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LEVEL II

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COMMERCIAL VESSEL SAFETY RISK ASSESSMENT STUDY

VOLUME II
RISK ASSESSMENT METHODOLOGY SURVEY

Planning Research Corporation
Systems Services Company
7600 Old Springhouse Road
McLean, VA 22102

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16. Abstract

This volume documents the results of a survey of risk assessment methodologies, performed as part two of a three part marine risk assessment study for the U. S. Coast Guard. Part one, a survey of data systems pertinant to marine risk assessments is documented in Volume I (AD-A077 719).

A set of exercises demonstrating the application of selected methodologies and data to evaluate the risks of hazardous chemical transport is discussed in Volume III.

For this portion of the study, 34 risk assessment studies were reviewed and 12 of these were selected for further analysis. These 12 represent a spectrum of methodologies for evaluating the various risk elements involved in hazardous material transport, including probability of an accident, probability of release of the hazardous material, physicochemical reactions of the released material with the water and/or air, and resulting damage to persons, property, and the environment.

Methods of evaluating accident and spill probabilities include statistical analysis of historical data, analytic equations expressing the kinematics of accident scenarios, computer simulation of ship movements, generation of fault trees relating the various possible event sequences leading to accidents, and subjective probability evaluation based on person judgment. Consequence models reviewed include computer models of the movement of oil spills on water and the physicochemical reactions of spills of hazardous chemicals such as LNG, chlorine, ammonia, etc. and their effects on persons and property.

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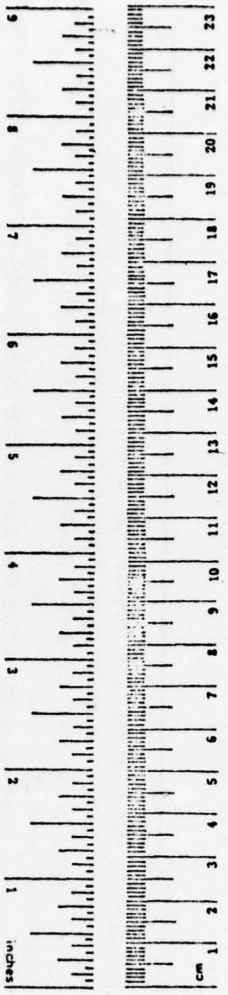
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

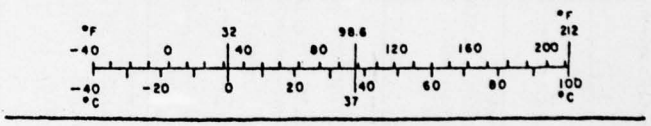
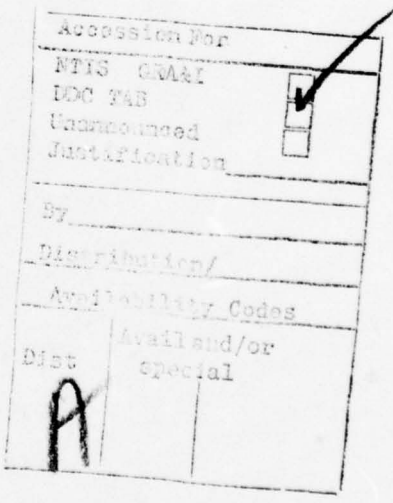


TABLE OF CONTENTS

		Page
List of Tables		v
List of Figures		vii
Executive Summary		1
I.	Introduction	5
II.	Risk Assessment Studies	7
A.	Risk Assessment Methodology Framework	7
B.	Approaches to Risk Assessment	8
C.	Studies Surveyed	9
III.	Description of the Risk Studies	15
A.	Spill Risk Analysis	17
B.	Vessel Safety Model	25
C.	Risk Assessment for an LNG Terminal at Matagorda Bay	29
D.	Risk Assessment for an LNG at Point Conception, California	33
E.	Vulnerability Model for Damage Assessment	37
F.	Cargo Spill Probability Analysis for the Deepwater Port Project	43
G.	Offshore Petroleum Transfer Systems for Washington State	47
H.	LOOP Deepwater Port Oil Spill Risk Analysis	53
I.	Spill Probability Analysis for Outer Continental Shelf Environmental Assessment	59
J.	Oil Spill Trajectory Studies for Outer Continental Shelf Environmental Assessment	63
K.	Oil Transport Model for SEADOCK	65
L.	Reactor Safety Study	69
IV.	Comparative Evaluation of the Risk Methodologies	75
A.	Casualty Probability	75
B.	Spill Probability	81
C.	Consequences	84
V.	Conclusions and Recommendations	89
A.	Conclusions	89
B.	Recommendations	92
Bibliography		95



LIST OF TABLES

		Page
Table 1.	Summary of Risk Assessment Studies	10
Table 2.	Risk Assessment Studies Evaluated	12
Table 3.	Casualty Probability Approaches for Nine Studies	13
Table 4.	Categorization of Casualty Probability Estimation Methods	76
Table 5.	Categorization of Spill Probability Estimation Methods	82
Table 6.	Spill Consequence Categorization	85
Table 7.	Applicability of Casualty Probability Methodologies to Evaluation of Marine Safety Measures	93

LIST OF FIGURES

		Page
Figure 1.	Generalized Flow Diagram of the Vulnerability Model	40
Figure 2.	Sample Event Tree	70
Figure 3.	Sample Fault Tree	72

EXECUTIVE SUMMARY

Risk methodology can be considered in terms of four elements. The first element is the probability of a vessel casualty: that is, collision, ramming, grounding, fire, explosion, etc. The second element is the probability of a spill, given that a casualty has occurred.

Next, the physical reactions of the spill material with the water and air must be determined. This reaction may result in a toxic cloud, oil pool, flammable vapor cloud, fire, or explosion, depending upon the material characteristics and the environment.

Finally, the damage caused by the spill is determined from the spill phenomenology and the resources at risk. This may be measured in terms of fatalities, injuries, property loss, or environmental damage.

The risk methodology survey was undertaken to determine the state-of-the-art in risk assessment for marine transport of hazardous materials. For this effort, 34 risk assessment studies were reviewed and 12 were selected as representative of the applicable methodologies.

The methodologies are evaluated in terms of their usefulness in performing two types of risk assessment analyses:

- Prediction of risks associated with existing or proposed marine operations (such as deepwater ports or LNG import terminals), and
- Evaluation of proposed safety measures.

The methodologies reviewed addressed various applications including:

- Safety analysis of LNG import terminals,
- Environmental impact of deepwater ports for oil tankers,
- Environmental impact of offshore oil developments,
- Safety analysis of a nuclear reactor,
- Evaluation of marine safety measures, and
- Evaluation of the effect of varying certain vessel parameters on vessel casualties.

There are several different approaches to the evaluation of each risk element. The casualty probability is generally the most difficult to estimate and, accordingly, has been addressed by the largest variety of methods. Because of this difficulty and the importance of this element, particular attention has been directed in this study toward evaluating the casualty probability approaches. The methods that have been applied to casualty probability estimation are as follows:

- The statistical method uses historical data on vessel casualties and vessel traffic to develop casualty probabilities.
- The analytic method involves kinematic equations expressing the probability of collision or ramming in terms of pertinent system variables.
- Computer simulation of ship movement can be used to estimate the probability of collision, ramming, or grounding.
- For the fault tree approach, trees are developed that indicate the logical sequences of events that lead to a casualty. Probabilities are assigned to basic events, such as a component failure, and the probability of system failure is computed from these basic event probabilities.
- The subjective approach develops probabilities from the results of questionnaires or from interviews of knowledgeable personnel.

For predicting the potential effects of proposed safety measures on casualty probabilities, the casualty report analysis approach has been developed. This approach is based upon detailed evaluation of narrative casualty reports to estimate the proportion of casualties that might have been prevented by a specified safety measure.

Each of these methods was utilized by at least one of the studies reviewed.

Consequence models reviewed include LNG spill effects and oil spill movement models. It was beyond the scope of this study to perform detailed analyses of the dynamics of LNG and oil spills; therefore, other studies were relied upon for these evaluations.

The twelve studies reviewed are:

- Spill Risk Analysis--Operations Research, Inc., Development and demonstration of models for assessing marine safety systems. Methods include casualty report analysis and kinematic equations.
- Vessel Safety Model--Transportation Systems Center. Development of a computer simulation model for evaluating vessel grounding and collision probabilities.
- Risk Assessment for an LNG Terminal at Matagorda Bay--Federal Power Commission. Statistical analysis of the probability of LNG spills and use of a Gaussian plume model for analyzing spill effects.

- Risk Assessment for an LNG Terminal at Point Conception, California--Science Applications, Inc. Application of a kinematic model for evaluating probabilities of LNG spills from vessel casualties and physical balance equations for spill effects evaluation.

- Vulnerability Model--Enviro Control, Inc. Development of a computer simulation model to assess the physical effects and consequences from spills of hazardous chemicals.

- Vessel Cargo Spill Probability Analysis--Woodward-Lundgren and Associates. Utilization of subjective probability estimates for oil spill risks from deepwater port vessel operations.

- Offshore Petroleum Transfer Risks--Oceanographic Institute of Washington. Statistical analysis of oil spill risks from tanker operations in the Puget Sound region and Delphi assessment of the impact of the spills.

- LOOP Deepwater Port Oil Spill Risk Analysis--A.D. Little Inc. Evaluation of oil spill probabilities for deepwater port operations by a combination of statistical and kinematic methods. Assessment of the impact of oil spills by spill trajectory simulation.

- Spill Probability Analysis for Outer Continental Shelf Environmental Assessment--Massachusetts Institute of Technology. Application of Bayesian statistical techniques for evaluating oil spill probabilities.

- Oil Spill Trajectory Studies for Outer Continental Shelf Environmental Assessments--Massachusetts Institute of Technology. Application of a computer simulation model for analyzing the trajectories of ocean oil spills.

- Oil Transport Model for SEADOCK--Texas A&M. Application of a stochastic model for movement of oil spills in the area of the proposed SEADOCK Deepwater Port in the Gulf of Mexico.

- Reactor Safety Study--Nuclear Regulatory Commission. Utilization of fault tree and event tree methods to evaluation of the risks of release of radioactive materials in nuclear power plant operations.

Analysis of the 12 studies discussed in this report, in addition to the 22 other studies reviewed for possible inclusion in the report, lead to the following conclusions relative to methodologies for assessing marine risks:

- Acceptable methods exist for predicting casualty and spill probabilities for most applications.

- Consequence estimations for LNG spills yield significantly different results among the various models. No single model is generally accepted as adequately representing the phenomena. The Coast Guard's Vulnerability Model addresses a large variety of chemicals but needs further development in several areas.

- Sophisticated oil spill movement models are not necessary for most evaluations of the potential impact of oil spills from vessel casualties. Relatively simple models with few data requirements are generally sufficient.

- Estimating the potential risk reduction effects of marine safety measures is a very difficult task, particularly for those measures that affect the casualty probability. Only two methods appear generally useful for this purpose: the subjective probability approach and casualty report analysis. These methods, however, are quite time consuming. Further, the latter method is dependent upon information contained in the narrative casualty reports.

- Current simulation models are not adequate for assessing most types of safety measures; however, it may be possible to enhance the value of such models by modifying them to treat additional safety measures.

The major recommendations resulting from the survey are:

- The safety measures of interest to the Coast Guard be defined and ranked in order of priority to further clarify the goals of the risk management methodology.

- Further research be conducted on the application of simulation methods for assessing risk mitigation measures.

- The subjective approach to risk mitigation assessment and risk prediction be tested and validated with results from a standard approach (such as the statistical).

- Further research be conducted to develop statistical regression relationships between vessel casualties and pertinent situational and vessel parameters.

I. INTRODUCTION

The purpose of the survey discussed in this volume is to determine the state-of-the-art of risk assessment methodologies applicable to marine transport of oil and hazardous chemicals. Two primary risk assessment goals are addressed in the studies surveyed:

- Prediction of risks associated with proposed or existing marine operations such as deepwater ports or liquefied natural gas terminals, and
- Evaluation of proposed marine safety measures.

Twelve methodologies were analyzed for this survey. These methodologies represent a cross-section of the various approaches to risk assessment and were selected from an initial group of 34 risk assessment studies.

Section II outlines the general structure of risk assessment models and provides a framework for the methodologies discussed. In section III, each of the 12 methodologies is summarized and evaluated in terms of the purposes for which it was developed and its application to the Coast Guard's marine risk management functions. Also, the primary data requirements, output parameters, and computer requirements, if any, are indicated for each.

The various approaches to each element of risk assessment, as well as other applicable studies, are discussed in section IV for the 12 methodologies surveyed. Survey conclusions are presented in section V, along with recommendations for further research in risk assessment methodology.

II. RISK ASSESSMENT STUDIES

A. Risk Assessment Methodology Framework

Risks involved in handling hazardous materials have been analyzed for all transportation modes as well as for certain facilities such as nuclear power plants, offshore oil drilling rigs, etc. Most of the methodologies applied to risk assessment for the transportation of hazardous materials involve the concept of an accident or casualty of the vehicle transporting the material which causes a rupture of the container and results in a release or spill of the material. The effects of the spill in terms of physical interaction with the air and water depend on the environmental conditions and the material characteristics. These effects--vapor clouds, pool fires, oil slicks, etc.--can cause fatalities, injuries, property loss, or environmental damage.

Models for assessing the risks of transporting hazardous materials can be considered in terms of four risk elements:

- Casualty Probability—probability of a vessel casualty occuring (collision, grounding, ramming, fire, etc.);
- Spill Probability—probability that a spill of given size occurs as a result of a casualty;
- Spill Effects--physical results of the liquid or gas spilled; and
- Consequences--fatalities, injuries, property damage, or ecological damage.

These elements can be combined to express the expected losses over the range of possible spill locations, casualty types, and spill sizes as indicated in the following equation.

L_n = expected loss of type n, where n represents fatalities, ecological resources destroyed, property losses, etc.

$P(C_{ik})$ = probability of a vessel casualty of type i at location k.

$P_k(S_j|C_{ik})$ = probability of spill of size j given a casualty of type i at location k.

$E_k(S_j)$ = potential effect of a spill of size j at location k (e.g., oil pool size, vapor cloud size, etc.)

$D_n(E_k(S_j))$ = potential damage of type n due to a spill of size j at location k based on the spill effects.

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The factors are summed over all casualty types of interest, all possible spill sizes (which depend on the casualty type, cargo type, vessel types, etc.), and all locations of interest.

The above equation is for illustrative purposes only and does not include all pertinent factors such as traffic density, ship speed, weather, etc. The effects of spills on water are time dependent, and the amount of damage depends, for example, on the extent of the oil slick when it reaches shore or the vapor cloud when it ignites. These variables are functions of the locations of the spill and the resources that may be affected and, in the case of flammable vapor clouds, of the possible ignition sources.

The spill effects and the consequences or damage can be estimated deterministically as in the Coast Guard's Vulnerability Model or, probabilistically, as in certain oil spill effect models. In the latter types, Monte Carlo simulations are used to predict the spill movement for a distribution of wind speed and directions and spill locations; damages are determined over the totality of situations simulated.

Because of data limitations, methodologies for estimating the various elements of the risk equation do not necessarily utilize all variables indicated. For example, probability of a ship casualty may be treated independently of location, and spill size may be treated independently of casualty type. When location is considered in the casualty probability estimate, it is usually in terms of categories such as harbors, channels, open seas, etc.

B. Approaches to Risk Assessment

Of the 34 studies surveyed, some address only one or two of these elements; others, such as LNG environmental impact analyses, address all four. Casualty probability is estimated by a variety of methods. The statistical approach utilizes historical data, which are sometimes adjusted for differences between the situation being analyzed and the situation existing when the casualties occurred. The analytic method applies kinematic equation--generally, random motion--models to express the casualty probability in terms of pertinent parameters such as traffic density, ship speed, ship length, etc. The simulation approach utilizes computer simulation of the movement of ships to determine the probability of casualties. For logic tree methods, event and/or fault trees are developed that express the possible sequences of occurrences leading to casualties, and probabilities are assigned to each element to derive the overall casualty probability.

Casualty report analysis involves systematic evaluation of narrative casualty reports to estimate the potential impact a specific proposed safety measure might have had on each

casualty. Finally, subjective judgment of experts is utilized by using questionnaires or the Delphi approach to estimate risks or the possible effects of safety measures.

Generally, the same categorization applies to spill probability models.

The spill effects for LNG and other hazardous materials are considered generally in terms of four possible phenomena: pool fires, vapor cloud fires, explosions, or toxic clouds. Vapor clouds treated in the studies were modeled on either Gaussian plume methods or physical balance equations. Oil spills were treated by use of analytic or simulation pool spread and trajectory models that predict impact along shorelines.

Consequences of hazardous material spills generally apply to the population, properties, and the environment in the area of the spill. The consequences to persons, usually in terms of fatalities, can be estimated by "cookie cutter" techniques, whereby all persons within a specified area are killed and all outside survive; or by distributional techniques, whereby a fatality probability based on a dose calculation is assigned for each area cell in and near the region of the fire, explosion, or toxic material, with the probability varying with both distance and time. Damage to properties is treated in a similar manner. Impact on the environment is generally expressed in terms of area polluted or amount of resources affected.

C. Studies Surveyed

Table 1 summarizes the 34 studies examined for this task in terms of four elements of risk assessment.

From the original list of 34 risk assessment studies of table 1, 12 studies were selected as candidates for inclusion in the survey report. These 12 studies are listed in table 2.

The studies were selected primarily to cover the various approaches to each risk assessment element: casualty probability, spill probability, spill effects, and consequences. Generally, the most difficult element to estimate accurately is the casualty probability. Not surprisingly, the largest variety of approaches is addressed to this element. Table 3 categorizes the studies according to the methodologies used to estimate casualty probability. Within some of the studies, different methods are used for different aspects of the problem, and, therefore, these studies are included in more than one casualty probability element category. For example, the ORI Spill Risk Analysis applies an analytic approach to casualty probability estimation and uses casualty report analysis for examining the effects of safety measures on accident frequencies. A. D. Little used an analytic model for impact casualties (collisions and rammings) and historical data for non-impact casualties (groundings, explosions, etc.).

Table 1. Summary of Risk Assessment Studies

					METHODOLOGY					
	STUDY	PREPARER	SPONSOR	APPLICATION	CASUALTY PROBABILITY	SPILL PROBABILITY	SPILL PHENOMENA	CONSEQUENCES	CARGO TYPES	RESOURCES AFFECTED
1.	Spill Risk Analysis	Operations Research, Inc.	Coast Guard	Safety system effectiveness & collision causes	a) Analysis of casualty reports b) Kinematic model	Analytic models – energy exchange & hull rupture	N/A	N/A	All	N/A
2.	Vessel Traffic Services	Computer Sciences Company	Coast Guard	Effectiveness of VTS	Statistical adjusted by factors from analysis of casualty reports	N/A	N/A	Casualty report data	All	Vessels, persc
3.	LNG Terminal Risk Assessment – L.A., Oxnard, Pt. Conception	Science Applications Inc.	Western LNG Terminal Co.	LNG facility environmental impact	Kinematic model adjusted by historical data	Analytic model – Minorsky equations	Pool fire; cloud model via balance equations – (simulation)	Cookie cutter	LNG	Population
4.	Matagordo Bay LNG Terminal	FPC	FPC	LNG facility environmental impact	Statistical – oil tankers adjusted for VTS	Statistical – oil spills adj. for LNG ships	Pool fire; cloud model via Gaussian plume	Cookie cutter	LNG	Population
5.	Pt. Conception LNG Terminal	El Paso Alaska/ Engr. Computer Optenomics	El Paso Alaska	LNG facility environmental impact	Statistical – oil tanker data adjusted for LNG ships	Statistical – oil spills adj. for LNG ships	Pool fire only	Cookie cutter	LNG	Population
6.	Oxnard LNG Terminal	Socio Economic Systems	City of Oxnard	LNG facility risk assessment	Statistical – oil tanker data adjusted for LNG ships	Statistical – oil spills adj. for LNG ships	Pool fire; cloud model via Gaussian plume	Cookie cutter	LNG	Population
7.	Vessel Safety Model	Transportation Systems Center	Coast Guard	–	Monte Carlo simulation of kinematics	N/A	N/A	N/A	All	N/A
8.	Vulnerability Model	Enviro Control, Inc.	Coast Guard	Hazardous material spills from vessels	N/A	N/A	Pool fire; cloud model via Gaussian plume, explosions	Distributional	LNG, chlorine, ammonia, gasoline, etc.	Population and structures
9.	Hazard Assessment Computer System	A. D. Little	Coast Guard	Hazardous material spills from vessels	N/A	N/A	Same as above	N/A	Hazardous chemicals	Population
10.	Reactor Safety	AEC	AEC	Nuclear generating plants	Event and fault tree	N/A	Gaussian plume	Cookie Cutter	Radioactive material	Population
11.	LOOP Environmental Impact Statement	A.D. Little, Inc.	Coast Guard	Deepwater port environmental impact	a) Non-impact casualties; statistical b) Impact casualties; kinematic (McDuff)	Statistical	Analytic trajectory models	Simulation	Oil	Coastline length
12.	Offshore Petroleum Transfer for Washington State	Oceanographic Institute of Washington	State Legislature, Ocean. Comm. of Washington	Oil tanker spills in Puget Sound region	Statistical (distributional)	Statistical (distributional)	Analytic trajectory models	Delphi method	Oil	Coastal ecology
13.	An Example Risk Calculation	Ecology & Environment, Inc.	–	LNG spills from vessels	Statistical – Oil spill data	Statistical	Gaussian plume	Cookie cutter	LNG	Population
14.	Vessel Cargo Spill Probability	Woodward Lundgren	Corps of Engineers	Deepwater port oil spill risk	Bayesian statistics using questionnaires	Bayesian statistics using questionnaires	N/A	N/A	Oil	N/A
15.	Offshore Oil and Gas Envir Assessment	Devanney & Stewart, MIT	Council on Environmental Quality	Oil spills from offshore pipelines, platforms & tankers	Bayesian statistics (distributional)	Bayesian statistics (distributional)	Spill trajectory simulation	N/A	Oil	Coastline
16.	Tanker Spill Analyses	Porricelli & Kieth, J.J. Henry, etc.	Coast Guard	Oil tanker spills (world wide)	Statistical summary of tanker casualties	Statistical summary of spills	N/A	N/A	Oil	N/A
17.	SOHIO West Coast Pipeline Project	Socio Economic Systems	Cal. Public Utilities Comm.	EIS for pipeline project for Long Beach	Statistical	Statistical	N/A	N/A	Oil	N/A
18.	Risk of Transporting Plutonium	Battelle	ERDA	Transportation of plutonium by truck	Fault tree	Fault tree	Gaussian plume	Cookie cutter	Plutonium	Population
19.	Integrated Risk Analysis System	University of S. Cal	DOT	Transportation by road & rail of hazardous material	Statistical	Statistical	N/A	Statistical	All	Population and property

Table 1. Summary of Risk Assessment Studies (continued)

					METHODOLOGY				
STUDY	PREPARER	SPONSOR	APPLICATION	CASUALTY PROBABILITY	SPILL PROBABILITY	SPILL PHENOMENA	CONSEQUENCES	CARGO TYPES	RESOURCES AFFECTED
20. Risk Model for Transport of Hazardous Materials	Holmes & Narver	Dept. of the Army	Transport of biological weapons	Fault tree	Fault tree	Gaussian plume	Distributional	Biological weapons	Persons, animals and property
21. Statistical Curve Fitting of Oil Spill Data	Rensselaer Polytechnic Institute	Coast Guard	Oil spill sizes	N/A	Statistical (distributional)	N/A	N/A	Oil	N/A
22. Oil Spill Risk Analysis for Mid-Atlantic Area	U.S. Geological Survey	U.S. Geological Survey	Risk to coastal areas from offshore oil spills	Bayesian statistics (Devanney & Stewart)	N/A	Spill trajectory simulation	Distributional	Oil	Coastal ecology & recreational areas
23. Management Oversight Risk Tree (MORT)	Aerojet Nuclear Co.	AEC	Risk reduction	Fault tree	N/A	N/A	Logic tree	N/A	Population
24. Generic Environmental Impact Assessment	Sandia	NRC	Environmental impact of radioactive material transport	N/A	N/A	N/A	Cookie cutter	Radioactive material	Population
25. Probability of Collision of Selected Routes	G.G. Sharpe, Inc.	MARAD	Collisions between nuclear VLCCs and other vessels	Kinematic	N/A	N/A	N/A	All	N/A
26. Grounding Probability Studies	G.G. Sharpe, Inc.	MARAD	Grounding of nuclear-powered cargo ships and tankers	Statistical	N/A	N/A	N/A	Bulk and dry cargo	N/A
27. Ship Operations in Restricted Waterways	Science Applications, Inc.	MARAD	Evaluate risk reduction techniques and improve operational efficiency	Simulation	N/A	N/A	N/A	General	N/A
28. Draft Vessel Traffic Analysis	John J. McMullen Assoc.	California Public Utilities Commission	Environmental impact report for Point Conception LNG Terminal	Simulation	N/A	N/A	N/A	LNG	N/A
29. Hazards of Spills of Anhydrous Ammonia on Water	A. D. Little, Inc.	Coast Guard	Prediction of anhydrous ammonia spill hazards	N/A	N/A	Analytic Models and experiments	N/A	Anhydrous ammonia	N/A
30. Computer Simulation Technique for Oil Spills	Coast Guard R&D Center (Lissauer, et al)	Coast Guard	Predict movement of oil spills along New Jersey-Delaware Coast	N/A	N/A	Computer simulation—deterministic	N/A	Oil	N/A
31. Mathematical Model for Predicting the Transport of Oil Slicks	Battelle Pacific Northwest Laboratories	—	Predict oil spill movement for spills in the Strait of Georgia	N/A	N/A	Computer model with stochastic and deterministic modes	N/A	Oil	N/A
32. Predicting the Fate of Oil in the Marine Environment	Texas A&M (Williams, et al)	SEADOCK Deepwater Port	Movement of oil spills in area of the SEADOCK Deepwater Port	N/A	N/A	Stochastic model	N/A	Oil	N/A
33. Coastal Effects of Offshore Systems	Office of Technology Assessment	Office of Technology Assessment	Impact of oil spills from offshore developments	Statistical (distributional)	Statistical (distributional)	N/A	N/A	Oil	N/A
34. Feasibility of Delphi Technique for Risk Estimation	University of S. Cal.	Department of Transportation	Risk of transporting hazardous materials	Subjective	Subjective	Subjective	Subjective	Hazardous materials	N/A

TABLE 2. RISK ASSESSMENT STUDIES EVALUATED

A. Spill Risk Analysis -- Operations Research, Inc.

B. Vessel Safety Model -- Transportation Systems Center

C. Risk Assessment for LNG Terminal at Matagorda Bay -- Federal Power Commission

D. LNG Terminal Risk Assessment Study for Point Conception, California -- Science Applications, Inc.

E. Vulnerability Model for Damage Assessment -- Enviro Control, Inc.

F. Cargo Spill Probability Analysis for the Deepwater Port Project -- Woodward-Lundgren and Associates

G. Offshore Petroleum Transfer Systems for Washington State -- Oceanographic Institute of Washington

H. LOOP Deepwater Port Oil Spill Risk Analysis -- A. D. Little, Inc.

I. Spill Probability Analysis for Outer Continental Shelf Environmental Assessment -- Massachusetts Institute of Technology

J. Oil Spill Trajectory Studies for Outer Continental Shelf Environmental Assessment -- Massachusetts Institute of Technology

K. Oil Transport Model for SEADOCK -- Texas A & M

L. The Reactor Safety Study -- Nuclear Regulatory Commission

STUDY	PREPARER	STATISTICAL	ANALYTICAL	SIMULATION	FAULT TREE	SUBJECTIVE	CASUALTY REPORT
SPILL RISK ANALYSIS	ORI		X				X
LNG TERMINAL RISKS	FPC	X					
LNG TERMINAL RISKS	SAI		X				
VESSEL SAFETY MODEL	TSC			X			
CARGO SPILL MODEL	W-L				X		
OFFSHORE PETROLEUM TRANSFER	OIW	X					
LOOP STUDY	ADL	X	X				
OUTER CONTINENTAL SHELF STUDY	MIT	X					
REACTOR SAFETY STUDY	NRC				X		

TABLE 3. CASUALTY PROBABILITY APPROACHES FOR NINE STUDIES

All models in the list address some aspect of vessel casualties except the Reactor Safety Study which treats risks of nuclear power plants. This study is included primarily because it is the most complete and detailed application to date of the fault/event tree approach to risk assessment.

As stated in the introduction to this report, the risk management methodology to be developed by this project must address spills of hazardous cargoes such as oil, LNG, chlorine, anhydrous ammonia, etc. Three types of models have been applied to assessing the effects and damage from such spills: (1) oil slick movement models, (2) models for specific hazardous chemicals such as LNG or anhydrous ammonia, and (3) models that treat a variety of hazardous chemicals whose spills can result in toxic or flammable clouds, pool fires, or explosions. The studies selected for this report cover spill effects models of each category.

III. DESCRIPTION OF THE RISK STUDIES

This section contains descriptions of the 12 studies selected for the survey. Some of the studies developed general methodologies for risk assessment while others analyzed risks for specific proposed developments such as LNG terminals or deepwater ports.

Each description briefly outlines the risk methodology utilized for the study. Applications of the methodology are discussed next in terms of analyses performed with the methodology and possible additional analyses. Data used or required for the model are listed next, followed by a brief list of the types of output. Computer requirements, if any, are described thereafter.

Each methodology is evaluated in the context of its particular purpose. Following this, possible application to the Coast Guard's risk assessment goals is addressed. Two types of risk assessment are considered:

- Estimating risks of existing or proposed marine developments such as LNG import terminals or deepwater ports.
- Evaluating probable impacts of proposed marine safety measures on risks (generally as inputs to cost-benefit analyses).

The symbols and notations used in the study summaries are taken directly from the study reports and were not revised for this report. Thus, the notation is not necessarily consistent between the studies.

A. Spill Risk Analysis

1. Documentation

Malcolm Fortson, et al., Maritime Accident Spill Risk Analysis Phase I: Methodology and Planning (Operations Research, Incorporated, prepared for the U.S. Coast Guard, February 1973).

William A. Dunn and Pierre M. Tullier, Spill Risk Analysis Program Phase II: Methodology and Demonstration (Operations Research, Incorporated, prepared for the U.S. Coast Guard, August 1974).

L. A. Stoehr, et al., Spill Risk Analysis Program: Methodology Development and Demonstration, 2 Volumes (Operations Research, Incorporated, prepared for the U.S. Coast Guard, April 1977).

2. Purpose

The purpose of this study performed for the U.S. Coast Guard was to develop a formal system for evaluating the effectiveness of proposed merchant marine safety programs in reducing vessel casualties. This was accomplished by estimating the change in risk expected to result from a proposed safety measure.

3. Scope

The study effort resulted in the development of two methodologies that can be applied to the analysis of vessel casualties. One of the methodologies, an analytic model, applies only to collisions while the other can be applied to any type of vessel casualty. Several cases were evaluated with these methodologies to demonstrate their applicability.

4. Methodology

Two methodologies were developed in the study. An analytic model (scenario) was developed that expresses the probability of ship collisions in terms of the physical parameters of the system - vessel size, speed, maneuverability, etc. A logical model (quasi-experimental method) was developed that applies a structured approach to evaluating casualty reports to estimate the effect of a proposed safety measure.

a. Scenario Model (Analytic Model)

The scenario model is a geometric model based upon the concept of a "collision region." A collision region for a ship relative to another ship is the locus of all possible positions of that ship where collision with the other ship is unavoidable. Two ships at a time are treated in the model.

The size of a collision region is a function of vessel characteristics such as speed, deceleration rate, response time, turning radius, and scenario parameters such as track separation.

Several submodels were developed. These are:

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- Parallel meeting and overtaking in a restricted channel.
- Long range crossing (open waters).
- Sudden appearance crossing.
- Head-on meeting.
- Energy exchange.
- Hull rupture.

For the parallel meeting and overtaking situation, the following assumptions apply:

- Collisions in a channel are caused by one of a pair of vessels turning across the path of the other.
- The probability of making this turn maneuver error is equally likely at all points along the ship's path (i.e., constant rate).

For two vessels in meeting or overtaking situation, the probability of collision is the probability of one of the vessels making an error turn and is given by:

$$P(C) = 1-\exp\left[-q\left(\frac{V^1 CR^1 + V^2 CR^2}{V^1 + V^2}\right)\right]$$

where:

V_i = Velocity of vessel i.
CR_i = Length of critical region for vessel i.
q = Turn error rate per unit distance traveled.

In order to calculate the probability that a collision results in a spill, the energy exchange and hull rupture submodels are applied. The energy exchange submodel computes the energy from a collision available for deforming the struck vessel's hull. The collision is assumed to be inelastic and the striking vessel is assumed not to absorb any of the dissipated energy.

The total energy of a collision depends upon the masses and velocities of the two vehicles. The amount of deformation energy is the total energy minus the linear and rotational energy components. The latter are based on the masses and velocities of the two ships and the point of impact on the struck ship.

The hull rupture model computes the probability of a spill from the collision energy. The energy required to rupture the hull (strain energy) is a required input. The model selects N points at uniform intervals along the hull and the deformation energy is computed at each point using the energy exchange model. The deformation energy is compared at each point with the strain energy. The probability of rupture given a collision occurs is then:

$$P(R) = \frac{N_R}{N}$$

where N_R is the number of times the deformation energy exceeds the strain energy for N collision points.

The long-range crossing submodel treats two vessels in a collision course. The model determines the latest time for the privileged vessel to begin maneuvering to avoid the collision. The solution of the geometric problem is based upon the ship's turning characteristics and velocity.

The sudden appearance scenario analysis determines how late a vessel may discover that it is on a collision course and still safely maneuver to avoid collision. Essentially, the same model is used as in the long-range crossing scenario.

Finally, the head-on scenario treats two vessels having reciprocal headings on the same track. The model determines the range at which one vessel must begin a turn in order to miss the other vessel.

b. Quasi-Experimental Method (Logical Model)

The quasi-experimental method (QEM) is a formalized technique for deriving qualitative information from narrative material. The method involves several steps. The discussion that follows pertains to vessel collisions, although the methodology could be applied to any type of casualty. First, a set of conditions for a collision-free encounter is developed based upon an analysis of a small sample of collision reports. Based on these conditions, a series of collision event diagrams are constructed which outline the various sequences of events that can lead to a collision. At least one of these events contradicts a condition for a collision-free encounter. From this series of event diagrams, a detailed safety analysis logic tree is constructed. This tree, similar to a fault tree, shows the various logical paths to a collision.

At this point, the methodology applies generally to vessel collisions. To evaluate a specific safety measure, such as a bridge-to-bridge radiotelephone system, a series of

questions, termed a Casualty Analysis Gauge, are developed from the logic tree. These questions are designed to establish whether the conditions and actions possible during the event described in a casualty record are such that the safety measure could have been effective; that is, could the collision have been avoided.

The Casualty Analysis Gauge is used to eliminate as much subjectivity as possible in evaluating the casualty reports.

5. Applications

a. Scenario Model

The Scenario Model was exercised to show the sensitivity of the results to changes in various input parameters. The majority of the exercises were made with the meeting and overtaking scenarios. The measure of effectiveness was percent change in collision frequency. Parameters varied included track separation, response time, deceleration capabilities, maneuverability, and ships' speeds. The exercises were performed for a pair of ships of the same type in a generalized waterway model. Various maneuvers were tested using the long-range crossing model with the latest time to begin a maneuver to avoid collision as the measure of effectiveness.

A sensitivity exercise was performed using the head-on meeting scenario with speed and maneuverability parameters varied.

Examples of possible model applications noted in the study final report include evaluating speed restrictions on hazardous cargo ships within a harbor, prohibitions on ships above a certain size entering a channel segment during a hazardous cargo ship passage, and prohibitions of ships overtaking hazardous cargo ships in certain areas.

b. Quasi-Experimental Method

The Quasi-Experimental Method was applied to three analyses:

- Effectiveness of a bridge-to-bridge radiotelephone system.
- Effectiveness of a collision avoidance radar system.
- A determination of collision causes.

For the bridge-to-bridge radiotelephone system, a sample of 436 collision reports covering the years 1964-1974 was analyzed by two independent researchers. Of these, agreement was achieved in 428 reports or 98 percent of the sample. The results indicated that bridge-to-bridge radiotelephone could have significantly decreased the collision rate. However, the rate decreased significantly after 1970, indicating the system came into wide use before the regulation requiring it was put into effect in 1973.

The collision avoidance radar system evaluation was performed with a sample of 198 collisions in which at least one vessel was 10,000 gross tons or more. The Casualty Analysis Gauge for this analysis consisted of 16 questions and required an average of 15-20 minutes to complete. The results indicated a possible decrease in collisions of 10-13 percent. There was an agreement between the two analysts in 97 percent of the cases.

The collision cause analysis was performed for a sample of 436 collision reports (the same sample as used for the bridge-to-bridge radiotelephone analysis) and a sample of 198 reports involving collision of larger vessels (the same sample as used for the collision avoidance radar analysis). The casualty analysis gauge consisted of 30 questions. The results indicated that for 80-90 percent of the collisions human factors, either rule violations or judgment errors, contributed to the accident.

6. Data Requirements

a. Scenario Model

The parameters required for the parallel meeting and overtaking collision scenario include:

- Vessel Characteristics - length, width, weight, pivot point, crabbing angle, strain energy (full hull rupture).
- Response - acceleration, deceleration, response times, turning radius, response maneuver.
- Scenario - initial speeds and courses, track separation.
- Turn error rate.

b. Quasi-Experimental Method

For this model, the Coast Guard's Vessel Casualty Reports were used. These reports, generally completed by the vessel masters and reviewed by Coast Guard personnel, include narrative summaries of the accident as well as information on the ships involved.

7. Outputs

a. Scenario Model

The primary outputs of the Scenario Model are the probability of collision and probability of hull rupture for the meeting and overtaking scenarios. For the long-range crossing, sudden appearance and head-on scenarios, the latest time and distance to begin maneuvers to avoid a collision are the primary outputs.

b. Quasi-Experimental Method

The primary output of the Quasi-Experimental Method is the expected percentage reduction in casualties from a specified safety measure.

8. Computer Requirements

The Scenario Model has been programmed in FORTRAN IV and has been run on an IBM 360/65 computer. A listing of the program is incuded in the 1977 final report.

9. General Evaluation

a. Scenario Model

The model is a relatively simple representation of a complex situation, namely a collision between two ships. Insight into the effects of varying such parameters as ship maneuverability can probably be gained using this model, as is indicated in the report. However, complex interactions such as those involving communications between ships are beyond the scope of this model. For that reason, evidently, the Quasi-Experimental Method was developed.

A problem with using the model to evaluate spill probabilities is that the value of each ship's strain energy (energy required to rupture the hull) must be determined by the user. Also, the strain energy is assumed constant along the ship's hull whereas in reality, as noted in the study report, it will vary according to location.

b. Quasi-Experimental Method

As pointed out in the ORI report, there are several problems associated with the application of the model. First, the results of the model represent the ideal; that is, the maximum effect assuming full and correct usage of the safety regulation. This is evident in the evaluation of the bridge-to-bridge radiotelephone system. In several cases where collisions were judged preventable by the system, the ships actually had the system installed and it was used.

Second, the analysis depends upon the completeness and accuracy of the casualty reports. Biases and errors in these will, of course, be reflected in the results. This is true of any methodology based upon historical data.

A more serious problem is the time required to perform the analysis. The Casualty Analysis Gauge for the collision avoidance system consisted of 16 questions. It was estimated to take an analyst 15 to 20 minutes to analyze a casualty report. The sample of 198 casualty reports for this evaluation thus required about 70 hours per analyst or about 17 man-days for the two analysts who reviewed the reports (each analyst reviewed all reports and the results were compared). An additional effort was required to develop the Casualty Analysis Gauge and analyze the results. The study report indicated that the time required per casualty report increased geometrically with the number of questions.

In spite of these problems, the method is a logical approach to solving the very difficult problem of estimating the possible effects of proposed vessel safety measures. It appears to succeed in removing much of the subjectivity in analyzing casualty reports by using the Casualty Analysis Gauge concept. The results for the two safety measures evaluated indicated agreement between two independent analysts of 97-98 percent.

10. Applicability to Coast Guard Needs

Both models were developed to aid in evaluating vessel safety measures. They are based upon estimating the relative change is casualties rather than in the absolute amount of decrease in casualties or casualty probability. Thus, in order to apply the models to cost-benefit analysis, other means must be used to determine the baseline numbers of casualties or casualty probability that a safety measure would affect so that a value for the benefit can be derived.

The Scenario Model is quite limited in scope, addressing only collisions. Evaluation of other types of casualties such as rammings and groundings would require additional models.

The Quasi-Experimental Method is general enough so that it can be applied to any casualty type for which there is sufficient historical information. As applied in the study, the method did not explicitly address spills. This is evidently because the data source, the Vessel Casualty Reporting System, does not generally record spills.

B. Vessel Safety Model

1. Documentation

D. T. Kahn, J. Woodward Talbot, Vessel Safety Model (Transportation Systems Center, prepared for the U.S. Coast Guard, January 1974).

Volume I: Analytic Development
Volume II: Users' Manual
Volume III: Programmers' Manual

2. Purpose

The Vessel Safety Model is a computer simulation program developed by the Transportation System Center of the Department of Transportation for the U.S. Coast Guard. Its purpose is to aid in the analysis of the effects of ship design, navigation aids, and regulatory practices on vessel safety.

3. Scope

The model computes the probabilities of vessel collisions and groundings in restricted waterways, based upon simulated ship tracks, waterway boundaries, and bottom contours. Spill probabilities are not included.

4. Methodology

The model is described in Volume I of the Final Report of the study. Volume II comprises the program Users' Manual and Volume III the Programmers' Manual. The model is a set of vessel motion equations and probability equations along with the general logic needed to perform the analysis. This discussion will outline the methodology as implemented in the program, which is not identical to that described in the analytic development volume (volume I).

The model simulates vessel movement in a restricted area. Vessel tracks may be specified in terms of velocity, heading, and length of track segment or by initial speed and heading and a series of commands: straight ahead at constant speed, accelerate, decelerate, turn left or turn right. If tracks are specified, the program translates the data into a series of commands. The simulation is performed in a series of time steps. Ship motion equations are solved for still water and air conditions (no wind or current effects) based upon the ship characteristics. The effects on ship motion of shallow water, hydrodynamic interactions between ships, or bank suction are not addressed in the model.

For each time period the probability of collision is calculated for each pair of ships. This probability is based on Gaussian distributions for the position errors about the vessel path. The standard deviations for the distributions, which are equal for the two directions,

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are developed from three input parameters: on-board navigation capability index (feet), human factor index (ratio) and harbor navigation index (ratio). The first two indices are specified for each ship and the third is specified for the problem being simulated. The probability of collision over an interval is determined by computing the probability that the distance between the two vessels is less than half the sum of the ship lengths plus the sum of the distances traversed by the two ships during the time interval. This is meant to reflect the distance at which the collision cannot be avoided.

The probability of grounding during a time interval is computed by determining the probability that the ship remains at least a distance from a grounding contour equal to one-half the ship's length plus the distance the ship moves during the interval. The grounding contour is based on the ship's safe sailing depth and the harbor bottom as specified by program inputs. The same position error parameters are used as in the collision probability computation.

In summary, the model simulates the tracks of a number of ships and computes the probabilities of collision and grounding. It does not simulate the collisions or groundings.

The report discusses some possible extensions to the program. First, more exact motion equations could be implemented. Such equations were developed for the Coast Guard by the Stevens Institute of Technology.[1] The Stevens equations express maneuvering performance of ships, reflecting the forcing functions due to rudders, propellers, water depth and control. Effects of side banks and shallow water are included, as well as wind and current forces. The results were correlated with full-scale trials on a tanker.

The program could, with some additional programming, be made to operate in an interactive mode so that the analyst could make changes in a ship's track based upon information on other ships in the area. Because of the structure of the program, this change would not require significant programming.

5. Applications

The calibration of the model was performed by simulating an actual vessel casualty incident in San Francisco harbor. The exercise showed that the motion equations performed reasonably well. However, no extensive validation exercises were run because of lack of time and funds.

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[1] H. Eda, Vessel Maneuvering Simulation (Stevens Institute of Technology, prepared for the U.S. Coast Guard, July 1976).

The report lists several possible analyses that could be conducted with the program:

- Alternative ship control subsystem designs.
- Alternative rules-of-the-road.
- Utilization of an autopilot.
- Navigational aids.
- Utilization of a collision avoidance system.
- Ship-to-ship communications.
- Vessel traffic services.
- Adverse weather.
- Component reliability.

It is not clear from the report, but it appears that the first four of these could be performed with the current program, requiring only changes in the position error factors or the track commands while the last five would require additional programming.

6. Data Requirements

Data used by the program include:

- Ship characteristics - length, beam, draft, maximum speed, horsepower (ahead and astern), displacement, windsail characteristics, response time, maximum rudder angle, and turning velocities.
- Harbor geometry and depth - coordinates of line segments delineating the harbor boundaries and bottom contours.
- Ship paths - initial speed and heading and a series of commands or speeds, headings, and track lengths for a series of track segments.
- Navigation and human factors indices which generate the position error distribution parameters.

7. Outputs

Data printed from a simulation run can include, for each time interval:

- Position of each ship.
- Cumulative probability of collision for each pair of ships.
- Cumulative probability of grounding for each ship.
- Distance between each pair of ships.

At the end of the run a frequency distribution can be printed which indicates the number of times ships come within various distances of each other. The point of closest approach can also be printed.

A routine is also available which plots the ships' tracks and harbor boundaries using a CALCOMP plotter.

8. Computer Requirements

The program is written in FORTRAN IV and has been run on the PDP-10, model KA. The ratio of real time to computer time was 24 to 1 with the probability collision calculation, 3.5 to 1 with the probability of grounding calculation, 2.5 to 1 with both calculations, and about 60 to 1 with ship movement simulation only. Model KA is a relatively slow version of the PDP-10 computer; the program has run significantly faster on later versions.

9. General Evaluation

The Vessel Safety Model is a relatively simple simulation program. As stated in the study report, it has been calibrated with some data from the Port of San Francisco but not validated. To achieve validation would require more precise input data and more extensive computer runs. Although the motion equations do not take into account effects of wind, current, shallow water, and side banks, they may be adequate for many applications of the model. The probability calculations depend primarily upon the error factors, which are program inputs. The selection of the values for these parameters is not an easy task since they are not directly relatable to ship control functions.

10. Applicability to Coast Guard Needs

The model might prove useful in assessing the effectiveness of certain types of proposed safety measures. However, it appears that some changes and additions in the program would be necessary to accomplish many such evaluations, as noted above. Complex interactions between ships would be difficult to handle with the currently implemented concept of determining collision and grounding probabilities. This is because the probabilities are not derived from simulated variations in ship movement but rather from statistical calculations based on the nominal track. On the other hand, simulating the variations in the ship tracks in a Monte Carlo mode would require a substantial number of runs to achieve a statistically valid sample of collisions and groundings. This could be quite expensive in terms of computer time.

C. Risk Assessment For An LNG Terminal At Matagorda Bay

1. Documentation

Matagorda Bay Project - Final Environmental Impact Statement. Federal Power Commission, September 1977.

2. Purpose

The study analyzed risks to the public due to marine transportation of liquefied natural gas. It formed part of the environmental impact statement for the proposed LNG import terminal at Matagorda Bay, Texas.

3. Scope

The probability of LNG spills from vessel casualties and their consequences in terms of expected public fatalities per year were addressed. Only collisions, rammings, and groundings were considered as possible causes for LNG spills from ships.

4. Methodology

The expected number of fatalities per year was computed from the following events.

(1) Annual probability of a casualty to an LNG tanker while in transit.

(2) Probability of an LNG spill in the event of a casualty.

(3) The formation of a flammable vapor cloud or pool fire from the spilled LNG.

(4) Expected fatalities from exposure to a flammable cloud or radiation from a pool fire.

a. Casualty and Spill Probabilities

The casualty probability was based upon fitting a regression line to tanker casualty and tanker trip data for four ports along the Texas Gulf Coast. The resulting rate was 4.6×10^{-3} tanker casualties per trip. This compares favorably with the regression results of 4.4×10^{-3} casualties per trip for 7 U.S. port areas documented in the study for Washington state (discussed in subsection III.G).

The casualty probability was partitioned into collision, ramming, and grounding factors based on the tanker casualty statistics in the Texas Gulf Coast area.

The general methodology applied by the FPC includes a casualty reduction factor for vessel traffic services based on a Coast Guard study.[1] However, since no vessel traffic services were envisioned for this application, the factor was not applied.

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[1] U.S. Coast Guard, Vessel Traffic System Analysis of Port Needs (August 1973).

The probability of a spill given a casualty was computed separately for each of the three casualty types. From worldwide analysis of tanker casualty data,[1,2] percentages of casualties resulting in spills were tabulated.

To account for differences between LNG and oil tankers, several factors were applied to the spill probabilities. Only spills of one LNG tank were considered as plausible. The double-hull construction of LNG tankers was estimated to reduce the spill probability of 85 percent for groundings and 25 percent for collisions, based on results of tanker casualty analyses.[3,4] Lateral bow thrusters and forward structural separation, which are design features of LNG tankers, were assumed to result in an 85 percent reduction in spills from rammings.

b. Consequences of a Spill

An LNG spill will result in a flammable vapor cloud or a pool fire. In the absence of an ignition source, a vapor cloud will drift downwind and spread in diameter until the vapor concentration becomes less than the lower flammability limit (LFL).

The FPC model results of an LFL of 0.75 mile indicated no potential hazard to the public since there were no persons living within that range of the proposed facility. However, since the authors of the Matagorda Bay study were aware of criticism that the distance was unreasonably small (see evaluation subsection), some adjustments were made in the model, a different vapor release rate was used, and a variety of wind speeds were applied that resulted in a range of LFL distances. The FPC did not necessarily agree that the model used is unrealistic, however, and these adjustments were made in the interests of conservatively estimating consequences.

Radiation hazards from pool fires were analyzed using an analytic model that expressed the distance from a fire at which heat radiation intensity falls below 5300 Btu/hour-foot^2. This distance can be computed in terms of spill size.

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[1] J. D. Porricelli, et al., "Tankers and the Ecology," Transactions of the Society of Naval Architects and Marine Engineers, Volume 97 (1971).

[2] J. J. Henry Co., Inc., An Analysis of Oil Outflows Due to Tanker Accidents, 1971-72 (November 1973).

[3] D. M. Bovet, Preliminary Analysis of Tanker Grounding and Collisions (U.S. Coast Guard, January 1973).

[4] J. P. Comstock and J. B. Robertson, Jr., "Survival of Collision Damage Versus the 1960 Convention on Safety of Life at Sea," Society of Naval Architects and Marine Engineers Transactions, Volume 69 (1969).

The study assumed a pool fire would result in 90 percent of the collisions and rammings because of resulting sparks. None of the groundings was assumed to result in pool fires. For cases where no pool fire results, the probability of igniting the vapor cloud as a function of distance from the spill was computed based on the population density. The total expected number of fatalities was computed by summing expected fatalities over all ignition source locations within the cloud lower flammable limit, taking into account the probability of ignition at each source.

The results for pool fires and cloud fires were combined with the appropriate probabilities to yield the total expected casualties per year and the probability of fatality per exposed person per year.

5. Applications

The FPC, now the Federal Energy Regulatory Commission of the Department of Energy, has used this general approach to environmental impact statements for proposed LNG import facilities in Oxnard, Los Angeles, Point Conception, and other U.S. locations.

6. Data Requirements

Casualty data for tankers were obtained from the Coast Guard's Vessel Casualty Reporting System. Exposure data were obtained from the Waterborne Commerce of the United States published by the U.S. Army Corps of Engineers.

Spill probabilities were developed from analyses of Worldwide Tanker Casualty data, derived from Lloyd's Weekly Reports.

Weather data for the LNG vapor cloud model were obtained from the National Weather Service's STAR data base for the Corpus Christi area.

7. Outputs

The primary model outputs are:

- Expected public fatalities per year.
- Probability of fatality per exposed person (person within potential hazard area) per year.

The measures were compared with risks from other man-made and natural sources.

8. Computer Requirements

The report does not reference any computer programs used for the study.

9. General Evaluation

The phenomenology of LNG vapor clouds is under dispute. The FPC uses a model that assumes neutral atmospheric stability values and which lead to much smaller LFL distances

than other LNG vapor cloud models. As discussed in a recent report by Jerry Havens assessing seven LNG vapor cloud models,[1] the FPC model resulted in a maximum distance to the LFL of 0.75 miles while the results of the other models ranged from 1 to 2 miles to 50 miles, with an average of about 10 to 15 miles.

Haven's evaluation concluded that the FPC model uses an unrealistically low vapor release rate (this was changed for this study) and neutral atmospheric stability characteristics, which he concluded were not justified.

The use of oil tanker casualty and spill data for LNG tankers can be justified on the basis of the paucity of casualty data for LNG tankers. The adjustment factors applied to the spill rates, based on analyses of tanker collisions and groundings, seem reasonable.

10. Applicability to Coast Guard Risk Assessment

The approach used by the FPC can be applied to the problem of assessing risks, assuming conditions are comparable to those for which the historical data pertain. It would not generally be useful for evaluating a proposed safety measure since historical data does not usually reflect the conditions that would exist under the measure.

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[1] Jerry Havens, Predictability of LNG Vapor Dispersion From Catastrophic Spills Into Water: An Assessment (U.S. Coast Guard, April 1977).

D. Risk Assessment For An LNG Terminal At Point Conception, California

1. Documentation

LNG Terminal Risk Assessment Study for Point Conception, California, Science Applications, Inc., prepared for Western LNG Terminal Company, Los Angeles, California, January 23, 1976.

2. Purpose

The purpose of the study performed for the Western LNG Terminal Company was to determine the level of risk from operation of a liquefied natural gas terminal at Point Conception, California. The report provided informational material for Western LNG Terminal Company's submission for approval to construct and operate the proposed terminal.

3. Scope

The study addressed LNG spill risks to the public located in proximity to the proposed site caused by:

- Normal operations - tankship, transfer system, storage tanks.
- Natural events - severe winds, earthquakes, tsunamis, and meteorites.
- Ship collisions.
- Airplane and missile impacts on the facility and vessels.

4. Methodology

Since this survey report is primarily concerned with the deleterious effects of vessel casualties, only the ship casualty portion of the SAI study will be described.

Only ship collisions were evaluated; rammings and groundings in the port area were not considered to generate enough force to cause tank ruptures.

To estimate the probability of a collision involving an LNG tanker, a collision model was developed. This model predicts the probability of two ships colliding in a given zone. The model is essentially geometric, being based on the ship speeds, headings, positions, and dimensions and the zone dimensions. The ships are assumed to move randomly within the zone.

The expected number of collisions per year for random motion within a zone is given by:

$$C_i = \frac{1}{\pi Y} \sum_{j=1}^{N-1} \left[\frac{w_i}{v_j} \left(2 \cos^{-1} \left(-\frac{V_i}{V_j} \right) - \pi \right) + 2 \frac{w_i}{V_i} \sin \cos^{-1} \left(-\frac{V_i}{V_j} \right) + \frac{w_j}{V_i} \pi + 2 \frac{\ell_i}{V_i} + 2 \frac{\ell_j}{V_j} \right] \quad (7)$$

for $V_j \geq V_i$

where:

W_i = Width of ship i.

ℓ_i = Length of ship i.

V_i = Velocity vector for ship i (feet per second).

N = Number of transits per year through the zone.

Y = Number of seconds per year.

If α is the fraction of the time that a ship behaves randomly in the zone of interest, the probability of a collision involving a specified LNG ship is approximately:

$$C_i^{(\alpha)} = 2\alpha C_i \tag{8}$$

and the total number of expected collisions for N transits is given by:

$$C^{(\alpha)} = \frac{1}{2} \sum_{i=1}^{N} C_i^{(\alpha)} \tag{9}$$

The collision parameter α was determined by calibrating the model to collision data obtained from 7 U.S. ports over a 6-year period. These data showed 7 collisions for 554,400 transits of ships greater than 1,000 tons.

Spill probability was derived from a theoretical method by V. U. Minorsky[1] for calculating ship penetration. The method involves computing the effective kinetic energy of the collision and the resistance of the ship's structure. The probability of cargo tank rupture was computed by comparing the normal component of the striking ship's velocity with a threshold velocity based on the energy equation and the ship's strength. This was computed for ships of various types travelling at various speeds and averaged to derive the overall probability of tank rupture from a collision. The results given in the report indicate an LNG ship collision probability of about 7×10^{-6} per year and a probability of 0.25 of a spill resulting in the event of a collision.

SAI has developed a pair of computerized models for predicting the dynamics of LNG vapor clouds. One model, termed SLICE, is a steady-state hydrodynamic representation of a

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[1] V. U. Minorsky, "An Analysis of Ship Collision With Reference to Protection of Nuclear Power Plants," Journal of Ship Research (The Society of Naval Architects and Marine Engineers, Volume 3, No. 2, October 1959).

vapor cloud valid for small spills, in which gravity spread velocities are less than the average wind speed.

For large spills, where gravity spread velocities are at least as great as the average wind speed, a three-dimensional time-dependent hydrodynamic model, called SIGMET 3-D, was developed. The model accounts for mass, momentum, and energy associated with an LNG spill. The set of differential equations are solved by a computer program using finite difference methods.

Ignition of an LNG vapor cloud depends primarily upon the ignition sources and vapor/air concentration. The vapor cloud model was used to predict the range from a spill of the cloud's lower flammable limit (LFL). Estimates of the number of ignition sources were based upon population density and a probability of ignition per source was assumed to be 10 percent. The overall probability of ignition was then developed for the LFL range of the cloud.

Thermal radiation effects for pool fires were analyzed by application of geometric relationships for thermal radiation flares at the receivers. Propagation of a flame throughout a vapor cloud was analyzed to determine the thermal radiation from the cloud. The radiation fluxes to targets outside the cloud were computed on a time-dependent basis and integrated over the appropriate timespan.

Fatalities were used as the measure of the consequences of the spills. Population at risk was determined from Bureau of Census data as a function of distance from the site.

5. Applications

The models and general approach to assessment of LNG risks have been applied by SAI to a number of other studies, including analyses of proposed LNG terminals at Los Angeles and Oxnard, California, and Everett, Massachusetts.

6. Data Requirements

Data for the study were obtained from the following sources:

- Ship collisions - U.S. Coast Guard Vessel Casualty Reports
- Ship traffic - Waterborne Commerce of the United States.
- Meteorological (for vapor cloud model) - National Weather Service STAR data.

7. Outputs

The primary outputs of the study were the expected number of fatalities from LNG spill fires.

8. Computer Requirements

The vapor cloud models have been run on a CDC 7600 computer. The more complex of the two models, SIGMET 3-D, requires 300,000 words of storage and approximately one-half hour of computation time for a typical case.

9. General Evaluation

The methodology used in the study is documented clearly and in detail. The analytic collision probability models, like most other such models, assume random ship motion within a specified zone. Historical data are then applied to calibrate the model. The validity of a random motion model is open to question and, in terms of magnitude, the calibration factor tends to override the resulting collision probability.

The kinetic energy model for ship collisions appears reasonable, resulting in about the same probability of spill given a collision as from historical data on oil tanker spills (see discussion of the FPC model for LNG risks).

The LNG cloud model is based upon solution of mass, momentum, and energy balance equations. Most other cloud models are based upon Gaussian vapor concentration profiles. In an evaluation of LNG vapor dispersion models,[1] Jerry Havens of the University of Arkansas showed that of 7 models analyzed, the SAI model resulted in a distance to 4 percent concentration level of 1.2 miles for a typical case, which is significantly less than the average range of 10 to 12 miles. Also, the SAI model yields larger downwind travel distances with high wind velocities, in contrast to the other models. The small distance to 5 percent concentration for the SAI model was judged by Havens to be due to the predicted highly turbulent motion and associated air entrainment induced during the gravity spread phase of the cloud, which has not been satisfactorily experimentally verified.

10. Applicability to Coast Guard Risk Assessment

The problem addressed by the study of assessing risks of proposed marine facilities is one that is common to Coast Guard interests. The analytic approach to estimation casualty probabilities is based upon a limited number of variables; thus it would not be useful for predicting the effects of proposed safety measures. The methodology for estimating spill risks, on the other hand, might be applicable to assessing safety measures involving ship structures. The computer models for predicting the cloud dynamics of LNG spills are of value for evaluating the consequences portion of the risk assessment process.

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[1] Jerry Havens, Predictability of LNG Vapor Dispersion From Catastrophic Spills Into Water: An Assessment (U.S. Coast Guard, April 1977).

E. Vulnerability Model For Damage Assessment

1. Documentation

Eisenberg, N. A., C. J. Lynch and R. J. Breeding. Vulnerability Model: A Simulation Systems for Assessing Damage Resulting From Marine Spills. CG-D-136-75, NTIS AD-A015245, prepared for Department of Transportation, U.S. Coast Guard, June 1975.

Rausch, A. H., et al. Continuing Development of the Vulnerability Model: A Simulation System for Assessing Damage Resulting From Marine Spills. Draft Final Report, prepared by Enviro Control, Inc., for the Department of Transportation, U.S. Coast Guard, February 1977.

Rausch, A. H. and C. K. Tsao. Third Stage Development of the Vulnerability Model: A Simulation System for Assessing Damage Resulting From Marine Spills. Draft Final Report, prepared for Department of Transportation, U.S. Coast Guard, Office of Research and Development, June 1977.

Rowley, R. M. and A. H. Rausch. Vulnerability Model User's Guide. Prepared for Department of Transportation, U.S. Coast Guard, Office of Research and Development, June 1977.

2. Purpose

The Vulnerability Model (VM) is a deterministic computer simulation sponsored by the Coast Guard, designed to provide quantitative measures of the consequences of marine spills of hazardous materials, flammable, detonatable, and toxic. The VM represents an extension of the Hazardous Assessment Computer System (HACS),[1] which addresses the spill phenomena but not the consequences.

3. Scope

The Vulnerability Model is a computer simulation designed to provide quantitative measures of the consequences of marine spills of hazardous materials. The model starts with a description of the nature of the spill itself, continues through the dispersion of the hazardous material, and includes assessing the immediate effects of the spill on surrounding vulnerable resources, namely, people and property (environmental damage is not considered).

The model is designed to ultimately treat any type of hazardous material carried in bulk quantities; currently the model treats liquid cargoes since these are the most significant hazardous cargoes. The materials may exist in gas, liquid, or solid phases as cargoes and may change phase upon release into the air or water environment. The

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[1] P. P. K. Raj and A. S. Kalelkar, Assessment Models in Support of the Hazard Assessment Handbook (prepared by Arthur D. Little, Inc. for the U.S. Coast Guard, January 1974).

materials may react, dissolve, or otherwise be admixed with surrounding air and water. Where appropriate, the model treats the mass transfer from a material spilled in or on the water to the air.

The VM can handle 900 chemicals in the damage-causing event simulation, as well as secondary fire formation resulting from primary fire. The model does not treat the movement of, or environmental damage caused by oil spills.

4. Methodology

The VM requires three types of descriptive data that define: (1) the material spilled, (2) the physical setting in which the spill occurs, and (3) the vulnerable resources that are subject to the effects of the spill. The spill is described in terms of its location and spill rate, the physical and chemical properties of the spilled material, and the quantity of the spill. The physical setting is described in terms of the geometric configuration of the shoreline(s), hydrologic/oceanographic properties, and meteorological data. Vulnerable resources are described in terms of demographic distribution, property distribution, and land/water use. The geographic area of concern may represent any user-defined location, a rectangular area measuring 10 miles in length and 5 miles in width being typical of anticipated applications. The physical setting and the distribution of vulnerable resources are described in terms of geographic cells that cover the area of concern.

The VM operates in two phases. Phase I simulates the spill itself, the physical and chemical transformations of the spilled substance, and its dissemination in space. This phase covers the time period from the initiation of the spill until a user-specified time has elapsed.

Phase I consists of several submodels, most of which are included in HACS, interconnected by an executive routine, with built-in logic dictating the sequence of submodel processing as a function of the spill development. Submodels depicting spill development simulate the following phenomena: (1) cargo venting, (2) surface spreading (with or without evaporation), (3) water mixing, (4) sinking and boiling, (5) air dispersion, and (6) fire and explosion. A time-history file of the spill sequence simulated during the first phase is retained in computer storage on magnetic tape and disk.

In phase II, the computer first matches this time-history file to the vulnerable resources map and assesses the effects of toxicity, explosion, and/or fire on the vulnerable resources as a function of time. Estimates of deaths and injuries to people and of damage to property are presented in computer-generated tables. Damages are summarized in the following terms:

- Toxicity
  - death
  - incapacitating injury
  - irritation
- Explosion
  - death
  - nonlethal injury
  - structural damage
- Fire
  - death
  - first-degree burn
  - building fire.

Some of the submodels had been designed previously under U.S. Coast Guard sponsorship (HACS). Others were designed specifically for the Vulnerability Model. A generalized flow diagram of the model is presented in figure 1.

5. Applications

The model has been applied to risk analyses for proposed LNG terminals at Oxnard and Point Conception, California.

6. Data Requirements

- Spill location and size and geometry of hull rupture.
- Atmospheric condition (stability class), current, and wind data for the region of the spill.
- Vulnerable resources subject to effects of spill obtainable from Census Bureau block statistics.

7. Outputs

- Time history on a cell-by-cell basis of physical consequences of spill; radiation intensity, overpressure, or toxic concentration.
- Damage assessment on a cell-by-cell basis to people (deaths and injuries and percentage thereof) and structures (monetary loss and percentage of value), printed out at end of each time increment.

8. Computer Requirements

The computer program is written in FORTRAN IV and is implemented on a CDC CYBER 175 computer.

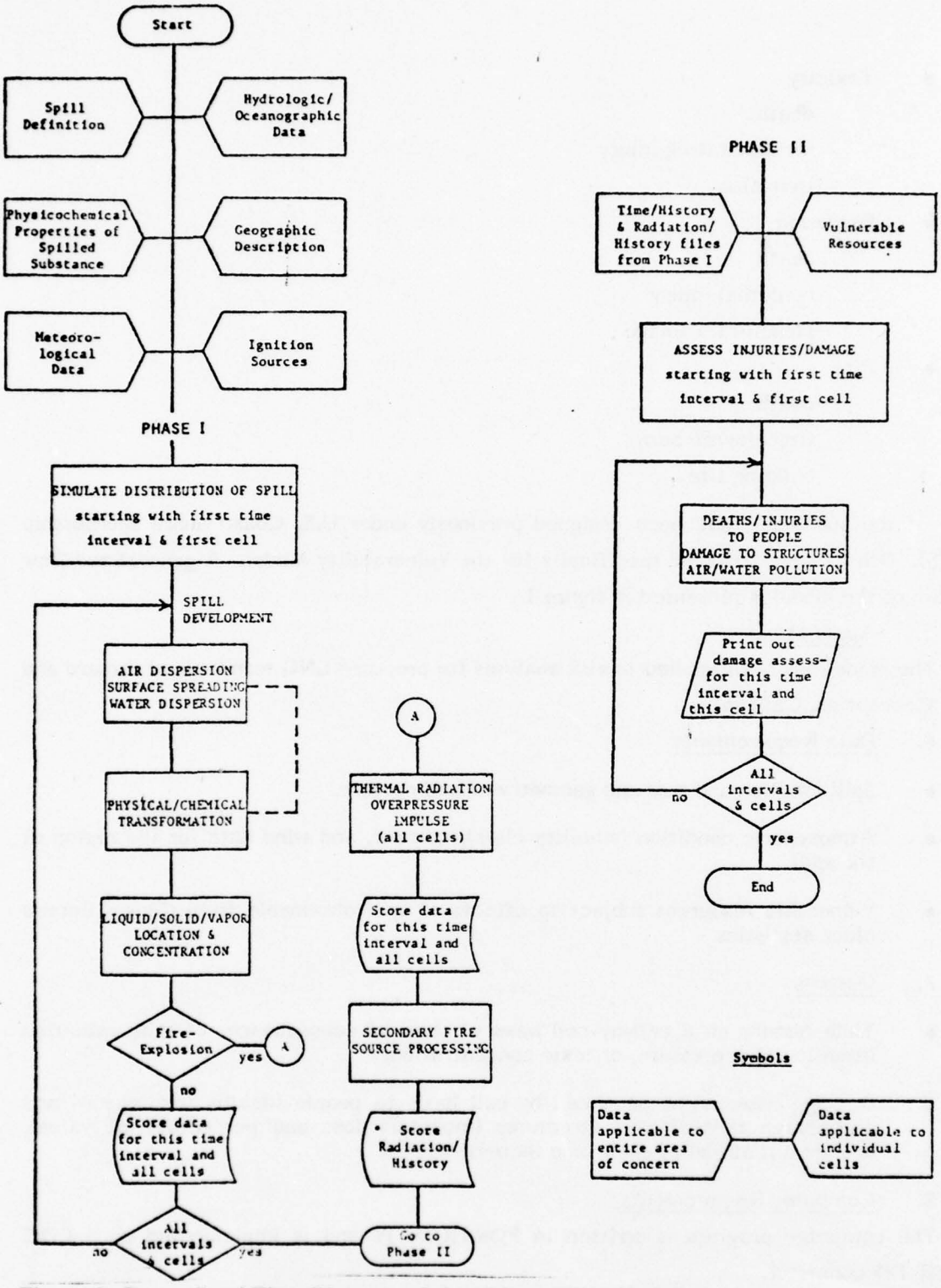

Figure 1. Generalized Flow Diagram of the Vulnerability Model

Source: Enviro Control, Inc., The Vulnerability Model for Damage Assessment of the Effects of Hazardous Spills, September 1977

9. General Evaluation

This is a complex computer model which, in essence, contains the physical scenario simulation capability of HACS plus a damage assessment capability. It has add-on capability to accommodate recent models constructed for HACS (sinking, dissolution, dispersion on and below water of insoluable and soluable chemicals) plus a secondary fire capability that HACS does not have. It represents the most extensive hazardous chemical spill model developed to date.

The physical assumptions upon which the physical simulation models depend are based upon extensive experimental and theoretical analyses. Detailed evaluation of the various phenomenological models are beyond the scope of this report. For intensive review of these models the reader is referred to two studies for the Coast Guard,[1] which discuss 12 of the VM models.

Problems exist with the mixing and dilution model in terms of the neglect of density forces acting on spills of soluble chemicals, which implies that the model does not accurately simulate the force of buoyancy. Also, the mixing, dilution, and evaporation model assumes neutral buoyancy and infinite solubility, instantaneous spills and uncoupled mixing and evaporation processes. The Coast Guard has issued a request for a proposal[2] that identifies these problems and solicits proposals for their solution.

One of the disadvantages of using the Vulnerability Model is that a certain amount of expertise is necessary to be able to generate correct inputs and to interpret the output. Although it has been designed to handle over 900 chemicals, only a relatively small number (about 15-20) have been exercised with the model. These include LPG, LNG, chlorine, gasoline, propane, anhydrous ammonia, vinyl chloride, plus a few others. Exercising the model for other chemicals may require a significant amount of effort to assure the validity of the results.

Further, the demographic data input requires a significant level of effort for urban areas of large size. At present, New Orleans, New York, and Los Angeles/Long Beach are the only large cities in the data base. Each urban area involves approximately 400 cells for which population, property value, and location must be specified.

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[1] Enviro Control, Inc., A Critical Review of Six Hazard Assessment Models, December 1975, and A Critical Review of Six Additional Hazard Assessment Models, March 1977 (prepared for the U.S. Coast Guard).

[2] U.S. Coast Guard, Request for Proposal CG-920622-A; Analytical and Experimental Study to Improve Computer Models for Mixing and Dilution of Water Soluable Hazardous Chemicals, February 16, 1979.

The population within a cell is treated by the model as being located at a single point within the cell. Consequently, if a toxic cloud, heat radiation, or detonation effects do not reach that point, none of the population or property on that cell is considered to be affected even though much of the cell may be covered by the spill effect. This creates problems in assessing relatively small spills whose effects cover only portions of the cells.

Another problem in exercising the model is that it is difficult to determine the proper value for the time steps and the simulated run time. For a large spill of a chemical such as anhydrous ammonia under stable atmospheric conditions, the simulation time can be several hours. However, the time to completion--when all possible fatalities have occurred--can only be determined after making the runs. There is no mechanism in the program to determine this completion time and no way for the user to estimate it before making the runs. Further, for a given simulation duration, if the time steps are too short, the computer processing time can become large and if the time steps are too large, events occurring completely within a time step will be missed. Thus, selection of the appropriate time step value is critical. Generally, this selection is also made by trial and error.

10. Applicability to Coast Guard Risk Assessment

Since one of the primary elements of a risk management system is the assessment of consequences from spills of hazardous chemicals, spill effect and consequence models are required. The Vulnerability Model is the most extensive model of this type. It can be used in conjunction with any of the casualty and spill probability models to determine expected losses from spills. However, because of the extensive input requirements and difficulties in operating the model, it is not expected to be useful in performing general risk cost-benefit analyses of hazardous material transport policies and safety measures. It is very useful for analyses involving specific chemicals and locations.

F. Cargo Spill Probability Analyis For The Deepwater Port Project

1. Documentation

Woodward-Lundgren and Associates, Cargo Spill Probability Analysis for the Deepwater Port Project, prepared for the Corps of Engineers, February 1973.

2. Purpose

The study was conducted for the Army Corps of Engineers to estimate probabilities of oil spills from proposed deepwater port facilities.

3. Scope

The study addressed only spill occurrence probabilities and not the consequences of the spills. The region of interest was the Atlantic Coast from Eastport, Maine to Norfolk, Virginia. All oil spills were considered, either from accidental or intentional causes.

4. Methodology

Because of the lack of pertinent historical data, the analysis was based upon use of subjective data. A Bayesian statistical approach was utilized to convert answers to questionnaires on spill probabilities and causes to probability estimates.

The study approach consisted of the following steps:

(a) Literature Review - establish factors or parameters which influence cargo spills.

(b) Implementation of Bayesian Approach.

- Formulation and implementation of preliminary questionnaire to identify factors which cause spills and their order of importance.
- Formulation of probability model based on information obtained from the questionnaire and literature review. The model was based on spill size, cause, and location.
- Formulation and implementation of second questionnaire to obtain probabilistic information to quantify the model. The second questionnaire was implemented through personal interviews.
- Analysis of results of the questionnaire to develop probabilistic relationships of cargo spills with respect to size, cause, and location.

(c) Utilization of the model to evaluate the probability of a spill as a function of controllable factors.

The preliminary questionnaire was completed by 45 experts in ship operations. In part I, 10 general factors that might cause or influence cargo spills were specified on the questionnaire, and several specific subfactors were listed for each general factor. The

respondents were asked to rank the general factors and the specific subfactors in order of importance. For example, human error was identified as a general factor, and its subfactors included carelessness, poor communication, and poor supervision.

Part II of the questionnaire addressed general conditions related to oil spills and their prevention.

The probability model expresses the probability of a spill in terms of spill causes, locations, and sizes. Relating spills to causes and sizes, the model used conditional probability expressions to develop spill probabilities. The spill probability is expressed by:

$$P(\text{Spill}) = \sum_{ij}\sum P(A_j S_i) \quad (1)$$

when:

A_j = Spill cause j.

S_i = Spill size level i.

$P(A_j S_i)$ = Joint probability of a spill of size level i induced by cause j.

Since the joint probability is summed over all possible causes and sizes, the overall spill probability results.

The joint probability term can be expressed as the product of a conditional and a nonconditional probability:

$$P(A_j S_i) = P(S_i \mid A_j)P(A_j) \quad (2)$$

where:

$P(S_i \mid A_j)$ = Probability of S_i given A_j has occurred.

$P(A_j)$ = Probability that A_j has occurred.

However, $P(S_i \mid A_j)$ is considered difficult to estimate subjectively. For example, $P(S_i \mid A_j)$ may represent the probability of a spill of very small size, S_i, given a human error, A_j, has occurred. Since human errors, which occur frequently, are not recorded and since most do not result in spills, confidence in estimations for this probability is quite low.

Therefore, the alternate formulation was used:

$$P(A_j S_i) = P(A_j \mid S_i)P(S_i) \quad (3)$$

where:

$P(A_j \mid S_i)$ = Probability that given a spill of size S_i, the spill cause was A_j.

$P(S_i)$ = Probability of a spill of size S_i.

Thus the overall spill probability is given by:

$$P(\text{Spill}) = \sum_{ji} \sum P(A_j | S_i) P(S_i) \quad (4)$$

The authors of the report felt that the term $P(A_j | S_i)$ and $P(S_i)$ were easier to estimate subjectively than the corresponding terms in equation 2. The second questionnaire was, therefore, oriented toward estimating these two probability terms. Spill locations were included in the same manner as size and cause.

For the second questionnaire, 18 people were interviewed. The questionnaire included 15 questions relating to spill frequency, size, location and cause, and three questions relating to the possible influence of increased use of supertankers on the likelihood of spills. A sample question was: out of 100 small spills occurring in the past month, how many do you believe would have been primarily caused by (a) human error, (b) mechanical failure, (c) inadequacies, or (d) all other causes? Determining the relative frequencies of answers to this question would yield the subjective conditional probability, $P(A_j | S_i)$, of cause A_j(for j = 1 to 4) given a spill of size S_i, where S_i indicates a small spill.

5. Applications

The study report contains a number of suggestions for possible applications of the results. For example, the conditional probabilities could be used to determine which causes and locations contribute most significantly to the spill probability, thereby indicating primary risk situations for which mitigating measures may be most effective.

6. Data Requirements

The preliminary questionnaire included questions on the importance of various factors that cause spills. Relative importance was measured by ranking the factors. In addition, the questionnaire dealt with general conditions related to oil spills and their prevention.

The second questionnaire addressed spill occurrence, spill size, location and cause in terms of subjective probabilities.

7. Outputs

The study presented tables of the conditional probabilities related spills to location, size, and cause and the probabilities of spills of various size ranges. In addition, results of expected supertanker impact on spills were given.

8. Computer Requirements

No computer usage was indicated.

9. General Evaluation

The methodology represents a subjective procedure for extenuating spill probabilities in the absence of historical or objective data. Its validity depends primarily upon the

ability of the respondent group to accurately estimate probabilities in the area of concern, although the formulation of the questions used in the procedure represents an attempt to minimize this problem. The precision of the results also, generally, depends upon the size of the respondent group.

The study did not attempt to validate the probability results by comparing them with those derived by other methods, although the rankings of ship-related factors for spills (collisions, rammings, groundings, etc.) based on results of the first questionnaire compared well with similar results from analysis of tanker casualty data.

10. Applicability to Coast Guard Risk Assessment

The technique developed in the study could be applied to the estimation of risks associated with existing or proposed operations. However, it may be most useful in attempting to assess the impacts of proposed safety measures on spill probabilities. For example, the method expresses spill probability in terms of causes. It would be possible to continue the process one step further and obtain subjective estimates on the possible effects of safety measures on mitigating the causes. The resulting decrease in spill probability could then be derived.

G. Offshore Petroleum Transfer Systems For Washington State

1. Documentation

Oceanographic Institute of Washington. Offshore Petroleum Transfer Systems for Washington State. Oceanographic Commission of Washington, Seattle, Washington, 1974.

2. Purpose

The purpose of the study was to determine the feasibility of offshore monobuoy and related petroleum transfer facilities in the state of Washington. The risk portion of the study addressed the probabilities and probable consequences of oil spills for both the transport and transfer operations.

3. Scope

The study addressed risks associated with 13 different facility arrangements defined by location, system configuration, and quantity of exported oil, which would come into the state in the next 20 + years. The hazard potential of each of these systems was considered to be primarily associated with chronic discharges due to tanker casualties. Tankers of 80,120 and 250,000 deadweight tons were considered.

4. Methodology

The analysis proceeded along two lines. First, using statistical techniques, an estimate was made of the most probable number of incidents, both of an acute and chronic nature that would result in the outflow of oil into Washington State waters. Second, a subjective, probabilistic approach employing the Delphi method was used to determine the damage levels likely to result from such spillage.

a. Casualty Probability

Based on a Bayesian statistical analysis by Devanney and Stewart,[1] the negative binomial distribution was used to describe the probability density of casualties in a given exposure interval. The equation is:

$$p(n \mid t, \nu, \tau) = \frac{(n+\nu-1)!\, t^n \tau^\nu}{n!\,(\nu-1)!\,(t+\tau)^{n+\nu}} \qquad (10)$$

where ν = observed casualties, τ is the observed vessel trips, and the mean casualty rate λ, is ν/τ. Given the mean casualty rate λ, and a variable exposure t, the mean number of casualties for a specific value of t is given by:

$$\text{mean}(n) = \lambda t$$

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[1] S.W. Devanney III and R. J. Stewart, "Bayesian Analysis of Oil Spill Statistics," Marine Technology, October 1974

Forecasted average (mean) number of tanker casualties was developed using this relationship. To determine a satisfactory exposure variable, a functional relationship between vessel casualties and a single characteristic of tanker operations was identified. This was accomplished by combining U.S. Coast Guard casualty data and U.S. Army Corps of Engineers data on vessel port calls from seven major port systems around the United States. The resulting functional relationship is:

$$C = 0.0044t$$

where C is the number of vessel casualties and t is the number of vessel port calls. For this study, the casualties and port calls were adjusted to consider only U.S. flag tankers. Based on the relationship $\lambda = \nu/\tau$ and using the data to determine the regression line yielded:

ν = 185 tanker casualties

τ = 41,908 tanker port calls

or λ = 0.0044 casualties per port call, the slope of the regression line.

Next, the annual number of expected tanker port calls for the period 1978 -2000 in Washington waters was estimated using combinations of volume of oil expected to come into the state, vessel sizes for the alternative port systems, and possible markets. The expected number of port calls and the relationship between port calls and casualties were used to forecast the incidence of tanker casualties in Washington waters. The projections were adjusted by historical casualty data for location (coast, Strait of Juan de Fuca, and North Sound), type of casualty, and the mitigating factor of vessel traffic system effectiveness.

b. Spill Frequency and Size

The numbers of expected spills due to tanker casualties were estimated by applying worldwide data on historical percentages of casualties leading to oil spills in coastal regions, harbor entrances, and harbors to the number of forecasted tanker casualties.

The exponential distribution (which is a special case of the gamma distribution) was used as a first approximation for the distribution of spill sizes where:

$$F(x) = 1 - e^{-\omega x}$$

$$\text{Mean } (x) = 1/\omega$$

$$\text{Variance } (x) = 1/\omega^2$$

The cumulative spill size densities at off-loading monobuoys, tankers, and pipelines for the various alternatives were determined in this way.

c. Consequences

Damage to the environment was estimated using the Delphi method. A group of ten persons familiar with physical oceanography, marine biology, and cleanup equipment procedures was asked to rate the severity of environmental damage caused by oil spills.

Spill scenarios were given to the panel. These scenarios specified the oil type, the quantity of oil spilled, and the location and season for each occurrence. Certain basic information was provided or assumed to be known, in order that the resultant subjective evaluation would have a level of commonality.

- First, the waters of Washington were divided in subregions based on bathymetric and shoreline features and weather considerations.
- Three different oils were considered; gasoline, Alaskan crude, and Navy Special.
- The four seasons were considered to account for the sensitivity of biota.
- Orders of magnitude of the quantity of oil were considered to represent a range of oil spill sizes (i.e., 100; ....; 1,000,000 gallons).

In addition, the following data were provided:

- Time and extent of the spreading of an oil spill.
- Typical distances along the waterways.
- The flushing action in Washington waters.
- The toxicity sensitivity ranges of different organisms for various oil substances.
- Statistics on commercial and sport fishing catches.

The experts evaluated the above factors taking into consideration spill sizes, oil types, and spill locations. The results were expressed in terms of severity levels of damage to the environment.

5. Applications

The risk methodology was applied to analysis of petroleum facilities offshore from Washington state, as discussed above. In addition, the regression relationship for casualties as a function of port calls developed for this analysis has been utilized in a number of other spill risk studies, including the FPC assessment of LNG risks discussed in section III.C.

6. Data Requirements

Spill data were obtained from Lloyd's Tanker Casualty/Spill files as analyzed by the J. J. Henry Company.[1]

Exposure data were obtained from U.S. Waterborne Commerce, published by the Army Corps of Engineers.

Casualty data were obtained from the U.S. Coast Guard Vessel Casualty Reporting System and Coast Guard Thirteenth District personnel.

7. Outputs

The primary outputs included:

- The number of casualties and spills from tankers for different alternatives projected in 5-year intervals to the year 2000.
- Cumulative probability distributions for spill size for tankers, monobuoys, and pipelines.
- Subjective severity levels of oil spill damage by region and spill size.

8. Computer Requirements

No computer programs were utilized for the study.

9. General Evaluation

The method applied in this study to determine the casualty rate provides a means of projecting tanker casualties by region. Refining the location of the casualties is limited by the VCRS data, which gives location by zones. The relative distribution of spills from the coastal region entrances to the harbor region is still valid if we review an update of J. J. Henry's data for 1973.[2] A better predictor by region would be the regression relationship obtained for number of spills versus port calls, which is similar to the casualty regression line. PRC performed this type of analysis for a deepwater port study.[3]

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[1] J. J. Henry Co., Inc., An Analysis of Oil Outflows Due to Tanker Accidents, 1971-72 (November 1973).

[2] James Card, Paul Ponce, Warren Snider, Tankship Accident and Resulting Oil Flows (presented at the 1975 Conference on Prevention and Control of Oil Pollution, San Francisco, March 1975).

[3] Planning Research Corporation, Deepwater Port Approach/Exit Hazard and Risk Assessment (prepared for the U.S. Coast Guard, February 1979, Planning Research Corporation, op. cit.).

The exponential fit of spill sizes for tankers, monobuoys, and pipelines was considered to be a crude approximation. More recent work by BDM,[1] Stewart and Devanney,[2] Paulson,[3] and PRC have utilized two and three parameter distributions for oil spill sizes.

10. Applicability to Coast Guard Risk Assessment

The regression method of estimating casualty and spill rates can be useful in assessing risks based on existing or projected exposure levels in terms of port calls per unit time.

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[1] BDM Corporation, Oil Spill Risk Assessment for OCS Oil and Gas Processing Facilities and Deepwater Ports, Volume II, December 1975.

[2] J. W. Devanney, III and R. J. Stewart, "Bayesian Analysis of Oil Spill Statistics" Marine Technology, October 1974.

[3] A. S. Paulson, et al., "A Risk Analytic Approach to Control of Large Volume Oil Spills," presented at the 1975 Conference on Prevention and Control of Oil Pollution, San Francisco, March 1975.

H. LOOP Deepwater Port Oil Spill Risk Analysis

1. Documentation

U.S. Coast Guard, Department of Transportation, Final Environmental Impact Statement, LOOP Deepwater Port License Application, 1976.

2. Purpose

The risk analysis was performed by A. D. Little, Inc., as a portion of the environmental impact statement for the LOOP deepwater port license application. The analysis provided an estimate of expected damage from LOOP deepwater port operations. Damage is measured in terms of expected lengths of shoreline impacted by oil spills.

3. Scope

The analysis addressed spills from casualties of tankers and auxiliary vessels, mooring buoys, the platform and booster station, pipelines, and storage domes. Tanker casualties were analyzed over the area from the approach to the Gulf of Mexico to the mooring buoy. Spills outside the coastal fairway were excluded. Operational volumes of two and three million barrels per day were evaluated.

4. Methodology

a. Spill Frequency

Spill frequencies from single point moorings (SPM's), pipelines, and terminals (platforms, booster stations, and storage domes) were estimated in terms of spills per volume handled, based on historical data.

Frequencies for spills resulting from tanker and auxiliary vessel casualties were estimated by casualty type and location type. Nonimpact casualty frequencies - breakdown, explosion, fire, structural failure, and capsizing - for tankers were estimated from data compiled on tankers by the J. J. Henry Company from Lloyd's Weekly[1] for the U.S. Coast Guard. Only data for larger vessels (over 10,000 deadweight tons) were used in the analysis. Only casualties occurring in coastal waters (within 50 miles of shore), harbor, and harbor entrances were considered as being applicable to the deepwater port environment. For the period covered by the J. J. Henry study, 1971-72, 38 casualties of these types and locations occurred. Vessel exposure for these spills was estimated from the worldwide fleet population for tankers larger than 10,000 DWT and average exposure time per tanker per year (based on operational statistics). The results were given in terms of average spills per vessel year.

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[1] J. J. Henry Co., Inc, An Analysis of Oil Outflows Due to Tanker Accidents, 1971-72 (November 1973).

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A similar analysis was performed for auxiliary vessels serving the deepwater port system. In this case, casualty data for tankers less than 30,000 DWT in coastal, harbor, harbor entrance, and pier locations (195 casualties of this type) were recorded for 1971-72.

For spills resulting from impact casualties - collisions and rammings - a geometric equation was applied. The reason given for not using historical data for these casualty types was that the specific nature of the traffic and obstructions in the area of interest precluded the use of such data. The equation applied for collision and ramming probabilities was developed by T. McDuff of Bureau Veritas[1] and was based on molecular collision theory. The collision potential, P, of a ship in a stream of traffic was expressed by:

$$P = 2XLS\sin\theta/2$$

where:

- X = Length of the track of the ship.
- L = Ship length.
- S = Density of ship in the stream.
- θ = Angle between the ship's track and the axis of the stream.

This equation yields results for P on the order of 0.10. McDuff calibrated the equation by applying a factor of 3×10^{-4} so that the results would correspond to historical data on collisions in the English Channel. The LOOP study applied the same factor.

The equation applied to rammings of moored tankers was:

$$P = XLS$$

The same calibration factor was used. Groundings were not treated because the depth of the water in the vicinity of the LOOP facility was judged to be sufficiently deep.

Both collision and ramming frequencies were computed applying the probabilities obtained from the above equations to the expected annual tanker traffic. The results were specified in terms of collisions and rammings per year.

b. Spill Size

Spill sizes were treated distributionally so that the probability of annual spill volumes greater than a specified value could be computed. A lognormal distribution was used. Two parameters used to specify the distribution were:

- Median, M.
- Standard ratio, R, whose natural logarithm is the standard deviation of the logarithms of the spill size values.

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[1] T. McDuff, "The Probability of Vessel Collisions," Ocean Industry (September 1974).

They are calculated as follows:

$$M = \exp\left(\frac{\Sigma \ln x_i}{N}\right)$$

$$R = \exp\ \{\sigma_{\ln x}\}$$

where:

x_i's = Spill size values.
$\sigma_{\ln x}$ = Standard deviation of the logarithms of the x_i's.
N = Number of spills.

Tanker spill size data, obtained from the J. J. Henry study, were categorized by casualty type and distributions were estimated for each type. Spill size distributions for SPMs, pipelines, and terminals were estimated by obtaining least-squares lognormal fits to the data. This was done because the data were given in ranges (½ to 5 tons, 5-30 tons, etc.) rather than in individual spill sizes.

From the spill frequencies and spill size distributions, spill volume profiles were obtained. These profiles expressed the number of spills per year exceeding specified levels for each spill category (SPMs, tanker collision, tanker breakdowns, etc.). The spill profiles were computed for different locations of the LOOP area so that the impact of the oil spills on the environment could be estimated.

c. Spill Consequences

To estimate the effects of oil spills, a model of oil slick movement was developed. The model is based on a theory developed by Fay[1] and applied by Fannelop and Waldman.[2] Radial spread of an oil slick with time is given as a function of the volume of the liquid, its surface tension, the viscosity of water, and the effective gravity of the liquid.

The trajectory of a slick is expressed as a function of the current speed and direction and the wind speed and direction. The velocity of the slick is computed as a resultant vector of the velocity of the current, combined with 3 percent of the velocity of the wind, with velocity considered as a vector (speed and direction).

Sinking and evaporation is treated in the model by assuming no loss in the first 2 days after a spill and 20 percent loss after 2 days. This assumption is based on studies of actual spills and theoretical calculations.

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[1] J. A. Fay, "The Spread of Oil Slick on a Calm Sea," Oil on the Sea (E. P. Hoult (ed.), New York: Plenum Press, 1969) pp. 53-63.

[2] T. K. Fannelop and G. D. Waldman, "Dynamics of Oil Slicks," AIAA J., Volume 10, No. 4, April 1972, pp. 506-510.

A Monte Carlo computer program was used to determine the effects of oil spills in terms of length of coastal land polluted. For a specified spill size at a specified location, the program tracked the oil slick over a 5-day period, using random changes in current and wind velocities every 24 hours. Historical data on wind and current velocities were used to develop the probabilities from which the random changes were determined. The results expressed the number of the simulated slicks that impacted the shoreline. A factor of 10 was used to translate slick diameter to length of shoreline affected.

The results were expressed in terms of the frequency of oil spills resulting in greater-than-R miles of shoreline affected for a range of values of R. This was done for three locations (platform operations, operations south of the platform, and operations between the platform and the shoreline). Oil sinkage and evaporation profiles were also generated in terms of frequency versus tons of sunken or evaporated oil.

5. Applications

The method developed was applied to analysis of oil spills for SEADOCK as well as LOOP.

6. Data Requirements

Data on oil spills were obtained from the following sources:

Tanker Spills:

- Worldwide tanker spill data based on analysis of Lloyd's Weekly Reports.[1]
- Coast Guard statistics on oil spills in U.S. waters.

SPM Spills:

- Oil spill data base generated for the Environmental Protection Agency.
- Shell Oil Company spill data.

Pipeline Spills:

- U.S. Coast Guard data on pipeline spills.
- DOT data on liquid pipeline spills.

Platforms, Booster Stations, and Storage Dome Spills:

- DOT data on pipeline spills at terminals.[2]
- U.S. Coast Guard data on pipeline terminal spills.

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[1] A. S. Paulson, et al., "A Risk Analytic Approach to Control of Large Volume Oil Spills," presented at the 1975 Conference on Prevention and Control of Oil Pollution, San Francisco, March 1975.

[2] U.S. Department of Transportation, Summary of Liquid Pipeline Accidents Reported on Form DOT-7000-1, January 1965 - December 1973.

Vessel Traffic:

- Waterborne Commerce of the United States.

Wind and Current Data:

- National Oceanic and Atmospheric Administration data for LOOP region.

7. Outputs

The primary outputs of the analysis were the shoreline impact risk profiles which expressed the annual frequency of more than a length of shoreline, R., affected by oil spills for a range of values of R; for example, 10 percent probability of more than 10 miles of shoreline affected per year by platform operations. Intermediate outputs include annual frequencies of spills of size greater than S for a range of values of S.

8. Computer Requirements

The report does not address the computer requirements for the methodology. The oil spill movement model is evidently a Monte Carlo computer program, but the other portions of the analysis could easily have been done manually.

9. General Evaluation

Of the models used for spill frequency and size, the least defensible is the McDuff kinematic model for vessel collisions and rammings. The model is obviously simplistic, accounting for only a few of the pertinent variables and treating the problem as one of random motion. The fact that a calibration factor of 3×10^{-4} had to be applied (multiplicatively) on a probability value of the order of 1/10 indicates that the calibration is the overriding factor. There is no evidence of any validation of the equation or the calibration factor by applying them to other situations for which the results are kown.

The oil spill results were presented in a meaningful way--probabilities of various lengths of coastline polluted, for two levels of activity (in million barrels per day). However, no justification for selecting the levels was given. The activity level was implicitly assumed to be constant with time.

10. Applicability to Coast Guard Needs

The analysis addressed the problem of estimating oil spill effects from a proposed operation - LOOP deepwater port. This type of problem represents one of the facets of risk management for vessel operations. The methodology is not directly applicable to evaluating the effects of mitigating measures, although the oil spill trajectory model could be useful in such an analysis.

I. Spill Probability Analysis for Outer Continental Shelf Environmental Assessment

1. Documentation

OCS Oil and Gas - An Environmental Assessment. A report to the President by the Council on Environmental Quality, April 1974.

Devanney, J. W., III and R. J. Stewart, "Bayesian Analysis of Oil Spill Statistics," Marine Technology, October 1974.

2. Purpose

This spill probability analysis formed a portion of an assessment of the effects of development of outercontinental shelf (OCS) oil and gas on the environment. The purpose of the analysis was to develop estimates of the size and frequency of oil spills from various hypothetical OCS developments.

3. Scope

The developments analyzed in this study would be located off the U.S. Atlantic Coast and the Gulf of Alaska. Possible spill sources include tankers, offshore platforms, and pipelines. A number of hypothetical developments in different locations were considered. Three projected levels of activity were analyzed.

4. Methodology

The spill risk models were developed by William Devanney and Robert Stewart of the Massachusetts Institute of Technology.

The historical oil spill data indicate that the range of spill sizes varies over several orders of magnitude, yet the great majority of spills occur in the small size ranges. In addition, the bulk of the oil spilled results from a few large spills. To address this problem, the study utilized a two-step Bayesian statistical approach. First, the Poisson function was used to express the probability distribution for the number of spills:

$$P(n \mid \lambda) = \frac{e^{-\lambda t}(\lambda t)^n}{n!} \qquad (1)$$

where t is the volume handled, λ the mean spill incidence rate in spills per unit handled, and n the number of spills. Since the value of λ was considered uncertain, the study assigned a probability density to it--the gamma distribution. This is called, in the Bayesian context, a non-informative conjugate prior distribution on λ. The gamma distribution for λ as a function of spill frequency and volume handled is:

$$f(\lambda \mid \nu, \tau) = e^{-\lambda\tau}(\lambda\tau)^{\nu-1}\tau/(\nu-1)! \qquad (2)$$

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where ν is the number of spills observed and τ is the volume handled over a period of time. For a large number of spills observed ν and amount of exposure τ, $\lambda = \nu/\tau$ is the mean spill rate.

Since λ is considered an uncertain quantity, Bayesian analysis provides the means by which historical spill data experience enters the analysis. Integration of the product of equations (1) and (2) over the range of λ yields the probability of ν spills from τ units of volume handled, which is expressed by the negative binomial density function:

$$p(n\ t,\ \nu,\tau) = \frac{(n+\nu-1)\ !\ t^{n}\tau^{\nu}}{n!(\nu-1)\ !\ (t+\tau)^{n+\nu}} \tag{3}$$

where ν is the number of spills observed and τ is the volume handled that resulted in those spills.

The study treated spill size using the same basic philosophy. The gamma density was assumed to express spill size x:

$$f(x\ \rho,\omega) = \frac{e^{-\omega x}(\omega x)^{\rho-1}\omega}{(\rho-1)!} \tag{4}$$

In this case ρ and ω are parameters that are subjected to a distribution. The distribution assumed for ν and ω was the gamma hyperpoisson:

$$f(\omega,\rho\,|\,m,s,p) = e^{-s\omega}m^{p-1}p^{\rho-1}/\Gamma(\rho)^{m}S(m,s,p) \tag{5}$$

where S (m,s,p) is a normalizing constant and m is the number of spills observed, s is the total amount spilled, and p is the product of all individual spill sizes.

Combining (4) and (5) results in the probability distribution for spill size, x, in terms of m, s, and p:

$$f(x\ m,s,p) = \int_{o}^{\infty} \frac{(xp)^{\rho-1}\ ((m+1)\rho)\,d\rho}{\Gamma(\rho)^{m+1}S(m,s,p)\ (x+s)^{(m+1)p}} \tag{6}$$

The distributions expressed in equations (3) and (6) were generated for various OCS development levels in terms of large scale spills and small scale spills from various sources with the dividing point equal to 1,000 barrels.

5. Applications

The models were applied in the OCS study as described. In addition, the probability model has been used for several other spill probability applications, namely in the Washington State Oil Transfer Study discussed earlier.

6. Data Requirements

The data used in the model included:

- U.S. Coast Guard PIRS data system for calendar year 1971 and 1972, and as amended in 1973. 15,600 oil spills were covered.

- ECO, Inc., files for 2,999 worldwide tanker casualties from 1969 to 1972 inclusive. 612 spills were analyzed by Porricelli and Keith.[1]

- EPA data base generated by Computer Sciences Company and upgraded by ECO. This file combined records of the Office of Pipeline Safety and the Environmental Protection Agency and portions of U.S. Geological Survey records and files from a number of U.S. state and Canadian agencies. 8,500 spills were recorded.

- MIT Georges Bank data based on U.S. Geological Survey study of large spills and a survey of tanker accidents by Westinform Ltd.

- Anglesey Defense Action Group data, based principally on Shell Oil data. 300 spills at single buoy moorings were recorded.

7. Outputs

The primary outputs of the spill probability models were:

- Probability density functions on the number of spills as a function of exposure and observed spills.

- Probability density for spill size as a function of number of spills observed, the sum of their sizes, and product of the sizes.

8. Computer Requirements

No computer programs were used for this study.

9. General Evaluation

The method proposed to determine the spill distribution (i.e., the negative binomial) is reasonable, given the data limitations. The value of using distributions to express spill frequency and size, rather than expected values, is apparent from perusal of spill data, which indicates a range of several orders of magnitude for spill sizes in any given year. The distributional approach allows probabilistic statements to be made regarding large, serious consequence spills that would not be reflected in average values. On the other hand, one could quarrel with the choice of the initial distribution for spill size, gamma and its conjugate prior, and the hypergeometric Poisson on the grounds that they do not properly fit the data and, therefore, do not adequately represent spill sizes in the small size ranges.

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[1] J. Porricelli and V. Keith, "An Analysis of Oil Outflows Due to Tanker Accidents," presented at the 1975 Conference on Prevention and Control of Oil Pollution, San Francisco, March 1975.

This apparently results from the variance widening effect of the hypergeometric Poisson. Other distributions might have given a better fit in the small size region (spills less than 1,000 barrels).

A serious problem with application to the approach is the difficulty in evaluating the spill size frequency expression (equation 6). This would require a computer program utilizing numerical integration which was not developed for the study.

10. Applicability to Coast Guard Risk Assessment

The distributional approach to spill size and frequency estimation presented in the study can be of value in estimating the effects of oil spills from existing or proposed operations. It cannot be directly utilized for assessing the impact of proposed safety measures.

J. Oil Spill Trajectory Studies for Outer Continental Shelf Environmental Assessment

1. Documentation

Stewart, R. J., J. W. Devanney, III, and W. Briggs, Oil Spill Trajectory Studies for Atlantic Coast and Gulf of Alaska, Masachusetts Institute of Technology, Report No. MITSG 74-20, April 1974.

OCS Oil and Gas - An Environmental Assessment. A report to the President by the Council on Environmental Quality, April 1974.

2. Purpose

The oil spill trajectory model was developed by the Massachusetts Institute of Technology for the Council on Environmental Quality to aid in assessing the potential impact of outer continental shelf (OCS) oil and gas production sites.

3. Scope

The model was used to determine the impact on the shoreline of oil spills along the Atlantic Coast and Gulf of Alaska. Both offshore production sites and nearshore terminal sites were analyzed.

4. Methodology

The MIT oil spill trajectory model is a computerized stochastic simulation of oil spill movement. The movement is expressed in terms of the wind velocity, tidal current velocity, and residual current velocity, where residual current is a combination of current factors with large fluctuation periods relative to the life of a spill. These factors include river flows, the Gulf stream, and large-scale geostrophic flows. The motion equation is:

$$\vec{U}_{oil} = 03\vec{U}_{wind} + \vec{U}_{tidal} + \vec{U}_{residual}$$

where the $\vec{U}$'s are vectors expressing speed and direction.

The model ignores shelf-wave phenomena and for offshore developments does not include the tidal current factor. To simulate random wind behavior through time, the model treats wind as a first-order Markov process, which allows a wind change every 3 hours. The Markovian wind state transition matrix contains transition probabilities that express the likelihood of the wind changing to a given state (direction and speed) based only on its present state.

For the analysis of offshore sites, 9 wind directions were considered resulting in a 9 x 9 transition matrix. For the 3 terminal sites, 16 wind directions and 3 wind speeds were considered, resulting in a 33 x 33 transition matrix.

Current velocity was updated periodically according to location. Loss of oil due to evaporation or dissolution was not included in the model.

The program simulates the movement of a large number of spills whose trajectories vary because of the probabilistic wind factors.

5. Applications

The model was applied to evaluate 13 potential offshore site spills in the Mid-Atlantic and South Atlantic, 9 potential sites in the Gulf of Alaska, and 3 potential nearshore terminal areas - Buzzards Bay, Delaware Bay, and Charleston Harbor.

6. Data Requirements

Wind data were obtained from the National Climatic Center in terms of hourly or 3-hourly data points for periods from 5 to 10 years. A computer program was developed to read the data tapes and develop the transition probabilities. The wind data were generally from shoreside weather stations.

Hourly current data for the nearshore sites were obtained from U.S. Coast and Geodetic Survey publications. Drift bottle data from the National Oceanographic Data Center were used for the offshore sites.

7. Outputs

The program computed for each spill site the potential impact in terms of probability of a spill reaching each section of the shoreline. The program also determined time to reach the shore and, for the analysis of nearshore terminals, the wind conditions at impact.

8. Computer Requirements

Details of the simulation program were not given in the documentation.

9. General Evaluation

The stochastic treatment of wind represents an advancement over steady-state models. The wind data were taken from measurements and may not reflect offshore conditions. As is the case for most spill movement model applications, the lack of good data is a significant problem.

10. Applicability to Coast Guard Risk Assessment

The model could be useful for analysis of risks associated with oil tanker operations. More data are required than for less sophisticated models. The added degree of accuracy contributed by using a stochastic process may not be needed in cost-benefit analyses involving tanker safety measures, since the other model parameters--spill probability, spill size, spill location--will generally not be precise.

K. Oil Transport Model for SEADOCK

1. Documentation

Williams, G. N., R. Hann, and W. P. James. "Predicting the Fate of Oil in the Marine Environment," Proceedings of Joint Conference on Prevention and Control of Oil Pollution, San Francisco, California, 25-27 March, 1975.

2. Purpose

The model was developed by Texas A & M Research Foundation to aid in assessing the environmental impact of operations at the proposed SEADOCK deepwater port off the Coast of Freeport, Texas.

3. Scope

The model addresses the movement of oil slicks in the SEADOCK area and treats both the surface and the subsurface aspects of the oil movement.

4. Methodology

The model uses a time-step computer simulation based on a first-order Markov process. The process involves monthly transition matrices for wind direction and speed and current direction and speed. At the beginning of each time step, the values of wind and wind current velocities to be applied during the time step are determined by sampling from the transition matrices. A matrix contains probabilities of the system changing to state S_i for all possible values of i, given the system is in state S_j at present. For example, the S_i values may represent the possible wind direction ranges.

The wind direction matrices include transition probabilities for 16 directional values for each month. For each wind direction value, monthly probability distributions are generated for wind speeds at 2.5 mile-per-hour intervals. Current direction and speed are treated similarly in the model. The basic time interval used was three hours.

The model simulates both surface oil slick transport and subsurface transport.

The transport model is based on the following equation:

$$\Delta \vec{P} = 0.03 \vec{W} + \vec{C}$$

where $\Delta \vec{P}$ = position change vector
$\vec{W}$ = wind vector
$\vec{C}$ = current vector

The wind and current terms are evaluated for three regions, defined by distance from the coast:

- greater than 5 miles - offshore wind and surface current

- 2 to 5 miles - offshore and onshore wind, surface current
- less than 2 miles - onshore wind, longshore current

Spreading of the slick is treated in terms of three regimes in the model:

- gravity - inertia
- gravity - viscous
- surface - tension

Decay of the oil is considered in terms of evaporation and dissolution according to the following equation:

$$C(t) = C_o \exp \left\{ (-K_e - K_d)\, t \right\}$$

where C = concentration of oil at time t
C_o = initial concentration of oil
K_e = evaporation coefficient
K_d = dissolution coefficient

The concentration is evaluated by different oil types or fractions in the slick, and the results are combined. Emulsification and precipitation of the oil are treated by applying a factor of 1 percent decay per time step. Biodegradation is not considered significant.

The subsurface model, which includes depth in addition to the two horizontal dimensions, treats the volume of oil dissolved (from the dissolution term in the slick model). The model treats the dispersion of the oil and calculates the maximum concentration with time. Transport of the subsurface oil is simulated by applying surface and mid-depth current vectors.

5. Applications

The model was used to simulate a 15,000-ton spill in the SEADOCK region. Possible future applications include prediction of the trajectory for an actual spill to aid in the oil spill contingency program as well as further analysis of the impact of SEADOCK operations on the environment.

6. Data Requirements

To obtain data for the transition matrices, wind and current measurements were taken over a 23-month period. Data were recorded at depths of 10, 35, and 65 feet. The analog data were digitalized, calibrated, and used to develop the transition probabilities for the matrices.

7. Outputs

The transport model computes shoreline impact location and time to reach shore for an oil slick. A simulation of a number of spills will result in probability distributions of impacts along the coastal profile, by month.

The subsurface model predicts the frequency of spills whose subsurface plumes reach a specified area with a maximum concentration of greater than 0.1 part per million.

8. Computer Requirements

The model is computerized. The details of the program and the computer used were not specified.

9. General Evaluation

The Texas A & M model is one of the most complete oil spill transport models available. In addition to treating the wind and current velocities stochastically, the model includes decay of the oil slick. However, to operate the model requires a great deal of wind and current data; therefore, it would not be useful for analyzing spills in areas other than the SEADOCK region unless extensive data were available.

10. Applicability to Coast Guard Risk Assessment

Because of the detailed data requirements, the model is not generally applicable to ocean areas other than that for which it was designed (SEADOCK), unless a large scale data collection effort is undertaken.

Because of the variations and imprecision in estimating spill probabilities and spill locations, it is probably not necessary to utilize a model of this degree of sophistication for shoreline impact estimation.

L. Reactor Safety Study

1. Documentation

Reactor Safety Study - An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400, U.S. Nuclear Regulatory Commission, October 1975.

2. Purpose

The purpose of the study was to estimate the risks involved in the operation of nuclear power plants in the United States and to compare these risks with non-nuclear risks to which society is exposed.

3. Scope

The study addressed accidents in pressurized water and boiling water nuclear power plants of the type currently in operation. Societal risk estimates were based on the operation of 100 such plants. Risks were measured in terms of expected fatalities, injuries and property contamination from release of radioactive material.

4. Methodology

The study consisted of three major tasks: (1) to identify the nuclear reactor accident sequences with potential deleterious consequences to the public and estimate their probabilities of occurrence, (2) calculate the consequences of various size releases of radioactive material resulting from the accidents, and (3) combine the probabilities and consequences to develop overall risks of the system.

a. Accident Probability

In the first task, event trees were used to determine the possible outcomes of an initiating event such as a pipe break. The outcomes depend upon the operability or nonoperability of those systems or components that affect the plant operation. In determining the possible outcomes, a series of accident sequences was developed.

Figure 2 (taken from the NRC study report) depicts an event tree for possible sequences following a pipe break in the primary system of a reactor. Several systems, noted by B, C, D and E on the diagram, may be affected by pipe break, subsequently leading to radioactive material being released to the atmosphere because of failure in the containment integrity. The original event contained all possible branches. The diagram represents a reduced tree, with all branches removed that do not reflect events of interest.

The probability for each sequence of events was computed from the probabilities for each event and those sequences that result in radioactive release were combined to develop the release probability.

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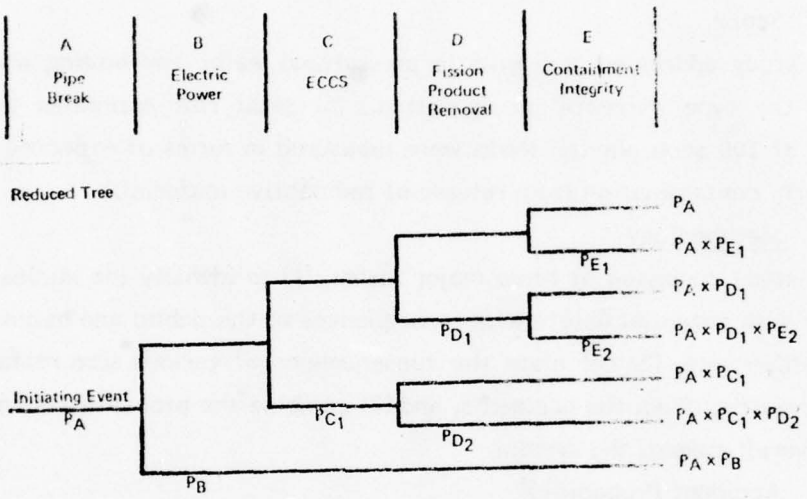

Note - Since the probability of failure, P, is generally less than 0.1, the probability of success (1-P) is always close to 1. Thus, the probability associated with the upper (success) branches in the tree is assumed to be 1.

Figure 2. Sample Event Tree

Source: Reactor Safety Study--An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, Main Report. WASH-1400, U.S. Nuclear Regulatory Commission, October 1975, page 55.

To estimate the event probabilities, fault trees were generated. A fault tree is used to identify the various combinations and sequences of failures that lead to specified system failure. A simplified fault tree for loss of electric power to a subsystem is shown for illustrative purposes. Hundreds of fault trees, each in much greater detail than that of figure 3, were developed for the study. The lowest levels of the fault trees represent basic component failures or human errors. Probabilities were assigned to these blocks and the resulting top level probabilities were computed according to the combinatorial rules indicated in the diagrams (ANDs and ORs). The top level probabilities were thus used in the event tree calculations to derive release probabilities.

Lognormal distributions were assumed for the basic failure probability distribution. A Monte Carlo computer program was used to develop the resultant probability distributions for the top events. This allowed the generation of statistical confidence intervals for the probability estimates.

c. Effects

An atmospheric dispersion model using Gaussian plume techniques was used to predict dispersal of radioactivity as a function of weather and amount of material released.

d. Consequences

A population model based on Census Bureau data was used to determine the number of people as a function of distance from the reactor. A consequence model calculated the doses and the resulting expected fatalities, injuries, and property contamination.

5. Applications

Fault and event tree methods have been applied to a variety of safety and reliability analyses including transportation systems, space systems, military equipment, etc. They have been applied to studies or oil transfer systems for deepwater ports,[1] risks associated with transporting radioactive materials by truck,[2] and transfer of LNG (the SAI study discussed above).

6. Data Requirements

Component failure rate data were obtained from over 50 sources. Human error probabilities were based from military and industrial experience for comparable tasks under similar stress levels.

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[1] L. Frenkel and W. Hathaway, Risk Analysis Methods for Deepwater Port Transfer Systems, U.S. Coast Guard, June 1976.

[2] T. I. McSweeney, et al, An Assessment of the Risk of Transporting Plutonium Nitrate by Truck, Battelle Pacific Northwest Laboratories, August 1975.

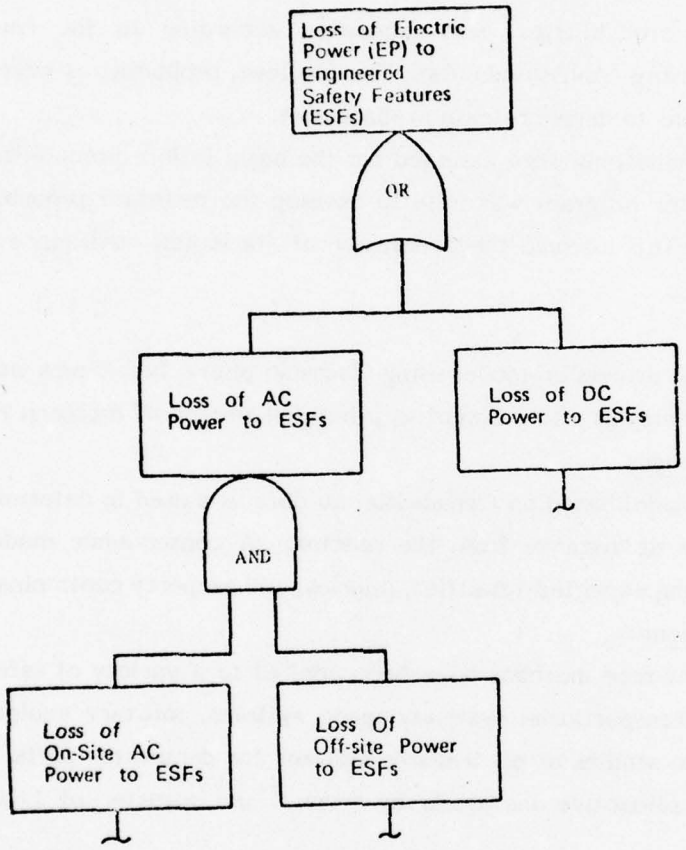

Figure 3. Sample Fault Tree

Source: Reactor Safety Study--An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, Main Report. WASH-1400, U. S. Nuclear Regulatory Commission, October, 1975.

7. Outputs

The primary results of the study are given in terms of the expected frequency of fatalities and property damage of various magnitudes compared with those occurring from natural and man-caused events.

8. Computer Requirements

A computer program called PREP-KITT was used in the evaluation of the fault trees. A Monte Carlo program, SAMPL, was used to develop top level probability distributions from component failure distributions. The atmospheric dispersion and consequence models were also programmed for the computer.

9. General Evaluation

The study represents one of the most extensive risk analyses performed to date. It was the first extensive quantitative analysis of nuclear reactors. It has been reviewed in detail by a number of interested groups. The most extensive evaluation of the study was performed by a review group headed by Dr. H. W. Lewis.[1] The group's report severely criticized several aspects of the study, including the inability to quantify human adaptability during the course of an accident, inadequate treatment of common cause failures, incomplete data, and questionable statistical analysis methods. The critique further points out that it is conceptually impossible to demonstrate completeness of fault trees and event trees; one can only attempt to demonstrate with reasonable assurance that only small contributions are omitted. However, the Lewis report concluded that "the fault-tree/event-tree approach coupled with an adequate data base is the best available tool with which to quantify (nuclear plant accident) probabilities."

The study accomplished several goals. First, it showed that (1) contrary to expert opinion, core meltdown accidents were not expected to be extremely rare events, and (2) most meltdown accidents were unlikely to cause much damage outside the installation.[2] Also, it provided a great deal of information that could be used to improve system safety.

10. Applicability to Coast Guard Risk Assessment

It is difficult to apply fault tree methods to estimating vessel casualty probabilities because of the complex human factors involved. Fault trees have been developed for vessel casualties to perform qualitative analysis. Quantitative analysis with fault trees has been

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[1] H. W. Lewis, et al., Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission, September 1978.

[2] Joel Primach, "Nuclear Reactor Safety, An Introduction to the Issues," Bulletin of Atomic Scientists, September 1975.

applied to the problem of material spills from transfer operations and to the estimation of the probability of a spill given an accident has occurred. However, little has been done on the estimation of vessel casualty probabilities using fault trees.

IV. COMPARATIVE EVALUATION OF THE RISK METHODOLOGIES

As stated in section II, the two primary applications of the risk methodologies surveyed are estimating risks and assessing the impacts of proposed safety measures related to transport of hazardous materials. Accomplishment of either task generally requires estimation of casualty and spill probabilities and the resulting consequences. Section III reviewed and evaluated 12 methodologies for evaluating risks. In this section, each of the risk elements (casualty probability, spill probability, spill effects, and damage) is discussed in terms of the various methodologies applied to each.

A. Casualty Probability

Table 4 categorizes the methods applied to the estimation of casualty probability. It is interesting to note that separate risk assessments by SAI and the FPC for a proposed LNG terminal at Oxnard, California resulted in significantly different probability estimates. The FPC study, which utilized the statistical approach outlined in section III.C, estimates the probability of an LNG spill from a vessel casualty to be 1 in 33 per year. The SAI study, which utilized the analytic method discussed in section III.D, indicated a spill probability of 1 in 180,000 per year. The same exposure rates were used. Most of the discrepancy is due to different assumptions about the effects traffic control procedures have on collision probabilities. SAI assumed a collision probability reduction factor of 0.003 for traffic control while the FPC did not assume any reduction. The remainder of the difference between the two can be attributed to differences in methodology and assumptions regarding the data.

1. Analytic Models

The problem of estimating casualty probabilities for risk assessment was addressed in a number of different ways in the studies outlined in the previous section. Analytic models such as those developed by SAI and ADL (McDuff Model) have been used for predicting vessel casualty probabilities. In addition, ORT used an analytic model (Scenario Model) to assess the effects of certain vessel and scenario parameter changes on vessel casualty probabilities. These models assume random motion of vessels within a specified envelope. The advantage of using analytic models is that the probability can be expressed in terms of certain critical parameters (vessel speed, size, density of vessels, etc.) This allows the probability estimation to be developed for the particular situation of interest based on the situational parameters rather than extrapolated from experience taken from other situations. However, there are serious problems with this approach. Many of the relationships

between situation/vessel parameters and vessel casualties are very complex and generally not amenable to analytic representation. Therefore, the models are generally relatively simple with a limited number of parameters.

Analytic models can be useful in estimating the relative effects of changes in certain vessels in situational parameters such as vessel speed or vessel spacing. However, it has not been demonstrated that they are of any value for evaluating most of the types of safety measures of concern to the Coast Guard such as communications systems, personnel training, navigation systems, and the like.

Utilizing analytic models for estimating casualty probabilities also presents problems. Each of the two models (SAI and ADL) used for that purpose apply multiplicative factors on the order of 10^{-4} to force the model results to be compatible with historical experience. This fact, in addition to the fact that the models have never been validated to any extent, brings into question the use of models for probability estimation.

TABLE 4

CATEGORIZATION OF CASUALTY PROBABILITY ESTIMATION METHODS

Method	Study
Analytic	ORI Spill Risk Analysis (A)* SAI LNG Risk Assessment (D) ADL LOOP Deepwater Port Study (H) (applied to impact casualties only)
Simulation	TSC Vessel Safety Model (B)
Fault Tree	NRC Reactor Safety Study (L)
Casualty Report Analysis	ORI Spill Risk Analysis (A)
Subjective	Woodward-Lundgren Vessel Cargo Spill Study (F)
Statistical	FPC LNG Risk Assessment (C) OIW Offshore Petroleum Transfer Study (G) MIT Oil Spill Probability Study (I) ADL LOOP Deepwater Port Study (H) (applied to nonimpact casualties)

* Letters denote subsection in Section III containing the study review.

2. Simulation Models

Simulation models, as exemplified by the Transportation Systems Center (TSC) model, can account for more complex representation relationships between vessel/situation parameters and casualty probabilities than can analytic models. However, if the model includes simulating casualties, an extremely large number of computer runs must be made to develop a significant number of simulated casualties because vessel casualties represent relatively rare events. The TSC model avoids this problem by simulating only the nominal ship tracks and computing the grounding and collision probabilities analytically, based on relative positions. However, this obviates the introduction of factors, such as communications between ships, that may directly affect the tracks of the ship. This model, therefore, is questionable with respect to the problem of estimating risks or assessing the effects of all but the most simple safety measures.

John J. McMullen Associates, Inc. has developed a computerized ship encounter simulation model for the California Public Utilities Commission.[1] This model, called the Marine Traffic Analyzer, simulates ship tracks using Monte Carlo sampling to represent variations from the nominal track. The model determines the point of closest approach for each pair of ships and indicates situations resulting in approach distances less than a given value. Avoidance maneuvers are not simulated nor does the model simulate collisions or rammings. Instead, it is designed to establish an encounter situation which can then be analyzed in detail by a real-time man-machine simulator such as the Maritime Administration's Computer Aided Operations Research Facility (CAORF).

Science Applications, Inc. has developed a computerized ship operations simulation model for the Maritime Administration.[2] This model is designed to simulate ship movement in restricted waterways to determine likelihoods of collisions, rammings, and groundings. The basic design allows for inclusion of harbor geometry; ship control parameterization; risk-avoidance maneuvers; effects of wind, currents, and shallow water on the hydrodynamics; and information acquisition and interpretation. Such a design, if properly implemented and validated, could be useful in evaluating mitigating measures. However, to date only the first of three planned phases of the project has been completed. The other two phases entailing completion and validation of the model have not yet been funded.

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[1] John J. McMullen Associates, Inc., Draft Vessel Traffic Analysis, Environmental Impact Report for Point Conception LNG Import Terminal, prepared for California Public Utilities Commission, December 1977.

[2] J. Wesley Miller, Joseph Schneider, and Frank Varcolik, Ship Operations in Restricted Waterways, Science Applications, Inc., prepared for the U.S. Department of Commerce Maritime Administration, July 1976.

Based on analysis of existing and proposed simulation models, it appears that further research directed toward the application of simulation techniques for assessing the potential effects of safety measures may prove fruitful.

3. Fault Tree Methods

The Fault Tree method allows estimation of failure or accident probabilities for systems for which insufficient historical data exist by analyzing the systems in terms of their component parts, for which there are data. Thus, when the event sequences leading to a system mishap can be well defined and the appropriate component data are available, as in the Reactor Safety Study, analysis of transfer operations can be quite useful. However, situations like vessel collisions involve a number of factors that are difficult to quantify; therefore, fault tree methods do not appear to be very useful in analyzing such situations quantitatively. However, they are sometimes useful in qualitative assessments of relationships and factors.

4. Statistical

Use of historical statistics for risk prediction is a valid approach when sufficient and appropriate data are available. In many cases, such as the FPC and SAI LNG studies, adjustment factors must be applied to account for differences between the vessel types and situations being evaluated and those from which the data were obtained. The values of these factors are, of course, often open to controversy.

Using statistical regression techniques to relate casualties to pertinent exposure parameters is a useful method for utilizing historical data to estimate results for a new situation. For example, casualty rate was estimated by regression techniques in terms of port calls in the studies by the Oceanographic Institute of Washington (OIW) and the FPC. This might allow casualty probability estimates to be made based on the projected number of port calls for a hypothesized situation such as a proposed LNG terminal. Possibly, this approach could be extended to encompass other pertinent variables such as vessel age and size.

An additional method for utilizing historical data for analyzing a particular situation is the application of data from similar situations (surrogate data) to enlarge the data base. This approach was used in a University of Southern California study for the Department of Transportation[1] which provided a computer system for aggregating data contained in a DOT data base from classes similar to that being analyzed. For example, if insufficient data are

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[1] James C. Card, "Effectiveness of Double Bottoms in Preventing Oil Outflow from Tanker Bottom Damage Incidents," Marine Technology, January 1975.

available for incidents involving a particular type of container, data corresponding to containers in the same class would be used. Similarly, if data on the effects of spilling a certain chemical are inadequate, data on similar chemicals would be applied. This also has been done to some extent in vessel safety analysis; for example, the application of oil tanker casualty data for LNG tanker analyses.

Because statistical techniques are based on historical data, they cannot directly reflect factors, such as proposed safety measures, that were not in existence during the period to which the data relate. Therefore, the statistical approach is not useful generally for assessing the impact of proposed safety measures. However, reduction factors based on other analyses can be applied to statistical estimates of the casualty probabilities to derive predicted casualties.

5. Casualty Report Analysis

This approach was utilized by ORI for assessing the effects of proposed safety measures. It was shown to be a feasible, albeit time-consuming, method for accomplishing this task. Because this method depends upon narrative casualty reports, its validity depends on the accuracy and completeness of the reports.

Another study that applied these approaches to the analysis of marine safety measures was the Offshore Vessel Traffic Management Study[1] performed by the DOT Transportation Systems Center. In that study, analysts evaluated several different safety measures by reviewing VCRS casualty reports and assigning values for each measure and each report, reflecting the probability that the specific casualty would have been prevented by that measure. The scores were combined for all casualty reports to develop a value for each safety measure.

Analysis of casualty reports cannot be used to estimate casualty probabilities, since it is based on the fact that a casualty has already occurred.

6. Subjective Approach

The subjective approach developed by Woodward-Lundgren for casualty and spill probability can be applied to almost any aspect of risk assessment. For example, a panel of experts could be queried on their estimation of the potential effects of training on casualties of specific types. The validity of the approach depends on the manner of presenting the questions, the knowledge of the panel members regarding the subject, and their ability to quantify accurately their perceptions in terms of probabilities.

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[1] Transportation Systems Center, Offshore Vessel Traffic Management (OVTM) System, prepared for the U.S. Coast Guard, August 1978.

It is generally easier to estimate probabilities of relatively large magnitude, e.g., 0.10, than those of small magnitude, e.g., 10^{-4}, simply because the latter events occur so seldom that the person's experience or knowledge does not include many of these events. Therefore, it is generally more valid to use subjective methods for estimating the effects of safety measures on risks (e.g., a one-third reduction in risk probability) than for estimating risk probabilities, e.g., a chance of one in ten thousand of a ship collision.

The subjective approach has been utilized in other transportation risk studies. For example, a study performed by the University of California[1] used the Delphi method to predict costs and accident frequencies for rail and highway transport of hydrogen sulfide. A three-stage Delphi technique was used with data on accidents involving transport of propane used to provide the baseline for the initial phase so that the panel members would have a common point of departure.

The study was successful in the sense that reasonable results were obtained. However, since no validation of the results with known data was performed, the accuracy of the estimates is not known.

Another study that utilized subjective methods was performed by Computer Sciences Corporation[2] for evaluating vessel traffic systems (VTS). The study attempted to estimate the potential reduction in casualties resulting from various VTS levels. Two alternative approaches were used: (1) estimating percentage reduction subjectively by casualty type (collision with vessel--overtaking; collision with vessel--meeting, etc.), and (2) evaluating the casualties on a case-by-case basis as to whether a casualty would have been prevented by the VTS using the causal factors listed in the Coast Guard's Vessel Casualty Reporting System.

The second approach is similar to but less rigorous than the ORI casualty report analysis method. No validation was performed.

Very little research has been done on the validity of subjective risk estimation. One analysis of subjective estimation of probability factors was performed by Oregon Research

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[1] Lloyd L. Philipson, Investigation of the Feasibility of the Delphi Technique for Estimating Risk Analysis Parameters, University of Southern California, prepared for the Department of Transportation, 30 April, 1974.

[2] Computer Sciences Corporation, Vessel Traffic Systems Issue Study, Volume 3. Computer Sciences Corporation, Report, prepared for the U.S. Coast Guard, March 1973.

Institute.[1] In that study, college students were asked to estimate ratios of frequencies of pairs of level events such as firearm accidents, tornadoes, heart disease, asthma, etc. The study report concluded that the ability of a person to reason probabilistically is questionable. However, the relationship between the questions addressed by that study and the problem of using experts to estimate vessel casualty risks seems tenuous for these reasons:

- The students were familiar with the events primarily from the media and not through direct experience, thus skewing the results in favor of the more spectacular events.
- Many of the events were extremely rare, such as 1 in 10^6 occurrences per year, making it difficult to estimate their occurrence frequencies, even in relation to other events.

One problem with using subjective methods for risk assessment is the time involved. Questionnaires must be developed, a panel must be selected, and the questionnaires must be distributed, completed, and evaluated. This must be done each time an evaluation is made.

A second problem is that the validity of the results can always be challenged because they are, after all, based on opinions.

Since little research has been done on the validity of subjective probability estimation, this appears to be a prime area for further study, particularly in the area of assessing differences in risk probabilities based on proposed changes.

B. Spill Probability

1. General

The probability of a spill can be estimated either directly by determining the probability of a spill-causing casualty or by first determining the probability of a casualty and then determining the probability of a spill given a casualty has occurred. Each of the methods applied to estimating casualty probability can also be used to estimate spill probability. However, in the studies surveyed, only four of the methods were applied to this element, as summarized in table 5.

2. Analytic Models

Both SAI and ORI used analytic approaches to estimate the probability of a spill given that a casualty has occurred. Both models applied physical relationships expressing the energy transfer and resistance factors. The results given by the SAI model for LNG ship collisions are comparable to those generated by the FPC based on historical data.

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[1] Paul Slovic, Baruch Fischoff, and Sarah Lichtenstein, Cognitive Processes and Societal Risk Taking, Oregon Research Institute, 1976.

Both models require strain absorption capability or resistance to be specified for the struck ship. This must be estimated from ship hull characteristics.

Analytic models for spill probability estimation generally can be used to assess the effects on the spill probability of certain safety or mitigating measures such as double hulls. For example, a double hull would be reflected in an increase in the resistance to an impact, thereby decreasing the spill probability.

Table 5

CATEGORIZATION OF SPILL PROBABILITY ESTIMATION METHODS

Method	Study
Analytic	ORI Spill Risk Analysis (A*) SAI LNG Risk Assessment (D)
Fault Tree	NRC Reactor Safety Study (L)
Subjective	Woodward-Lundgren Vessel Cargo Spill Study (F)
Statistical	FPC LNG Risk Assessment (C) ADL LOOP Deepwater Port Study (H) OIW Offshore Petroleum Transfer Study (G) MIT Oil Spill Probability Study (I)

*Letters denote subsection in section III containing the study review.

3. Simulation Models

The simulation approach as implemented by the Transportation Systems Center was used only for estimating casualty probabilities and not spill probabilities. Conceivably, spill probability for collisions, rammings, or groundings could be treated by simulation based on the expected stresses generated by an impact and the strengths of the structures involved.

4. Fault Tree Methods

The spill of a hazardous material, given that a casualty has occurred, is generally a fairly simple event: either the hull ruptures enough to spill or it doesn't. This type of situation does not lend itself to fault tree methods, which are primarily used for complex operations involving several possible sequences of events. Fault tree methods are most useful in marine spill probability assessments to determine the spill risk of operations, like transfers of hazardous materials, that involve sequences of events and decisions.[1]

[1] L. Frenkel and W. Hathaway, Risk Analysis Methods for Deepwater Port Transfer Systems, U.S. Coast Guard, June 1976.

5. Statistical Methods

Each of the four studies that used statistical methods to estimate casualty probabilities also applied them to spill probability estimation. Depending on the data used, spill probabilities can be derived directly from statistics on spills or by determining casualty probabilities from one data base and applying factors developed from another data base that express the probability of a spill given a casualty.

The OIW and FPC studies used data from the Coast Guard's Vessel Casualty Reporting System (which contains little data on spills) for casualty data and data from the Worldwide Tanker Casualty File to develop the spill probability factors. The ADL and MIT studies used the Worldwide Tanker Casualty File to obtain the spill probabilities directly.

The primary advantage of using the VCRS for casualties is that the location of the casualty is more specifically defined than in the Worldwide Tanker Casualty File and, therefore, can be used to analyze risks related to U.S. ports and harbors. The disadvantage is that spill data are not generally included.

The ADL and FPC studies applied averages for spill rates and volume spilled while OIW and MIT used spill distributions. They each used the same distribution type for spill frequencies--the negative binomial. OIW used an exponential distribution for spill size while MIT derived a distribution based on a Bayesian statistical technique. The latter distribution is much more difficult to compute and it is not clear that it expresses the true spill size distribution better than the exponential.

Using distributions rather than average values for oil spills can be quite useful because of the large variation in spill sizes. While spill frequencies are fairly consistent between years, spill volume fluctuates dramatically. A single large spill like that from the Torrey Canyon in 1967 can dominate the total volume spilled from vessel casualties in a year. It may be more meaningful to predict the probability of large-scale spills occuring rather than the expected amount spilled because of this large variance. Of course, with distributional methods both measures can be obtained.

As is the case for casualty probability estimation, where the appropriate data are insufficient, surrogate data could be used for spill probability estimation (providing applicable data are available).

6. Casualty Report Analysis

The ORI casualty report analysis method did not address spill probabilities because the data used for the analysis (the Coast Guard's Vessel Casualty Reporting System) did not generally contain information on spills. Had the data contained this information, the method

could have been used to develop estimates of differences in spill probabilities for various safety measures in the same manner as for casualty probabilities.

However, other studies have been performed utilizing damage data from casualty reports to predict effects of vessel structural changes in spill probabilities. For example, James Card[1] analyzed casualty reports from several sources to determine the extent of damage from vessel casualties. The damage data were then analyzed to estimate the proportion of spills that would have been prevented had the vessels had double bottoms.

7. Subjective Methods

The Woodward-Lundgren study addressed spill probabilities directly. The comments in the subsection on casualty probability estimation also apply to spill probability estimation.

C. Consequences

1. General

Consequence models may include both spill effects and damage estimation (e.g., the Vulnerability Model) or just the effects (e.g., most oil transport models). Also, consequence models may be considered in terms of the types of hazardous materials treated. Table 6 lists this information for the studies evaluated in this report.

2. LNG Effects Models

Three of the models treat LNG spill effects: the FPC, SAI, and Vulnerability models. As discussed in the evaluations of the studies, the FPC and SAI models result in very small distances to the lower flammable limit of an LNG vapor cloud. The Vulnerability Model results are close to the norm for seven LNG effects models evaluated by Jerry Havens of the University of Arkansas.[2] The current version of the model does not, however, include gravity spread/air entrainment effects, which can be significant for large-scale, rapid spills. The Vulnerability Model treats a number of other hazardous chemicals such as chlorine, anhydrous ammonia, etc. It contains a damage assessment routine based on distributions of population and property.

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[1] James C. Card, "Effectiveness of Double Bottoms in Preventing Oil Outflow from Tanker Bottom Damage Incidents," Maritime Technology, January 1975.

[2] Jerry Havens, Predictability of LNG Vapor Dispersion from Catastrophic Spills into Water: An Assessment, U.S. Coast Guard, April 1977.

Table 6

SPILL CONSEQUENCE CATEGORIZATION

LNG Consequences	SAI LNG Risk Assessment (D*) FPC LNG Risk Assessment (C) Vulnerability Model (E)
Other Hazardous Chemical Consequences	Vulnerability Model (E)
Oil Spill Transport	ADL LOOP Deepwater Port Study (H) Texas A&M Transport Model (K) MIT Oil Spill Trajectory Study (J)
Oil Spill Consequences (Bayesian Approach)	OIW Offshore Petroleum Transfer Study (G)

*Letters denote subsection in section III containing the study review.

To estimate damage from LNG clouds, the FPC and SAI studies applied overlays which represent the extent of an LNG flammable cloud on population and property distributions in the neighborhood of the LNG terminals.

The primary problems with using a sophisticated simulation model like the VM for chemical spill effects are the efforts involved in obtaining and inputting the appropriate data--particularly population data--and the computer expense. For risk assessments involving transport of hazardous chemicals, generally it is not necessary to determine to a high degree of precision because of the variability in the critical parameters such as weather conditions, spill size, and the spill location. Generally the consequences vary widely for even small changes in the values of these parameters, particularly the weather conditions. It would be useful for risk assessment purposes to have a set of analytic or empirical relationships that express the spill effects generically in terms of a few parameters such as spill size and chemical type, assuming nominal weather and other conditions. A set of damage contours reflecting the effects could be overlaid on a population distribution to estimate the consequences. One such relationship has been developed by A.D. Little[1] for toxic vapor cloud extent in terms of mass of the chemical and critical toxic concentration for nominal weather conditions.

3. Oil Transport Models

Three of the reviewed studies utilized transport models to assess impacts of oil spills on coastlines; Texas A & M, ADL, and MIT. All three models use computer simulation

[1] A.D. Little, Inc. A Model Economic and Safety Analysis of the Transportation of Hazardous Substances in Bulk, prepared for the Maritime Administration, May 1974.

programs to treat the movement of the slicks stochastically. Changes in current and wind velocities can occur in a statistically random fashion at prescribed time intervals during the simulation. All three models assume wind effects on slick movement are equal to 3 percent of the current effects.

The Texas A & M model is the most sophisticated of the three since it takes into account evaporation and dissolution of the oil during transport as well as stochastic movement of the slick. This model treats current direction and speed changes as well as wind direction and speed changes as a Markov process using 3-hour intervals. To obtain realistic wind and current data for the model, a 2-year instrumented data collection program was undertaken in the SEADOCK region of the Gulf of Mexico.

The MIT model does not treat losses due to evaporation or dissolution during transport. Wind direction is treated stochastically in 3-hour intervals by application of Markov transition matrices. Wind speed changes are determined for each direction change. Current speed and direction are treated as constant throughout each region of the simulation.

Current and wind speeds and directions for the ADL model are treated by sampling from the appropriate statistical distributions every 24 simulated hours. Thus, this model is theoretically less precise than the Texas A & M and MIT models. The model treats oil losses from evaporation and dissolution by applying a 20 percent loss factor after two days from the spill event and none before.

The OIW study went one step further than the oil spills studies discussed above by estimating the potential effects of spills on the environment of the region. A Delphi technique was used for this assessment.

The oil spill movement models reviewed, as well as many other spill movement models, are generally designed to predict impacts on the shoreline of spills from offshore oil production sites or terminals. They can be used to estimate environmental impacts or to aid in determining deployment of containment and collection systems for reducing the effects of oil spills. The latter purpose generally requires more precision.

Assessments of oil spill risks from vessel casualties do not generally require sophisticated or detailed oil transport models since the spill probabilities and spill locations cannot be determined precisely. Evaluation of impacts of oil spills are usually made in terms of shoreline affected. Since the number and location of tanker spills in a region are random variables, it is not likely that the particular transport model applied will have much affect on the predicted amount of shoreline affected. Since the more sophisticated models, such as the Texas A & M model, require extensive amounts of data, they are difficult to apply to regions other than that for which they were developed.

In general, although a number of oil spill transport and transformation models have been developed, the state-of-the-art is still at a relatively elementary stage. According to a recent MIT study, "Even under idealized conditions, the present capability to quantify the effects of winds and waves on oil slick advection is poor."[1] In addition, the study report states that the effects on oil spills of tidal, density driven, and general ocean currents, which can be important for far offshore regions, are not well known. Neither are slick spreading and weathering characteristics well defined with the exception of evaporation. The study report concludes that transport modeling is most accurate for protected areas; for exposed environments, better understanding of the phenomena and improved data are needed.

Another study on oil spill models performed by the Oceanographic Institute of Washington[2] reaches similar conclusions: that both detailed knowledge of the phenomenology and accurate data are lacking. The study report further points out that many models are site-specific, and the more general models are based on rather gross data.

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[1] Keith D. Stolzenbach, et al, A Review and Evaluation of Basic Techniques for Predicting the Behavior of Surface Oil Slicks, Massachusetts Institute of Technology, March 1977.

[2] Robert Rath and Bradley Francis, Modeling Methods for Predicting Oil Spill Movement, Oceanographic Institute of Washington, prepared for the Oceanographic Commission of Washington, March 1977.

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The purpose of the effort documented in this study was to determine the state-of-the-art for risk assessment by reviewing and evaluating a number of risk studies. This section contains several general conclusions regarding the application of the reviewed methodologies to marine risk assessment.

The risk assessment methodologies reviewed in this study address either of two questions related to marine transport of hazardous materials:

- Risk prediction--What are the expected risks associated with a particular situation such as a proposed deep-water port or LNG terminal?
- Risk mitigation--What are the expected benefits of implementing specific safety measures?

The conclusions regarding the applications of the various methodologies to these questions are necessarily general because of the general nature of the problem. The risk mitigation assessment problem is particularly complex because of the wide range of possible safety measures of interest.

1. Risk Prediction

If risk is measured in terms of the expected impact of vessel casualty spills on persons, property or the environment, risk prediction requires estimation of the four basic elements of risk assessment discussed earlier:

- Probability of a casualty,
- Probability of a spill in the event of a casualty,
- Effects of the spilled material (toxic cloud, fire, explosion, etc.), and
- Damage caused by the spill effects.

The most promising method for estimating the vessel casualty probability appears to be the use of historical casualty and traffic data where sufficient applicable data are available. Statistical regression techniques relating casualties to pertinent parameters such as port calls can be useful in applying the statistical approach to situations for which little data exist, e.g., proposed port facilities.

In cases where the vessel or event parameters for the situation being analyzed differ significantly from the situation to which the data pertain, adjustment factors can be applied. These factors may be derived from subjective judgment, casualty report analysis, or

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other means. Surrogate data can also be useful where data reflecting the exact situation/vessel parameters are insufficient and where the appropriate surrogate data are available.

Based upon the studies analyzed for this report, computer simulation has not yet been applied to casualty probability estimation. However, this method may be useful in analyzing well-defined situations such as simple port configurations. Additional modeling, programming, and validating effort may be necessary if this is to be accomplished efficiently and accurately.

Possibly, analytic models can provide sufficient accuracy in estimating casualty probabilities in certain situations. However, the limited number of parameters and simplistic relationships that are utilized in such models cast doubt on their general validity. Further, for the models analyzed, no validation seems to have been performed.

Fault tree methods do not appear promising for estimating vessel casualty probabilities. Such methods are useful primarily for risk/safety analyses where the relationships between accident-causing events can be explicitly defined and quantified, which is generally not the case in vessel casualty analysis.

Casualty report analysis was developed for evaluating the potential effects of vessel safety measures in terms of risk reduction and is not applicable to casualty probability estimation.

The use of subjective judgment for estimating casualty probabilities is questionable. However, further analysis of the validity of this approach would be of value as it could be used to analyze situations for which historical data do not apply.

Spill probabilities can be estimated directly from historical data, if available; derived from analytic models that express the energy and structural resistance relationships; or developed from subjective estimates. Because of the wide variation in oil spill sizes, it is useful to utilize spill frequency and size distributions for predicting the effects of oil spills rather than expected values.

Consequence modeling is still a subject of controversy for many hazardous chemical types. Because of the recent interest in importing LNG, a number of LNG effects models have been developed. However, there is no general consensus on the phenomenology; therefore, the models often yield widely disparate results. The treatment of LNG vapor clouds by the Coast Guard's Vulnerability Model appears to be reasonable, and the results are more in line with those achieved by other models than are the SAI and FPC LNG model results. In addition, the Vulnerability Model treats a large number of other chemicals and estimates damage to persons and property. Development of the analytic relationships for certain of the VM submodels is continuing.

There are a number of models of varying degrees of sophistication used to predict the movement of oil spills on the ocean and the impact on the shoreline. The more sophisticated models require detailed wind and current data, which are generally difficult to obtain. Because the occurrence, size, and location of oil spills from vessel casualties are random variables, precise representations of oil spill movements are generally not necessary. Thus, the simpler models such as ADL's model for LOOP would probably suffice for estimating the impact of tanker casualties. In analyzing the effects of spills from fixed locations such as a deepwater port terminal or offshore drilling unit, the more sophisticated models may be of value. However, the state-of-the-art of oil spill movement models is at a relatively primitive stage, and a great deal of research is necessary to develop accurate representation of oil slick movement in open sea areas.

Damages from oil spills are generally characterized by amount of shoreline affected. There is no general methodology for assessing the consequences of an oil spill in terms of loss of income from tourism, fishing, etc., or environmental damages. This problem has been treated for specific areas by subjectively estimating severity of damage to the area.

2. Risk Mitigation Assessment

The second risk assessment goal--estimation of risk mitigation--represents a much more difficult task, particularly for those safety measures that affect the casualty probability. Historical data are not generally useful for this purpose since the proposed measure will, if it operates as intended, change the conditions under which the data were generated. Existing analytic and simulation models are restricted to a few vessel and situation parameters such as vessel speed, vessel maneuverability, lane separation, etc. It would probably be possible to adapt current simulation models for evaluation of more complex safety measures, but the computer running time required to achieve a significant sample size might make it infeasible for general application. This is a possible subject for further research. Fault trees could be useful in assessing safety measures in a qualitative sense but probably not in performing quantitative evaluations.

Two methods have quite general applicability: casualty report analysis and subjective judgment. The former method was developed for evaluating marine safety measures and it represents a feasible approach. However, it is somewhat time-consuming and is limited to the information contained in narrative casualty reports.

The subjective approach is not limited by anything other than the ability of the respondents to assess and quantify the potential effects of the safety measures. This, of course, is the big question: what is the accuracy of subjective predictions for the situations

of interest in marine risk assessment? The Woodward-Lundgren study did not attempt to validate its subjective estimates. It would be useful to perform such a validation on a similar exercise.

The time involved in utilizing either of these two approaches for safety analyses can be quite significant since: questionnaires must be developed for the specific safety measure in question, either a panel must be organized for the subjective approach or a number of casualty reports must be analyzed for the casualty report analysis approach, and the results must be evaluated.

Safety measures affecting the probability of a spill once a casualty has occured--generally relating to structural changes--can be treated by analyzing damages incurred in the past and determining those which would not have resulted in spills had the measure been in effect. This approach is similar in concept to ORI's casualty report analysis, which was applied only to casualty probability estimation. A second approach involves altering the vessel strength inputs to the analytic impact models. In addition, subjective methods can be applied to estimation of the effects in spill probabilities of mitigating measures. Thus, this type of safety measure generally can be satisfactorily addressed.

The consequence portion of risk assessment generally is not affected by safety measures except indirectly through reduction of the probabilities of the consequences. Oil spill cleanup and containment measures can be evaluated using an oil spill movement model to determine the reduced amount of oil impacting on the shoreline.

Table 7 summarizes the casualty probability methodologies that apply to evaluation of various types of safety measures. The categories are general; there may be certain measures in a category that do not correspond to the evaluations depicted in the chart.

B. Recommendations

To further the goal of developing a management system for evaluating risks and assessing mitigating measures for marine transport of oil and hazardous materials, the following recommendations are made:

- The safety measures of interest to the Coast Guard be defined and ranked in order of priority to further clarify the goals of the risk management methodology.
- Further research be conducted on the development and application of computer simulation methods for assessing risk mitigation measures.

APPLICABILITY CODE:

G - Generally applicable
P - Partially applicable
(applies to some measures)
N - Not applicable

SAFETY MEASURE CATEGORY	PRIMARY RISK ELEMENT AFFECTED	METHODOLOGY					
		Casualty Report Analysis	Subjective Probability	Analytic Models	Computer Simulation	Historical Statistics	Fault Tree Models
Navigation Aids, Communications	Casualty Probability	G	G	N	P*	N	N
Vessel Control	Casualty Probability	G	G	G	G	N	N
Vessel Structure	Spill Probability	G	G	G	P*	N	N
Personnel Licensing/ Training	Casualty Probability	N	G	N	N	N	N
Inspection and Maintenance	Casualty Probability	N	G	N	N	N	N
Operational Procedures	Casualty Probability	P	G	P	P	N	N

*Existing models could probably be modified to treat these measures.

Table 7. Applicability of Casualty Probability Methodologies to Evaluation of Marine Safety Measures

- The subjective approach to risk mitigation assessment and risk prediction be tested and validated with results from a standard approach (such as the statistical).

- Further analysis be conducted to develop regression relationships between vessel casualties and pertinent situation and vessel parameters.

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