engineers (USCE) to determine the presence of hazardous materials in barge tows on the Ohio River System. The Ohio River Division Office, USCE, collected the data over a six-month period from every tow that passed through three checkpoints: McAlpine Locks, Mile 607 Ohio River; Greenup Locks, Mile 341 Ohio River; and Winfield Locks, Mile 31 Kanawha River. The lockmaster verbally collected the information from the towboat as it traversed the lock. For the purposes of this study all commodities listed under Subchapters O or D, Code of Federal Regulations, Title 46(10) were considered to be hazardous materials. Appendix C contains the two hazardous materials listings. No attempt was made to determine the number of barges in the tow, the specific hazardous commodity or combination of commodities being transported, or the location of the hazardous material in the tow.

The data collected, which is reported in Appendix B, Table I, indicates that approximately 44% of the upbound tows and 20% of the downbound tows contain hazardous materials. If the upbound and downbound data are combined, the frequency of tows containing hazardous materials is 31%. These differences in P(H) values illustrate the importance of carefully specifying the question to be examined; e.g., P(H) will have different values for different rivers, cargoes, years, or seasons.

This kind of information is difficult to obtain. It is not normally collected and is often inadequate. It would be desirable for the USCG to collect this type of data regularly, preferably including additional detail to permit the investigation of specific questions. This subject is further discussed in Section II.B.2.

2. P(I|H): Probability that a Shipment is Involved in an Incident, Given that the Shipment Contains a Hazardous Material

In this report the term incident is defined as any undesirable marine occurrence involving a barge tow; a casualty is a vessel of any type which suffers damage, loss of life, or release of cargo; an accident is any incident in which there is at least one casualty.

A search for historical data to evaluate the factor P(I|H) led to the USCG, which maintains statistical files on the following marine occurrences involving commercial vessels:

1. actual physical damage to property in excess of $1500
2. material damage affecting the seaworthiness or efficiency of a vessel
3. stranding or grounding
4. loss of life
5. injury causing any person to remain incapacitated for a period in excess of 72 hours

Although casualty files have been kept for many years, the Coast Guard has only recently begun to maintain casualty data in a manner adaptable to electronic computer storage and retrieval procedures. Computer files of the casualty data reporting system, which now exist for fiscal years 1969 through 1974, are organized into five geographical regions: Inland Atlantic, Inland Gulf, Inland Pacific, Western Rivers, and Great Lakes. The Western Rivers region is the area of interest for the purposes of this study. Twenty-nine major vessel categories, including tank ships, tank barges, and hazardous materials barges, are listed in Table II of Appendix B. A more detailed subdivision of these three major vessel types, based upon the design of the vessel or upon the type of cargo to be carried, is provided in Table III. Table IV is a listing of 31 accident categories.

However, several areas of major importance are lacking in the USCG system of casualty data collection. It does not distinguish between empty and cargo-carrying vessels which become casualties. The number of barges and their locations within the tow are not reported. The direction of the tow (upbound or downbound) is not given. The rivers are partitioned into contiguous segments of 10-mile lengths; only the segment is identified in reporting the location of an accident. River features such as bends, bridges, etc., which may contribute to an accident are not reported.

The results of several studies which utilized the data available for fiscal years 1969 through 1972 are presented in Tables V through X, Appendix B. Although the unavailability of traffic density figures for the Western Rivers is a hindrance in the estimation of P(I|H), the Panel believes that gross determinations are possible using the existing data. A more accurate value must await the availability of more detailed information.

The Panel recommends that the USCG modify its casualty reporting system to include the following information:

a. Direction of all tows (upbound or downbound) which have accidents.
b. Presence or absence of cargo in barges which become casualties.
c. Number of barges in tows which have accidents.
d. Exact location (in the tow) of barges which become casualties.
e. Presence in any tow which has an accident of a barge containing a hazardous material, whether or not the barge became a casualty.
f. River features such as bends, bridges, etc., at the accident site.

The Panel further recommends that the USCG initiate a program to provide accurate year-round traffic density figures for the full lengths of all Western Rivers.

3. $P(R|IH)$: Probability that a Release of Hazardous Material Occurs Given that an Incident Occurs to a Shipment which Contains Hazardous Material

The Panel initially investigated historical data as a potential source of information on the factor $P(R|IH)$. The USCG casualty reporting system provided minimal information, namely, the occurrence of a spill. Quantities of spilled materials are not recorded. Table XI, Appendix B, is a summary of the data obtained from this source.

The USCG pollution reporting system, another source of historical data, was established in 1970 and required the reporting of all spills of any amount of oil, chemical, or any other polluting substance. The requirement was reduced in 1974 to include only oil. Data compiled for the years 1970 through 1972 is presented in Table XII of Appendix B.

Major differences between the USCG reporting systems are:

a. The casualty reporting data is based on fiscal years; the pollution reporting system is based on calendar years.
b. The two systems organize the data into different geographical regions.
c. The pollution reporting system does not specify individual rivers, geographical locations, or vessel types.

The Panel concludes that the data from the two systems cannot be sufficiently integrated to permit even gross estimates of the factor $P(R|IH)$.

The Panel recommends that the USCG standardize the data collection and organization procedures for the casualty reporting and the pollution reporting systems so that they supplement each other. The Panel further recommends that the casualty reporting system be expanded to include the quantity of cargo spilled.

4. $P(E|RIH)$: Probability that Deleterious Effects Occur, Given a Release of Hazardous Materials in a Shipment which Contains a Hazardous Material and is Involved in an Incident

The probability of deleterious effects is a function of the type and level of damage or loss and is object-specific. Types of losses include the total number or fraction of fatalities or casualties in a population, the area or value of property damaged or destroyed, or time lost due to disruption of normal activities. The level or magnitude of loss or damage will differ, depending on the concentration of local human activity and on the possible mechanisms of damage; for example, radiation from fire, engulfment in fire, blast wave from explosion, primary and secondary fragments from explosion, pollution or toxic fumes.

In general, at the present time, sufficient accident experience is not available to permit the determination of the factor P(E|RIH) for all cases even though there are exceptions.(11,12,13)

Appendix D is a suggested checklist of the kinds of information which are required to estimate damage from fire and explosions. A similar outline is required to estimate damage from other types of accidents.

Even in the absence of statistics, estimates of P(E|RIH) can be made on an object-specific basis. To illustrate the procedures which are involved in this evaluation the reader is referred to Appendix E. Here we consider as examples, five events or phenomena which occur during an accident and can lead to damage. These are:

I. Release of solids or liquids with low vapor pressure

   A. Pollutant
   B. Flammable

II. Release of cryogenic or high vapor pressure liquids

   A. Toxic and/or asphyxiant
   B. Flammable

III. "Empty" or partially filled fuel tank explosion

IV. Cargo fire

V. Condensed flammable which explodes

Items I. and II. involve the actual release of at least a portion of the contents of the vessel while types III., IV., and V. can produce very deleterious effects without appreciable initial release of the contents. In all cases the quantity of material which is released or otherwise involved in the accident and its type must be known or postulated before an evaluation of the size of the region which is affected can be made. This information, coupled with a knowledge of such things as the structures present, population density, etc., can then be used to determine the value of P(E|RIH) in terms of a specified level of damage, increase of risk, etc., depending on the specific risk analysis model that is being used.

REFERENCES

1. Advanced Solvent: A Network Analyzer Program. Report No. PAPAS-4. January 1973, Revision 2 - February-1975. Prepared by Stephen R. Percy, Systems Analysis Division, Plans Office, Picatinny Arsenal, Dover, New Jersey.
2. Pritsker, A.A.B., GERT: Graphical Evaluation and Review Technique. The Rand Corporation, RM-4973-NASA, Santa Monica, California, April 1966.
3. Pritsker, A.A.B., The GASP IV Simulation Language. John Wiley & Sons, New York, 1974.
4. Moeller, G. L., VERT - A Tool to Assess Risk. 1972, U. S. Army Management Training Agency, Rock Island Arsenal, Illinois.
5. Compendium on Risk Analysis Techniques, AMSAA Special Pub. No. 4, July 1972. Edited by E. M. Atzinger and W. J. Brooks, Army Materiel Systems Analysis Agency, Aberdeen Proving Ground, MD.
6. Philipson, Lloyd L., Investigation of the Feasibility of the Delphi Technique for Estimating Risk Analysis Parameters. Report No. TES-20-74-5, Office of Hazardous Materials, DOT, Contract No. DOT-OS-20114/1, April 1974.
7. ALMC Instruction Materials, United States Army Logistics Management Center, Fort Lee, Virginia.
8. Raiffa, Howard, Decision Analysis. Addison - Wesley, Rading, Massachusetts, July 1970.
9. Lifson, M. W., Decision and Risk Analysis for Practicing Engineers. Cahners Books, Boston, Massachusetts, 1972.
10. US Coast Guard, Department of Transportation. 46 CFR 30.25 - Tank Vessels; Commodities Regulated.
11. Doyle, W. H., Estimating Losses, Paper presented at the Central States Section of the Combustion Institute meeting, Houston, Texas, April 1970.
12. Napadensky, H. S. and Bodle, W. W., Safe Siting of Petrochemical Plants, presented at the National Symposium on Occupational Safety and Health, Carnegie Institution, Washington, DC, June 1973.
13. Milly, G. H., Atmospheric Diffusion and Generalized Munition Expenditures, Operations Research Group Study No. 17, US Army Chemical Center Maryland, May 1958; Re-issued January 1962.

III. REVIEWS AND EVALUATIONS OF RISK ANALYSIS STUDIES

At the 1974 New London Workshop Conference the Panel on Risk Analysis and Hazard Evaluation identified 27 existing risk analysis reports. Some of these were later found to be proprietary or were unavailable for other reasons; additional studies were later placed on the list. The conferees were assigned the responsibility for acquiring and reviewing specific reports. The Panel developed an evaluation protocol to be followed in assessing the applicability of each study to the needs of the U. S. Coast Guard. Appendix F contains the Review and Evaluation Format and 12 evaluations which were subsequently completed.

Since the authors of some of the evaluations participated in the original studies, the evaluations may vary in objectivity. Multiple reviews of each risk study were precluded by time limitations. Despite obvious differences in the treatment of portions of the Panel's protocol by each reviewer, the survey permits a comparison of the problems investigated, analytic techniques attempted, data utilized, and output expressions obtained. The Panel believes that this survey is an aid to a potential user in selecting methodologies applicable to his needs.

It is apparent from these summaries that the nature of the question asked affects the selection of an approach to a solution. The reports consider problems which are route-specific, commodity-specific, and severity-specific. The analytical methods employed include network, fault tree, and factorial analysis. Risks are expressed as probabilities, expected values, rates, and distribution functions.

The Panel concludes that a single risk model is not feasible for general use. Risk analyses must be developed for each specific application. The Panel recommends that the U. S. Coast Guard provide a centralized review function to facilitate the identification and evaluation of future risk methodologies. For this purpose the Panel suggests the use of the review and evaluation format found in Appendix F (a).

APPENDIX A

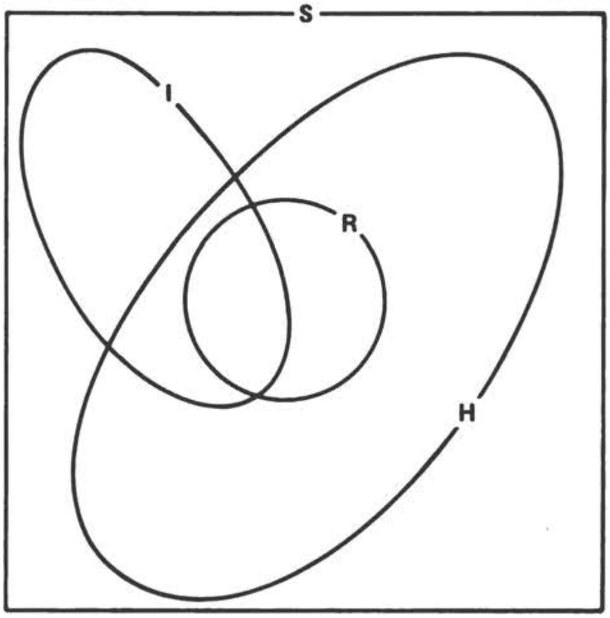
THE RISK EQUATION

A Hypothetical Example

The following example is included to illustrate the risk equation introduced in Section II B. The notation has been slightly changed to reflect set-theoretic concepts. The example is purely hypothetical; it is not intended to represent an actual situation.

Assume that 10,000 cargo-carrying vessels have transited a certain region in a specified time period; assume 4,000 vessels have contained hazardous cargoes. Suppose that 250 incidents occurred, of which 125 involved vessels with hazardous cargoes; of these 100 released hazardous materials.

These sets of vessels are finite but are represented here by a Venn diagram for illustrative purposes:



Where:

S = the set of all transiting vessels
H = the set of all transiting vessels which carry hazardous materials
I = the set of all transiting vessels which are involved in an incident
R = the set of all transiting vessels which have a release of hazardous cargo

Then:

$I \cap H$ = the set of all transiting vessels which carry hazardous materials and which are involved in an incident

$R \cap I \cap H$ = the set of all transiting vessels which carry hazardous materials, which are involved in an incident, and which have a release of hazardous cargo

The probabilities associated with these sets, based on the relative frequencies of occurrence are:

$$P(S) = 1$$

$$P(H) = \frac{4{,}000}{10{,}000} = 0.4$$

$$P(I) = \frac{250}{10{,}000} = 0.025$$

$$P(I \cap H) = \frac{125}{10{,}000} = 0.0125$$

$$P(R \cap I \cap H) = \frac{100}{10{,}000} = 0.01$$

$$P(I | H) = \frac{125}{4{,}000} = 0.03125$$

$$P(R | I \cap H) = \frac{100}{125} = 0.8$$

The probability of a release of hazardous material resulting from the occurrence of an incident to a vessel which contains hazardous cargo can be calculated in alternative ways, depending upon the availability of data for the conditional probabilities:

$$\begin{aligned} P(R \cap I \cap H) &= P(R | I \cap H) \cdot P(I \cap H) \\ &= P(R | I \cap H) \cdot P(I \cap H) \cdot P(H) \\ &= P(H)\ P(I | H)\ P(R | I \cap H) \\ &= (0.4)\ (0.03125)\ (0.8) \\ &= 0.01 \end{aligned}$$

This is equivalent to the first three factors in the risk equation in Section II B of this report.

Assume, further, that investigations following the release of hazardous materials have yielded statistics on two types of damage effects:

1) Area, in square miles, of a circular region centered on the release site, within which explosion and fire have caused identifiable property damage.

Assume that the hypothetical data on damage area have been classified (grouped) into cells and analyzed as follows:

Index (i)	Area (mi^2) (A_i)	Observed Frequency (f_i)	
1	0.125	2	Sample mean: $\overline{X}_A = 0.6013$
2	0.250	4	
3	0.375	14	Sample standard
4	0.500	22	deviation: $S_A = 0.1944$
5	0.625	26	
6	0.750	17	$= k-1-\ell$, where k = number of cells
7	0.875	11	$= 8-1-2$ and ℓ = number of parameters estimated (μ and σ)
8	1.000	4	$= 5$

The damage area, A, is regarded as a continuous variable. Using $\overline{X}_A$ and S_A as estimates for μ and σ, respectively, a normal curve has been fitted to the data. A chi-square test for goodness-of-fit gives a value of 1.2. Since $1.2 < \chi^2_{0.05,5} = 11.1$, the hypothesis is accepted that the data is a sample taken from a normally distributed population with $\mu = 0.6013$ and $\sigma = 0.1944$.

2) Casualties, in the number of persons having identifiable injuries resulting from the release. An assumption is made that the size of the exposed population remains constant, say 30,000 persons, during the specified time period.

Assume that the hypothetical data on casualties have been tabulated and analyzed as follows:

Index (j)	Number of Casualties (C_j)	Observed Frequency (g_j)	
1	0	41	Sample mean: $\overline{X}_C = 0.98$
2	1	33	
3	2	17	$= k-1-\ell$, where k = number of cells
4	3	6	$= 6-1-1$ and ℓ = number of parameters estimated (μ)
5	4	2	$= 4$
6	5	1	

The number of persons injured is regarded as a discrete variable, C. Using $\overline{X}_C$ as an estimate for μ, a Poisson distribution has been fitted to the data. A chi-square test for goodness-of-fit gives a value of 2.94. Since $2.94 < \chi^2_{0.05,4} = 9.49$, the hypothesis is accepted that the data is a sample from a population with a Poisson distribution with $\mu = 0.98$. Therefore, the probability frequency function is:

$$g(x) = \frac{e^{-a}a^x}{x!} = \frac{(0.3753)\ (0.98)^x}{x!}$$

and the probability distribution function is:

$$G(x) = (0.3753) \sum_{t=o}^{x} \frac{(0.98)^t}{t!}$$

The uncertainty associated with a specific type and level of damage resulting from the release of hazardous material following an incident to a vessel carrying hazardous cargo can be quantified by substituting the appropriate data into the risk equation. For example:

a) What is the risk of obtaining 0.4 mi^2, or less, of property damage by blast or fire?

$$\begin{aligned} P[E \leqslant 0.4 \text{ mi}^2 \cap R \cap I \cap H] &= P[R \cap I \cap H] \cdot P[E \leqslant 0.4 \mid R \cap I \cap H] \\ &= (0.01) \cdot P\left[X \leqslant \frac{0.4-0.6013}{0.1944} \;\middle|\; R \cap I \cap H\right] \\ &= (0.01) \cdot P[X \leqslant -1.035] \\ &= (0.01)\ (0.15) \\ &= 0.0015 \end{aligned}$$

b) What is the risk that blast or fire damage will affect an area greater than 0.625 mi^2?

$$\begin{aligned} P[E > 0.625 \cap R \cap I \cap H] = &= P[R \cap I \cap H] \cdot P[E > 0.625 \mid R \cap I \cap H] \\ &= (0.01) \ \{1-P[E \leqslant 0.625 \mid R \cap I \cap H]\} \\ &= (0.01) \left\{1-P\left[X \leqslant \frac{0.625-0.6013}{0.1944}\right]\right\} \\ &= (0.01) \ \{1-P[X \leqslant 0.122]\} \\ &= (0.01)\ (1-0.5485) \\ &= (0.01)\ (0.4515) \\ &= 0.004515 \end{aligned}$$

c) What is the risk that at least 2 persons (in a population of 300,000) suffer injuries?

$$\begin{aligned}
P[E \geqslant 2 \text{ persons} \cap R \cap I \cap H] &= P[R \cap I \cap H] \cdot P[E \geqslant 2 | R \cap I \cap H] \\
&= (0.01) \left\{ 1 - P[E < 2 | R \cap I \cap H] \right\} \\
&= (0.01) \left\{ 1 - G(1) \right\} \\
&= (0.01) \left\{ 1 - (0.3753) \sum_{t=0}^{1} \frac{(0.98)^t}{t!} \right\} \\
&= (0.01)\ (1 - 0.7431) \\
&= 0.002569
\end{aligned}$$

d) What is the risk that casualties exceed 0.002% of the population?

(300,000) (0.00002) = 6 persons

$$\begin{aligned}
P[E > 6 \text{ persons} \cap R \cap I \cap H] &= P[R \cap I \cap H] \quad P[E > 6 | R \cap I \cap H] \\
&= (0.01) \left\{ 1 - P[E \leqslant 6 | R \cap I \cap H] \right\} \\
&= (0.01) \left\{ 1 - G(6) \right\} \\
&= (0.01) \left\{ 1 - (0.3753) \sum_{t=0}^{6} \frac{(0.98)^t}{t!} \right\} \\
&= (0.01)\ (1 - 0.99987) \\
&= (0.01)\ (0.00013) \\
&= 1.3 \text{ x } 10^{-6}
\end{aligned}$$

The hazard value introduced in Section I A of this report was an attempt to provide a basis for comparison of two systems using the expected values of loss for each. The examples in this appendix suggest that two systems can be compared on the basis of their respective risk values for a given type and level of deleterious effects. For example, if the risk of obtaining at least 2 casualties is $2.5\text{x}10^{-3}$ for System A and $1.25\text{x}10^{-3}$ for System B, the relative risk of System A with respect to System B is $\frac{2.5\text{x}10^{-3}}{1.25\text{x}10^{-3}} = 2$.

APPENDIX B

DATA COLLECTED FOR THE EVALUATION OF THE PANEL'S RISK EQUATION

TABLE I Frequency of Tows with Hazardous Cargoes*
(Ohio and Kanawha Rivers) February-July 1973

	Feb	Mar	Apr	May	Jun	Jul	6 Months	
							Total	%
McAlpine Lock								
Upbound Tows								
Hazardous	117	124	139	131	107	111	729	55.5
Non-Hazardous	101	98	93	91	98	104	585	44.5
Total	218	222	232	222	205	215	1314	100.0
Downbound Tows								
Hazardous	50	48	41	45	48	43	275	20.7
Non-Hazardous	168	177	183	178	165	182	1053	79.3
Total	218	225	224	223	213	225	1328	100.0
Greenup Lock								
Upbound Tows								
Hazardous	104	116	106	113	122	99	660	49.0
Non-Hazardous	107	115	123	120	115	107	687	51.0
Total	211	231	229	233	237	206	1347	100.0
Downbound Tows								
Hazardous	62	57	46	50	52	59	326	24.2
Non-Hazardous	148	176	181	178	190	149	1022	75.8
Total	210	233	227	228	242	208	1348	100.0
Winfield Lock								
Upbound Tows								
Hazardous	44	44	44	46	43	37	258	23.3
Non-Hazardous	105	182	130	148	151	131	847	76.7
Total	149	226	174	194	194	168	1105	100.0
Downbound Tows								
Hazardous	27	22	19	22	22	20	132	12.5
Non-Hazardous	116	190	139	158	174	147	924	87.5
Total	143	212	158	180	196	167	1056	100.0

*For the purposes of this table, hazardous cargoes are those containing commodities listed as hazardous materials in Subchapter O or D of CFR, Title 46.

TABLE II Major Vessel Categories

1 - Artificial Island or fixed structure, including mobile drill rigs
2 - Cargo Vessel (freight), inspected US vessels only
3 - Cargo barges (freight), see also 28
4 - Commercial vessels that carry freight and offshore supply vessels
5 - Construction and wrecking vessels, including vessels such as drill tenders, pile drivers, derrick barges, drill ships and barges
6 - Dredges, self-propelled
7 - Dredges, non-self propelled
8 - Fishing vessels (excluding sport fishing, charter fishing vessels)
9 - Tugs and towboats
10 - Passenger vessels (other than ferries) over 65 feet and 100 or more G.T.
11 - Passenger vessels (other than ferries) over 65 feet and less than 100 G.T.
12 - Passenger vessels (other than ferries) not more than 65 feet
13 - Ferries over 65 feet and 100 or more G.T., carrying passenger or passengers and vehicles
15 - Ferries not more than 65 feet, carrying passengers or passengers and vehicles
16 - Passenger barges (including ferry barges)
17 - Tankships
18 - Tank barges (inflammable and combustible cargoes) (see also 29)
19 - Public vessels (passenger)
20 - Public vessels (cargo), excluding GAA vessels
21 - Public vessels (tanker), including USNS tankers
22 - Public vessels (other)
23 - All other US vessels and crafts such as pleasure, research, cableships, seismographic or those not otherwise classified above
24 - Foreign flag vessels (passenger)
25 - Foreign flag vessels (freight)
26 - Foreign flag vessels (tanker)
27 - Foreign flag vessels (other)
28 - Cargo barges (dangerous and hazardous cargoes)
29 - Tank barges (dangerous and hazardous cargoes)

TABLE III Specific Type of Vessel

17 Tank Vessels

30	T-2
31	Ex T-2, e.g. jumborized
32	T-1
33	T-3
34	T-5
97	Dangerous Cargo (tetra ethyl lead, methyl lead, aqua ammonia)
99	Other, NOC (inland or small coastal)

18 Tank Barges (Inflammable and Combustible Cargoes), and

29 Tank Barges (Dangerous and Hazardous Cargoes)

35	Liquid cargo barge unspecified
36	Single skinned liquid barge
37	Double skinned liquid barge (including clean petrochemicals, e.g. aromatics, trichloride)
38	Cylinder tank open hopper and void
39	Cylinder tank decked over
40	Other liquid barge, e.g. brine, drilling mud, etc.
41	LPG/LIG (butane, open hopper/propylene)
42	Chlorine
43	Sulfur, liquid
44	Ammonia, pressure tank
45	Ammonia, low temperature
46	Low temperature, other
47	Acid, sulfuric
48	Acid, other
49	Caustic, unspecified
50	Caustic soda, liquid
51	Caustic soda, high temperature
52	High temperature, other
69	Styrene, adiponitrile, acrylonitrile, paraxylene, vinyl acetate, ethyl benzene, alkyl benzene
71	"A" ethyl ether
99	Ammonia sulfate liquid (self unloaded) fertilizer, other

TABLE IV Type of Accident

1 - Collision with vessel, meeting situation
2 - Collision with vessel, crossing situation
3 - Collision with vessel, overtaking situation
4 - Collision with vessel, anchored or moored
5 - Collision with vessel while docking or undocking
6 - Collision with vessel in fog (takes precedence over 1, 2, 3)
7 - Collision with vessel, NOC
8 - Collision with floating or submerged objects (other than ground)
9 - Collision with fixed objects, piers, bridges, etc.
10 - Collision with ice or ice fields
11 - Collision with aids to navigation, fixed or floating
12 - Collision, other than with vessel, NOC (offshore rigs, seaplanes)
13 - Explosion and/or fire involving liquid bulk cargo (includes vapors)
14 - Explosion and/or fire involving general cargo
15 - Explosion and/or fire involving vessel's fuel (includes vapors)
16 - Fire, vessel structure
17 - Fire, vessel equipment (only when damage to vessel structure is incidental, minor or absent) including crank case explosions
18 - Explosion, boiler (whether or not fire results)
19 - Explosion, pressure vessels and compressed gas cylinders
20 - Explosion and/or fire - not otherwise classified
21 - Grounding with damage
22 - Groundings, no damage
23 - Founderings
24 - Capsizing with or without sinking
25 - Flooding, swamping, without sinking
26 - Heavy weather damage and weather generally
27 - Cargo damage, no damage to vessel
28 - Material failure, vessel structure
29 - Material failure, machinery and associated engineering equipment
30 - Material failure, equipment (other) including cargo gear, propeller shaft
31 - Casualty not otherwise classified, undetermined or insufficient information - earthquake, barge breakaway

TABLE V Number of Casualties of all Types
For Tank Ships and Tank Barges of Major Types 17, 18 & 29
For Fiscal Years 1969, 1970, 1971 and 1972

Accident Type	Inland Atlantic		Inland Gulf		Inland Pacific		Western Rivers		Great Lakes		Sub-Totals		Totals
	17	18,29	17	18,29	17	18,29	17	18,29	17	18,29	17	18,29	
1	6	26	2	264		1		108	1	2	9	401	410
2	1	8		17	1			2			2	27	29
3	1	1	3	26	1	2		19		1	5	49	54
4	1	25	4	82	5	3		40	2	1	12	151	163
5	1	5	3	2	1			2			5	9	14
6	2	6	2	32	2			14			6	52	58
7	2	11	2	20		3		12	1		5	46	51
8	5	14	4	21	1	1		20	3	4	13	60	73
9	11	69	8	168	10	11		148	14	7	43	403	446
10	1	1			5	1			4		10	2	12
11	1	5	2	27	1	2		2	1		5	36	41
12													0
13	1	1		6		2		1			1	10	11
14						1						1	1
15						1						1	1
16													0
17		1			1			3			1	4	5
18	1										1		1
19													0
20	4	6		7		2		11	1		5	26	31
21	17	58	2	62	4	4		73	3	3	26	200	226
22	23	38	16	30	4		3	24	2		48	92	140
23		1		5				2				8	8
24		1		4				1				6	6
25		2		2	1	1					1	5	6
26			1	1	1						2	1	3
27	1	1			2						3	1	4
28		2		6		3		8		1		20	20
29	7	1	1	2	6			1	3		17	4	21
30	1	2	1	6	8	1		3			10	12	22
31	3	2		6	1			13	2	1	6	22	28
TOTALS	90	287	51	796	55	39	3	507	37	20	236	1649	1885

TABLE VI

Number of Casualties of All Types for All Specific
Type 17 and 18 Vessels
For Fiscal Years 1969, 1970, 1971 and 1972

Vessel Type	Inland Atlantic	Inland Gulf	Inland Pacific	Western Rivers	Great Lakes	Totals
1730	8	4	25		15	52
31	41	33	14	1		89
32	5		1			6
33	1	5				6
34	3	1	1		1	6
97	1	2	2			5
1835	82	237	10	134	4	467
36	190	450	23	254	9	926
37		27		42	4	73
38		3		3		6
39						
40	2	6	2	8	2	20
41		7		9	1	17
42				5		5
43	4	8		6		18
44		3	1	3		7
45		3		8		11
46		3				3
47	1	9	1	2		13
48		4	1	5		10
49		5				5
50	5	12		16		33
51						
52						
69	1	8		6		15
71		1				1
99	2	10	7	17		36
TOTALS	346	841	88	519	36	1830
% of Total	18.9	45.9	4.8	28.4	2.0	

TABLE VII

Ranking of Accident Types for the Geographical Regions For Type 17, 18, & 29 Vessels For Fiscal Years 1969, 1970, 1971 & 1972

Accident Ranking	Inland Atlantic	Inland Gulf	Inland Pacific	Western Rivers	Great Lakes	Combined Regional Totals*	
						Accident Type	%
1st	9	1	9	9	9	9	23.7
2nd	21	9	30	1	8	1	21.8
3rd	22	4	4	21	21	21	12.0
4th	1	21	21	4	10	4	8.6
5th	4	22		22		22	7.4
6th	8	6		8		8	3.9

Accident Type	Description
1	Meeting collision
4	Collisions with anchored or moored vessel
6	Collision with vessel in fog
8	Striking a floating or submerged object
9	Striking fixed objects
10	Collision with ice
21	Groundings with damage
22	Groundings without damage
30	Material failure, equipment (other)

*The Combined Regional Totals are from Table V.

TABLE VIII

Accident and Casualty Rates for Some Geographical Locations On Four Western Rivers for Type 17, 18 and 29 Vessels For Fiscal Years 1969, 1970, 1971 and 1972

River and Mile	Accidents Per Year	Casualties Per Year	Distinctive River Features
Lower Miss.			
90-100	12.5	38.25	New Orleans; one bridge; one bend*
10-20	7.75	29.25	None
0-10	7.5	14.21	None
80-90	7.0	21.5	One bend
120-130	6.5	11.75	Two bends
100-110	5.5	32.0	New Orleans, one bridge; one bend
20-30	5.25	7.5	One bend
220-230	5.0	9.5	One bend
230-240	4.5	7.0	Baton Rouge; one bridge; two bends
Ohio			
840-850	4.25	10.25	Two locks and dams
600-610	4.0	11.5	Louisville; one lock and dam; six bridges
720-730	3.75	7.75	One lock and dam; one bridge; one bend
820-830	3.5	6.5	One lock and dam
300-310	3.0	5.25	One bridge; one bend
Upper Miss.			
170-180	6.5	24.75	St. Louis; three bridges
40-50	3.25	10.0	One bridge; one bend
200-210	3.0	6.25	Two bridges
50-60	2.75	7.0	One bridge; one bend
Illinois			
40-50	2.75	4.25	One bridge
160-170	2.0	4.0	Peoria; six bridges; two bends

*A Bend is a turn of greater than 60°

TABLE IX Casualty Type Frequency for High Accident Rate Locations on the Three Western Rivers Expressed as Percent of the Total Number of Casualties

River and Mile \ Accident Type	Meeting (1)	Crossing (2)	Anchored or moored (4)	Docking or undocking (5)	Fog (6)	Nonoperating (7)	Floating or submerged objects (8)	Fixed objects (9)	Groundings (damage) (21)	Groundings (no damage) (22)	Founderings (23)	Capsizings (24)	Structural failure (28)	Not otherwise classified (31)
Lower Mississippi														
0-10	15				39	13								
10-20					14		14		12					
20-30	10		10			10		13		13		10		
80-90	23		51											
90-100	11		28	8	7	7		11						
100-110			60					8						
120-130			44					12						16
220-230		8	19	11	11	8			8					11
230-240	17					26				26				
Upper Mississippi														
40-50								32	34					15
50-60					15			52		15				
170-180			51						16					16
200-210	19							50						
Ohio														
300-310	29		19										14	
600-610			15					40	30					
720-730								58	23					
840-850								71			12			
870-880								81					8	

TABLE X Accident Type Frequency for High Accident Rate Locations on Three Western Rivers Expressed as Percent of the Total Number of Accidents

Accident Type River and Mile	Meeting (1)	Anchored or moored (4)	Fog (6)	Nonoperating (7)	Floating or submerged objects (8)	Fixed objects (9)	Explosion or fire (20)	Groundings (damage) (21)	Groundings (no damage) (22)	Founderings (23)	Capsizing (24)	Heavy Weather (26)	Structural failure (28)	Equipment failure (30)	Not otherwise classified (31)
Lower Miss															
0-10	11		32	14								14			
10-20			9		13			19							
20-30		9		9	9	14			9						9
80-90	18	42													
90-100		21				16	7							7	
100-110		21				13									13
120-130		33				14									
220-230		35									15				
230-240		60													
Upper Miss															
40-50						20		38							
50-60						40	30								
170-180		22				11		11		11					22
200-210						50	14								
Ohio															
300-310		17								17		17	17		
600-610		13			13	38		19							
720-730						53		27							
840-850						71									
870-880						79									

TABLE XI

Accident, Casualty and Spill Summaries for the Western Rivers For Type 17, 18 and 29 Vessels for Fiscal Years 1969, 1970, 1971 and 1972

Name of River	River Length (Miles)	Number of Accidents	Number of Casualties For All Type Vessels	Number of Casualties Type 17, 18 & 29 Vessels	Number of Spills of Cargo	Accidents Per River Mile	Casualties Per Accident	% of Total Casualties That Are Type 17, 18 & 29 Vessels	% of Total Casualties Resulting In Spills
Lower Mississippi	966	501	1443	244	40	0.52	2.88	16.9	2.77
Ohio	981	308	710	120	16	0.31	2.30	16.9	2.25
Upper Mississippi	857	190	500	80	12	0.22	2.63	16.0	2.40
Illinois	333	85	178	40	1	0.25	2.09	22.4	0.56
Tennessee	652			12					
Missouri	753			5					
Cumberland	318			5					
Kanawha	90			3					
Arkansas	500			2					

TABLE XII

Summary of Data from the Pollution Incident Reporting System USCG
(Calendar Years 1970, 1971 and 1972)

MAJOR CATEGORIES	1970	1971	1972	Average
I. General Location				
A. Inland				
number of spills	126	631	682	480
% of total spills for all regions	3.4	7.2	6.9	5.8
volume spilled (gallons) x 10^6	(0.82)	(1.41)	(2.27)	(1.50)
% of total volume spilled for all regions	5.4	16.0	12.1	11.1
II. Specific Location				
A. Rivers (all)				
number of spills	47	252	340	213
% of total spills for all regions	1.3	2.9	3.4	2.5
volume spilled (gallons) x 10^6	(0.91)	(0.70)	(1.79)	(1.13)
% of total volume spilled for all regions	6.0	8.0	9.5	7.8
III. Sources				
A. Tank Barges				
number of spills	381	929	930	747
% of total spills	10.3	9.5	8.3	9.3
volume spilled (gallons) x 10^6	(1.65)	(1.20)	(3.74)	(2.19)
% of total volume spilled	10.8	13.6	19.9	14.7
IV. Causes				
A. Collisions in all regions				
number of collisions with spills	29	62	111	67
% of total spills in all regions	1.9	0.7	1.1	1.2
volume spilled (gallons) x 10^6	(0.74)	(1.46)	(1.46)	(1.22)
% of total volume spilled in all regions	5.0	16.5	7.7	9.7
B. Groundings in all regions				
number of groundings with spills	26	54	46	42
% of total spills in all regions	1.7	0.6	0.5	0.9
volume spilled (gallons) x 10^6	(0.31)	(0.90)	(0.76)	(0.65)
% of total volume spilled in all regions	2.0	10.1	4.0	5.3

APPENDIX C

LISTINGS OF HAZARDOUS MATERIALS

Subchapters O and D, 46CFR 30.25

Subchapter O

Acetaldehyde
Acetic acid
Acetic anhydride
Acetone cyanohydrin
Acetonitrile
Acrylonitrile
Adiponitrile
Allyl alcohol
Allyl chloride
Aminoethylethanolamine
Ammonia, Anhydrous
Ammonium hydroxide (not to exceed 28 percent NH_3)
Aniline
Benzene
Butadiene, inhibited
Butyl acrylate (n-)
Butyl acrylate (iso)
Butyraldehyde (n-)
Butyraldehyde (iso)
Camphor oil
Carbolic oil
Carbon bisulfide
Carbon tetrachloride
Caustic potash solution
Caustic soda solution
Chlorine
Chlorobenzene
Chloroform
Chlorohydrins (crude)
Chlorosulfonic acid
Cresols
Crotonaldehyde
Dichlorodifluoromethane
Dichloropropane
Dichloropropene
Diethanolamine
Diethylenetriamine
Diisopropanolamine
Dimethylamine
Epichlorohydrin
Ethyl acrylate
Ethyl chloride
Ethylene cyanohydrin
Ethylenediamine
Ethylene dichloride
Ethyleneimide
Ethylene oxide
Ethyl ether
2-Ethyl-3-propylacrolein
Formaldehyde solution
Formic acid
Furfural
Hydrochloric acid
Hydrofluoric acid
Hydrogen chloride
Hydrogen fluoride
Isoprene
Methyl acrylate
Methyl bromide
Methyl chloride
Methyl methacrylate
Monochlorodifluoromethane
Monoethanolamine
Monoisopropanolamine
Morpholine
Motor fuel antiknock compounds containing lead alkyls
Oleum
Phenol
Phosphoric acid
Phosphorus
Propionic acid
Propylene oxide
Styrene
Sulfur (liquid)
Sulfuric acid
Sulfuric acid, spent
Triethanolamine
Triethylenetetramine

Vinyl acetate
Vinyl chloride
Vinylidene chloride, inhibited

Subchapter D

Acetone
Amyl acetate
n-Amyl alcohol
Asphalt
Asphalt blending stocks:
  Roofers flux
  Straight run residue
Butane
n-Butyl acetate
sec-Butyl acetate
n-Butyl alcohol
sec-Butyl alcohol
tert-Butyl alcohol
Butylene
Corn syrup
Cyclohexane
Cumene
p-Cymene
n-Decyl alcohol
Decaldehyde
1-Decene
Dextrose solution
Diacetone alcohol
Dicyclopentadiene
Diethylbenzene
Diethylene glycol
Diethylene glycol monoethyl ether
Diethylene glycol monomethyl ether
Diisobutyl carbinol
Diisobutylene
Dioctyl phthalate
Dipropylene glycol
Distillates:
  Straight run
  Flashed feed stocks
Dodecanol
Dodecene
1-Dodecene
Ethane
Ethoxy triglycol
Ethoxylated dodecanol
Ethoxylated pentadecanol
Ethoxylated tetradecanol
Ethoxylated tridecanol
Ethyl acetate
Ethyl alcohol
Ethyl benzene
Ethyl butanol
2-Ethyl hexanol
Ethyl hexyl tallate
Ethylene
Ethylene glycol
Ethylene glycol monobutyl ether
Ethylene glycol monoethyl ether
Ethylene glycol monoethyl ether acetate
Ethylene glycol monomethyl ether
Gas oil:
  Cracked
Gasolines:
  Automotive (containing not over 4.23 grams lead per gallon)
  Aviation (containing not over 4.86 grams lead per gallon)
  Casinghead (natural)
  Polymer
  Straight run
Gasoline blending stocks:
  Alkylates
  Reformates
Glycerine
Heptane
Heptanol
1-Heptene
Hexane
Hexanol
1-Hexene
Hexylene glycol
Isobutyl acetate
Isobutyl alcohol
Isodecyl alcohol
Isodecaldehyde
Isohexane
Isooctyl alcohol
Isooctylaldehyde

- Isopentane
- Isopropyl acetate
- Isopropyl alcohol
- Jet fuels:
  - JP-1 (kerosene)
  - JP-3
  - JP-4
  - JP-5 (kerosene, heavy)
- Kerosene
- Latex, liquid synthetic
- Linear alcohols (12-15 carbon)
- Methane
- Methyl alcohol
- Methyl amyl acetate
- Methyl amyl alcohol
- Methyl ethyl ketone
- Methyl isobutyl ketone
- Methyl isobutyl carbinol
- Mineral spirits
- Molasses, all
- Naphtha:
  - Coal tar
  - Solvent
  - Stoddard solvent
  - VM&P (75 percent Naphtha)
- Naphthalene, molten
- Nonanol
- Nonene
- 1-Nonene
- Nonylphenol
- Octanol
- 1-Octene
- Oils:
  - Clarified
  - Crude
  - Diesel
  - Edible oils, including:
    - Castor
    - Cotton seed
    - Fish
    - Olive
    - Peanut
    - Soya bean
    - Vegetable
  - Fuel oils:
    - No. 1 (kerosene)
    - No. 1-D
    - No. 2
    - No. 2-D
    - No. 4
    - No. 5
    - No. 6
- Miscellaneous oils, including:
  - Absorption
  - Coal tar
  - Lubricating
  - Mineral seal
  - Mineral
  - Motor
  - Neatsfoot
  - Penetrating
  - Range
  - Resin
  - Rosin
  - Sperm
  - Spindle
  - Spray
  - Tail
  - Tanner's
  - Turbine
  - Road
  - Transformer
- Pentadecanol
- n-Pentane
- 1-Pentene
- Petrolatum
- Petroleum naphtha
- Polybutene
- Polypropylene glycol methyl ether
- Propylene
- Propylene butylene polymer
- Propylene tetramer
- Propane
- Propionaldehyde
- n-Propyl acetate
- n-Propyl alcohol
- Propylene glycol
- Sorbitol
- Tallow

Tetradecanol
1-Tetradecene
Tetrahydronaphthalene
Toluene
Tridecanol
1-Tridecene
Triethyl benzene
Triethylene glycol
Turpentine
Undecanol
1-Undecene
Valeraldehyde
Vinyl toluene
Waxes:
  Carnauba
  Paraffin
m-Xylene
o-Xylene
p-Xylene

APPENDIX D

ACCIDENT CHECKLIST
DAMAGE FROM FIRE AND EXPLOSION

Information to be Acquired After an Accidental Explosion or Fire

1. Description of conditions prior to the accident
2. Description of events leading to the accident
3. Statement of causes of accident
    - Indicate whether this is a preliminary judgment or a formally established finding.
4. Sketches or photographs of area before and after the accident
    - Include photographs of accident site (aerial view, if area is large), detailed views of damaged buildings and equipment, and typical and unusual debris.
    - Show important features, such as location of buildings, obstructions, and hills. Identify features such as stairs, doors, and windows, if damage is confined to one building.
    - Record location of photographed items and features such as material, weight, and size.
    - Indicate directional effects, if they exist.
5. Descriptions of explosions or fires
    - Record number of explosions or fires.
    - Record times between explosions or fires.
    - Describe sequence of events.
6. List of materials in
    - Record quantities of each material.
    - Describe container, configuration, and confinement of material.
    - Report the hazards classification and labelling of each material.

DAMAGE MECHANISM	MAXIMUM DISTANCE AFFECTED
Blast	
Fire	
Fragments	
Toxic Vapors	

SURVEY OF DAMAGE
(Buildings, Equipment, Etc.)

Type of Building or Equipment

Include age and type of construction (e.g., reinforced concrete, non-reinforced concrete, frame, other frangible).
Record damage details such as numbers, spacing, sizes and materials of studs affected.

LEVEL OF DAMAGE	AFFECTED AREA	NUMBER OF BUILDINGS AFFECTED	MAXIMUM DISTANCE FROM SOURCE	DETAILS OF DAMAGE			
				SIDE WALLS	BACK WALLS	WALLS FACING EXPLOSION	OTHER (DESCRIBE)
Total Destruction							
Demolition Necessary							
Extensive Damage							
Less Damage							
Minor Damage (e.g. glass, shingles, etc.)							
No Damage (but located in damage zone)							
Other (describe)							
Directional Effects (describe)							

EFFECTS AT EXPLOSION SITE	DESCRIPTION
Apparent Crater Size	Diameter: Depth:
Actual Crater Size (not including ejected material which fell back into crater)	Diameter: Depth:
Nature of Parent Ground (e.g., sand, soil, rock)	
Appearance of Metal, Concrete, Wood, etc., at Site (e.g., melted, charred, eroded, etc.)	

GLASS BREAKAGE

LOCATION OF GLASS	SIZE OF PLATE GLASS	SIZE OF WINDOW GLASS	LEVEL OF DAMAGE Glass is ... (Check appropriate block)				
			EMBEDDED IN OPPOSITE WALL	THROWN ACROSS THE ROOM	EMBEDDED IN FURNITURE OR OTHER MATERIAL	LOCATED NEAR WINDOW FRAME	BROKEN, BUT LOCATED
Side Wall							
Back Wall							
Wall Facing Explosion							

FRAGMENTS, MISSILES, OR DEBRIS

	DESCRIBE OR CHECK ( )	DISTANCE FROM SOURCE	EFFECTS ON OBJECTS STRUCK	REMARKS
FRAGMENT DESCRIPTION (Size, weight, material, etc.)				
FRAGMENT SOURCE • Primary fragments (originating from source of explosion • Secondary fragments (originating from other buildings or equipment				
FRAGMENT DENSITY • Number of fragments/ft^2 • Distance for maximum density				
FRAGMENT OF GREATEST WEIGHT				
FIRES CAUSED BY FRAGMENTS • Number of fires				

EFFECTS ON PEOPLE

Cause	Number Affected		Distance from Source	Remarks
	Death	Injury		
Blast (Detail effect such as ear drum damage, lung damage, translation, etc.)				
Building collapse				
Missiles/fragments/debris				
Falling objects				
Flying glass				
Toxic vapors				

APPENDIX E

DAMAGE MECHANISMS

Introduction

Typical examples of sequences of events that can occur after a spill and the interaction of mechamisms that can produce fatalities are shown in Figures 1 and 2. In any accident or hazard analysis one usually first prepares a logic diagram similar to these.

The five events which are used as examples in Section IIB4 each contains a number of possible damage producing mechanisms which can lead to damage to structures, injury, fatalities, etc. In Table I of this Appendix the most obvious damage producing mechanisms are listed for each of these events. Each of the damage producing mechanisms mentioned in Table I will be discussed, primarily to indicate selected references which are available to aid in the evaluation of the P(E|RIH) term for any object-specific case under consideration. The mechanisms listed in Table I are:

1. Pollution
2. Toxic and/or asphixiant gas
3. Blast wave
4. Primary fragments
5. Fireball
6. Sustained fire at source

In addition, secondary damage mechanisms can occur. Secondary damage mechanisms are:

1. The production of secondary fragments, and
2. Fire spread

The Panel did not consider radiological materials or etiological agents.

Specific Damage Producing Mechanisms

A. Primary

1. Pollution: River or Stream Contamination

The effect of a spill of hazardous liquid material on a stream or river depends upon the solubility, volatility, and specific gravity of the contaminants. There are three limiting cases of interest:

a. nonsoluble material lighter than water,
b. nonsoluble material heavier than water,
c. soluble material.

The physical properties of many materials are not described by these limits; e.g., a substance may be partially soluble, with or without appreciable

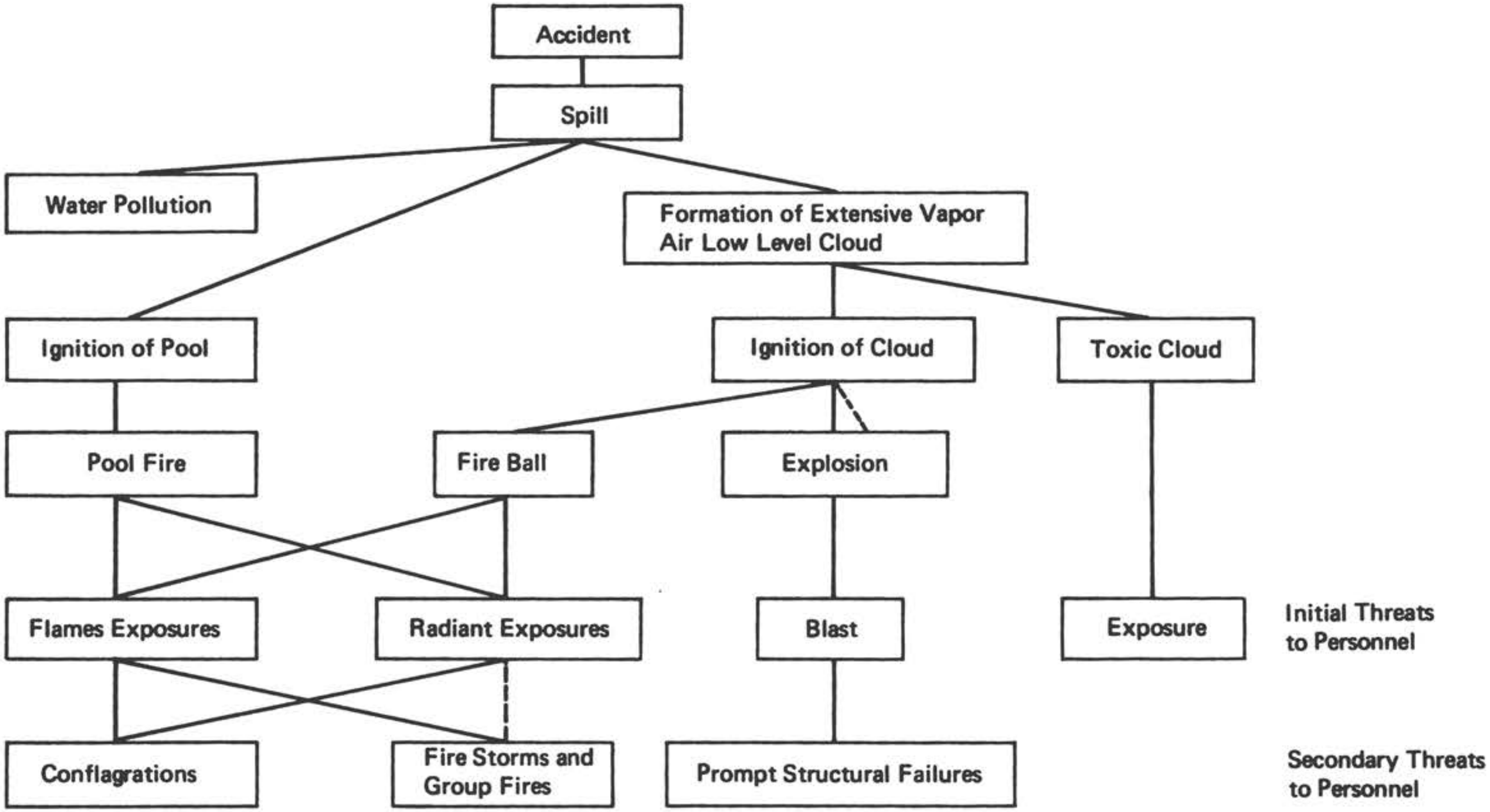


FIGURE 1 Initial and secondary threats created by accidents involving liquids or liquified gases.

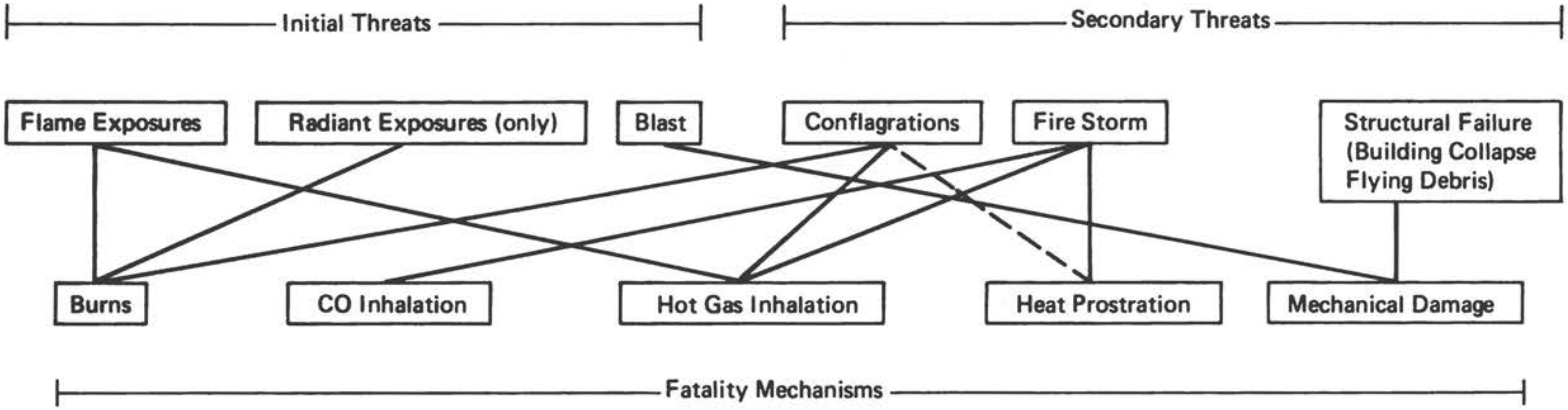


FIGURE 2 Likely injury and fatality modes associated with various threats (fire and explosion only).

TABLE I Damage Mechanisms by Event

I. Release of solids or liquids with low vapor pressure

- A. Pollutant
    - 1. Water pollution
- B. Flammable
    - 1. Sustained fire at source
        - a. Pool fires

II. Release of cryogenic or high vapor pressure liquids

- A. Toxic and/or asphyxiant
    - 1. Toxic and/or asphyxiant cloud formation
- B. Flammable
    - 1. Fire-delayed ignition
        - a. Fireball
        - b. Sustained fire at source
            - i. Torches/plumes
    - 2. Explosion-delayed ignition
        - a. Blast wave
        - b. Fireball
        - c. Sustained fire at source

III. "Empty" or partially filled fuel tank explosions

- A. Blast wave
- B. Fragments
- C. Fireball
- D. Sustained fire at source
    - 1. Pool fire
    - 2. Torches/plumes

IV. Cargo fire

- A. Sustained fire at source
    - 1. Interior fire
    - 2. Pool fire

V. Condensed flammable which explodes*

- A. Blast wave
- B. Fragments
- C. Fireball

---

*Condensed flammable - not shipped as explosive but capable of sustaining high order detonation.

volatility. Consideration of the limiting situations, however, establishes a range in which the real situation may be bracketed.

In the case of a nonsoluble or slightly soluble liquid lighter than water, the dispersion across the channel is relatively rapid, and the contaminant pool travels downstream at less than the velocity of the stream. There has been no general study of this case adequate for estimating the velocity and pool size of the contaminant as a function of time. An estimate of the pool size of a volatile material is necessary to evaluate the formation (by evaporation) of a vapor cloud which may constitute a further hazard of fire or toxicity. The collection of data on the surface travel of a contaminant and on the longitudinal spread of the pool would permit assessment of a specific situation, using iterative procedures on a large computer. This would require a detailed study such as the one discussed in Appendix Fii(b).

The case of a material heavier than water has received even less consideration than the first case. It is perhaps not as serious a situation, except when the materials are of slight or intermediate solubility. In this case, mass transfer coefficients from the engineering literature may provide a reasonable basis for estimating contamination.

Soluble material has been the subject of the most useful studies in estimating stream contamination. The US Geological Survey has published the results of time-of-travel experiments using dye tracers in rivers and streams of widely varying sizes.(1) Generalization of the data on peak contamination travel time and concentration has been previously published by the Committee on Hazardous Materials and provided to the Coast Guard.(2) This methodology can be used to estimate the arrival downstream of the peak concentration but has not yet been generalized to give the leading edge of a specific hazardous concentration below the peak value. Nor has it been generalized to consider a continuous source, as from an undetected leak, a slowly soluble liquid or solid heavier than water.

The methodology can certainly be used to compare leaks of different sizes to assess relative risk, since peak concentration can be calculated. This enables an estimate of the downstream distance a dangerous concentration might travel. It also provides an estimate of travel time, permitting timely suspension of downstream operations. It also provides guidance for testing the concentration of the contaminant, assuming the availability of toxicity data. At the least, it is useful for estimating the order of magnitude of the parameters of concentration and time, to assist judgment in responding to emergency situations.

2. Toxic or Asphyxiant Gas

When a volatile agent is spilled, it may either form a pool or flash immediately to vapor, depending upon the volatility, quantity, and available heat source. A very large spill of highly volatile cryogenic material causes cooling, and in some cases such as an accompanying explosion, a large cold atmospheric cloud is formed which flows like a liquid under gravitational force to lower terrain. Further downwind the contaminated cloud gains heat from its surroundings.

When the cloud has finally warmed - this happens very rapidly for smaller releases - it is transported by the low-level (surface) winds and distributed by turbulent diffusion. This latter mechanism also applies to continuous leaks from faulty or ruptured containers, if the leak rate is sufficiently low for the substance to evaporate without the formation of pools.

Much experimental work conducted by the military services and by the Atomic Energy Commission has been based on earlier theoretical work of the dissemination of pollutants from chimney stacks. This work, coupled with estimates of contaminants toxicities to man, will provide means for estimating the area of danger resulting from the release of toxic vapors.

There are four separate areas for which input is available for such estimation:

a. evaporation from a pool of volatile liquid,
b. diffusion from an instanteous point-source,
c. diffusion from a continuous source,
d. toxicity of vapors to man by inhalation (other routes of entry are less common and are negligible in magnitude compared to inhalation)

All of these areas have been discussed in the report of the Cargo Size Limitations Panel, which was forwarded to the Coast Guard in July 1970.(2) Included are graphs, table and calculations on the first three of the areas above, and some information on toxicity. The theoretical basis for the diffusion process is available in the open literature; perhaps the best known text is Reference 3.

It is here emphasized that virtually no data exist which are directly applicable to the fourth area, toxicity. Toxicity data in the literature usually apply to lower animals, or very rarely, estimates of acceptable levels for persons working with the compounds for long periods; e.g., continuous exposure for eight hours a day, five days a week. The need is for an estimate of the maximum concentration of specific compounds that could be tolerated by the public for a single exposure in an accident.

Given this toxicity data, the physical properties of the contaminant, meteorological data, and either the spill magnitude or spill rate, estimates can be developed of the downwind threat and time available for evacuation. The information available in the cited report has been utilized for this kind of estimation.

3. Blast Wave

In order to evaluate the P(E|RIH) term when a blast wave occurs, one must currently rely on simple scaling laws because detailed blast wave behavior for different types of accidental explosions are not sufficiently well understood at the present time. (4)

For this evaluation one usually invokes the concept of TNT equivalency for calculating the explosion potential $(Wt_{TNT})_P$ of flammable vapors or explosive substances in a transportation environment. The equation for TNT equivalency is based on the total combustion energy stored in the material.(5, 6)

$$\frac{H_{HC}W_{HC}}{H_{TNT}} = \frac{H_{HC}W_{HC}}{1800} = (Wt_{TNT})_P \qquad (1)$$

where H_{HC} = heat of combustion of the vapor material in Btu/lb, W_{HC} - weight of the material spilled in pounds and H_{TNT} = 1800, the heat of explosion of TNT in Btu/lb.

The TNT equivalencies of various actual accidental explosions have been estimated by evaluating the blast damage as a function of distance from the explosion center. Typically the distance (in feet) to window breakage and various degrees of structural damage are determined. Then each type of damage is assigned a scaled distance. Approximate values are shown in Table II as a crude guide. It must be emphasized that there are large differences between structures in a given class, such as "commercial," and their vulnerability to a given blast load can vary substantially depending upon the details of the design and construction. Also the damage will depend upon the duration of the load, or on the positive impulse, which in turn depend upon the quantity of material that is involved in the accident and the specific explosion type. Some details of the effects of blast loading on people are shown in Figure 3, which provides guidance as to expected "kill" mechanisms.

Finally, to calculate the TNT equivalency in percent for an accidental explosion, equation (2) is used:

$$\text{percent TNT equivalence} = \frac{(Wt_{TNT})_D}{(Wt_{TNT})_P} \times 100 \qquad (2)$$

where

$$(Wt_{TNT})_D = \left(\frac{\text{Distance at which damage is observed}}{\lambda \quad \text{(from Table 3)}}\right)^3 \qquad (3)^*$$

For accidental vapor cloud explosions, the TNT equivalence ranges up to 10 percent, well below the expected value, calculated from equation (1). Accidental explosions of liquid propellants have ranged up to about 5 percent TNT equivalent. For high explosives in a transportation environment, the yield rarely exceeds 15 percent TNT equivalent. However, it may be higher if one considers only a single barge in a manifest.

Thus for any object-specific study one would assume a specific quantity of a specific hazardous material and a specific location for the explosion to occur. Using the estimated maximum TNT equivalency data from this section and the population concentration or value of structures in that location, one could estimate, from projected blast severity contours, the expected level of damage or lives lost.

Blast waves can also produce secondary effects which cause damage. The production of secondary fragments and ignition of widely spread fires are two important examples of secondary effects caused by blast waves. These will be discussed below in the section on secondary mechanisms.

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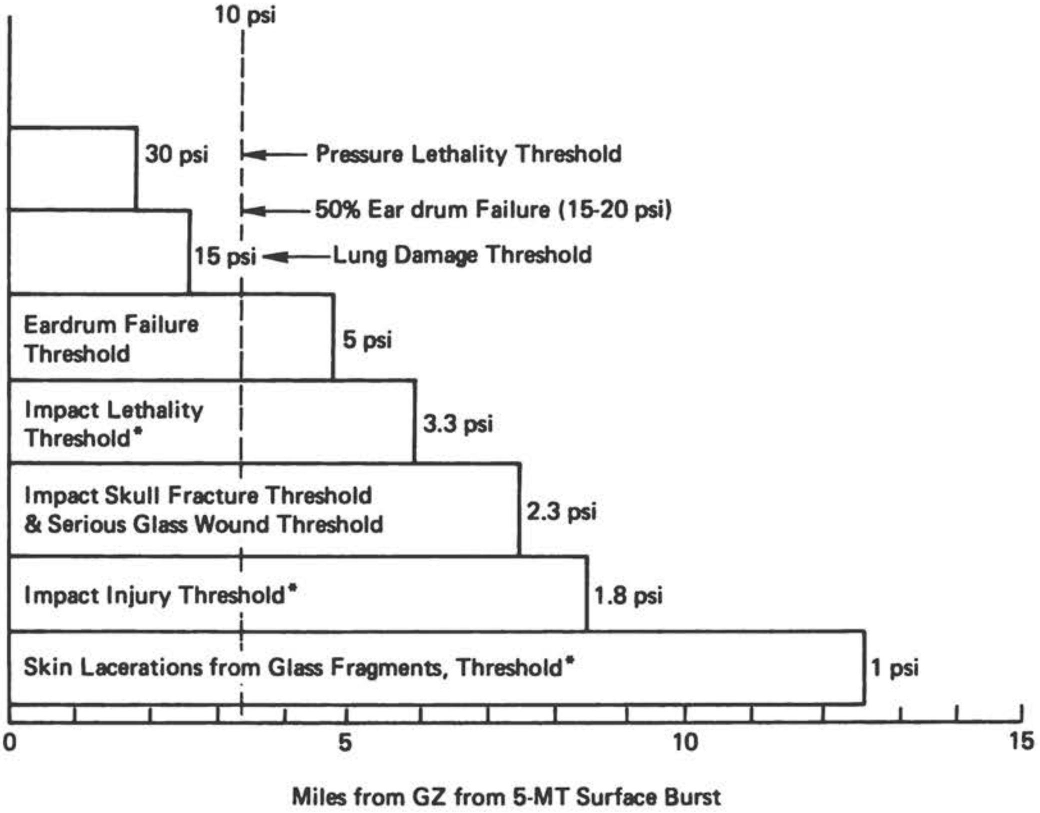
* λ is the scaled distance in ft/(lb)$^{1/3}$ and the distance in feet.



*For impact injury or death to occur at stated overpressure, the body must be thrown at least 10 feet before impact. Otherwise, a higher overpressure is required to achieve necessary velocity. Glass fragments must also travel at least 10 feet.

FIGURE 3 Blast injury thresholds in open(7).

NOTE: GZ - Ground Zero

TABLE II Blast Effects Guide(7)

Pressure Level (psi)	($ft/lb^{1/3}$)	Effect on People (%)			Property Damage	
		Safe	Hurt	Dead	Commercial	Small Residences
0.1-0.25	250-125	100	0	0	Lower limit of window breakage uncertainty range[a]	
0.25-1	125-145	100[b]	0	0	Only window damage	
1-2	45-27	75	25	0	Light	Moderate
2-5	27-14	50	45	5	Moderate	Severe
5-12	14-9	10	40	50	Severe	Complete destruction

4. Fragments

Primary fragments from an exploding container are of two main types: (1) small fragments from a frangible vessel, and (2) relatively large fragments produced by the tearing of a ductile vessel. Other large primary fragments include ship hardware, piping, etc. A good evaluation of fragmentation patterns from frangible vessels has been presented by Baker et al.(8) In a similar manner, Siewert has discussed in detail the properties of ductile fragments from fuel cars bathed in fire.(9) In general, the estimation of fragment damage patterns is very difficult because of the statistical nature of the phenomena.

5. Fireball

The duration of fireballs, since they are associated with explosions, is relatively short, of the order of 0.2 $W^{1/3}$, where duration is in seconds and W (the weight of the exploding material) is in pounds.(10,11,12)

Irradiance received by objects exposed to a fireball depends upon the size, temperatures and emissivity of the fireball and to a lesser extent upon the attenuation by the intervening atmosphere. Of key importance is the percentage of the energy radiated as prompt radiation. The percentages range from 17 to 42 percent for ordinary hydrocarbon fuel fires,(13) which may be contrasted to the value of 35 percent for nuclear fireballs.(14) In addition, values of 20 and 27 percent have been measured for propane and TNT fireballs,(12) respectively.

Attenuation of the radiation by the atmosphere can be obtained using the tramsmission data presented in Reference 15.

---

[a] Window damage depends upon pane area, thickness of glass, mounting frame, shape, etc.

[b] Some people hurt by flying glass

In addition to knowing the irradiance and duration associated with the fireball, it is desirable to know the size and location of the fireball as it rises into the atmosphere. In cases in which this information is not available, it is recommended that one estimate the size and location of the fireball from other fireball data such as for cordite,(10) propellants,(11) propane(12) and TNT. Typically, the diameter of the fireball(11) in feet is of the order of $5W^{1/3}$.

Calculation of the irradiance field about a fireball may be performed in one of two ways. The more accurate way is to integrate the irradiance intercepted by the target from each incremental solid angle subtended by the fireball. An example of this technique is given in Reference 16. By including only the visible portions of the fireball, one can account for partial obscuration of the fireball by intervening structures.

A more approximate method is to assume that the radiation is emitted by a point source in which the unattenuated radiation decreases as $1/r^2$, where r = slant distance from the point source. Unfortunately, the latter approach is not very accurate at close distances where the fireball subtends large solid angles. At such distances the irradiance will decrease inversely with r to a power somewhat less than 2.

6. Sustained Fire at Source

a. <u>Pool Fires</u> The characteristics of fires involving pools of liquid fuels depends upon the size of the pool, type of fuel, and atmospheric conditions such as wind and lapse rate. Means for predicting the external irradiance field outside of pool fires are presented in Reference 17 as a function of type and size of fire, wind velocity, and distance.

Radiant intensities incident upon surfaces within pool fires depend upon height above the pool, and to a lesser degree on orientation of the surface. Peak intensities are generally achieved, at heights of 1 to 3 feet above the pool, for pool sizes up to 2000 feet. Measured radiant intensities are presented in Reference 18 for JP-4 fuel. These values are typical of the irradiances found in the hotter regions of pool fires involving conventional hydrocarbon fuels such as gasoline, kerosine, and benzene, and can vary by as much as ± 25 percent within apparently identical fires.

b. <u>Torches/Plumes</u> The heating capabilities of torches/plumes vary widely and depend upon the fuels involved, jet sizes and velocities, and location of the exposed item. In this regard there is considerable information in the literature describing the radiant emissions from rocket plumes.(19,20)

B. Secondary Mechanisms

1. Secondary Fragments

Secondary fragments are fragments produced by the blast wave itself. One of the most important contributors of injuries to people is glass fragments produced when blast waves encounter windows. Table II and Figure 3 give overpressure levels for typical glass breakage and threshold levels for injuries to people from glass fragments. Additional information may be found in

References 21, 22, and 23.

2. Fire Spread

If not controlled, fires within urban areas can spread at rates as high as 0.5 mile/hr.(16) Rapid fire spread in densely built up areas could possibly lead to group fires or firestorms in which the indrafts of air reach velocities as high as 40 to 50 mph.(24)

Two mechanisms are important in spreading fire from building to building. These are firebrands that have the potential for spreading fire over distances of the order of hundreds of feet, and flame radiation which has the potential for rapidly spreading fire to buildings less than 100 feet away. Means for computing the probabilities of spreading fire by each of the above mechanisms are described in Reference 25. These probabilities depend upon the type and size of buildings, internal and external fuels, spacings between buildings, and wind velocity. Assessment of the rate of spread of fire as a function of time can be made using a computer code developed for OCD (DCPA) to study fire development in urban areas following a nuclear attack.(16) In turn, one can predict the occurrence of a group fire or firestorm by determining the peak heat release rates over various areas and using the criterion presented in Reference 24.

Based upon an unpublished analysis of World War II fatalities, it is estimated that in firestorms the number of fatalities per burning building can range from one to two orders of magnitude greater than that caused by ordinary building fires. On average, there is roughly one fatality per 100 ordinary building fires.(26)

a. Susceptibility of Structures to Fire The most common ignition sources in and adjacent to structures are fabrics, paper and wood. Data are presented in References 27 and 28 describing the irradiances necessary to spontaneously ignite wood, textiles and fiberboard. Pilot ignitions, in which combustible vapors are ignited by sparks, etc., require approximately half the thermal inputs described in the above references.

In cases in which the radiation must first pass through window panes, one should multiply the irradiance by the transmittance of the window panes. Transmittance data are given in Reference 29 as a function of wavelength.

b. Susceptibility of People to Fires

(1) Skin Burns In addition to depending upon the irradiance and exposure time, the production of skin burns depends upon the wavelength of the radiation and upon the degree of skin pigmentation. To a first-order approximation, one can neglect the wavelength dependence and use data such as reported in Reference 30. While more refined determinations could be obtained by analysis similar to that reported in Reference 31, it is not warranted in view of the approximate nature of the irradiance predictions.

One feature of the problem does, however, deserve comment. That is that individuals exposed to intense radiation will sense pain before burn production and react by turning away. Here one should either limit the exposure time to typical reaction times, or use an effective irradiance for cases in which the surfaces are re-exposed. If one assumes that the individual continues to turn in a uniform fashion, then effective irradiance may be arrived at by dividing the peak irradiance by π.

(2) Inhalation of Hot Gases. Inhalation of hot gases can cause lung injury and death depending upon the enthalpy of the gas inhaled. From studies of pulmonary injuries due to the inhalation of hot dry air,(32) it was found that 500°C dry air did not injure the lungs. On the other hand, from the same studies it was found that the lungs were injured in four out of six exposures when 100°C steam was inhaled. Enthalpy of the steam at 100°C is of the same order of magnitude as the enthalpy values associated with the combustion gases generated from conventional fuels, while the enthalpy of dry air at 500°C is about one order of magnitude less.

REFERENCES

1. Kilpatrick, F.A., Martens, L.A., and Wilson, J.F., Jr.,"Measurement of Time of Travel and Dispersion by Dye Tracing," Techniques of Water-Resources Investigations of the US Geological Survey (1970)

2. National Academy of Sciences-National Research Council, Factors Involved in Cargo Size Limitations, Appendix V, Report to the US Coast Guard, NAS-NAE, Washington, DC (July 29, 1970) NTIS AD720295

3. Pasquill, F., Atmospheric Diffusion, D. Van Nostrand Company Ltd. (1962)

4. Strehlow, R. A. and Baker, W. E., The Characterization and Evaluation of Accidental Explosions, NASA-CR-134779. 87pp. (June 1975)

5. Brasie, W.C. and Simpson, D.W.,"Guidelines for Estimating Damages from Chemical Explosions," Loss Prevention 3 (1969)

6. Burgess, D.S. and Zabetakis, M.G., Detonation of a Flammable Cloud Following a Propane Pipe Line Break, The December 9, 1970 Explosion in Port Hudson, MO., RI 7752, US Department of the Interior, Bureau of Mines, Washington, DC (1973)

7. "Introduction to Nuclear Emergency Operations," Chapter 1, DCPA Attack Environment Manual, Research Directorate, DCPA, Panel 7 (June 1972)

8. Baker, W.E., Parr, V.B., Bessey, R.L. and Cox, P.A., Assembly and Analysis of Fragmentation Data for Liquid Propellant Vessels, NASA-CR-134538, Southwest Research Institute, San Antonio, TX, Contract No. NAS-3-16009. 236pp (January 1974) NTIS N7415625

9. Siewert, R.D., Evacuation Areas for Transportation Accidents Involving Propellant Tank Pressure Bursts, NASA-TM-X-68277. NASA Lewis Research Center, Cleveland, OH (1972) NTIS N7329987

10. Jarrett, D.E., "Derivation of the British Explosives Safety Distances," Prevention of and Protection Against Accidental Explosions of Munitions, Fuels and Other Hazardous Mixtures, Annals of the New York Academy of Sciences 152(1). pp18-35 (October 1968)

11. High, R.W., The Saturn Fireball, ibid., pp441-451

12. Pattman, J.D.R., Thermal Radiation and Fireball Temperatures, Operation Distant Plain 1966, DASA Report 1947-1, pp183-202 (September 1967)

13. Zabetakis, M.G. and Burgess, D.S., Research on the Hazards Associated with the Production and Handling of Liquid Hydrogen, RI 5707, US Department of the Interior, Bureau of Mines (1961)

14. Gibbons, M.G., Transmissivity of the Atmosphere for Thermal Radiation from Nuclear Weapons, UNSRDL-TR-1060 for OCD on Work Unit No. 5700 (August 1966)

15. Yates, H., Total Transmission of the Atmosphere in the Near Infrared, Naval Research Laboratory Report 3858 (September 1951)

16. Takata, A.N., Development and Application of a Complete Fire-Spread Model, IITRI Report for OCD on Contract NOO-228-67-C-1498 (June 1968)

17. Takata, A.N., Review of Fire Hazard Distances, IITRI Report for Armed Services Explosive Safety Board for Contract DAHCO4-70-C-0013 (April 1970)

18. Townsend, W., et al.,'Comparison of Thermally Coated and Uninsulated Rail Tank Cars Filled with LPG Subjected to a Fire Environment," FRA-OR and D75-32 (December 1974)

19. Ludwig, C.B., et al., Study of Exhaust Plume Radiation Predictions, General Dynamics, Convair Report GDC-DBE 66-017 (December 1966)

20. Krahow, B., et al., "Use of the Curtis-Godson Approximation in Calculation of Radiant Heating by Inhomogeneous Hot Gases," Appl Optics 5 (1966)

21. Reed, J.W., Tape, B.J., Minor, J.E. and Dehart, R.C., "Evaluation of Windowpane Damage Intensity in San Antonio Resulting from Medina Facility Explosion on November 13, 1963," Annals of the New York Academy of Sciences, Volume 152, Article 1 (October 28, 1968)

22. Custard, G.H. and Thayer, J.R., Target Response to Explosive Blast, final report by Falcon Research and Development for Armed Services Explosive Safety Board under Contract No. DAHCO4-69-C-0095 (September 1970)

23. Reed, J.W., "Wind Damage to Windows as Estimated from Explosion Tests," conference preprint, Second US National Conference on Wind Engineering Research (22-25 June 1975)

24. Lommasson, T.E. and Keller, J.A., A Macroscopic View of Fire Phenomenology and Mortality Prediction, Dikewood Corporation Report DC-TN-1058-1 for Defense Atomic Support Agency on Contract DASA-01-67-C-0008 (December 13, 1966)

25. Takata, A.N., Fire Spread Model Adaptation, IITRI Report for DCPA on Contract DAHC-20-72-C-0152 (October 1972)

26. "Fires and Fire Losses Classified, 1961," Quarterly of the National Fire Fire Protection Assoc 56(2), pp180-181 (October 1962)

27. Lawson, D.I. and Sims, D.L., "The Ignition of Wood by Radiation," British J Appl Phy 3, pp288-292 (1952)

28. Sims, D.L. and Walters, J.E.I., The Ignition of Textiles by Radiation, Dept of Scientific and Industrial Research and Fire Offices Committee, Joint Fire and Research Organizations, FPE Note No. 60 (November 1951)

29. Downs, L.W. and Bruce, H.D., Effect of Window Glass in Protecting Materials from Ignition by Thermal Radiation, AFSWP (now DASA) Report 792 (November 1955)

30. Perkins, J.B., Pearse, H.E. and Kingsley, H.D., Studies on Flash Burns: The Relation of the Time and Intensity of Applied Thermal Energy to the Severity of Burns, Univ of Rochester Atomic Energy Report UR-217 (1952)

31. Takata, A.N., Thermal Model of Laser Induced Eye Damage, IITRI Report for Aerospace Medical Division (AFSC) of Brooks AFB, Contract F41609-74-C-0005 (October 1974)

32. Moritz, A.R., Henriques, F.C. and McLean, R., "The Effects of Inhaled Heat on the Air Passages and Lungs," Am J Path 21 (1945)

APPENDIX F

RISK ANALYSIS STUDIES

(i) Review and Evaluation Format

1. Description of model

1.1 Study identification
1.1.1 Title
1.1.2 Contractor
1.1.3 NTIS or other reference number
1.1.4 Date
1.1.5 Author(s)
1.1.6 Sponsor

1.2 Synopsis
1.2.1 Objective or purpose
1.2.2 Intended use
1.2.3 Actual user
1.2.4 Use to which put
1.2.5 User's evaluation
1.2.5.1 Special skill or equipment requirements
1.2.5.2 Ease of use
1.2.5.3 Number of persons in organization who use it
1.2.5.4 Suggested improvements
1.2.6 Originator's suggested improvements

1.3 Description (3 page limit)
1.3.1 General approach
1.3.2 Degree of simplification or assumptions such as: transportation mode, size, range (rail-bulk, etc.); accident type, range (collision, rupture, over-pressure); range of release mechanisms (valve fault, container wall rupture, pipe or hose break); range of casual categproes (design fault, operator errors, maintenance faults); healthy population or range of age and health; time-space dimensionality of release and dispersion; meteorological or hydrological parameters (temperature, pressure, wind and current direction and velocity stability)
1.3.3 Technique categories internal to methodology (network analysis, engineering analysis of container/vehicle rupture, fault tree analysis, scenario analysis, Gaussian plume vapor dispersion, laminar (or turbulent) water dispersion, biologic or radiologic decay analysis, dose-response curve analysis
1.3.4 Process description--sequence of operations in methodology, general description of data/information passed from one module of the methodology to the next.

1.3.5 Calculation methods--computer model, programable calculator model, hand calculator/slide rule model, structured judgment method
1.3.6 Computer/Calculator program availability:
Model--source, form, language and machine (if applicable)
Sample machine processable input data--source, form
Documentation (in addition to referenced technical report)--source, form

2. Inputs to model

2.1 Generic description of data used
2.2 Sources of data
2.3 Examples of numerical values
2.4 Definitions of units

3. Outputs produced with model

3.1 Generic description
3.2 Examples of numbers
3.3 Definitions of units
3.4 Was model tested against historical experience
3.5 Did analysis process identify new control areas

4. Adaptability of model to Coast Guard needs

4.1 Coast Guard regulatory function(s) involved (see attached list of functions)
4.2 Sample question(s) or decision(s) within the functions for which model could provide data (P_M, P_I, P_R, P_E, etc.)
4.3 Modifications to model/method required to permit each application
4.3.1 Information bearing on that question or decision available from model
4.3.2 Additional input data required for each application
4.3.3 Possible sources for data of 4.3.2

(ii) Reviews and Evaluations

(a) A Risk Model For the Transport of Hazardous Materials

Reviewed by
Stan Kaplan, Holmes and Narver, Inc.

1. Description of model

1.1 Study identification
1.1.1 Title
A Risk Model for the Transport of Hazardous Materials
1.1.2 Contractor
Holmes and Narver, Inc., Los Angeles, CA
1.1.3 Reference number
DAAA 13-68-C-0190
1.1.4 Date
August 1969
1.1.5 Author(s)
B. J. Garrick, W. C. Gekler, O. C. Baldonado, H. C. Elder, J. E. Shapley
1.1.6 Sponsor
Department of the Army, Ft. Detrick, MD

1.2 Synopsis
1.2.1 Objective or purpose

Provide a methodology to be used in evaluating risk of proposed routes and methods of transportation of biological weapons.

1.2.2 Intended use
1.2.3 Actual user
Fort Detrick, MD
1.2.4 Actual application
Used to select routes and methods for biological weapons transport.
1.2.5 User's evaluation
1.2.6 Originator's suggested improvements

1.3 Description
1.3.1 General approach

The approach is to view proposed transport path, P, as a set of nodes and links, S. For each node and link, S, the probability P(S,Q), is computed of a release of magnitude Q at that node or link. Also computed is the number, N(S,Q) of infections resulting from the release Q at S. The expected infections at S is then:

$$E(S) = \sum_{Q} P(S,Q)\ N(S,Q),$$

and the risk for the path, P, is the sum over all links and nodes in P.

$$R(\underline{P}) = \sum_{S \in \underline{P}} E(S)$$

The probabilities P(S,Q) are computed from a fault tree analysis of the vehicle or container at each S. The consequences N(S,Q) are computed from the population density in the vicinity of S, Gaussian-type dispersion expressions, decay rates, aerosolization and infectivity properties of the biological materials.

1.3.2 Assumptions and simplifications

Various simplifications were used and choices of level of detail made in this application, but these are not intrinsic to the methodology. (It is necessary, however, always to discretize continuous variables such as Q and S.)

1.3.3 Technique categories

Fault trees, Gaussian dispersions, treatment of both point and line source geometry and both instantaneous release and continued, slow-leak type releases.

1.3.4 Process description

Process flow is: identify components of path, do fault tree analysis of each path element, compute dispersion, dosage and expected consequences of releases. Compute expected values for each S, and for each proposed path. Repeat as required for other varied parameters (containers, timing, vehicle type, etc.).

1.3.5 Calculation methods

Calculations are done by a cluster of modular computer programs:
SAFTE/MINCUT-to evaluate fault trees
BWARE-to computer effect of release
BIOTRANS-to compute risk for each path

1.3.6 Computer/calculator availability

Programs available through Ft. Detrick or Holmes and Narver, Inc.

2. Inputs to model

2.1 Generic description of data used

a) Description of transport path, vehicles, packaging, escorting, timing, protective capsules, transhipment points, handling methods, etc.

b) Detailed engineering description of containers

c) Description of population in neighborhood of each transport line and node

d) Description of weather, wind, etc., at each node and link

e) Description of agent characteristics and susceptibility of population

f) Data on accident rates and deficiency rates in containers, vehicles, etc.

2.2 Sources of data

a) Ft. Detrick, MD

b) Engineering drawings and specifications

c) US statistical abstracts

d) Documents from Environmental Sciences and Services Administration, Army Chemical Center, American Society of Mechanical Engineers

e) Department of Transportation, The Johns Hopkins University studies, US Air Force

2.3 Examples of numerical values

For example, an input datum on collision rates for motor carriers of general freight is 2.20 accidents per million vehicle miles.

3. Outputs produced with model

3.1 General description

The output produced by the model is the risk associated with each proposed transport action, measured into expected number of people infected per trip. For example for the use of normal delivery, path 1, the risk is 1.33×10^{-6} infections per trip.

4. Adaptability of model to USCG needs

4.1 USCG regulatory functions involved

The essence of the Holmes and Narver approach is a formulation and a methodology for assigning numerical characterizations of risk to any proposed transport action. As such, this formulation is applicable to any regulatory function requiring such numerical characterization.

4.2 Sample question

Should movement of a given shipment be permitted from point A to B at a fixed time?

4.3 Modifications to model a method to permit application

4.3.1 Information bearing on the question available from the model

The information relative to this decision which the model would provide is: a) an identification of who and what is at risk in the proposed shipment, e.g. people, domestic animals, wildlife, property, etc.; b) for each at risk, a curve showing the probability versus degree of damage.

4.3.2 Additional input data required for each application

For general application the Holmes and Narver approach, as applied to the bio-weapons study, should be generalized in two respects:

a) It should be explicitly recognized in the methodology that risk is a vector, i.e., a multiple valued quantity. That is, in any proposed shipment there is risk to life, property, environment, etc.

b) Rather than simply speaking in terms of "expected values" of damage, the methodology should report instead a complete curve showing probability versus degree of damage.

(b) Vulnerability Model for Marine Spills of Hazardous Materials

Reviewed by

Reviewed by John A. Dwyer, US Coast Guard

1. Description of model

1.1 Study identification

1.1.1 Title

Vulnerability Model for Marine Spills of Hazardous Materials

1.1.2 Contractor

Enviro Control, Inc., Rockville, MD

1.1.3 Reference number

1.1.4 Date

Spring 1975

1.1.5 Authors

Cornelius J. Lynch, Norman A. Eisenberg, and John D. Morton

1.1.6 Sponsor

US Coast Guard, Office of Research and Development

1.2 Synopsis

1.2.1 Objective or purpose

The vulnerability model estimates the deaths, injuries and both property and environmental damage caused by a maritime spill of a hazardous material. It does this through a computerized simulation of the spill itself, the transformation and dispersion of the spilled commodity, and the effect of its damage mechanisms on the vulnerable resources in the area.

1.2.2 Intended use

The model will be used in the damage assessment phase of the Risk Management System currently under development.

1.2.3 Actual user

US Coast Guard

1.2.4 Actual application

Presently the model is being implemented on an IBM 360/65 computer. The simulation program is written in standard FORTRAN IV. Currently the model is limited to simulating spills of 5 hazardous materials, LNG, chlorine, methanol, gasoline and anhydrous ammonia.

1.2.5 User's suggested improvements

Planned improvements to the model call for enlarging the list of hazardous materials as well as refining some of the dispersion and transformation submodels. Secondary effects of the spill, such as the spreading of fires or the release of an additional hazardous substance due to the original spill, will also be addressed in future efforts.

1.3 Description

1.3.1 General approach

The Vulnerability Model operates in two phases as shown in Figure 1. [of this Study]. The first phase simulates the spill of the hazardous substance and its transformation and dispersion. The area of concern is blocked into mutually exclusive cells whose shape and size are selected by the user.

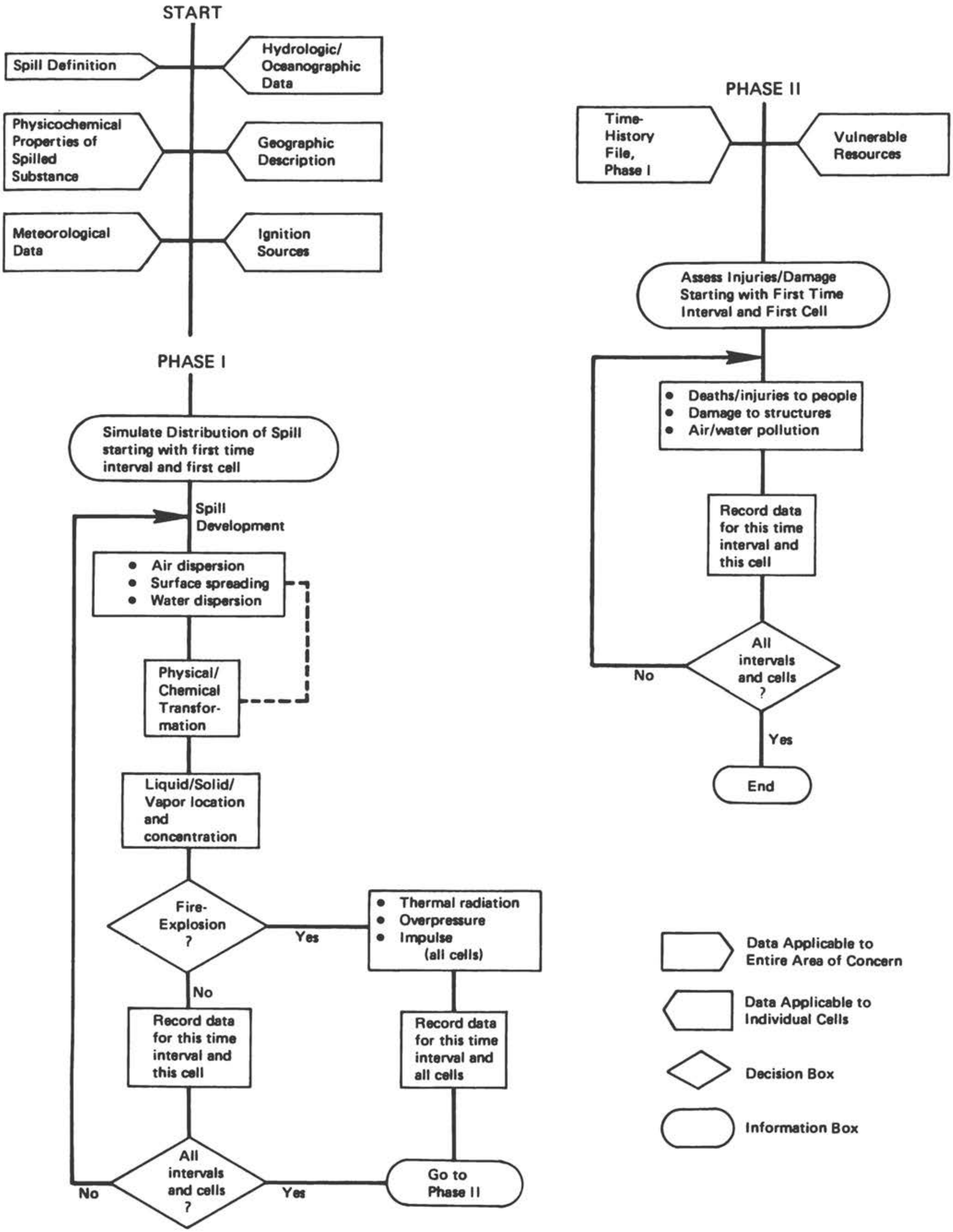


FIGURE 1 Generalized flow diagram of the vulnerability model

Each cell is identified by the coordinates of some contained point measured from some reference origin, its surface type (land or water), and its land use. Cells are chosen to maintain homogeneity and to facilitate data collection efforts.

1.3.2 Degree of simplification or assumptions

1.3.3 Technique categories internal to methodology

An executive routine executes the appropriate series of submodels for the particular substance and the environmental conditions. These submodels, many of which have been developed for the Coast Guard's Chemical Hazard Response Information System (CHRIS), describe the physical phenomena resulting from the spill; surface spreading, boiling and evaporation, pool burning and thermal radiation generation, vapor plume formation, etc. The dispersion of the hazardous commodity as observed from the identifying point of each cell is calculated and recorded for a series of user specified time steps until the hazards have been reduced to negligible levels or a time limit has been reached.

When simulating spills of flammable materials, the user may specify the location of ignition sources in any cells. If the hazardous commodity reaches an ignition source in a flammable concentration and the ignition source is capable of igniting that commodity as specified by the NFPA classification scheme then combustion occurs. The user may also specify that the igntion source will cause an explosion. Whenever conflagration or detonation occurs the amount of the substance consumed is calculated. Based on this the effects of combustion (thermal radiation, flame temperature and duration, peak overpressures, etc.) are determined and recorded for each cell effected. In the second phase of the Vulnerability Model the record of spill effects are superimposed on a map of the vulnerable resources in the area. The cells are now described by the quantity and type of resources they contain. For each cell and each time step the deaths, injuries and damage is calculated for each damage mechanism (toxic concentration, dosage, thermal radiation, overpressure, etc.). These damage estimating models have been developed especially for the Vulnerability Model. Those for toxicity effects consist of probit analyses which relate concentration or dosage to the percent of the population killed, injured or irritated. The population may be divided into subgroups (age bracket, indoor/outdoor) according to differences in their susceptability to the damage mechanism.

Other damage submodels estimate the response of the resources based on engineering analysis. An example is the burning vapor cloud model where the temperature and duration of the flame fron is used to estimate the ignition of structures.

2. Inputs to model

2.1 Generic description of data used

Phase one begins with a description of the spill, defining its location, size, spill rate and type of commodity. Location and commodity type are input information by the user. Size and rate may be included as input or calculated by the model when tank volume and the hole diameter are specified. A file containing the physical and chemical properties of the substance is read and a description of the meteorological and hydrologic conditions are input.

3. Outputs produced with model

3.1 Generic description

These damage submodels produce the final output of the Vulnerability Model, the number of deaths, injuries, dollar amount of structural damage, and degree of pollution caused by the spill. Each type of loss is identified by the cell and time step in which it occurs and the damage mechanism responsible. The estimates of damage produced will be tested against records of past spill experiences.

4. Applicability of model to Coast Guard needs

In applying the model to different areas a good deal of data collection must be performed, but the data are available from accessible sources (census, weather statistics, tax rolls, etc.). Most properties of the chemicals spilled have already been collected for the CHRIS system, but for some substances the toxicity data may be difficult to gather and interpret.

Since the Vulnerability Model provides information concerning the consequences of a spill, its output can be used in evaluating the benefit of any proposed Coast Guard regulation aimed at preventing spills or accidents to ships that may result in spills.

(c) Cargo Spill Probability Analysis for the Deep Water Port Project - Final Report

Reviewed by
Richard A. Goldman, USCG Reserve, DOT

1. Description of Model

1.1 Study identification

1.1.1 Title

Cargo Spill Probability Analysis for the Deep Water Port Project - Final Report

1.1.2 Contractor

Woodward-Lundgren and Associates, Oakland, CA

1.1.3 Reference number

Contract number DACW 61-73-C-0349, Corps of Engineers, Philadelphia, PA

1.1.4 Date

February 1973

1.1.5 Authors

Keshavan Nair, Haresh C. Shah, Wayne S. Smith and Dinesh S. Shah

1.1.6 Sponsor

Corps of Engineers, Philadelphia, PA

1.2 Synopsis

1.2.1 Objectives

The primary objective of this study was to identify the causative factors in spills and to subjectively order conditional probabilities relating these factors, i.e., size of spill (none, very small, small, medium, large, very large), primary cause of spill (human error, mechanical failure, inadequacies, all others), and locations of spills (aboard ship at open sea, aboard ship in coastal waters, aboard ship entering or exiting port, at dock during loading and unloading operations, at inshore facilities and refineries). A secondary objective was to develop estimates of the above conditional probabilities.

Another objective of this report is the pedagogical objective of illustrating the technique for developing a Bayesian analysis of a complex probabilistic process.

1.2.2 Intended use

The model is primarily used to identify causative factors in oil spills, e.g., primary causes (simple carelessness, poor supervision, poor communication, ignorance, fatigue, language, hose failures, connection failures, valve failures, steering gear failures, navigational equipment failures, hull failures, inadequate equipment, inadequate design, inadequate training of personnel, inadequate number of personnel, acts of God, size of ship, number of ships, transfer operations, etc.), spill locations (aboard ship at open sea, aboard ship in coastal areas, aboard ship entering or exiting port, at dock during loading and unloading operation, at inshore facilities and refineries), and size categories of spills (no spill, very small spill, small spill, medium spill, large spill, very large spill).

The model may then be used to examine the sensitivity of overall spill probabilities to changes in individual conditional probabilities resulting from changed conditions. The changed conditions are: (1) maintain present conditions constant; (2) construct a supertanker facility within a port or bay; and (3) construct a deep water supertanker facility.

1.2.3 Actual user

Coast Guard Office of Research and Development, the Coast Guard Risk Analysis Advisory Board.

1.2.4 Actual application

1.2.5 User's evaluation

1.2.6 Originator's suggested improvement

Study the consequences of a spill, by Bayesian Analysis, in terms of economic consequences, ecological consequences, and physical consequences.

Study, by Bayesian Analysis, corrective actions and their likely effect.

1.3 Description

1.3.1 General approach

The general approach of this model is to use Bayesian analysis to develop a probabilistic model of oil spills. Bayesian analysis is used to identify the causative factors in spills and subjectively order conditional probabilities relating to the size of the spill, the primary cause of the spill, and the location of the spill.

A ten-question written questionnaire was prepared and sent to forty-five knowledgeable individuals (see Section 2 - Inputs to Model). The purpose of the preliminary questionnaire was to identify possible factors which could cause or influence cargo spills.

The responses to the first questionnaire subjectively identified relationships between causative factors, spill sizes, and spill locations.

A second questionnaire was then designed to obtain expert opinions of the occurrence of specific sizes of cargo spills, basic causes of the spills, and probable locations of the spills.

The responses to the second questionnaire were used to calculate the estimated values of the probability functions.

1.3.2 Degree of simplification; assumptions

The simplifications and assumptions are those inherent in a Bayesian analysis. An additional simplification is the "single cause" theory of accidents inherent in the analysis.

1.3.3 Techniques internal to methodology

Standard operational use of probability functions.

2. Inputs to model

2.1 Generic description of data used

The first (written) questionnaire was a two-part questionnaire. In the first part, forty-one causative factors were listed in nine broad classes. These were to be rated in order of importance. The second part of the questionnaire consisted of eight questions. These questions asked for opinions on the inevitability of spills, the use of historical data to predict spill probabilities, the effect of changes in vessel operation and design on spills, the effect of supertankers on the number of spills, an opinion as to these factors in part one that are susceptible of reduction, present operating procedures, and present design procedures.

The second questionnaire asked for estimates of various conditional probabilities, e.g., size given a spill occurred, cause given a spill of specified size has occurred, location given that a spill occurred from a specified case, location of spill given that a spill of a specified size having a specified cause occurred, effect of increasing ship size on number of spills, the causes of this increase or decrease in the number of spills, and the sizes of spills from larger ships.

2.2 Sources of data

The sources of data were knowledgeable individuals in government, regulatory agencies, and industry.

2.3 Examples of numerical values

For the first questionnaire, the causative factors leading to oil spills were ranked as follows: a) collisions, b) groundings, c) rammings, d) structural failures, e) breakdowns, f) fire, g) explosions.

In the second questionnaire, extensive conditional probabilities relating cause, size, and location are reported.

3. Outputs produced with model

3.1 Generic description

The outputs are conditional probabilities relating spill causes, spill sizes, and spill locations.

3.2 Examples of numbers

The conditional probabilities are reported in twelve tables.

3.3 Definitions of units

3.4 Test of model against historical experience

The ordering of spill causes is compared to tanker casualties (1969-1970 data) and polluting incidents from tanker casualties (1969-1970 data).

Factor	Subjective Ranking	Actual Casualties	Actual Polluting Incidents
Collisions	1	2	1
Groundings	2	1	2
Rammings	3	3	4
Structural failures	4	4	3
Breakdowns	5	5	7
Fire	6	6	5
Explosions	7	7	6
Other	---	8	8

3.5 Identification of new control areas

The research suggested that traffic control, special supertanker facilities within the harbor, and special offshore supertanker facilities offer possibilities for reduction of spill probabilities.

4. Applicability of model to Coast Guard needs

4.1 Coast Guard regulatory function involved

This study is applicable to the following functions of the Coast Guard:

a) Standards and exceptions for vessel designs and equipment.

b) Maritime accident investigation and record keeping.

c) Requirements for shipboard stowage and containment of hazardous materials.

d) Requirements for handling dangerous cargoes within or contiguous to waterfront facilities.

e) Promulgation of nautical rules of the road.

f) Control of oil and hazardous substances pollution.

g) Movement of hazardous substances in ports.

4.2 Sample of question or decisions within the function for which the model could provide data

The following hypothetical questions might be addressed by the methods developed in this study:

a) What is the collision reduction potential and the spill reduction potential resulting therefrom of a specified change in vessel operations, e.g., speed limitations, bridge to bridge radio, traffic control?

b) What is the spill reduction potential of changes in vessel design, e.g., greater separation between cargo tanks and hull?

4.3 Modification to model/method to permit each application

The principal modification to the model is in the structure of the questions. A second modification to the model would be to use the Bayesian technique to construct a fault tree.

4.3.1 Information bearing on that question or decision available from model

4.3.2 Additional input data required for each application

Further questions in the questionnaire.

(d) Spill Risk Analysis Program - Phase II Methodology Development and Demonstration

Reviewed by
William A. Dunn, Operations Research, Inc.

1. Description of model

1.1 Study identification

1.1.1 Title

Spill Risk Analysis Program - Phase II; Methodology Development and Demonstration

1.1.2 Contractor

Operations Research, Inc., Silver Spring, MD

1.1.3 Reference number

An NTIS accession number will be available soon
ORI Technical Report 840, Final Draft; Contract No. DOT-CG-31571-A

1.1.4 Date

3 June 1974

1.1.5 Authors

William A. Dunn and Pierre M. Tullier

1.1.6 Sponsor

US Coast Guard Headquarters, Department of Transportation, Washington, DC

1.2 Synopsis

1.2.1 Objectives

There were two study objectives:

a) To develop a methodology for evaluating alternative Coast Guard actions designed to reduce the number of casualties and spills of hazardous or polluting materials.

b) To demonstrate the applicability of the method by evaluating the effectiveness of specific Coast Guard action.

1.2.2 Intended use

The purpose of the analytical model is to analyze specific Coast Guard actions which would influence the physical parameters of the marine transportation system. Examples of such actions are the limitation of speeds and the increase of traffic separation in ports or channels.

The purpose of the logical model is to examine the probable effects of regulatory and enforcement actions which cannot be credibly modeled analytically. It is also intended to provide the regulatory decision-maker with a means of assessing the effectiveness of his actions after implementation.

The study also proposes a program of research in human engineering which may aid the Coast Guard in determining personnel qualifications, licensing, and man-equipment interfaces.

1.2.3 Actual user

The actual user of the ORI models are the Coast Guard Office of Research and Development and the Coast Guard Risk Analysis Advisory Board.

1.2.4 Actual application

Studies are underway by ORI on the analytical model to incorporate new parameters such as acceleration, turning, and the specification of time constraints on human decision and action responses relating to collision situations.

The quasi-experimental methods of the logical model are being used to analyze all of the scenarios which lead to spill potential collisions.

The human engineering results are being used by the Coast Guard to implement research on task analysis and training curriculum development.

1.2.5 User's evaluation

These models and submodels have demonstrated the applicability of the methodology for Coast Guard regulatory decision-making. The analytical model has afforded a method for conducting sensitivity analysis of possible Coast Guard regulatory actions. The logical model has proven to be a very general method for measuring the potential reduction in spills by a regulatory action.

1.2.5.1 Special requirements

For the analytical model, it is necessary to understand the kinematics of ship motion, the concepts of conditional probability, and the engineering concept of hull structure and failure.

For the logical model, it is necessary to understand a Safety Analysis Logic Tree (SALT) and to be able to utilize a Casualty Analysis Gauge in analyzing collision reports.

For the human engineering research, it is necessary to understand the tasks involved in operations on the bridge of a ship as well as the man-machine interfaces which produce responses to emergency situations.

1.2.5.2 Ease of use

The results of this study are not yet ready for general use. Inasmuch as the accomplished objectives were to develop a methodology and demonstrate its applicability, more work must be done before it will be suitable for general use. The computer program used in the sensitivity analysis must be expanded and written for general use by the Coast Guard.

1.2.5.3 Number of persons using it

1.2.5.4 Suggested improvements

The study effort has been extended by the Coast Guard to generalize and extend the analytical modeling and to exercise the logical model.

1.2.6 Originator's suggested improvements

ORI has suggested a number of improvements, among which are the development of a full range of collision scenarios, a generalized model of a waterway and a complete analysis of rammings and groundings.

1.3 Description

1.3.1 General approach

The ORI study describes research and results in the development and demonstration of formal measures of effectiveness for merchant marine safety regulation and enforcement. The model developed utilizes both analytic and logical techniques. The model has primarily been demonstrated for vessel collisions. The analytical model contains three submodels: the scenario (maneuvering) submodel, the energy exchange submodel and the hull rupture submodel.

The general approach of this study was to model the essential features of the collision-spill problem wherever possible. It was aimed at developing a methodology for evaluating alternative Coast Guard actions and demonstrating its applicability. This approach was successful in modeling both the physical parameters of the collision-spill process such as vessel speeds and hull rupture resistance, and changes in operating procedures such as the effects of providing better information to the pilot or master of a ship. A communication system improvement was evaluated using this method.

1.3.2 Degree of simplification: assumptions

The degree of simplification is variable and may be selected by the user depending on the particular questions under study.

1.3.3 Techniques internal to methodology

Among the techniques used in developing the methodology were the construction of Safety Analysis Logic Trees, engineering analysis of hull plate rupture, maneuvering scenario analysis, human engineering analysis, construction and use of Casualty Analysis Gauges and a new sampling technique which permits an estimate of the casualty reduction potential of a possible change in the marine transportation system.

1.3.4 Process description

The running of the analytical model and the conduct of the sensitivity analysis was done on a time-sharing computer, but the program is not yet ready for general use.

Use of the logical model involves the structuring of an appropriate Casualty Analysis Gauge and its application in the detailed reading of the Coast Guard's casualty reports.

1.3.5 Calculation methods

In the analytical model, computer calculations were utilized. In the logical model, a method of structured judgment was used.

1.3.6 Computer/program availability

The computer program for the analytical model is not yet ready for general use but the current contract effort will complete this development.

2. Inputs to model

2.1 Generic description of data used

The analytical model utilizes such input data as: vessel speeds, vessel lengths, vessel track separation, deceleration capability, deadweight, radius of ship's turn, the impact angle, speeds and relative position of the strike, hull plate thickness, web frame spacing, hull materials properties, stem angle of striking ship, relative strike point between web frames, and average stress limits of the hull plate in membrane strain.

In the logical model the inputs are the historical casualty records for all vessels which could have resulted in a significant spill.

2.2 Sources of data

In the analytical model, sources of data are engineering handbooks and ship characteristics.

In the logical model, sources of data are the Coast Guard's vessel casualty reports.

2.3 Examples of numerical values

Examples of numerical values used in the study are:

a) Length of ship - 600 feet
b) Speed of ship - 8 knots
c) Maximum deceleration capability - 0.05 ft/sec^2

d) Minimum turning radius - 2,000 feet
e) Deadweight - 35,000 tons
f) Strain energy absorption capability - 10^8 ft/lbs
g) Track separation - 400 feet

2.4 Definitions of units

Units are given in the US foot-pound-second standards as illustrated in above examples.

3. Outputs produced with model

3.1 Generic description

Outputs are relative changes in the expected number of spills resulting from a hypothetical Coast Guard action. Other outputs are the sensitivity of this measure of effectiveness to the various system parameters.

3.2 Examples of numbers

Numerical results are expressed in expected percent reduction of collisions or spills resulting from the action or set of actions under study.

3.3 Definitions of units

3.4 Test of model against historical experience

There are no tests or validations of the model against historical experience.

3.5 Identification of new control areas

The research suggested that a special deceleration capability for particularly hazardous cargo carriers might be an alternative to the rigid control (elimination) of other vessel traffic.

4. Applicability of model to Coast Guard needs

4.1 Coast Guard regulatory functions involved

This study is applicable to the following functions of the Coast Guard:

a) Vessel traffic systems
b) Licensing and documentation of merchant marine officers and seamen
c) Safety equipment requirements and the use of such equipment (B2BRT, radar, etc.)
d) Standards and exceptions for vessel designs and equipment
e) Maritime accident investigation and record-keeping
f) Promulgation of nautical rules of the road
g) Installation and maintenance of aids to navigation including buoys, lights, and electronic navigation systems
h) Movement of hazardous cargoes in ports
i) Development of Captain of the Port guidelines

4.2 Sample of questions or decisions within the functions for which the model could provide data

The following hypothetical questions might be addressed by the methods developed in this study:

a) What is the collision or spill reduction potential of imposing speed limitations in selected channels for certain types or classes of vessels?

b) What is the collision or spill reduction potential of improving communications between the bridges of a specified class of vessel under certain conditions?

c) How effective could increased hull rupture resistance be in reducing spills?

4.3 Modification to model/method required to permit each application

Since the study was specifically conducted for the Coast Guard, there were no special modifications required prior to its use by Coast Guard regulatory decision-makers.

(e) Risk Analysis of the Oil Transportation System: A Report to the 43rd Legislature, State of Washington by Oceanographic Institute of Washington

Reviewed by
Richard A. Goldman, USCG Reserve, DOT

1. Description of model

1.1 Study identification

1.1.1 Title

Risk Analysis of the Oil Transportation System: A Report to the 43rd Legislature, State of Washington, by the Oceanographic Institute of Washington.

1.1.2 Contractor

Oceanographic Institute of Washington

1.1.3 NTIS or other reference number

1.1.4 Date

8 September 1972

1.1.5 Authors

Griffith C. Evans, Jr., Robert B. Gardner, Calvin T. Cunningham, Clayton T. McDok, Joseph T. Pizzo, Jack T. Show, John L. Umlauf, Carlos H. Vargas

1.1.6 Sponsors

Oceanographic Commission of Washington

1.2 Synopsis

1.2.1 Objective

The objective of this study is to bring together in one volume the information needed to define the problems arising from the transportation of petroleum into and through the State of Washington. The study further seeks to provide the reader with the basic background information needed to understand the terminology and technology of the various modes of petroleum transportation, the various scenarios of ecological and economic trauma resulting from petroleum transportation accidents, and the methods of spill clean up.

Of particular interest is a comparison of the various studies of the amounts of petroleum spilled, the movement and dispersion of spilled petroleum in the environment, and the effect of this petroleum on the eco-system.

1.2.2 Intended use

The intended use of the study was to provide working material for the Washington State Legislature in dealing with the development of petroleum transportation in the State of Washington. The study assumes that Puget Sound will be the primary point of entry of Alaskan oil into the continental United States and seeks to provide a comprehensive but understandable background document for members of the Washington State Legislature.

1.3 Description

1.3.1 General approach

This is a comprehensive study of the risks arising in oil transportation with special emphasis on the risks arising in a state serving as a major port of entry for crude oil. The study describes the various modes of oil and petroleum product transportation, the interfaces between these modes, the state of the art of the modes, and the nature and likelihood of accidents from each mode and intermodal interface. Risks are evaluated for each accident type. Various models are described and used including statistical inference, fault tree analysis, mechanistic models, and empirical studies.

The general approach of this study is to compare and contract various models and analyses of specific problems, describing the effects of oil spills on the eco-system. Studies of analyses of bottoms samples are described, various estimates of spills (quantity) versus total oil carried are compared, mathematical and empirical studies of oil dispersion and weathering are described and compared with the "best" and "worst" cases illustrated, and qualitative models of acute and chronic toxicity are described.

The study describes, illustrates, and analyzes such impact studies as the Evans analysis of estuary bottom samples; such spillage quantity studies and models as the Milford Haven Study, Blumer's Model, Dedera's report, and Coast Guard's "Marine Transportation System of the Alaska Pipeline System," and Benyon's report; such pollutant dispersion models and studies as Muench's dye diffusion study, Vagner's computer model of oil spread, the Blokher equation, the White-Hess model of Narragansett Bay, the various computer model and scale model studies of Puget Sound, the Schwartzberg oil spread models, and the Fay equation. These models are compared and the comparisons and criticisms in the literature are noted.

1.3.2 Degree of simplification or assumptions

The study attempts to evaluate theoretical models using experimental studies and empirical data. Thus, dye diffusivity models in an actual body of water are compared with results obtained in a hydraulic scale model of the same body of water, and a computer model of the body of water. Similarly, mechanistic models giving different weight to different forces (wind, current, surface tension, etc.) are described and comparisons are possible.

1.3.3 Techniques internal to the methodology

The techniques used in each model are briefly described. A full bibliography is provided so that particular models and methodologies may be investigated. The techniques are referred to generically, e.g., mechanistic simulation, stochastic simulation, empirical data from real systems, data from controlled experiments, etc.

1.3.4 Process description

This study is an integrated compendium of various studies. The processes involved range from stochastic models of estuaries to measurements of estuarian flora and fauna one or more years after a spill.

1.3.5 Calculation methods

The calculation methods range from simple multiplication of probabilities to complex stochastic models of estuaries.

1.3.6 Computer/calculator program availability

Computer program availability varies from model to model. Some of the University of Washington models are indicated as having listings available.

2. Inputs to model

2.1 Generic description of data used

Inputs used in the ecological models include vessel miles, ton-miles, number of spills, amounts spilled, (oil chemistry) nature of cargoes and pollutants, bottom samples, water chemistry, marine biochemistry (population levels, tissue analyses), weather, and currents.

2.2 Sources of data

The sources of data are the various studies and models described in the text.

3. Outputs produced with model

3.1 Generic description

The output of the risk study is a general, detailed, critical survey of the literature of risk analysis of the oil transportation system. The numerical values in the study represent "minimums," "maximums," and "best estimates" of risk and hazard as drawn from the literature surveyed.

3.2 Examples of numbers

3.3 Definitions of units

3.4 Was model tested against historical experience

Surveyed literature was compared with historical experience, whenever available, e.g., the White-Hess model of Narragansett Bay.

3.5 Did analysis process identify new control areas

This study does not identify new controls as such. It draws upon studies that analyzed specific areas such as licensing and documentation of merchant marine officers and seamen, vessel designs, vessel condition, maritime accident investigation and analysis, shipboard containment of petroleum, cargo transfer, including waterfront facilities and pipelines, and collision prevention, including rules of the road, aids to navigation, traffic control.

4. Adaptability of model to Coast Guard needs

4.1 Coast Guard regulatory functions involved

The literature surveyed in this study touches upon all of the Coast Guard regulatory functions including licensing and documentation of merchant marine officers and seamen, vessel design, vessel inspection, accident investigation and statistical analysis, containment of petroleum, regulation of transfer operations, collision avoidance (including rules of the road, aids to navigation, bridge-to-bridge radio, radar), clean up procedures, and pipeline regulations.

4.2 Sample questions or decisions within the functions for which model could provide data

This study is intended for use by a legislative body and provides background information for most legislative policy questions involving marine transportation of petroleum.

4.3 Modifications to model/method required for each application

In many instances it will be necessary to go to the original literature in order to obtain the detailed information needed for regulatory action.

4.3.1 Information bearing on that decision or question available from the model

The nature and summary of the information is contained in the study. Particular information is available from the referenced literature.

(f) An Example Risk Calculation

Reviewed by

Richard A. Goldman, USCG Reserve, DOT

1. Description of model

1.1 Study identification

1.1.1 Title

An Example Risk Calculation

1.1.2 Contractor

Ecology and Environment, Inc., Buffalo, NY

1.1.3 Reference number

1.1.4 Date

1973

1.1.5 Authors

L. L. Depowski, F. B. Silvestro, and A. Sowyrda

1.1.6 Sponsor

This study is a synthesis of several different studies done independently for several different energy companies.

1.2 Synopsis

1.2.1 Objective

There are two objectives to this study:

a) To develop numerical estimates of populations exposed to risk under one set of assumptions and compare these estimates with estimates developed under differing sets of assumptions, thereby demonstrating the validity of these assumptions.

b) To develop numerical estimates of populations exposed to risk under one set of conditions and compare these estimates with estimates for different conditions, thereby demonstrating the efficacy of the changed conditions.

1.2.2 Intended use

The analytical model is primarily used to analyze the effects of specific actions including Coast Guard regulatory actions on the risks associated with liquefied natural gas (LNG) transport. These actions influence traffic patterns in channels and harbors, and vessel characteristics, and include collision avoidance radar, bridge to bridge radio, bow thrusters, double bottoms, cofferdams, traffic control, and limitation of cargo transfer to designated areas.

1.2.3 Actual user

The actual users of the model were a number of independent energy transportation companies.

1.2.4 Actual application

The methods of the model are used to obtain estimates of the populations exposed to risk by LNG shipments and the sensitivities of these estimates to corrective actions.

1.2.5 User's evaluation

The model affords a method for estimating the sensitivity of risk to precautionary and regulatory actions and estimating the potential reduction in LNG spills from such actions.

1.2.5.1 Special requirements

In order to use the model it is helpful to have historical data showing incidents by location.

1.2.5.2 Ease of use

The principle judgment decision made in using this model is determining the effect of a given regulatory action on the probability of a spill occurring and the nature of the spill. Once this judgment is made, the model is easy to use.

1.2.5.3 Number of persons in organization who use it

1.2.5.4 Suggested improvement

1.2.6 Originator's suggested improvement

Originators would use a broader data base

1.3 Description

1.3.1 General approach

This study describes the use of historical oil spill data to generate predictions of LNG spill probabilities. The spill probabilities are combined with mechanistic models, e.g., plume dispersion models, to predict risk zones and calculate populations at risk within the risk zones. The model uses analytical techniques to analyze related historical oil spill data. One submodel is used, the plume dispersion model.

The general approach of this study is to use historical oil spill data (location, type of accident, type of failure), marine accident data for the body of water under study (collisions, groundings, etc.), and LNG shipment data to estimate probabilities and severities of LNG spills. Vapor plume models and annual wind roses are used to estimate areas at risk. The estimates of the areas at risk are used with population density data to calculate populations at risk.

1.3.2 Degree of simplification: assumptions

The degree of simplification depends on the quantity of data available; however, cargo size is assumed constant and release mechanisms, casual categories and meteorological parameters are assumed to follow historical experience.

1.3.3 Techniques internal to methodology

Among the techniques used were calculations of probabilities from statistical data and simple arithmetical operations. Gaussian plume dispersion was used to calculate the gas plume.

1.3.4 Process description

The model involves simple arithmetical calculations

1.3.5 Calculation methods

In the model hand calculators are used.

1.3.6 Computer/calculator program availability

2. Inputs to model

2.1 Generic description of data used

The model utilizes historical data on: accidents on the body of water in question, types of tanker casualties, spills resulting from types of casualties, and locations of spills; also estimates and data on port calls, LNG discharge rate, annual wind roses, and population density.

2.2 Sources of data

Open literature accident data is used.

2.3 Examples of numerical values

Examples of numerical values used in the study are:

6,100 tankers: 14 port calls per tanker per year; 170,800 port calls in two year period studied

1,416 tanker casualties in the two-year period studied: 366 groundings (25.9%); 338 collisions (23.9%); 222 rammings (15.7%); 216 structural failures (15.3%); 144 breakdowns (10.2%); 95 fires (6.7%); 32 explosions (2.2%); 3 other (0.2%)

269 tanker casualties that led to spills: 81 collisions (30.5%); 70 groundings (26.0%); 51 structural failures (18.6%); 24 rammings (8.9%); 20 fires (7.4%); 16 explosions (5.9%); 4 breakdowns (1.5%); 3 other (1.2%); 62 coastal (23%); 57 at harbor entrances (21%); 51 at sea (19%); 45 in harbors (17%); 43 at piers (16%); 11 unknown (4%)

124 involved loss or heavy damage to ship

50% in cargo

62 LNG spills estimated for the two-year period

0.00029 spill/ship/port visit

300 tanker visits per year to estuary

0.087 spills per year for estuary

1,550 Bbl/min spill rate

0.5% gas concentration: 4.92 ratio of horizontal to vertical standard deviations; 9,300 foot downwind

1,000-5,000 people/square mile

470 people within 1/2% vapor plume

41 persons per year exposed to 1/2% concentration of methane in estuary

1/5 of accidents in estuary near point in question

8 persons per year near point in question exposed to more than 1/2% methane

2.4 Definitions of units

As illustrated above.

3. Outputs produced with model

3.1 Generic description

Outputs are numbers of persons exposed to risk of LNG spills and changes in numbers of persons exposed to risk.

3.2 Examples of numbers

Numerical results are expressed in spills per year and population within the gas plume generated by the spill.

3.3 Definitions of units

3.4 Was model tested against historical experience

There are no tests against historical experience of LNG spills. The model is an extrapolation of historical experience of oil spills.

3.5 Did analysis process identify new control areas

The model suggested traffic control, double bottoms, and cofferdams.

4. Adaptability of model to Coast Guard needs

4.1 Coast Guard regulatory functions involved

This study is applicable to the following functions of the Coast Guard:

a) Vessel traffic systems
b) Standards and exceptions for vessel designs
c) Maritime accident investigation and record keeping
d) Promulgation of nautical rules of the road
e) Movement of hazardous cargoes in port
f) Development of Captain of the Port guidelines

4.2 Sample questions or decisions with the functions for which model could provide data

The following hypothetical question might be addressed by the methods developed in this study:

Given the collision, grounding, or ramming potential of an action, what then is the LNG spill reduction potential of that action?

4.3 Modifications to model/method to permit each application

No special modifications are required to permit its use by the Coast Guard.

(g) The Risk of Catastrophic Spills of Toxic Chemicals

Reviewed by
John A. Simmons, Science Applications, Inc.

1. Description of model

1.1 Study identification

1.1.1 Title
The Risk of Catastrophic Spills of Toxic Chemicals

1.1.2 Contractors
SAI Services (Science Applications, Inc), McLean, VA

1.1.3 Reference number

1.1.4 Date
December 14, 1973

1.1.5 Authors
John A. Simmons, Robert C. Erdmann, and Barry N. Naft

1.1.6 Sponsor
University of California, Los Angeles

1.2 Synopsis

1.2.1 Objective

The model is used to evaluate the risk of accidental spills of volatile, toxic chemicals. Risk is expressed as accident frequency versus consequence (expected mortalities) or the average annual number of expected mortalities. The effects of organized evacuation of people downwind of the spill may be included.

1.2.2 Intended use
Same as 1.2.1

1.2.3 Actual user
The model has been used by SAI

1.2.4 Actual application

To calculate the risk of the rail transport of liquid chlorine to people, nationwide. The purpose of this calculation was to compare the risk of this activity with the risk of other activities, especially the operation of nuclear power plants.

1.2.5 User's evaluation

1.2.5.1 Special equipment

The calculations may be performed on a desk calculator, the most difficult part being the estimation of the area covered by a lethal dose utilizing the Gaussian plume formula.

1.2.5.2 Ease of use

The model is easy to use and suggested improvements are of the nature to increase the applicability of the model (see suggested modifications for Coast Guard use).

1.3 Model Description

1.3.1 General approach

The model utilizes spill frequency data, meteorological data, demographic data and toxicological data to estimate mortalities and frequency of occurrence, representative of an entire transportation activity of a volatile, toxic chemical. The consequence, N mortalities, is defined as :

$$N = \rho A \text{ (mortalities)},$$

where ρ is the population density near the accidental spill and A the area covered by a lethal dose (ppm-min from toxicological data). Frequency, F(N) of an accident with consequence N is defined as

$$F(N) = f_A \cdot f_\rho \cdot f_s$$

where f_A is the frequency of the lethal area (km^2) (dependent primarily on meteorological conditions covering plume dispersion) f_ρ the frequency of occurrence of the population density (persons/km^2), and f_s is the frequency of a large spill (year^{-1}). Risk, R, is defined as:

$$R = \int^{N_{max}} Nf(N)dN,$$

where N_{max} is the accident involving the largest consequence, corresponding to the maximum population density, inversion conditions and a low wind speed, By this definition risk becomes average mortalities per year. Alternatively, useful presentations are a histogram of:

$\int_N^{N+\langle N} F\ (N)\ dN$ versus N and $\int_N^{N_{max}} F(N)dN$ (the frequency of accidents with consequences greater than N) versus N. This latter presentation is particularly useful for comparing risks of a variety of activities.

1.3.2 Degree of simplification or assumptions

For estimation of area, the Gausian plume description is assumed to be valid. The plume standard deviations are those for the Pasquill stability categories modified to account for the buoyancy of the vapor. The source factor, Q, is assumed to be given by either of two limiting forms: an instantaneous puff or a steady plume. The former is generally the more significant in spills of volatile liquids, and the magnitude is estimated by assuming adiabatic vaporization. Lethal dosage, $\int \chi dt$, is estimated from data in the literature. The term f_A is derived from US Weather Bureau summaries of the joint frequencies of wind speed and Pasquill stability category. The terms ρ and f_ρ are obtained from demographic data for areas surrounding the transportation routes of interest. Often such data are not available, and the population density distribution of a region for which such data are available is assumed.

In this model f_s is obtained from historical data which must be interpreted with care since the data base may be limited statistically.

Computationally, the model requires only a desk calculator or a slide rule.

2. Inputs

2.1 Generic description of data

2.2 Sources of data

LD_{50} value is used for lethal dose, which for chlorine vapor was estimated to be 1000 ppm-min at concentrations 35 ppm.

The source term is kilograms of vapor released from the rupture of the container. In the case of liquid chlorine, a rail tank car carries 90 tons, and if all of this is spilled in a wreck, 17.5% flashes adiabatically, assuming a representative initial liquid temperature of 70°F (calculated from known physical properties).

Values of σ_y and σ_z are given by D. B. Turner for the Pasquill stability categories used. In the case of chlorine, the vapor plume is negatively buoyant, and based on experimental studies, $\sigma_z = 0.2\ \sigma_y$ was assumed.

Tables of the joint frequencies of wind speed and stability category are required for the transportation route. For the chlorine study this was approximated by averaging such data for thirteen locations in the eastern US (obtainable from the National Climatic Center).

Population density distribution near railroads in tabular form is required: fraction of transportation route versus an incremental range of population density. In application to liquid chlorine transport, this was not found for eastern US railroads and instead the population density distribution (by percent of area) for Ohio (US Census Bureau) was assumed.

Frequency of accidents (year^{-1}) leading to the release of all or some given fraction of the toxic cargo is obtained from historical data or an analysis of the accident chains. For the chlorine study, only accidents involving the loss of the entire contents of a rail tank car were considered. An accident frequency of 10^{-1} year^{-1} was selected based in part on accident data for chlorine tank cars in particular and all accidents for similar tank cars.

3. Outputs

3.1 Generic description

Expected average annual mortalities and the frequency of accidents causing a given number of mortalities are estimated. For the chlorine rail tank car study these results are shown in the graph (p. 85). By actual experience over 50 years, only one person has died as the result of a rail tank car accident. This is very much less than the average annual expectation of 13 deaths. The reason for the difference is that the model does not include mitigating action such as evacuation, which in the case of chlorine accidents has been prompt and effective.

4. Adaptability to Coast Guard needs

4.1 Coast Guard regulatory functions involved

In its present form and perhaps with minor modifications, the model is directly applicable for determining the overall adequacy of existing standards and rules for exceptions for water transport of volatile liquids. In this

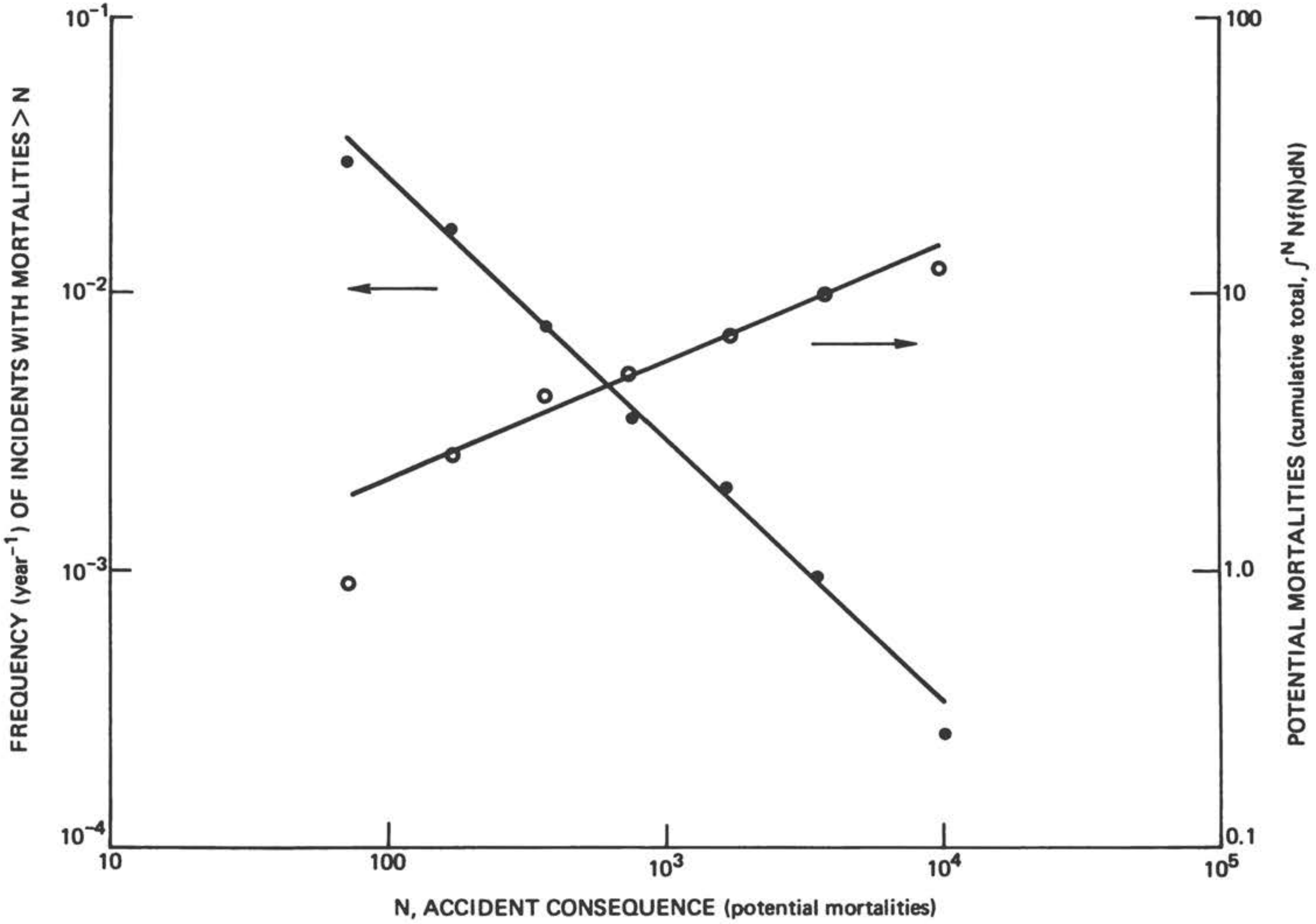


FIGURE 1 Risk of chlorine rail tank car spills

application, the level of risk given by the model would serve as the index of "adequacy". For this application data on lethal dosages and flammability limits would be required, and data on spill frequency (for whatever cause) of specific liquid cargoes are required. Thus, the model requires as input the product of P_M, P_I and P_R and computes risk = $P_E \cdot (P_M \cdot P_I \cdot P_R)$. The model does not identify the reasons for adequacy or inadequacy of existing regulations to meet an acceptable level of risk. The model does provide a means to compare the risk of transport of different liquids and by different modes.

With the additional calculations of risk versus selected separation distances, the model may be used to establish water and waterfront safety zones.

(h) Chemical Hazard Response Information System (CHRIS)

Reviewed by
Michael Parnarouskis, USCG

1. Description of Model

1.1 Identification
1.1.1 Title
Chemical Hazard Response Information System (CHRIS)
1.1.2 Contractor
Arthur D. Little, Inc., Cambridge, MA
1.1.3 Identification number
1.1.4 Date
1.1.5 Authors
A. Kalelkar, E. Atkinson, J. Hagopian
1.1.6 Sponsor
US Coast Guard

1.2 Synopsis
1.2.1 Objective or purpose

The Chemical Hazard Response Information System (CHRIS) is designed to provide information needed for decision-making by responsible Coast Guard personnel during emergencies that occur during the water transport of hazardous chemical compounds. Information supplied through CHRIS can also be used by the Coast Guard in its efforts to achieve better safety procedures and so prevent accidents.

CHRIS consists of four handbooks or manuals, a regional contingency plan, a hazard assessment computer system (HACS) and a supervising organization at Coast Guard Headquarters.

1.3 Description
1.3.1 General approach

Manual 1, "A Condensed Guide to Chemical Hazards", contains all the information needed to help personnel make the proper response in an emergency situation. It is the only manual that will be carried to the actual scene of the accident and is intended for use by port security personnel. It will be used to determine immediate responses that will safeguard life and property and prevent environmental contamination.

Manual 2, "Hazardous Chemical Data", is the cornerstone of the CHRIS system. For every compound listed in CHRIS, Manual 2 will supply the specific chemical, physical and biological data that is needed to use the rest of the CHRIS system.

Manual 3, "Hazard Assessment Handbook", describes procedures to be used for estimating the quantity of a hazardous material that may be released in an accident situation. It also describes how to estimate the concentration of a compound in both air and water as a function of time and distance from the spill. Methods for predicting the resulting toxicity, fire and explosion effects are also contained in this Manual.

Manual 4, "Response Methods Handbook", was written specifically for use by Coast Guard personnel who have some training or experience in hazard and pollution response. This manual describes the procedures to be used in cleaning up spills or leaks and has a listing of all currently available equipment that can be used in such situations.

In addition to these four manuals, a manual which contains data pertinent to a specific region or locale is included in the CHRIS system. This manual contains a listing of physical resources that could be used in responding to a spill or accident, and those vulnerable resources, such as water supplies and water intakes that could be affected by such an incident. In addition, potential sources of pollution, geographical and environmental features, cooperating agencies and recognized experts with identified spills are also listed.

The final section of CHRIS is "Hazard Assessment Computer System (HACS)." This is a computerized version of manual 3 which permits trained personnel at Headquarters to obtain very detailed hazard evaluations quickly upon request of on-scene personnel.

2. Inputs to model

2.1 Generic description of data used

The following pieces of information are necessary inputs to both the CHRIS and HACS systems:

a) the name of the chemical being spilled or discharged
b) the time at which the spill or discharge began
c) the location of the spill
d) the amount of the chemical that was originally being carried aboard the vessel
e) the wind speed and direction
f) the cloud cover at the spill site
g) the set and drift of the current
h) if in a tidal area, the maximum amplitude of tidal velocity
i) the width and depth of the waterway
j) if gas is being vented, the size of the hole

This information, plus the chemical, physical and biological data found in Manual 2, are all the primary information that is needed to perform a hazard analysis using either Manual 3 or HACS. However, additional data, such as the rate of release of the chemical, the size of the tank, the height of the liquid above the hole or above water level, the temperature of the air and water, the size of any pool that may form, the reaction between the chemical and water, or any other piece of information, would help the specialists in obtaining a more refined and accurate hazard assessment.

2.2 Sources of data

This input information can be obtained from many sources; among these, the most important are: Captain or crew of the vessel; shipping papers, cargo manifests; cargo information cards, warning signs, placards; shipping agent; nearby vessels or observers; weather bureau.

If specific information sources, such as those given above cannot supply the desired data, estimates for some of these inputs can be made by on-scene personnel.

3. Outputs produced with model

3.1 Generic description

The output from CHRIS provides both cautionary and corrective responses. Initially, the personnel on the scene, through Manual 1, are provided with information that will allow them to correctly respond to the immediate hazard. The other CHRIS manuals, which are used by personnel back at the office or base, provide an assessment of the severity of the hazard and supply additional response techniques that can be used by personnel at the scene of the incident.

In addition to this cautionary response information, CHIRS also provides corrective response techniques that can be used to ameliorate the situation. Included in this output are methods for stopping leaks containing spills, collecting and recovery of chemicals and for physically and chemically treating a spill to remove the hazard.

4. Adaptability of model to Coast Guard needs

In essence, CHRIS provides information that allows Coast Guard personnel involved in a chemical spill to make responsible judgments as to methods of controlling and eliminating the hazards associated with such an incident.

(i) Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants

Reviewed by
John A. Simmons, Science Applications, Inc.

1. Description of model

1.1 Identification
1.1.1 Title

Reactor Safety Study, An Assessment of Accident Risks in US Commercial Nuclear Power Plants

1.1.2 Contractor

Not applicable

1.1.3 Reference number

Report number WASH-1400

1.1.4 Date

August 1974

1.1.5 Authors

Not listed

1.1.6 Sponsor

US Atomic Energy Commission

1.2 Synopsis
1.2.1 Objective or purpose

The objective of this study was to assess quantitatively the risk to the public from nuclear reactor accidents. A second objective was to develop a methodology for the assessment and to determine its limitations. A third objective was an independent check of the effectiveness of the reactor safety practices of industry and government.

1.2.5 User's evaluation

The method is straightforward but requires enormous attention to details. Understanding and data are required for the reactor and its safeguard systems, operating procedures, test and maintenance schedules, accident sequences and how they are modified by the complete or partial action of the safeguard systems, dispersion of radioactive debris following an accident, and the links between radiation dose and death and disease. The method is unique in that the interaction of accident sequences and the operability of safeguard systems are modeled with combinations of event and fault trees. Unavailability because of test and maintenance of equipment and human operator error were included in the fault tree models of the failure of systems. These techniques should prove useful for evaluating the level of overall risk obtained with existing Coast Guard regulations. The ability of the techniques to identify new items for control or the need for tighter regulations for items now covered has not been determined and demonstrated.

1.3 Model description
1.3.1 General approach

The study dealt with possible accidents in nuclear reactor power plants which would cause the release of large amounts of radioactive materials outside of the plant, endangering the surrounding population. It was determined that such a release could occur only if the accident involves melting of the reactor core. Such accidents can be initiated by the sudden loss of coolant (such as the rupture of the reactor vessel or a break in the coolant piping) or by certain reactor transients. Because of the similarity of the amounts and types of radioactivity released via many of these accidents, the releases were grouped into a few categories.

The study consisted of three main tasks: (1) determination of the probability and magnitude of radioactive releases; (2) determination of the consequences of radioactive releases; (3) assessment of the overall risk of nuclear power plants.

1.3.2 Degree of simplification or assumptions

Risk was defined in terms of the probability and the consequence of all accidents. Presentation was a histogram or graph of probability versus consequence, which was compared with accidents from natural causes (e.g., tornadoes, lightning) and from man's activities including other industries. Consequence was expressed as deaths, injuries, and the dollar value of damages. These were estimated based on the ground areas receiving various levels of radiation dose and the number of people living in that area. The probability of a given consequence essentially was the product of four terms: (1) the probability of all accident sequences resulting in the release of a given amount of radioactive material; (2) the probability of meteorological conditions governing dispersion and thereby the ground area receiving a given radiation dose; (3) the probability that a certain number of people live in the affected areas; (4) the probability that a given dose will cause death or injury (both long term and short term). The number of people affected was obtained from population density distributions near reactor sites. Dispersion was modeled with the appropriate Gaussian plume formula. Meteorological data were used to define 25 weather categories in terms of rain (1), wind speed (4) and atmospheric stability classes (6) and their probability of occurrence.

1.3.4 Process description

The key to this analysis was the use of event trees, supplemented by additional analyses, to accomplish a systematic and realistic determination of the radioactive release magnitudes and probabilities associated with potential nuclear power plant accidents. Event trees were used to identify the many possible accident sequences leading from the initiating events to a given release category. Many of the events in the sequences involved failures of one or more systems and the probability of failure was determined with the aid of fault trees. Fault trees connected system failure to the failure of subsystems, their components, operator error, and down-time for test and maintenance. Through an interactive process, the highest probability sequences for each category of release were identified and the probability quantified. Each successive iteration reduced the uncertainties in the probability values as needed by improving the validity of failure probabilities and understanding of system interactions and the effects of physical processes. In this iterative process particular attention was given to "common mode" failures of systems (i.e., non-independent failures). The results were the probability of those accident sequences which contributed significantly to the probability of each category of release of radioactive materials.

2. Inputs to model

2.1 Generic description of data

These are of two types, numerical data and plant design and operational information. The latter include detailed drawings of piping, instrumentation, wiring and electrical systems, drawings of the relative physical location of systems and subsystems, the normal operation of the plant, models of processes occurring under accident conditions (e.g., the core melt process), human operator functions, and schedules for testing and maintenance of systems and equipment. This information is used to construct the event and fault trees. Some of the numerical data is needed to determine the probabilities of the event and fault trees, including component failure rates. The remainder of the numerical data include the meteorological data (joint probability distribution of windspeed and atmospheric stability category), plant radioactive material inventories, radiation dose, disease and injury relationships and the population density distribution near the plant.

2.2 Sources of data

Numerical data and information relating to the nuclear power plant may be obtained from the plant management and the several documents required by the AEC for licensing. Applicable component failure rate data may be obtained from reports on the operating experience of nuclear power plants and of other industrial plants. AEC-sponsored studies have generated information concerning the expected physical processes following various types of accidents.

3. Outputs produced with model

3.1 Generic description

One output is the prediction of the probability of the dominant (most likely) accident sequences leading to each category of releases of radioactive materials. An example is shown in the Table at the end of this study.

Another output is the graphical display of consequence (either death, injury or property damage) versus predicted frequency of occurrence (per year per 100 nuclear reactors).

3.4 Test of model

Wherever possible the model was tested against historical data. Accidents leading to meltdown of the reactor core were predicted to occur about 6×10^{-5} per reactor-year. This is consistent with the experience of no core meltdowns after 2,000 reactor-years for all types of reactors. The experienced failure rate of some reactor subsystems was found to agree well with the predicted failure rate based on a fault tree model and the general failure rates experienced for components, human operator error and downtime for testing and maintenance.

4. Adaptability to Coast Guard needs

It would seem obvious that the techniques developed in this study are directly applicable to Coast Guard requirements such as standards and exceptions for vessel and equipment design, inspection of vessels, requirements for stowage, containment and handling hazardous cargoes, promulgation of nautical rules, anchorage regulations, movement of hazardous cargoes in ports, establishment of safety zones on water and in waterfront areas, and prescription of safety equipment.

However, as noted in the final comments of the study report, the techniques were developed for risk analysis and not for improving safety. The methods have not been used to develop or compare candidate safety measures. Experience is needed to demonstrate this application. Even the ability to accurately predict risk has not been verified, in general. However, with conservative assumptions the true risk will be lower than predicted, and this is argued to be the situation for the nuclear reactor study.

An important point is that the technique cannot guarantee that all accident sequences are considered, but the systematic event tree approach, together with special knowledge of the physical processes that must occur to cause a release, reduces the likelihood that any significant sequences are missed.

TABLE 1 BWR Dominant Accident Sequences of Each Event Tree vs. Release Category

	Release Categories					
					Core Melt	No Core Melt
	1	2	3	4	5	6
Large Loca Dominant Accident Sequences (A)	AE-α 2×10^{-9}	AE-β 1×10^{-8}	AJ-γ' 2×10^{-9}	AJ-γ 1×10^{-8} AE-γ 1×10^{-7}	AGJ-δ 6×10^{-11} AEG-δ 8×10^{-10}	A 1×10^{-4}
A Probabilities	3×10^{-9}	1×10^{-8}	4×10^{-8}	1×10^{-7}	2×10^{-8}	
Small Loca Dominant Accident Sequences (S_1)	S_1E-α 2×10^{-9} S_1J-α 3×10^{-10} S_1I-α 4×10^{-10} S_1HI-α 4×10^{-10}	S_1E-β 1×10^{-7} S_1HI-β 3×10^{-8}	S_1C-γ 3×10^{-9} S_1J-γ' 7×10^{-9} S_1I-γ' 7×10^{-9} S_1C-β 6×10^{-10}	S_1J-γ 3×10^{-8} S_1I-γ 4×10^{-8} S_1HI-γ 4×10^{-8}	S_1GJ-δ 2×10^{-10} S_1GI-δ 2×10^{-10} S_1EG-ϵ 1×10^{-10} S_1GHI-δ 2×10^{-10}	
S_1 Probabilities	8×10^{-9}	1×10^{-7}	3×10^{-8}	1×10^{-7}	1×10^{-8}	
Small Loca Dominant Accident Sequences (S_2)	S_2J-α 1×10^{-9} S_2I-α 1×10^{-9} S_2HI-α 1×10^{-9}	S_2HI-β 1×10^{-7}	S_2J-γ' 2×10^{-8} S_2I-γ' 2×10^{-8}	S_2J-γ 1×10^{-7} S_2I-γ 1×10^{-7} S_2HI-γ 1×10^{-7}	S_2CG-δ 6×10^{-11} S_2GHI-δ 6×10^{-9}	
S_2 Probabilities	2×10^{-8}	1×10^{-7}	9×10^{-8}	4×10^{-7}	4×10^{-8}	
Transient Dominant Accident Sequences (T)	TW-α 2×10^{-7} TQUV-α 2×10^{-8} TC-α 2×10^{-7}	TQUV-β 1×10^{-7} TC-β 6×10^{-7}	TC-γ 3×10^{-6} TW-γ' 3×10^{-6} TQUV-γ' 3×10^{-7}	TW-γ 2×10^{-5} TQUV-γ 2×10^{-6}		
T Probabilities	9×10^{-7}	2×10^{-6}	1×10^{-5}	3×10^{-5}		
Pressure Vessel Rupture Accidents (R)		P.V. rupt. 1×10^{-8} Oxidizing Atmosphere		P.V. rupt. 1×10^{-7} Non-oxidizing Atmosphere		
R Probabilities		1×10^{-8}		1×10^{-7}		
Summation of All Accident Sequences per Release Categories						
Median (50% value)	9×10^{-7}	2×10^{-6}	1×10^{-5}	3×10^{-5}	3×10^{-6}	1×10^{-4}
Lower Bound (5% value)	1×10^{-7}	4×10^{-7}	2×10^{-6}	4×10^{-6}	4×10^{-7}	1×10^{-5}
Upper Bound (95% value)	1×10^{-5}	2×10^{-5}	8×10^{-5}	2×10^{-4}	2×10^{-5}	1×10^{-3}

KEY TO BWR ACCIDENT SEQUENCE SYMBOLS

A - Rupture of reactor coolant boundary with an equivalent diameter of greater than six inches.
B - Failure of electric power to ESFs.
C - Failure of the reactor protection system.
D - Failure of vapor suppression.
E - Failure of emergency core cooling injection.
F - Failure of emergency core cooling functionability.
G - Failure of containment isolation to limit leakage to less than 100 volume percent per day.
H - Failure of core spray recirculation system.
I - Failure of low pressure recirculation system.
J - Failure of high pressure service water system.
M - Failure of safety/relief valves to open.
P - Failure of safety/relief valves to reclose after opening.
Q - Failure of normal feedwater system to provide core make-up water.
S_1- Small pipe break with an equivalent diameter of about 2"-6".
S_2- Small pipe break with an equivalent diameter of about 1/2"-2".
T - Transient event.
U - Failure of HPCI or RCIC to provide core make-up water.
V - Failure of low pressure ECCS to provide core make-up water.
W - Failure to remove residual core heat.
α - Containment failure due to steam explosion in vessel.
β - Containment failure due to steam explosion in containment.
γ - Containment failure due to overpressure.
δ - Containment isolation failure in drywell.
ϵ - Containment isolation failure in wetwell.
ζ - Containment leakage greater than 2400 volume percent per day.
η - Reactor building isolation failure.
θ - Standby gas treatment system failure.

(j) Probabilities of Collision and Damage Affecting The General Dynamics 125,000m^3 LNG SHIP

Reviewed by

John A. Simmons, Science Applications, Inc.

1. Description of model

1.1 Identification

1.1.1 Title

Probabilities of Collision and Damage Affecting the General Dynamics 125,000m^3 LNG Ship*

1.1.2 Contractor

Arthur D. Little, Cambridge, MA

1.1.3 Reference number

Federal Power Commission, Docket Nos. CP73-47, et al, Hearing Exhibit Nos. DSA-1 and DSA-2

1.1.4 Date

1.1.5 Author

Donald S. Allen

1.1.6 Sponsor

EASCOGAS LNG, Inc.

1.2 Synopsis

1.2.1 Objective or purpose

This model was developed and used to estimate the likelihood of a collision of a LNG tanker with another ship, resulting in the release of some or all the LNG cargo. The frequency is expressed as releases per trip or per year for a given harbor and a given number of annual trips.

1.2.2 Intended use

1.2.3 Actual user

1.2.4 Actual application

The model was used to estimate the frequency of accidental spills of LNG in New York Harbor and Narragansett Bay in connection with the supply of EASCOGAS LNG, Inc. terminals. The model incorporates the effects of ship traffic and vessel characteristics including hull resistance to collision. The latter is based on a semi-empirical relationship between calculated collision kinetic energy and hull penetration as derived from accident data. The model is somewhat complex but is applicable to all ship-ship collisions. However, the results should be used with much caution since rather restrictive assumptions are used.

1.2.5 User's evaluation

1.3 Model description

1.3.1 General approach

The model consists of three parts: (1) Estimation of the probability that an LNG tankership will be involved in a collision in a given harbor; (2) Estimation of the probability of tank rupture given a collision; (3) Estimation of the probable damages caused to the environment if a tank rupture occurs. Estimate (3) merely assumes that a person within 2 kilometers of the collision and tank rupture "will be endangered" if the wind is blowing in the

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*LNG denotes Liquefied Natural Gas

right direction (assumed to be 25 percent of the time). The collision is assumed to be equally likely everywhere along its route through the harbor. This treatment is over-simplified and does not take into account very important factors such as spill rate, meteorological conditions, flammability limits, likehood of ignition sources (especially those close to the collision location), etc. These and other factors can be taken into account to obtain a more definitive estimate of fatalities and injuries.

Collision probability is obtained in a semi-empirical manner. It is assumed that the expected number of collisions is directly proportional to a collision potential. This latter is assumed to be proportional only to the sum of the lengths of the two ships involved. In a given harbor, h, the collision potential, C_h, for a LNG tankship per trip is:

$$C_h = S_h(L + \overline{L}_h),$$

where S_h is the average number of other ships moving about in the harbor during the period of the LNG tankship's transit, L is the length of the LNG tankship and $\overline{L}_h$ is the average length of the other ships moving about in the harbor. Now, C_h is the collision potential for one LNG tankship transit in the harbor. For n tankship transits per year, the expected number of collisions K_h, is proportional to nC_h:

$$K_h = q_o n C_h,$$

where q_o is a proportionality constant. It was shown that $q_o = K_o/C_o$, where K_o is the expected number of collisions for all ships in all harbors and C_o is the collision potential in all harbors,

$$C_o = \sum_h S_h^2 \overline{L}_h$$

Both K_o and C_o may be obtained from data: the former from accident records and S_h and $\overline{L}_h$ from harbor transit records compiled by the Army Corps of Engineers (annual reports, Waterborne Commerce of the United States).* A key assumption implied by this model is that the only variable characteristic of shipping which affects collisions is the length of the ships. Obviously other characteristics such as special traffic controls and maneuverability influence collision likelihood, but these have been lumped into the constant q_o. Thus, these characteristics are assumed to be the same for all ships in this model. This, of course, is not true for LNG tankships.

The probability of tank rupture, given the collision is based on the consideration of the following factors: (1) the location of the collision impact on the two ships involved; (2) the velocity and angle of impact; (3) the likelihood of being the struck ship; (4) the displacement of the striking ship. The collision location is important since the strength of the hull may vary from place to place and only a portion of the hull contains cargo tanks. The susceptibility of the hull to damage is determined via Minorsky's empirical

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*Actually these reports only list the draft, H, of shipping in each harbor. In this model L/H = 20 was assumed to be representative.

correlation between collision kinetic energy and hull resistance*:

$$E \doteq 414.5\ R + 121{,}900 \text{ Tons - Knots}^2,$$

where E is the collision kinetic energy and R is the hull resistance. Hull resistance, in this correlation, depends only on plates oriented longitudinally to the direction of the striking ship (buckling failure). In the struck ship (struck beam on) these usually consist of the deck plates, transverse bulkheads (when hit squarely) and bottom plates. From collision geometry and drawings of the hulls of the ships involved one can compute the resistance factor as the product of the depth of penetration, the base width of the penetration and the thickness of the plate (units of ft^2 - in). Collision kinetic energy is defined by the formula:

$$E = \frac{D_1\ D_2}{1.43\ D_2 + 2\ D_1} (V_{D_2} \cos\theta)^2 ,$$

where D_1 and D_2 are the displacements (tons) of the struck and striking ships, respectively, V_{D_2} is the velocity of the striking ship and θ is angle of the striking ship relative to the normal to the side of the struck ship. For a given value of R, based on penetration needed to rupture a tank, the minimum value of $V_{D_2}{}^{o}$ ($\theta = 0^{o}$) required for the striking ship is obtained from the above relationship. Based on filed reports on collisions, it is assumed that speeds at impact are uniformly distributed between 0 and 12 knots. Also the angle, θ, is uniformly distributed between 0 and 180°. Now, if $V_{D_2} \cos^2\theta \geq V_{D_2}{}^{o}$, collision damage will result**. Therefore, the probability of tank damage, given a collision angle θ and displacements D_1 and D_2, is $1 - (V_{D_2}{}^{o} \sec^2)/12$. The probability that the struck ship is the ship of interest, the LNG tankship, say, is assumed to be equal to the ratio of the length of the struck ship to the sum of the lengths of the two ships. Assuming further that $L \propto D^{1/3}$ then this probability factor is $1/(1 + (D_2/D_1)^{1/3})$. Finally, combining these relationships and integrating over the angle, θ, the probability of cargo tank rupture given a collision with a ship of displacement D_2 is obtained:

$$1/\left\{1 + (D_2/D_1)^{1/3}\right\}(2/\pi)\left\{\cos^{-1} \overset{o}{V}{}^{1/2} - [\overset{o}{V}(1 - \overset{o}{V})]^{1/2}\right\},$$

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*Minorsky, V.A., "An Analysis of Ship Collisions with reference to Protection of Nuclear Power Plants", J. Ship Research, October 1959, pp. 1-4.

**$\text{Cos}^2\theta$ rather than the geometrically expected $\cos\theta$ is used. The reasons for this were not given.

where $\overset{o}{V} = V_{D_2}{}^{o}/12$. The probability that the striking ship will have a displacement D_2 is obtained from Army Corps of Engineers' data and was shown to follow a lognormal distribution. Calculation of tank rupture probability via these relations is done numerically with the aid of a computer.

A problem with this model is definition of the penetration needed to rupture a cargo tank, especially for double hull vessels. In use of this model it was assumed that the striking ship must penetrate through both hulls of the LNG tankship to the cargo tank in order to cause rupture. No consideration was given to the possibility that rupture could occur via a partial penetration and displacement of the double hull structural members into the cargo tank. Minorsky's correlation does not include data on collisions of double hulled vessels.

2. Inputs to model

2.1 Generic description of data

Struck ship (e.g., LNG tankship) characteristics: length (feet), displacement (tons), hull structure and cargo tank locations.

Harbor ship traffic: the displacement (tons), frequency ships arriving and leaving (trips per year) and the time for transit through the harbor.

Striking ship characteristics: bow shape and structure of representative ships.

Before the model can be used, considerable judgment must be used to derive values for the hull resistance, R(ft^2 - in), from the structural drawings.

2.2 Sources of Data

3. Outputs produced with model

3.1 Generic description

The expected frequency (per year) of collisions and specified damage to ship hulls and cargo are estimated for any harbor. The model was applied to LNG tankships in the Staten Island and Narragansett Bay areas but was not tested against historical data. The following results were obtained for the General Dynamics 125,000m^3 tankship:

	New York - New Jersey Channels	Narragansett Bay
Annual Number of Trips	53	29
Collision Potential	1.34×10^7	1.63×10^6
Expected Collisions Per Year	3.25×10^{-3}	3.95×10^{-4}
Tank Rupture Probability Given a Collision	0.028	0.028
Expected Tank Ruptures Per Year	9.1×10^{-5}	1.1×10^{-5}

4. Adaptability to Coast Guard needs

Since the model is empirical, utilizing accident data for existing ships and regulations, the model is most suitable for assessment of safety and hazards under existing conditions, which was the manner in which it was used for LNG tankships. However, even for this application the model's validity is open to question. LNG tankships use a new type of hull structure, which were not included in the Minorsky data base for collisions. The model would not be suitable for assessing the effects of new regulations on vessel inspections, navigational control, standards of vessel design and equipment, etc. since the effects of these (either on collision frequency or damage extent) are not specifically included in the model.

(k) Airplane Crash Risk to Ground Population

Reviewed by

John A. Simmons, Science Applications, Inc.

1. Description of model

1.1 Identification

1.1.1 Title

Airplane Crash Risk to Ground Population

1.1.2 Contractor

UCLA, School of Engineering and Applied Science

1.1.3 Reference number

Report No. UCLA-ENG-7424

1.1.4 Date

March 1974

1.1.5 Authors

K. A. Solomon, R. C. Erdmann, T. E. Hicks, and D. Okrent

1.1.6 Sponsor

U.S. Atomic Energy Commission

1.2 Synopsis

1.2.1 Objective or purpose

The objective was to estimate the risk to people on the ground posed by the crash of large aircraft. The highest consequence events, such as crashes into occupied sports arenas, office buildings and shopping centers, are treated in detail. The estimation was based on the consideration of the following factors: (1) the probability of an aircraft crash and its variation with geometric relationship to intended flight path; (2) geometric relations between flight paths in use and ground sites with unusually high concentrations of people (e.g., a horse race track); (3) patterns of general population density near airports and their variation with time; (4) probable damage to public structures and attendant threat to occupants via an aircraft impact. The risk analysis considered in detail the population and air traffic operations at the Los Angeles International Airport (LAX) and the Hollywood-Burbank Airport. For projecting the results nationwide, it was assumed that these airports are typical of commercial United States airports. Because the model was used only once, with satisfactory results, it was never fully computerized and exists essentially as a methodolgy.

1.3 Model description

1.3.1 General approach

Key quantities in this model are the probability of an aircraft crash at a given location, the number of people at that location and the fraction of fatalities and injuries caused by the crash.

The probability, $PT(r,z,\phi,\theta,t)$, of a plane crash onto a "target" area is represented by the product of several factors:

$$PT(r,z,\phi,\theta,t) = A_1 A_0 R(r) \Theta(\theta) T(t);$$

r = distance from crash point to touchdown point on the runway;
z = height of target structure;
ϕ = glide angle preceding crash;
θ = angle subtended by normal flight path and the line between the crash site and the runway;
t = time;
A_1 = target area of structure (mi^2), a function of z and ϕ;
A_o = crash probability per mile square at the point $r = 1$ mi and $\theta = 0^o$;
$R(r)$ = dependence of crash probability on r;
$\Theta(\theta)$ = dependence of crash probability on θ;
$T(t)$ = dependence of crash probability on t

The target area of a building or other structure is the area of the base together with the "shadow" area obtained by projection at the crash glide angle, ϕ. This angle is not well known but was assumed to be 20°. The values for the other factors were obtained from data compiled and published by the Federal Aviation Administration. From these data for the years 1965 - 1972, the probability of a crash per square mile ($r \leq 5$ mi) per flight is 4×10^{-9} for all airports. Further analysis of the same data gives A_o, 1.5×10^{-7} crashes per flight (± 20%). $R(r)$ is somewhat different for landings and take-offs and varies from 1 at $r = 1$ mile to 0.08 to 0.4 at $r > 5$ miles. For $\Theta(\theta)$, the highest fraction of crashes occurs along the flight path, 83% for $\theta \leq 10°$. For $80° \leq \theta \leq 90°$, the fraction of crashes drops to 0.8%. Although a crash is more likely to occur at night, the vast majority of commercial air operations takes place during the day. Hence approximately 80% of all air traffic accidents occur during daylight hours.

The total probability of a crash into a high-occupancy site is given by the product of $PT(r,z,\phi,\theta,t)$ and number of flights. Since damage and fatalities also depend on the type of aircraft involved, the number of flights was classified by aircraft size. Only the crashes of the largest craft, 747's, DC-10's and L-1011's, were considered. For example, there are approximately 200,000 landing operations per year at LAX and of these approximately 1/3 are jumbo jets. The Hollywood Park race track is on the flight path of landings at LAX; its area is approximately 0.03 mi^2.

$\frac{PT}{A_1 T(t)}$ for this site is 1.1×10^{-8} per operation per square mile. Hence the total probability of a jumbo jet crashing into the Hollywood Park race track is

$$\frac{PT}{T(t)} = (1.1 \times 10^{-8})(0.03)\ (2 \times 10^{5})\ (1/3) = 2.2 \times 10^{-5} \text{ per year.}$$

The probability that the site is actually occupied with people is obtained from appropriate information. For example, the same Hollywood Park race track is known to be open approximately 1/3 of the days of the year and during approximately 3/4 of the day. Since 80% of all crashes occur during daylight hours, the probability of a crash of a jumbo jet into Hollywood Park while occupied is

$$PT = 2.2 \times 10^{-5} \times 0.8 \times 1/3 \times 3/4 = 4.4 \times 10^{-6} \text{ per year.}$$

The consequence of the crash depends on an estimate of the number of people at the site and the damage done by the aircraft. The former is estimated from appropriate data. For example, the capacity of Hollywood Park is known to be approximately 50,000 persons. Estimates of casualties were based on this number. Damage consists of structural damage to buildings, a fire of burning fuel, and the scabbing area, which is the ground area covered by the aircraft between the point of impact and the point where it stops. Scabbing areas may be derived from accident data. Structural damage is estimated from experimental data for the impact of large projectiles (up to 6,000 lbs) and theoretical analyses of the crash of aircraft into nuclear reactor containment vessels. For example, consideration of this information suggests that a direct or partial hit on the Hollywood Park grandstand by a jumbo jet would cause partial collapse. If the park were fully occupied (50,000 persons) it was estimated that 21,700 persons would be killed via all damage modes in a direct hit. An "average crash" would produce a lesser number of fatalities.

Similar estimates were made for other high occupancy sites near LAX and the Hollywood-Burbank airports. For other areas, fatalities were estimated from the product of the average population density and the scabbing area.

2. Inputs to model

2.1 Generic description of data used

To evaluate the risk of damage and casualties from aircraft crashes near airports, the following data are required:

a) number of take-offs and landings for heavy, medium and small aircraft;

b) orientation of the runways and flight paths, and the fraction of usage of each in both directions (when applicable);

c) location of special structures of interest relative to the runways and flight paths;

d) population densities near the airport;

e) the time period of occupancy and capacity of the special sites;

f) the height and strength of the special structures.

2.2 Sources of data

These data may be obtained from either local government or the airport authorities.

3. Outputs produced with model

3.1 Generic description

A very useful output of this model is the estimate of the probability (per year or per flight) of a crash of a given type of aircraft at a specific location or into a specific structure. With information from other sources, the damage to the structure also may be estimated. The probability that the crash occurs when the site is occupied by a known number of persons also is estimated by the model. Finally, the number of the fatalities caused by the crash also may be obtained. However, the method for estimating the number of fatalities at a high-occupancy site is not clearly stated.

3.2 Examples of numbers

3.3 Definitions of units

3.4 Test of model

The model was not tested against historical data. Considerable additional work would be required for this.

4. Adaptability to Coast Guard needs

Insofar that the model is concerned specifically with the crashes of aircraft, there appears to be no general application to Coast Guard regulatory functions. However, the model does appear to have some value insofar that shipping routes and terminal facilities may be located near airports and their flight paths. Thus, the model could be of use to help guide the selection of permissible sites for handling hazardous materials with respect to their likelihood of being struck by a crashing aircraft.

(1) The Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck

Reviewed by

L. D. Williams, Battelle-Pacific Northwest Labs.

1. Description of model

1.1 Study identification

1.1.1 Title

The Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck

1.1.2 Contractor

Pacfic Northwest Laboratories (PNL), also known as Battelle-Northwest

1.1.3 Reference number

BNW-1846

1.1.4 Date

July 1975

1.1.5 Authors

T. I. McSweeney, et al.

1.1.6 Sponsor

ERDA Division of Waste Management and Transportation

1.2 Synopsis

1.2.1 Objective or purpose

Develop and apply a methodology to evaluate the risk in the transport of hazardous materials

1.2.2 Intended use

To determine the risk in the transport of hazardous materials, identify the major factors contributing to the risk, and to put the risk into perspective through comparison to other societal risks.

1.2.3 Actual user

Battelle-Northwest Labs.

1.2.4 Use to which put

As given in 1.2.2

1.2.5 User's evaluation

1.2.5.1 Special equipment requirements

Computer with FORTRAN V compiler

1.2.5.2 Ease of use

Currently moderate, being improved

1.2.5.3 Number of persons in organization who use it

Nine

1.2.5.4 Suggested improvements

Increase data bases; simplify code input

1.2.6 Originator's suggested improvements

Same as 1.2.5.4

1.3 Description

1.3.1 General approach

The Battelle-Northwest Labs. risk assessment model provides a systematic method for handling the data germane to analysis of the safety of the transport environment. The model uses one fundamental equation:

$$R = \sum_{i} R_i \qquad (1)$$

The total system risk R is the sum of the risks of all accidental releases as denoted by the subscript i. Only accidental releases are presently considered in the model. The risk of an individual release is the product of the consequences of the release and the probability of its occurrence. This equation could be expanded into a single, long, complex equation. In the current formulation of the model, each term in Equation (1) is expended into two expressions which have more physical significance. The expanded equation for R_i is:

$$R_i = \left(A\ F_{R_i} \times P_{R_i}\right) \times \sum_{q}\left(C_{E_{i,q}} \times P_{Eq}\right) \qquad (2)$$

The first factor, $A\ F_{R_i}$ is the product of the amount of material present in a shipment times the fraction of that material lost to the environment in the i^{th} release sequence. This factor can be thought of as a source term for the i^{th} chain of events or failures which end with a release of radioactive material. The second factor, P_{R_i}, is the probability that the release sequence will happen during transport. The first expression, $A\ F_{R_i} \times P_{R_i}$, can be thought of as a probabilistic source term for each identi-release sequence.

The factor $C_{E_{i,q}}$ in the second part of equation (2) is the consequences of a unit release. The subscript q is added to show that the factor is a function of the specific weather condition existing at the time of the release and the population exposed to the release. The factor represents the effect of a unit release on the exposed population in terms of either a whole body dose to man or to a specific organ. The final factor, P_{E_q}, is the probability of encountering a particular set of weather conditions within a specific population zone. The expression $\sum_{q}(C_{E_{i,q}} \times P_{Eq})$ can be thought of as the consequences of a unit release of radioactive material (unit source term) under probabilistically weighted weather conditions and population distributions.

Equation (2) is the pivotal equation in the risk model. Two preparatory steps are needed before the terms can be evaluated. These are the system description and the release sequence identification steps. Following these two steps is the release sequence evaluation step which utilizes Equations (1) and (2). The final step is to evaluate or assess the significance of the risk level determined for the transport system being evaluated.

1.3.2 Degree of simplification or assumptions

There are no simplifications intrinsic to the methodology. However, time and cost constraints will cause introduction of some simplifying assumptions into an analysis. The initial application of the model is considered quite detailed with few simplifying assumptions.

1.3.3 Technique categories internal to methodology

a) Fault tree analysis
b) Engineering analysis of container failure

c) Gaussian plume vapor dispersion
d) Biologic and radiologic decay analysis
e) Variable release duration analysis

1.3.4 Process description

Process flow is: describe system (specify material shipped, the amount, origin and destination; specify material characteristics, specify transport mode and carrier, specify container and amount of material per container, specify route, restrictions, population and weather zones), identify release sequences, identify data sources to evaluate release sequences (container closure error data, mechanical failure data, transport mode accident data, material dispersal characteristics data, route, population and weather characteristics data, data on health effects of material shipped), evaluate release sequences and calculate risk (determine probability of release sequence occurrence, determine amount released for each release sequence, calculate probability of encountering a specific population and weather characteristic, calculate consequences of a release for each population and weather characteristic, calculate risk), identify major contributors to risk, assess risk relative to other societal risks.

1.3.5 Calculations are made with two computer codes:

a) FAULT - develops release sequences from fault trees,
b) HEAD - performs risk calculations.

1.3.6 Computer/calculator program availability

Computer codes currently unavailable for distribution. Will be available from Battelle-Northwest Labs. at a later date.

2. Inputs to model

2.1 Generic description of data used

a) Transport distances, routes, modes.
b) Detailed engineering description and analysis of vehicles and shipping containers.
c) Meteorological conditions description.
d) Failure thresholds of containment barriers.
e) Likelihood of substandard containers.
f) Population distributions.
g) Dispersal characteristics of released materials.
h) Accident environment description.
i) Shipment characteristics (number of containers, etc.)
j) Health effects of material.

2.2 Sources of Data

Source of data: surveys; analyses; engineering drawings; literature; statistical abstracts.

2.3 Examples of numerical values

The occurrence rate of fires is 0.016 per truck accident

2.4 Definitions of units

Same as 2.3

3. Outputs produced with model

3.1 Generic description

a) The risk in transportation of the material.

b) Ranked listing of the 30 most probable release sequences (a release sequence is a combination of events leading to failure of the barriers between the material and man's environment).

c) Ranked listing of the 30 highest risk (probability times consequences) release sequences.

d) Probability-consequence spectrum for the possible releases.

e) Listing of all events and conditions that contribute to each release sequence and their individual likelihood of occurrence.

f) Analysis of the sensitivity of the risk to particular system characteristics (e.g., the impact resistance of a container)

g) Expression of the risk to the population near an accident in terms of health effects.

h) Comparison of the risk to other societal risks.

3.2 Examples of numbers

Expected value of 3.5×10^{-7} deaths per 1500-mile shipment.

3.3 Definitions of units

Same as 3.2

3.4 Was model tested against historical experience

For the cases analyzed to date, there have been no releases in transport. The model results are consistent with this experience; however, this cannot be considered as a demonstrative test.

3.5 Did analysis process identify new control areas

The model identified areas deserving of consideration for the application of additional controls. It also identified areas where additional R&D to better determine system characteristics would be desirable.

4. Adaptability of model to Coast Guard needs

4.1 Coast Guard regulatory functions involved

a) Requirements for shipboard stowage and containment of hazardous materials.

b) Maritime accident investigation and record keeping.

c) Requirements for handling dangerous cargoes within or contiguous to waterfront facilities.

d) Promulgation of nautical rules of the road.

e) Control of oil and hazardous-substances pollution.

f) Movement of hazardous cargoes in ports.

4.2 Sample questions within the functions for which model could provide data

a) How do stowage and contaiment requirements influence the risk of an accident?

b) What questions should be asked in an accident investigation? By identifying the factors and interactions which can ultimately lead to an accident, the model serves as a basis for the development of comprehensive accident investigation techniques. What data should be kept and in what form? Use of the model would ensure that no important factor influencing safety is omitted from record keeping.

c) What facets of the movement of dangerous cargoes are most important to safety?

d) What will be the effect of the proposed rules on safety in hazardous material transport?

e) Are the possibilities and consequences of accidental releases acceptable? If not, how can they be reduced?

f) How safe are movement methods for hazardous materials?

4.3 Modifications to model/method required to permit each application

4.3.1 Information bearing on that question or decision available from model.

The model methodology is applicable to providing all of the information needed as specified in 4.2. The risk analysis computer code provides the skeleton and the detailed output capabilities to generate the needed information. Specifically, the model would provide: a) a ranked listing of the 30 most probable release sequences (a combination of events leading to loss of all barriers between the material and man's environment); b) a ranked listing of the 30 highest risk (probability times consequences) release sequence; c) the total risk in an operation; d) a probability-consequence spectrum; e) listing of all events and conditions that contribute to each release sequence and their individual likelihood of occurrence; f) an analysis of the sensitivity of the risk to particular system characteristics; g) expression of the risk in terms of health effects; and h) comparison of risk to other societal risks.

4.3.2 Additional input data required for each application

Input data required for each application would be the items listed in 2.1

4.3.3 Possible sources for data

Coast Guard records, insurance data, container design drawings, various data compilations.