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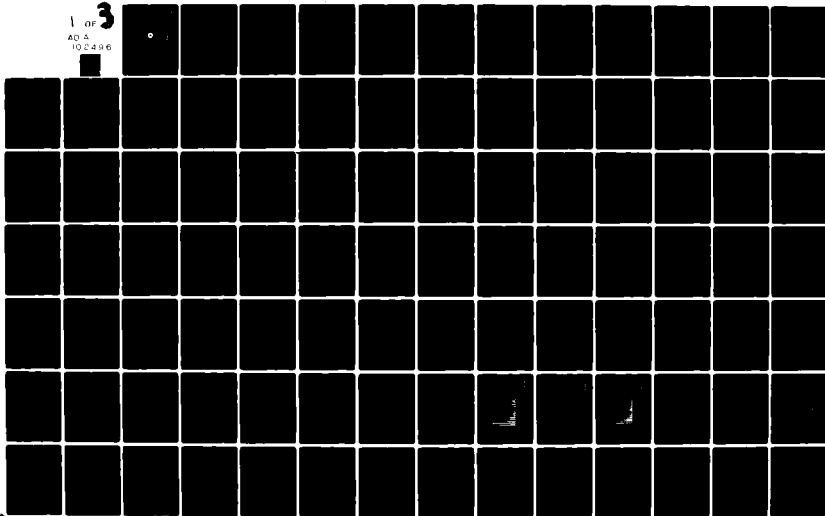
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PUGET SOUND TANKER SIZE OPTIMIZATION

LEVEL II

Oceanographic Institute of Washington
152 Denny Way
Seattle, WA 98109

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16. Abstract Relationships between oil tanker risk and certain quantifiable tanker and port activity characteristics are determined, with a special emphasis on tanker size. A model is developed which optimizes the average tanker size which should be used in a port system to minimize the risk of oil spillage. The study uses statistical techniques to analyze historical worldwide data in order to develop risk relationships. Calculus was used to minimize the risk of spillage based upon different risk indicators. The basic risk indicators developed in the analysis are the number of casualty spills, the total volume of casualty spills, and the total volumes of all spills (including operational). The development of optimal cases is dependent upon the assumption of constant tonnage throughput in a port system.		
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UNIT CONVERSIONS

barrel	=	42.13 U.S. gallons
metric ton ¹	=	7.31 barrels
metric ton	=	1,000 kilograms
metric ton	=	2,204.6 pounds
metric ton	=	308 U.S. gallons
metric ton	=	256 Imperial gallons
metric ton	=	1.16 kilolitres
1,000,000 metric tons per year	=	20,027 barrels per day
100,000 barrels per day	=	4,993,160 metric tons per year

¹ Deadweight tonnage is expressed in metric tons in this report

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GLOSSARY AND ABBREVIATIONS

Casualty Spill:	A spill involving a hull rupture caused by any of the following: groundings, collisions, fires, rammings, explosions and incidents of breaking mooring, capsizing, structural failure, heavy weather damage, loss of anchor and breakdown.
Coastal:	Defined for this study to include waters within 50 miles of land.
Combination Carriers:	Vessels designed to transport petroleum products and other cargo, either liquid or solid (e.g., ores, chemicals, molasses).
Correlation:	A measure of the relationship between a function of the independent variable(s) and the dependent variable in a sample, $+1$ indicating a perfect relationship and 0 indicating statistical independence.
DWT:	Deadweight tonnage.
Deadweight Tonnage:	The number of metric tons that a vessel will lift when loaded in salt water; commonly used to indicate the actual carrying capacity of a vessel in metric tons.
Exposure Variables:	The quantifiable factors which, through their functional relationships with risk indicators, express the inherent level of risk (i.e., the probability of an undesired event) in any active operation or system. For example, port calls and deadweight tonnage have been shown to be two of several exposure variables to express the risks of oil spill frequency and volume.
Greater Puget Sound:	Defined for this study as including the Strait of Juan de Fuca, Puget Sound and the Strait of Georgia.
Heteroscedasticity:	A condition of a relationship characterized by a non-constant variance; i.e., the variance of the dependent variable is contingent upon the values of the independent variable(s).
Hindcast:	A statistical calculation determining probable conditions during the studied period.
Homoscedasticity:	A condition of a relationship characterized by a constant variance; i.e., the variance of the dependent variable is constant for all values of the independent variable(s).
KDWT:	One thousand deadweight tons.

Linear Relationship: A dependency of a single dependent variable on one or more independent variables expressed as a function of the independent variable(s) in which the coefficients in the function appear in an additive manner.

MDWT: One million deadweight tons.

Metric Ton: Weight of 1,000 kilograms, or 2,204.6 pounds, used for recording spillage and deadweight tonnage.

Multivariate Regression: A statistical method for finding the hypersurface that best defines the relationship between a dependent variable and two or more independent variables.

Nonlinear Relationship: A dependency of a single dependent variable on one or more independent variables expressed as a function of the independent variable(s) in which the coefficients in the function appear in a non-additive manner.

OIW: Oceanographic Institute of Washington.

Operational Spill: A spill not involving a hull rupture but caused by operational activities aboard a vessel such as loadings, unloadings, tank transfers, bilge pumping and tank washings.

Port: A tanker's place of destination which is equipped with terminal facilities.

Port Call: A visit by a tanker at a terminal facility for the loading or unloading of petroleum products; this excludes passings.

Port Group: Defined for this study as a group of three port systems, selected by application of any of several criteria.

Port System: Defined for this study as a grouping of ports based on proximity.

Risk Indicator: A measure of a defined hazard (e.g., volume of spillage from casualty spills).

Simple Linear Regression: Statistical method for finding the equation of a line that best defines the relationship between the dependent variable and a single independent variable.

Tanker Years: Defined for this study as the the sum of time (in years) a tanker was recorded to be in existence during 1976-1979 minus the recorded laid-up periods.

Ton: Unless otherwise specified in the text, this term refers to a metric ton.

Tonnage Throughput: The sum of deadweight tonnage times the number of port calls, not the quantity of oil transported.

VTs: Vessel Traffic Service.

World Fleet: Defined for this study as a fleet of 4,055 tankers in existence during 1976-1979 which meet the following requirements: vessel's deadweight tonnage is greater than or equal to 5,000 DWT, vessel is of non-Communist flag, and vessel is strictly an oil carrier (tanker).

EXECUTIVE SUMMARY

BACKGROUND

The U.S. Coast Guard, within whose jurisdiction rulemaking and enforcement lies, authorized this study to address possible relationships between tanker risk and certain quantifiable tanker and port activity characteristics. The results are to be applied to the minimization of tanker risk in Puget Sound. It is also desirable that the methods have applicability to other ports or port systems in the United States and throughout the world.

Historically, tanker size has been perceived by some as an important factor in tanker risk. In 1975, the Washington State Legislature enacted legislation specifying a 125,000 deadweight ton limit on tank vessels in a designated area within Greater Puget Sound (68)*. Portions of this law were declared unconstitutional by the U.S. Supreme Court in 1978, and the state tanker size limit was struck down. Shortly thereafter, the U.S. Secretary of Transportation issued an interim ruling extending the tanker ban pending permanent rulemaking actions. The temporary measure, extended twice, remains in effect pending a decision on permanent measures (69). As it prepares to issue permanent rules, the Coast Guard must decide whether to implement, modify, or delete the tanker size limit (70,71).

SCOPE

This study by the Oceanographic Institute of Washington (OIW) provides quantitative evidence to aid the Coast Guard in evaluating the effects of certain specific policy decisions upon tanker spill risk. Its purpose is to determine a historically derived optimal tanker size which represents the minimum risk of spillage from oil tankers in Greater Puget Sound, with applicability to other port systems. It also addresses the importance of other tanker characteristics, such as age, and determines what, if any, relationships exist among tanker size, age, and other exposure variables.

* - References are indicated throughout the text by a number in parenthesis, such as (68), and are listed in Section 7.

The study was not intended to and does not recommend an optimal tanker size limit. It is recognized that the minimization of tanker spill risk is simply one of many criteria to be considered in the decision-making process. This study thus results in the optimization of a subset of the issue. In a similar manner, other optimums of different subsets could result in very different optimal policy decisions. Examples of other potentially optimized criteria include risk of environmental damage, economic cost (or benefit), and social, legal, and political impacts.

The ultimate policy decision regarding the tanker size limit must attempt to weigh all of these various factors and determine a policy which maximizes the total benefit (or minimizes the total cost) based upon their interaction. This study provides quantitative information about the impacts of possible policies upon one aspect of the issue, thus improving the ability to assess possible trade-offs.

Within this framework, the study addresses the statistical risk of oil spillage, and its potential relationship to various tanker and port characteristics. The study does not address the relative merits of various alternative risk-reduction measures. Thus, tug assistance or escort and alternative traffic management systems are not studied.

GENERAL APPROACH

The methodology most commonly utilized in risk assessments is statistical analysis. This method quantifies and models historical experience in order to gain an understanding of the interaction of various factors. The results can then be applied in many cases to estimate the impacts of changes in those factors.

This study follows this approach. In the past, such analyses have often led to diverse and occasionally conflicting results (9-27). It is a purpose of this study to overcome the obstacles encountered previously via several principal improvements:

- Expanded and more reliable data bases
- Use of actual port call data
- Use of multiple variables in the analyses
- Determination of optimal values for variables

A statistical analysis cannot address factors about which no information is available, or which are not in some way quantified. The results of the analysis cannot assess the effect of changes which are not in the statistical relationships. For example, effects of changes in crew training or the requirement of tug assistance could only be quantified in a relationship between tanker spillage and tanker size if those variables were a part of that relationship. Also, the application of statistical results of an historical model is limited to the domain of the analysis. For example, since 5000 deadweight ton tankers are the smallest considered in the analysis, then the effects of using 2500 deadweight ton tankers could not be evaluated.

The utility of the statistical results of this study lies in evaluating the effects upon tanker spillage of changes among those documented variables for which valid relationships were found. The results obtained were essentially used to hindcast the effect of alternative scenarios upon tanker spill risk. That is, the statistical model was used to determine what "would have happened" during the period being analyzed had a different set of conditions been experienced. This might be related to what "will happen" given those conditions only under the assumption that all other conditions remain unchanged.

In order to perform the analyses, there must be sufficient data to characterize each of the risk indicators and each of the appropriate exposure variables. Although data are available from U.S. sources and are sufficient to perform some risk analyses, most U.S. ports are incapable of handling very large tankers. Thus it was necessary to obtain worldwide data in order to suitably address tanker size. In order to obtain valid results from this study, it was necessary to verify and cross-check the worldwide tanker spill data bases to ensure reliability.

Following data collection, factor analysis was used to evaluate the potential exposure variables and determine which ones should be used in an analytical relationship with the risk indicators. Linear and multivariate analyses were then utilized to determine the mathematical relationship between the essential exposure variables and the risk indicators. When indicated, nonlinear functions of exposure variables were also considered in efforts to determine mathematical relationships. Levels of confidence were determined for developed mathematical relationships. Last, differential calculus was employed to determine the conditions which minimize the various risk indicators and the sensitivity of the solution to the input variables was examined.

DATA BASES

The identification of the best sources of information to obtain satisfactory data bases was long and arduous. The procedure utilized was to contact some 55 governmental agencies, private organizations and port authorities throughout the world. This was followed, if appropriate, by a personal visit. The collection of data was based on the development of a studied world fleet consisting of a specific collection of 4,055 tankers. All vessels appearing in the Lloyd's Register of Ships as oil tankers of greater than 5000 dead-weight tons and having non-communist flags of registry were included. Combination carriers, liquefied gas carriers, tank barges, and chemical tankers were not included. Only petroleum and petroleum product spill incidents involving this specific world fleet were included, and activity levels were determined based upon only those tankers. Thus the analysis has the advantage that all variables relate to precisely the same tanker fleet.

The emphasis during data collection and verification was placed upon the years 1976-1979. This was primarily due to the limitation of computerized port call data to those years. Additionally, many sources of spill data either did not extend to earlier years or were not as thorough for those years. Thus, incident verification was not as thorough for the years 1975 and earlier as for the years 1976-1979. Therefore, due to the much greater confidence placed in the 1976-1979 data, the analysis focused on those four years.

High confidence is placed in the set of data bases developed because they are confined to a statistically valid period and area; are assembled from many diverse domestic and foreign sources representing different users and interest groups; and have been verified to remove as many inconsistencies as possible.

Tanker Register

The purpose of the OIW Tanker Register is the documentation of tank vessel characteristics for the world tanker fleet. It also provides for vessel identification, as few tanker identifiers are absolute.

The Tanker Register is a compilation of data on the studied fleet of oil carriers from Lloyd's Register of Ships, and covers the years 1976-1979 (33).

From this source, a fleet was selected which would consist of the set of tankers to be addressed in this study. Only tankers of greater than 5000

deadweight tons were included in order to exclude coastal and intraharbor tankers, for which documentation is poor (54). Again due to poor documentation, communist flag vessels were also excluded. Finally, combination carriers were excluded due to their very different physical characteristics. The result is a file of 4055 oil tankers. Subsequently, information concerning the laid-up status of vessels and numbers of port calls were provided from other sources (50,29).

Some tanker characteristics were occasionally not provided in the source information. For those cases, estimated values were included using relationships with other characteristics derived from the analysis of complete entries.

Port Call Data

The port call data were derived from Lloyd's Vessel Movement File (29). This file exists in computerized form only for the years 1976-1979. For this reason, the analysis was restricted to this time period. It provides the basis for determining tanker and port activity levels, allowing for the development of port call and tonnage throughput exposure variables, based upon actual data.

The data base documents tanker port calls by vessels included in the Tanker Register. For these tankers, the number of port calls made each year is known. Additionally, the number of port calls made by tankers at each port where the tanker has called is also known. This allows for the development of measures of activity for both tankers and ports. It does not provide chronological information, so origin/destination pairings were not possible.

Casualty Spill File

The purpose of the Casualty Spill File data base is to document spill incidents for subsequent analysis. It is a compilation of worldwide spill data and includes all reported oil spills which involve a breach of vessel integrity. Thus, a hull or tank rupture would be included, and a hose rupture or valve failure would not, unless a subsequent event (e.g., fire or explosion) resulted in further damage. It incorporates information from thirteen different sources from around the world (37-48). These sources include

government agencies, industry groups, research institutes, classification societies, and others. Inconsistencies among data bases led to a method of verification, via cross-checking among sources. Using this method, spill incidents included in the file were limited primarily to those reported in more than one source. The resulting file contains 190 spills, of which 175 had recorded spill volumes.

Operational Spill File

While many data bases were located describing the circumstances surrounding the occurrence of tanker spills, only one of these data bases appears to describe the occurrence and volume of operational oil spills world-wide. This is the data provided by the International Tanker Owners Pollution Federation Limited (TOVALOP) (44). This data base consists of voluntary reports by member owners and therefore the confidentiality of the information was protected by excluding tanker identification when the data were provided to OIW. Due to the inability to verify that the reported spills are caused by tankers in the studied fleet, the Operational Spill File may contain some inconsistencies with regard to the studied world fleet.

Port Characteristics File

A data base was established documenting available port characteristics for the most active tanker ports world-wide. The ports were chosen based upon the number of port calls reported in the Lloyd's Vessel Movement File for the years 1976-1979 (29).

The port characteristics file was initially intended to include a variety of physical characteristics for consideration in subsequent analysis, in addition to tanker activity information. Unfortunately, no sources discovered documented physical characteristics in a consistent or systematic manner. Indeed, the only characteristic provided with any reliability was the number of oil tanker berths at the port (55,56). Additional efforts were made to procure information concerning perceived port safety via contacts in the oil industry (59). These efforts did not result in any quantifiable data. Thus, this file is essentially limited to the documentation of port activity.

The use of individual ports was considered for developing subsequent relationships to oil spills. This was found to be infeasible due to imprecise identification of casualty spill location. In many cases spills in a bay or enclosed waterway could not be satisfactorily identified with a specific port. Thus, the use of port systems was found to be the preferred alternative.

For each major port, a port system was identified based upon topographical considerations. Sixty port systems were identified, which contained the seventy-three most active oil ports in the world, based upon number of port calls made. Greater Puget Sound is included in these sixty port systems.

STATISTICAL ANALYSES AND RESULTS

Prior to the introduction of analytical methods and results, several key premises need to be addressed.

Standard statistical techniques which indicate the natural variability of the data allow one to discuss with some assurance the average amount of oil spilled under a given set of circumstances. Since it is reasonable to assume that the vast majority of all large spills have been reported and that most of the vessel owners are reporting spills to the various governments as required by law, and to the tanker owners/operators groups as requested, one can gain some assurance that the averages generated during this analysis are valid.

The analysis was based upon historical data. The study addresses the spilling history of tankers and not the spilling future of tankers. During much of these studies, four years of experience have been used to determine relationships between the risks and parameters describing tanker operations. It is not OIW's intent to suggest that these relationships will hold for all time. Strictly speaking, they should be interpreted as models of what has already happened and not as forecasts or predictions of what will happen in the future.

The analyses were concerned with determining relationships using quantifiable data. Because not all aspects of tanker operations are recorded and available for study, the efforts had to be directed to those operations which were quantifiable and recorded by various groups.

For those characteristics which were analyzed, the determination of a relationship does not imply causality. For example, port calls do not cause spills; they simply measure the exposure to the potential for oil spillage.

Finally, this study of tanker oil spills is based upon an assumption that the occurrence and volume of oil spills can be expressed as some function of the physical characteristics of tankers and/or of the activity level of ports or tankers. This assumption, which has been verified in this and other studies, carries with it implicitly the assumption that tankers of similar characteristics or ports of similar characteristics will have similar spill histories. So there is good and sufficient reason for the analysis to be based upon it. However, the assumption effectively rules out the possibility of this study finding that a particular tanker has an unsafe characteristic, different from all tankers of similar size, power, age, or activity.

Comparison of Spilling Tankers With All Tankers

The consideration of tankers involved in casualty spills as a "spilling fleet" leads to the natural question: how do the characteristics of this fleet differ from those of all tankers?

The two fleets were found to display the same distribution of characteristics. This leads to the conclusion that there is no reason to believe the tankers that have had spills behave any differently from those that have not been responsible for spills. Spilling tankers do not, on the average, tend to be larger or smaller, overpowered or underpowered, older or younger, or less or more active than non-spilling tankers. Thus, tankers in the spilling fleet can be considered a representative subset of the studied world tanker fleet. In subsequent analyses, and in particular for the analysis of spill volumes, the characteristics of the studied fleet can be used as appropriate exposure variables. Without this result, no assumptions could be made that the world fleet characteristics are valid exposure variables.

Analysis of World Fleet Spill Relationships

During this analysis, the data were sorted to provide four different perspectives according to: deadweight tonnage; age; activity level, as measured by port calls per tanker year; and port systems. Each of these perspectives emphasizes a different aspect of the tanker safety issue.

When addressing spill frequency, port calls was the only exposure variable which consistently had a coefficient significantly different from zero. The relationship determined was:

$$(\text{Number of Casualty Spills}) = -5.573 + 8.607 \times 10^{-4} * (\text{Port Calls})^1$$

The correlation of this equation is $r=0.67$. The constant term was not significantly different from zero at the 95% level, and can be regarded as unnecessary. This relationship was determined based upon groups of 200 tankers (hence the large constant), which average over 17,000 port calls. Thus the application of this rate to small groups of tankers with far fewer port calls could not be made with great confidence.

The implication of this result is that to minimize risk of casualty spill occurrence for a given group of tankers, minimize their activity. This is hardly a novel concept. The fewer port calls made by a class of tankers, the lower the resulting risk of spillage. As deadweight tonnage is not a significant variable in this relationship, this would also mean that fewer port calls by larger tankers could also reduce this risk. However, the consideration of other factors, such as port characteristics, could (and does) introduce tanker size as an important variable.

Spill volumes (measured in metric tons) and their relationships to tanker characteristics were addressed. In developing these relationships, the average volume for each deadweight tonnage range was used. This method accepts that the volume of an individual spill cannot be predicted with great confidence due to extreme variability (from 1 to 275,000 tons), but that average volumes are desirable indicators of spill volume trends.

Numerous different versions of this analysis were performed, based upon spills with reported spill volumes. All produced virtually identical linear relationships between casualty spill size and deadweight tonnage, with no other significant variables. The relationship used subsequently is based upon the 150 casualty spills in inland and coastal waters with recorded volumes. It is:

$$(\text{Average Volume Spilled}) = 348 + 0.0652 * (\text{Deadweight Tonnage})$$

The study of operational spills yielded a linear relationship for spill occurrence. This relationship is:

¹ - Throughout this report, an asterisk (*) is used to represent multiplication of terms.

$$(\text{Number of Operational Spills}) = 4.95 \times 10^{-3} * (\text{Port Calls})$$

Operational spill volume was not found to be related to any of the exposure variables tested. On this basis, it was determined that the average volume spilled is 224 tons. The combination of many small spills and occasional very large spills produces this average.

When tankers were grouped according to age, a quadratic relationship was found between spills/tanker year and age of tanker. This is:

$$(\text{Spills}/100 \text{ tanker years}) = -0.0064 * (\text{Age})^2 + 0.185 * (\text{Age}) + 0.611$$

This quadratic model yields a correlation of $r = 0.66$. The result of this model depicts a peak in spill frequency at about 15 years old. The data confirm this.

Several other relationships uncovered reflect a statistical relationship between age and tanker size. As large tankers are relatively new, it might be expected that older tankers are on the average smaller than newer ones. Indeed, the correlation between average deadweight tonnage per age group and age is $r = 0.95$. This indicates that older tankers are smaller. It does not indicate that tankers get smaller as they get older, nor that smaller tankers necessarily survive longer. There simply are not yet any very large, very old tankers.

The data also were analyzed from the perspective of port systems. For this analysis, sixty port systems were identified based upon the most active individual tanker ports. Within these port systems, sixty-eight spills were identified. Analysis showed that three exposure variables were found to be highly significant in predicting the number of spills. The multivariate relationship found for a port system from this method was:

$$\begin{aligned} (\text{Number of Casualty} \\ \text{Spills/year}) &= 1.518 \times 10^{-3} * (\text{Port Calls/Year}) \\ &- 1.188 \times 10^{-2} * (\text{Tonnage Throughput in MDWT/Year}) \\ &+ 7.445 \times 10^{-3} * (\text{Average Deadweight Tonnage in KDWT}) \\ &- 0.720 \end{aligned}$$

The correlation of this relationship is $r=0.92$. This relationship was developed by creating twenty groups of three port systems based upon number of port calls.

The analysis of spill volumes yielded no valid relationships. This implies that it is tanker, not port, characteristics which determine spill volume.

MINIMIZATION OF RISK INDICATORS

The statistical analysis above results in four equations useful in optimizing spill risk in port systems. These equations relate to the casualty spill occurrence, casualty spill volume, operational spill occurrence, and operational spill volume. The four equations are:

$$\begin{aligned} \text{SPILLS (casualty)} = & 1.518 \times 10^{-3} \text{ PC} - 1.188 \times 10^{-2} \text{ THPT} \\ & + 7.445 \times 10^{-3} \text{ DWT} - 0.720 \end{aligned} \quad (1)$$

$$\text{SPILLS (operational)} = 4.95 \times 10^{-3} \text{ PC} \quad (2)$$

$$\text{VOL (casualty spill)} = 348 + 65.2 * (\text{DWT}^2) \quad (3)$$

$$\text{VOL (operational spill)} = 224 \quad (4)$$

where

PC = number of port calls per year in a port system

THPT = tonnage throughput in MDWT per year in a port system

DWT = average tanker size in KDWT per year in a port system

DWT2 = tanker size in KDWT

These equations can be used to develop several different indicators of risk. While many such risk indicators can be identified, three are presented here which are readily available from the above equations. These risk indicators, developed for port systems, are:

- Number of Casualty Spills
- Total Volume of Casualty Spills
- Total Volume of All Spills

Other potential risk indicators, such as risk of very large spills, were considered, but were not quantifiable from the results obtained. While it may be possible to quantify these through subsequent analysis, it is beyond the applicability of the current analyses.

The minimization of each of the three risk indicators can be achieved through the use of differential calculus. Also used in the optimization procedure is the relationship for a port system of three variables:

$$(\text{Tonnage Throughput}) = \sum_{\text{all vessels}} (\text{Number of Port Calls}) * (\text{Deadweight Tonnage})$$

This yields at the port system level the relationship:

$$(\text{Average Deadweight Tonnage}) = (\text{Tonnage Throughput}) / (\text{Number of Port Calls})$$

The three risk equations and the relationships which optimize them are:

(1) Number of Casualty Spills

$$\begin{aligned} \text{Spills (casualties)} &= 1.518 * (\text{THPT}/\text{DWT}) - (1.188 \times 10^{-2}) * \text{THPT} \\ &\quad + (7.445 \times 10^{-3}) * \text{DWT} - 0.720 \end{aligned}$$

$$\text{DWT}(\text{optimum}) = 14.28 * (\text{THPT})^{1/2}$$

(2) Total Volume from Casualty Spills

$$\begin{aligned} \text{CASVOL} &= 528.3 * \text{THPT}/\text{DWT} + 0.4854 * \text{DWT}^2 - (0.7746 * \text{THPT} + 44.35) * \text{DWT} \\ &\quad + (94.9 * \text{THPT} - 250.6) \end{aligned}$$

$$\begin{aligned} [\text{DWT}(\text{optimum})]^3 &= (0.7979 * \text{THPT} + 45.68) * [\text{DWT}(\text{optimum})]^2 \\ &\quad + 544.2 * \text{THPT} \end{aligned}$$

(3) Total Volume from All Spills

$$\text{TOTVOL} = 1637 * (\text{THPT}/\text{DWT}) + 0.4854 * (\text{DWT})^2 - [0.7746 * (\text{THPT}) + 44.35] * \text{DWT} \\ + [94.9 * (\text{THPT}) - 250.6]$$

$$[\text{DWT}(\text{optimum})]^3 = [0.7979 * (\text{THPT}) + 45.68] * [\text{DWT}(\text{optimum})]^2 + 1686 * (\text{THPT})$$

These three relationships provide three different criteria for optimizing average tanker size. These relationships can be applied to Greater Puget Sound to determine optimal average deadweight tonnages. These results are provided in Table ES-1. They assume a constant tonnage throughput scenario, based upon a demand for oil which is insensitive to the manner of delivery. That is, the amount of oil needed is not dependent upon the tanker fleet mix which would be used to deliver it. Additionally, this assumes that the rate of tanker utilization remains constant, as tonnage throughput measures tanker capacity, not actual amount delivered.

The results shown in Table ES-1 indicate that the minimization of any of the three risk indicators yields a similar optimal average deadweight tonnage of about 70,000 for Greater Puget Sound. The close agreement between these optimal values is not unexpected, as the risk indicators being optimized are highly related, and in fact sequentially developed.

The equations for the risk indicators result in a decreasing level of risk as average deadweight tonnage increases from 51,430 to the respective optimal sizes. Beyond this point, the risk indicators again begin to increase. Depending on the risk indicator, the level of risk again reaches the level experienced at 51,430 somewhere in the range from 87,000 to 100,000. The points at which the risk levels equal the risk levels given the current average deadweight tonnage of 51,430 are approximately: 100,000 for Number of Casualties; 87,000 for Casualty Spill Volume; and 97,000 for Total Spill Volume. For all values between 51,430 and these upper limits, the level of risk as measured by the respective risk indicator is less than the current risk level.

When considering the applicability of the models developed to Greater Puget Sound, it must be considered whether Greater Puget Sound is in some way unique, and whether that uniqueness reduces the accuracy of the model.

TABLE ES-1

OPTIMIZED AVERAGE TANKER SIZE FOR THREE RISK INDICATORS FOR GREATER PUGET SOUND, 1976-1979

	GREATER PUGET SOUND ¹ 1976-1979		MINIMIZED RISK INDICATORS		
			NUMBER OF CASUALTY SPILLS	VOLUME FROM CASUALTY SPILLS	TOTAL SPILL VOLUME ²
<u>PORT SYSTEM VARIABLES</u>					
TONNAGE THROUGHPUT IN MDWT/YEAR ³	25.25		25.25	25.25	25.25
OPTIMAL AVERAGE DEADWEIGHT TONNAGE	51,430		71,750	68,740	73,670
OPTIMAL NUMBER OF PORT CALLS/YEAR	491		352	367	0
<u>RISK INDICATORS</u>	HISTORICAL EXPERIENCE	ESTIMATED LEVEL OF RISK			
NUMBER OF CASUALTY SPILLS/YEAR ⁴	0.0	0.11	0.048	0.049	0.049
CASUALTY SPILL VOLUME/YEAR IN TONS	0	404	245	240	253
TOTAL SPILL VOLUME/YEAR IN TONS ²	231	946	635	647	633

- ¹ - Using actual rather than optimal values for throughput, vessel size, and port calls. Estimated level of risk are values determined from the spill models. Historical experience describes spills recorded in the data bases.
- ² - Including casualty and operational spillage.
- ³ - Defined as the sum of the deadweight tonnage times the number of port calls, not the quantity of oil transported.
- ⁴ - Expressions of frequency are useful indicators of future events, but caution must be taken to avoid misinterpretation of these estimated values. "One spill every 'X' years" expresses a calculated rate and does not indicate when a spill may occur.

All sixty port systems studied are in some way unique. The findings of this study indicate that certain measures of port activity provide a commonality among those disparate elements which enables the estimation of frequency of spill occurrence.

One measure of the applicability of the model is its accuracy in estimating what has already taken place.

For the years 1976-1979, no casualty spills have been reported for Greater Puget Sound. This in itself is not unusual. In fact, twenty-eight of the sixty port systems studied had no casualty spills reported in this period. Using the model developed above, 0.44 spills were estimated for this time period. Based upon that, and assuming a Poisson distribution of spill occurrence with time, zero is the most likely number of spills to have occurred, with a probability of 64%. Thus, the model is a reasonable predictor of actual occurrence of casualty spills in Greater Puget Sound for this period.

Past OIW study has also noted that while Greater Puget Sound has had no recorded casualty spills, the occurrence of casualties (non-spilling) involving tankers has been consistent with that for other U.S. ports (1). In fact, the tanker casualty rate for Greater Puget Sound has been higher than the average rate developed for eight major U.S. ports. Fortunately, no tanker casualties have been reported as resulting in spills.

Operational spillage in Greater Puget Sound is also comparable to that predicted from the model for the years 1976-1979. For Greater Puget Sound, thirteen operational spills were identified, with an estimated volume of 925 tons, for the years 1976-1979. The model estimates ten spills with a total volume of 2,240 tons for the same period.

When predicting numbers of spills, it can be seen that the models are quite accurate for both casualty and operational spills. When total spill volumes are then determined, the estimated spill volumes are higher than the actual spill volumes. This result is not unexpected, due to the distribution of individual spill volumes. Individual tanker spill volumes have been found to follow distributions with the characteristic that the majority of spill volumes are smaller than the average spill volumes (14). This is due to the infrequency of extremely large spills which have a large influence upon average spill size. Thus, in the case of relatively few spills, it is most likely that the average spill size is lower than the average spill size of the entire data base, due to the low likelihood of an extremely large spill. Such

is the case in Greater Puget Sound. To ignore the possibility of such very large spills, however, would ignore the overwhelming impact that such spills have. In short, given a "long enough" time frame, the estimated spill volume would be the expected average spill volume.

Stated another way, the present level of risk inherent in this system is higher than the actual experience to date. The fact that there have been zero casualty oil spills in Greater Puget Sound during the study period, for example, does not indicate that there is zero chance of such spills in the future. The level of risk in any active operation or system is always greater than zero.

Finally, when considering the uniqueness of Greater Puget Sound, it must be noted that the single most unique feature during the years 1976-1979 was the existing 125,000 deadweight ton limit, imposed through regulation rather than due to physical constraints. When considering the excellent safety record of this area in the past, the possibility that it may be related, in part, to this limit cannot be discarded.

CONCLUSIONS, RECOMMENDATIONS AND COMMENTS

The results of this analysis are properly interpreted as hindcasts of the spilling history of tankers. While strong heuristic arguments can be advanced for using recent descriptions of spillage to plan for the future, such use of the information is technically outside of the scope of this project. Also, the relationships developed are not necessarily causal. For example, tanker size does not cause an oil spill, but is a reliable indicator of the volume of spills.

A number of different optimal cases were developed. These were based upon different risk indicators. No identification of the "best" indicator was made. The various indicators are simply presented as potentially useful for application and evaluation. No relative value of the indicators is presented here.

The analysis of operational spills uncovered no relationship between individual spill volume and any of the tested exposure variables. Thus, the average spill volume of 224 tons can be viewed as constant with respect to these variables. The frequency of operational spills is related to number of port calls made. Thus, the use of larger tankers making fewer port calls

would reduce the risk of operational spillage. At the same time, the estimated average size of casualty spills would increase. Depending on how the casualty spill frequency relationship is affected, this could result in an increase in total oil spilled.

Finally, the development of optimal cases is dependent on the tonnage throughput in a port system. As an example, consider the case where twice the tonnage throughput of Greater Puget Sound exists. The average deadweight tonnage for the three optimal scenarios for Greater Puget Sound increases at least 25%. The number of port calls increase 40% to 60%. The frequencies of casualty spills increase by a factor of four, and the total oil spillage by a factor of three. This points out one reason for the excellent safety record in Greater Puget Sound. There is relatively little throughput, and the corresponding risk of casualty spillage is quite low. Other factors not quantified are undoubtedly also important, but the record of the last four years is not significantly different from that indicated from the models.

Conclusions

Within the constraints of this study, the following conclusions are drawn:

1. There is a quantifiable relationship between oil spill risk and tanker size. Oil spill frequency is linearly related to tanker size, port calls, and throughput. Oil spill volume is linearly related to tanker size. The relationship between tanker size and total oil spillage is thus nonlinear and multivariate.
2. Optimal average tanker sizes for port systems (about 70,000 deadweight tons for Greater Puget Sound) have been determined for three risk indicators. However, an optimal upper limit on individual tanker size (e.g., 125,000 deadweight tons) has not been determined.
3. At current throughput levels for the Greater Puget Sound port system, three optimal average tanker sizes, based upon spill frequency and volume, not including risk of damage, were found to be:

- a. About 72,000 average deadweight tons for minimizing the number of spills which might result from tanker casualties.
 - b. About 69,000 average deadweight tons for minimizing the volume of spills which might result from tanker casualties.
 - c. About 74,000 average deadweight tons for minimizing the total volume of spills which might result from tanker casualties and operations.
4. The optimal average tanker size increases nonlinearly with throughput in a port system.
5. With the current 125,000 deadweight ton limit in effect, the average size of tankers calling in Greater Puget Sound during the study period was about 51,000 deadweight tons (or about 20,000 less than the three optimal averages determined in this study). A range of values for average deadweight tonnage has been identified for which the three risk indicators are equal to, or less than, the estimated current risk.
6. Statistically meaningful relationships were not found relating tanker age and spill risk. This does not mean that such a relationship does not exist. A general trend was observed in the data indicating a slight peak in spill frequency near 15 years of age.

Recommendations

From the results of the study, the following recommendations are made:

1. It should be determined whether risk reduction through limitations upon tanker characteristics such as size would be more beneficial than through any other risk management measures, such as improved Vessel Traffic Service.
2. If a tanker size limit rule is made final, the size selected should reflect consideration and trade-offs among additional factors, including

economic, social, environmental, legal, and political concerns. This study indicates that to minimize the risk indicators discussed, the size limit selected should be greater than 70,000 deadweight tons.

3. Further investigations of tanker size and spill risk should concentrate upon three areas: the physical characteristics of ports (including weather and sea conditions); the risk of occurrence of large spills; and the risk of damage due to oil spillage.

Comments

If tanker size had been found to be an invalid exposure variable, this study would have drawn and published that conclusion. Such results could have removed any quantitative basis for the present rulemaking approach to risk reduction through restricting tanker size. This study shows that tanker size is a proper exposure variable. Thus, there is a limited basis for this rulemaking approach. It is by no means the only basis or only rulemaking approach which should be considered in the decision-making process of the Coast Guard.

Many possible courses of action are available. Although this is by no means an exhaustive list, they include:

- Maintain the current tanker size limit at 125,000 deadweight tons
- Introduce a new upper size limit on tanker size
- Introduce a lower limit on tanker size
- Remove all tanker size limitations
- Introduce limitations on other tanker characteristics or activities

Maintaining the current tanker size limit would result in the level of risk estimated for Greater Puget Sound by the models developed in this study. The purposes served by the original imposition of the limit would continue to be served at the same level of effectiveness. This effectiveness needs to be weighed against any costs incurred due to the limitation, and compared to alternative policies.

The introduction of a new upper limit on individual tanker size could result in either a higher or lower size than the current 125,000 deadweight tons. It would be expected that raising (lowering) the size limit would raise

(lower) the average tanker size. In terms of spill risk, a higher limit would result in a lower overall spill risk for limited changes in average deadweight tonnage, and lowering the limit would raise the spill risk. The impact of a change in the size limit upon average size would need to be determined before the effect of a change could be quantified. For example, there are very few tankers in the range from 160,000 to 200,000 deadweight tons. Thus, varying the limit through this interval would have very little impact on vessels available to call. It should be noted that a large increase in average size could increase spill risk. Additionally, an increase in the size limit would increase the estimated average spill size due to casualties. Again, factors not addressed in this study, such as risk of environmental damage, would need to be considered.

The introduction of a lower limit on tanker size, essentially excluding tankers below a given size, would be expected to result in an increase in average deadweight tonnage. Again, for a limited range this would result in a decreased spill risk. The impacts of an imposed lower limit upon average tanker size would need to be determined. Additionally, impacts upon industry could be expected to be large, as many sites might be excluded from tanker calls due to limited size facilities.

The imposition of a lower limit is not an exclusive option. In conjunction with such a limit, an upper size limit could also be imposed. In such a case, the impacts of the two limits would tend to offset each other to some degree. Possible advantages of such a policy would lie outside the realm of this study.

The removal of tanker size limitations would likely result in an increase in average deadweight tonnage. Depending upon the extent of that increase, the risk of spillage could go down. For a large increase, the spill risk could increase. Other risks not accounted for in this study, such as the risk of large spills, might be expected to increase.

Finally, the introduction of limitations upon tanker characteristics other than size would have no effect upon the spill risk determined in this study, except as such limitations might affect the average deadweight tonnage. The overall impacts of such possible limitations should be evaluated outside the realm of this study.

SECTION 1. BACKGROUND

Advance notice of Coast Guard proposed rules for tank vessels in Puget Sound appeared in the Federal Register on 27 March 1978. Public hearings were held in Washington State in April, 1978. The proposed rules, which would amend the Puget Sound Vessel Traffic Service (VTS) Regulations contained in 33 CFR Part 161, were published in the Federal Register on 12 April 1979. These rules were based in part upon comments and suggestions received in response to the advance notice. A Draft Environmental Impact Statement (DEIS) on the same subject was issued by the Coast Guard on 26 April 1979. Additional public hearings were held in Washington State on 11-14 June 1979. The comment period ended on 14 September 1979.

Coast Guard authority for jurisdiction in these matters derives principally from the Ports and Waterways Safety Act of 1972, as amended by the Port and Tanker Safety Act of 1978. The federal program for marine transportation safety and environmental protection is made up of several related programs which provide safety services and a code of regulations governing the marine transportation industry. In the Puget Sound area, one of the primary coast Guard activities concerned with implementation of the program is the Puget Sound Vessel Traffic Service (VTS), for which the original regulations were issued in the Federal Register on 10 July 1974. On 9 June 1977, minor revisions were incorporated. The currently proposed rules would amend these same regulations.

The current 125,000 deadweight ton (DWT) ban on tank vessels in certain Washington waters was initiated in 1975 under authority of the Washington Tanker Law, which was passed by the Washington State Legislature with the "intent and purpose to . . . decrease the likelihood of oil spills on Puget Sound and its shorelines. . . ." On 2 March 1978, however, the U.S. Supreme Court declared portions of the Washington Tanker Law invalid, and struck down the 125,000 DWT tank vessel ban (Ray v. Arco), citing constitutional grounds and the authority of the Coast Guard under the Ports and Waterways Safety Act.

During the time when litigation concerning this law was in progress, the ban remained in effect and tank vessel operators refrained from using ships greater than 125,000 DWT in Puget Sound.

On 14 March 1978, less than two weeks after the U.S. Supreme Court decision, the Secretary of the Department of Transportation issued an interim ruling extending the ban on tankships greater than 125,000 DWT in the same waters previously designated by the Washington State Tanker Law. The expressed purpose of the interim rule was to maintain the existing level of vessel operation control and environmental protection provided in Puget Sound until the Coast Guard investigated and initiated permanent rulemaking actions. The rule was to remain in effect until 9 September 1978; however, on 8 September the Secretary extended the expiration date until 30 June 1979 to provide the Coast Guard with enough time to complete the permanent rulemaking process. On 21 June, the Secretary again extended the ban, for an indefinite period of time. On 21 July 1980, it was proposed in the Federal Register that the rule be amended to read that tank vessels larger than 125,000 deadweight tons bound for a port or place in the United States may not operate in waters of the United States lying east of a straight line extending from Discovery Island Light to New Dungeness Light and to all points in the Puget Sound area north and south of those lights. The final rule was published on 22 December 1980 (Federal Register) and became effective on 1 February 1981.

As the Coast Guard prepares to issue a final environmental impact statement and final rules, it must decide whether to implement, modify, or delete the proposed rule on tanker size limits for Puget Sound. Whatever the choice, the Coast Guard must then be able to support its decision with a rationale that would both survive possible legal challenge and set precedents which are workable on a national scale. The following information places this dilemma in a broader perspective and defines the specific problem which this study is intended to resolve.

Given the history of the debate and the reception of the interim and proposed rules on tanker size limits for Puget Sound, it is now appropriate to extend the state-of-the-art of quantitative analysis on this subject. The proper procedure is to minimize the risk of spillage by applying existing, but unused, analytical methods to the problem. These techniques can be used to integrate a number of important parameters bearing on tanker size limitations.

Data bases have been examined thoroughly to determine, for example, the correlations, if any, between vessel size, vessel age, and spill size. Exposure variables have been analyzed, uncovering relationships among certain key factors (such as port calls, vessel age, tonnage, and throughput) which

yield an estimated optimally safe average tanker size. The question of a proper size limit for Puget Sound in the future is a related one which depends upon many other factors such as economic and social constraints, but with these analytical results it can be approached on a more scientific basis than ever before.

1.1 RISK REDUCTION ALTERNATIVES

The transportation system for moving oil by water from point A to point B can be thought of as consisting of four elements:

- Vessel
- Personnel
- Information and Control Systems
- Environment

Simply stated, the vessel contains the cargo and the personnel (both ashore and afloat) use information, mechanisms, and skills to control the passage of the vessel through the natural and man-made environment. Inherent in this transportation system is a certain level of risk of failure. In terms of cargo spillage, this level of risk may be segregated into various components, including:

- Risk of Spillage
 - Occurrence of casualty or operational incident
 - Spillage from casualty or operational incident
 - Magnitude of spillage
- Risk of Damage
 - Environmental
 - Economic
 - Social

Numerous mitigating measures (or risk reduction alternatives) have been identified during recent years to reduce the various components of risk inherent in the transportation system.

In understanding the present problem, it is important to recall that the Coast Guard did not make the initial selection of tanker size limits as a risk reduction factor. This decision, together with the recommendation for tug escorts, was made by the Washington State Legislature in 1975. Today, both are still in effect and are candidates for adoption as permanent rules. In 1975, the whole list of alternatives was available for selection, but by 1979, when the Coast Guard issued its DEIS, the list for Puget Sound had effectively been shortened by previous events. Constraints had evolved. Even after the U.S. Supreme Court decision struck down the state tanker size limit, the issue did not disappear. Other mitigating measures have and may again come into and fall out of favor, but this one has strong public and, therefore, political appeal. In the absence of new information or events, the tanker size limit issue is unlikely to disappear.

In simplified terms, analytical techniques utilized in past studies have led to two generally accepted but limited conclusions:

- Smaller tankers have the potential for more spills in delivering a given volume of oil than larger tankers.
- Larger tankers have the potential for larger spills per incident than smaller tankers.

As important as they are, these two conclusions are of minimal assistance in making a decision about whether or not to impose a 125,000 DWT limit. Neither supports the selection of any specific trade-off size.

1.2 PURPOSE

The purpose of this study is to assist the Coast Guard in its rulemaking and environmental impact statement processes concerning tank vessel operations in Puget Sound by determining a historically derived optimal tanker size (125,000 DWT or more or less) which represents the minimum risk of spillage from oil tankers in Greater Puget Sound. The methodology developed should be applicable to other ports, or port systems, in the United States and throughout the world. It was also the purpose of this study to determine if there is a relationship among tanker size, age, and other exposure variables. If a relationship does exist, then the relationship would be optimized with respect to the frequency and volume of oil spilled in Greater Puget Sound.

1.3 SCOPE

Two aspects of the proposed rules appear to have received the most comment and be the most controversial: (1) the 125,000 DWT tanker size limit; and (2) the tug escort and assistance provisions. This study addresses the first point only and is limited to the optimization of vessel size based on historical data, as depicted in Figure 1-1. For study purposes, existing conditions will be assumed to continue; future scenarios involving new ports and pipelines with new throughputs are not included in the scope of work. Forecasting of accidents and spillage also are beyond the scope of work. However, hindcasting for different levels of throughput in Puget Sound has been calculated to obtain the optimal average size tanker which would minimize risk. That is, if conditions remain the same in Puget Sound as they were during the period studied, then the optimal average size tanker for different throughputs can be hindcasted.

The study analyzes the risk of spillage only, not the risk of damage. After scrutinizing the study results, impacts (such as potential damage from spillage and the effects on crude oil transportation costs) should be addressed. It is assumed that such assessments will be made by the Coast Guard. Consideration of impacts could cause an adjustment to the historically derived optimal figures determined by OIW. These new, adjusted figures would then be used to arrive at a final rulemaking decision. Since the impact analysis is beyond this scope of work, OIW does not recommend a specific tanker size limit for Greater Puget Sound. There are other reasons beyond environmental damage which preclude the recommendation of a rule on a tanker size limit for Greater Puget Sound. These include the consideration of socio-economic, environmental, and legal and political factors beyond the scope of this study.

Although it is recognized that there is an inherent danger in optimizing a subset of a system, in this case tanker size is the one part that can be quantified. Many of the other concerns are subjective and based on value judgements. It is best to tie down this aspect of the debate, which should help raise the level of the debate and offer a new opportunity for settlement. Thus, the U.S. Coast Guard can use tanker size optimization as one input into its rulemaking process.

The study does not examine whether a rule on size may be more or less effective than some other risk-reduction rule. For example, the Eastern

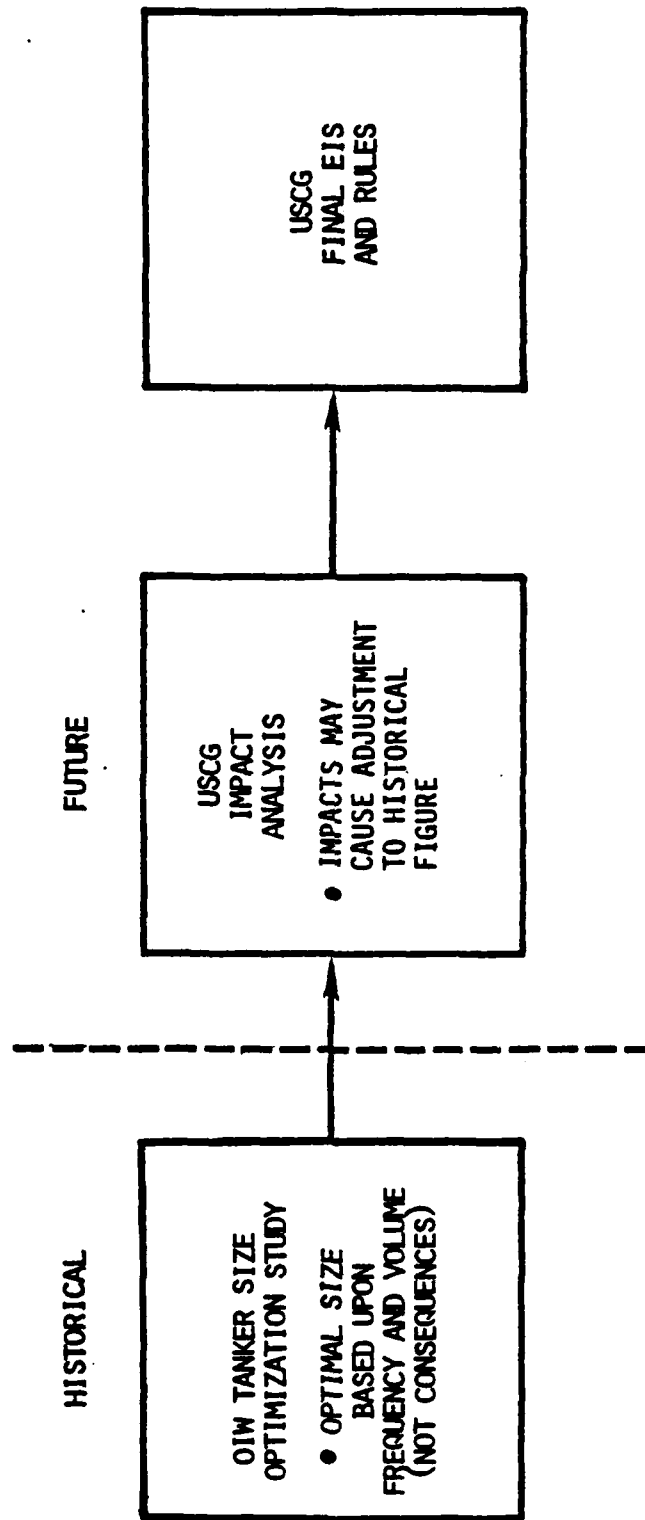


FIGURE 1-1. ADJUSTMENTS OF HISTORICAL OPTIMIZATION RESULTS FOR FUTURE IMPACTS

Canada Traffic Regulation System (ECAREG) enforces safety regulations by examining the performance of the ship and captain. The U.S. Coast Guard Vessel Traffic Service (VTS), tug escort and tug assistance are other examples of risk-reducing measures which are not addressed in this report.

The analysis was based on all available nationwide, foreign, and world port data. All tank vessels were considered. The analysis was based on all sizes of spills. The results of the analysis were applied to current constraints in Greater Puget Sound (defined for this study as including the Strait of Juan de Fuca, Puget Sound, and the Strait of Georgia). The methods, however, have wide applicability for other port systems in the nation.

There are other limitations to the study. For example, although fires and explosions were included in the data base for casualty-caused spills, no attempt was made to relate large explosions to large tankers. Such a relation could be investigated, but it was not within the scope of this study.

1.4 OBJECTIVES

The objectives of this study are as follows:

- To collect the best data bases available from national, foreign, and world sources for the analysis.
- To determine the exposure variables and risk indicators most relevant to tanker size limits in internal U.S. waters.
- To develop new correlations between the exposure variables and risk indicators.
- To develop and demonstrate a general optimization methodology applicable to Greater Puget Sound and other port systems.

1.5 RESULTS

The study was designed to achieve as many as four major results, one from each of four parts of the analysis. It was possible that an optimal size, an

optimal age, an optimal combination of variables and an evaluation of exposure variables and risk indicators could have been determined from the mathematical relationships identified. It was also possible that tank vessel age might have been optimized and that tank vessel size could not be optimized, or vice-versa.

The first part of the analysis examined the risk of oil spillage as it is controlled by tank vessel size. The analysis identified and evaluated potential exposure variables and sought to determine a mathematical relationship between this exposure variable and the risk indicators. In addition, one of the following alternate conclusions could also have been reached:

- a. A determination of the optimal tank vessel size with respect to a minimization of spill risk indicator; or
- b. A determination that the spillage risk from tank vessels is not dependent upon vessel size; i.e., that tank vessel size is not a valid exposure variable (that there is no functional relationship between either the frequency or volume spilled with vessel size); or
- c. A determination that the data do not as yet support any conclusions that oil spillage risk from tank vessels is dependent upon size; i.e., that size may or may not be a valid exposure variable.

The second part of the analysis examined the risk of oil spillage as it is controlled by tank vessel age. The analysis could have followed the same procedures as outlined above except that age, not size, could have been optimized with respect to risk. One of the following alternate conclusions could also have been reached:

- a. A determination of the optimal tank vessel age with respect to a minimization of the spillage risk;
- b. A determination that the risk of tank vessel spillage is not dependent upon vessel age; i.e., that age is not a valid exposure variable; or

- c. A determination that the data do not as yet support any conclusions that oil spillage risk of tank vessels is dependent upon age; i.e., that age may or may not be a valid exposure variable.

The next part of the analysis examined the risk of tank vessel oil spillage as it is controlled by all valid exposure variables. The analysis followed the same procedures outlined above except that a combination of exposure variables could have been optimized with respect to risk. One of the following alternate conclusions could also have been reached:

- a. A determination of the optimal set of values for the entire list of valid exposure variables with respect to a minimization of the risk.
- b. A determination that none of the potential risk indicators are dependent upon any of the potential exposure variables.
- c. A determination that the data do not as yet support any conclusions that oil spillage risk from tank vessels is dependent upon any of the potential exposure variables.

The final part of the analysis provides an evaluation of the exposure variables and the risk indicators. It determined which variables are highly correlated with the indicators and the mathematical relationships between variables and indicators.

Other useful study results include:

- The development of an improved data base for further vessel safety research.
- A comprehensive examination of several risk exposure variables.
- The development of a general methodology for evaluating vessel safety and tank vessel size in other waterways.
- The development of a process for examining other risk exposure variables and impacts.

SECTION 2. GENERAL APPROACH

This section presents the general technical approach for solving the problem stated in Section 1, and accomplishing the purpose, objectives, and results stated in Section 1. Subsection 2.1 is an overview of the conclusions of some previous studies and indicates some of the difficulties encountered by or reported by these studies. Subsection 2.2 outlines recent improvements in the data and several unique features of OIW's approach to the problem.

2.1 PREVIOUS STUDIES AND DATA BASES

The methodology most commonly utilized in risk assessments is statistical analysis. It uses past experience and puts that experience into meaningful, usable form. When adequate and pertinent data are available for statistical analysis, the results can often be used directly or indirectly in evaluation of alternatives, e.g., small versus large tankers. In tanker risk analysis the usual procedure has been to derive a linear relation between one dependent variable (casualties or spills) and one independent variable (port calls or volume throughput or distance or time). The dependent variable (the risk) will be hereafter referred to as a risk indicator. The independent variables, i.e., the variables that can be measured and used to characterize a port or vessel, will be referred to as exposure variables. Any one of a number of exposure variables could be used, and each may have significant advantages and shortcomings. Great care must be used in statistical analysis in choosing a proper exposure variable, and in the treatment of inadequate (or incomplete) data bases.

In some cases it is known that the data are sufficient to obtain high correlations between risk indicators and certain exposure variables. Examples are OIW's relationships between the frequency of casualties and spills with vessel port calls and volume throughput (1-8).^{*} Others have developed relationships between casualties, spills, and volume of spillage versus vessel age (9-27). However, when the exposure variable is tank vessel size, the results

^{*} References are located in Section 7.

of the analyses are not definitive and some of the conclusions are contradictory.

The diversity of the results indicates that the previous studies are inconclusive and inconsistent. Part of the diversity may be due to the availability of data used in the different studies; sometimes as little as two years of data were analyzed and sometimes the data covered only those years when there were few very large tankers. Part of the inconclusiveness is due to the selection of different risk indicators and exposure variables. Each study uses one risk indicator and one exposure variable in each analysis of the data. Also, certain studies have applied worldwide spillage data without distinguishing between incidents at sea and incidents within port systems.

2.2 IMPROVEMENTS IN TECHNIQUES AND DATA

There are five unique features of the OIW approach which have overcome previously encountered difficulties.

- Expanded, reliable data (more ports and more reliable data)
- Use of actual port call data instead of estimates
- Restriction of the data and the analysis to inland and coastal areas
- Use of multiple variables in the analysis
- One studied worldwide fleet

The following paragraphs discuss each of these five features.

In order to perform the analysis, there must be sufficient data to characterize each of the risk indicators and each of the appropriate exposure variables. Although data are available from U.S. sources and are sufficient to perform some risk analyses, most U.S. ports are incapable of handling very large tankers. In order to obtain valid tanker size limit results from this study, it is necessary to verify and cross-check the worldwide data bases which include large tankers. A discussion of the data bases obtained and utilized is contained in Section 3.

The second unique feature of this study was the use of actual port call data describing the activity of vessels in the studied worldwide fleet. Prior

studies by OIW and other investigators have established that the number of port calls is a very important exposure variable. Many analyses have used port calls to estimate the frequency of oil spills but have been forced to make assumptions in order to calculate the port call values (26,28). By obtaining these data directly from Lloyds of London, OIW has eliminated a possible source of error in its analyses (29,30).

The third feature of this study was to restrict the data used in the analysis to ports and coastal areas. Risk in these areas has been shown to be intrinsically different from risk on the open sea presumably because of the different environmental conditions encountered in unprotected waters (31). Using U.S. data, OIW has published, for several years, high correlations between certain exposure variables and risk indicators within port systems (1-8). A recent Coast Guard study of world ports was reported to conclude that somewhere in the 100,000 to 200,000 DWT range, it becomes increasingly difficult to determine proper control measures (32). Since Greater Puget Sound is a port system and risk in a port system is different from risk on the open sea, only port system data are relevant to this analysis.

The fourth unique feature of this study was the use of multiple exposure variables in the analysis. More than one variable is needed in the analysis because more than one variable is known to be important in the risk relationships. Using just one exposure variable is a good first order approach but it may also be naive when the situation is known to be complex. An example of the interrelationships of variables is the possible association of size and age: very large tankers are comparatively young tankers.

The fifth feature is that all of the data describing port calls, tanker characteristics, port activity, casualty spills and operational spills have been carefully constructed so that they all relate to a studied worldwide fleet of tankers. All 4,055 oil tankers (not chemical or combination carriers or tank barges) registered in the Lloyd's Register of Shipping (1975-1980) (33) in non-Communist countries with deadweight tonnages greater than or equal to 5,000 DWT were included. By restricting all OIW data bases to include only information concerning this studied fleet, OIW has insured that all of the data describe the same tankers. This consistency has been lacking in previous studies but for these analyses, OIW has followed the actions of a specific fleet for a number of years and determined relationships for these tankers.

2.3 OIW ANALYTIC APPROACH

A simplified study flowchart is shown in Figure 2-1. This flowchart outlines the basic analytic steps that have been utilized to perform the study. But before any of these steps could be applied, a list of potential exposure variables and risk indicators had to be compiled. The use of a single exposure variable cannot take into account the many factors which contribute to risk. In order to make a breakthrough in tank vessel risk analysis, an effort was made to integrate a number of individual relationships. Such an analysis required an examination of the relationships which exist between a number of risk indicators and exposure variables.

Through heuristic arguments and earlier studies, lists of potential exposure variables and risk indicators have been advanced. Since it was necessary in this study to establish quantitative relationships between risk indicators and exposure variables, a method was selected to determine which variables from these lists had quantitative relationships with risk indicators. When this method was applied to the historical data of tank vessel spills in port areas, a reduced list of variables was selected.

All of the statistical techniques rate, rank or group the list of input variables according to some scheme. It is important to remember that the only outcome of any of the techniques is the selection or rejection of variables that were input to the technique. Instead of thinking of the techniques as selecting the important variables (which is only true if these variables are included in the input list), it is more precise to think of the techniques as rejecting nonessential variables from a list of potential variables.

Heuristic criteria are needed in this creative effort, just as inductive reasoning and flexibility in the approach are necessary ingredients of any study which advances the state-of-the-art. But none of these techniques are quantitative and will not be the primary techniques for eliminating non-essential variables. Aside from pure mathematics (and perhaps not even then) every study contains arguments, postulates and assumptions that cannot be proved. It was the intent of this study to go beyond opinion and perception and to use a quantitative, defensible technique.

Examination of the correlations between the risk indicators and the exposure variables was a valuable technique for establishing the strength of linear relationships (34). Ignoring the issue of linearity, the disadvantage

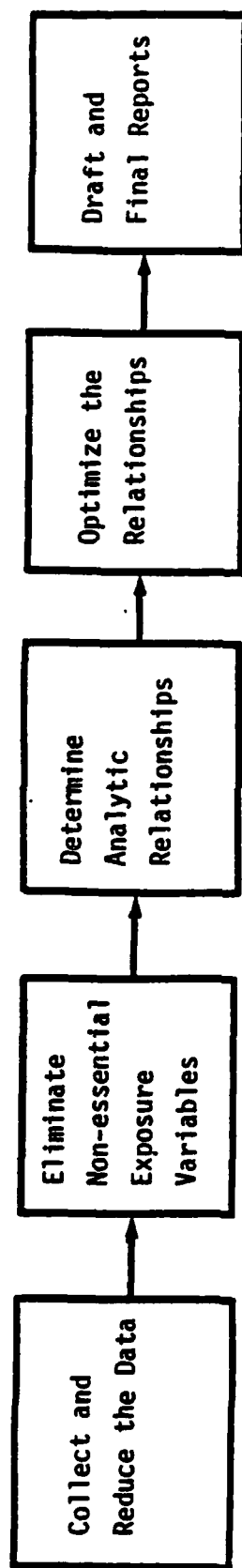


FIGURE 2-1. SIMPLIFIED STUDY FLOW CHART

of examining correlations is in subjectively defining an acceptable correlation. The variables may be ranked by the strength of the correlations, but there is no clear indication of where one must "draw the line" and include those variables with a higher correlation and reject those with a lower correlation.

Scatter plots of the variables and the risk indicators were produced and examined. On such plots, a linear relationship between the two sets of numbers would be displayed as a straight line. Similarly, if the risk indicator is related to the square of the exposure variable, the locus of points on a scatter plot will be a parabolic curve. Other relationships (such as square root and logarithmic) have their own distinctive curves. Thus, by examining the scatter plot of a risk indicator versus a potential exposure variable, one can obtain an indication of the relationship between the two quantities. Then a correlation between the risk indicator and the square (or square root or logarithm, as indicated) of the exposure variable, and other standard statistical tests, can be used to confirm the relationship.

After selection of the essential exposure variables, the mathematical relationship between these variables and the risk indicators must be determined. Multiple regression techniques are the most common and widely used methods to calculate these relationships for two or more variables, given sufficient data (35). In essence, multiple regression techniques determine the mathematical coefficients for each exposure variable which, as a whole, best fit the data by utilizing a least-squares error criterion (34,36). If a linear model were inadequate, there are a number of ways to handle nonlinear situations, e.g., to find a simple nonlinear form through the use of polynomial regression. Multiple regression analysis has been chosen as the preferred technique for this part of the study because of its versatility and adaptability to different situations.

The classical method for finding the minimum solution to an analytic function is by means of calculus. The derivative leads directly to the local maxima and minima with respect to the exposure variable. Finding the minimum, and ensuring that it is a global minimum, is a straightforward procedure.

2.4 SUMMARY OF OIW ANALYTIC APPROACH

The analysis has been accomplished by minimizing the risks associated with different tanker sizes and a combination of valid exposure variables. The techniques selected were factor analysis, multiple regression analysis and optimization techniques based on calculus. In the past, relationships have been derived between a single risk indicator and a single exposure variable. This study investigated, through nationwide and foreign data bases, several risk indicators and a large number of exposure variables. Factor analysis was utilized to identify the minimum number of variables which can be used. Multiple regression techniques were then utilized to integrate the risk indicators with the exposure variables. The resulting equations were then minimized by the use of calculus. The analysis is applicable to any of the sixty worldwide port systems investigated by OIW, which includes Greater Puget Sound. The results of the optimization may be modified by the Coast Guard in its rulemaking process because of costs, environmental impacts, damage assessments and other considerations.

SECTION 3. DATA BASES

The identification of the best sources of information to obtain satisfactory data bases was long and arduous. The procedure utilized was to write letters worldwide to some 55 governmental agencies, private organizations and port authorities (see Appendix A). This was followed by numerous phone calls and, if appropriate, by a personal visit. The process was lengthy due in part to delays in correspondence via overseas mail. Many requests for information or assistance in locating sources of information received no response. This was particularly true in the Far East, presumably due to cultural barriers. Personal visits to Europe and Canada were essential in obtaining the best data base possible as some sources reluctant to provide their data bases because of propriety and confidentiality responded favorably to personal discussions and reassurances.

The emphasis during data collection and verification was placed upon the years 1976 through 1979. This was primarily due to the limitation of computerized port call data to these years. Additionally, many sources of spill data either did not extend to earlier years or were not as thorough for those years. Thus incident verification was not as complete for the years 1975 and earlier. Further discussion of the dichotomy of the data and additional reasons why data from the years 1976 - 1979 were used can be found in Subsection 4.2.

3.1 CASUALTY SPILL FILE

The purpose of this data base is to document spill incidents in a manner convenient for subsequent analysis. Work on this information focused on two areas: collection of data to be included, and structuring of the data for input. The former addresses the scope and content of the data base; the latter addresses style.

The Casualty Spill File is a compilation of worldwide spill data. It integrates information from thirteen different sources from around the world. These sources include government agencies, industry groups, research institutes, classification societies, and others.

A. United States Sources

One source of worldwide tanker casualties and spills is the U.S. Coast Guard Tanker Casualty File for the years 1969-1977 (37). This file has been updated by obtaining information for 1978 and 1979 from the Maritime Data Network, Ltd. (MARDATA) (38). This information was furnished to OIW by the U.S. Coast Guard. A source of oil spill data in U.S. waters is the U.S. Coast Guard Pollution Incident Reporting System (PIRS) (39).

The above information has been augmented, updated and verified by the use of other sources on worldwide casualties and spills. These sources include the Worldwide Directory of Major Oil Spills Involving Tankers (1972-1979)^o from the Center for Short-Lived Phenomena, Oil and Hazardous Materials Spill Incidents (1970-1977) from the Environmental Protection Agency, and major worldwide spills by Liberian vessels compiled by the New York Office of the Bureau of Maritime Affairs of the Republic of Liberia (40,41,42).

B. Foreign Sources

Most of the foreign data bases were acquired as the result of personal visits.

a. United Kingdom. OIW obtained the ICS Tanker Casualty Bulletin for the years 1975-1979, published by the International Chamber of Shipping (43). In the future, this annual report will be available from Lloyd's Register of Shipping. Confidential data were obtained from the Tanker Owners Voluntary Agreement Concerning Liability for Oil Pollution (TOVALOP) (44). The confidentiality of this data base was protected by excluding tanker identification. This data base is concerned with pollution incidents involving tankers, including operational spills. This is apparently the only worldwide source which includes operational spills. TOVALOP also furnished a list of major worldwide spills from 1974-1979.

b. France. The data base on worldwide casualties and spills of the French Petroleum Institute has been utilized (45). This source lists information for the years 1955-1980.

c. Norway. The data base on worldwide casualties and spills of Det Norske Veritas (1965-1979) has been obtained and utilized (46).

d. Canada. The data base obtained from Canada is a combined one. That is, the Environmental Protection Service has a data base which has as a source

the data base of the National Analysis of Trends in Emergencies Systems (NATES) (47). This data base was searched for pollution incidents in eastern Canada (the Maritime Provinces, excluding Newfoundland), the names of the ships involved were identified by name, and this information was sent to the Eastern Canada Traffic Regulation System (ECAREG) for verification.

Information on worldwide spills was augmented by the Spill Technology Newsletter (1967-1978) of the Canadian Environmental Protection Services, which has a listing of the 35 largest worldwide spills during this period (48).

While an extensive amount of information is available, the accuracy of the information is often questionable. It is not unusual to find discrepancies between data bases regarding details of incidents. In fact, it is far more unusual to find agreement. In addition, consistency within a given data base is often lacking. More details concerning this problem are provided in the descriptions of the data bases in this section.

Inconsistencies between data bases led to a method of verification via crosschecking between sources. Using this method, spill incidents included were primarily those reported in more than one source. It should be noted that an incident for which spillage is reported in any data base is included if occurrence of the incident can be verified elsewhere, regardless of whether any spillage is reported in the verifying source. This approach was taken because many of the data bases include preliminary casualty reports. In those cases, details of spillage may not have been known at the time the report was made.

The evolution of the data base as two tanker spill files came about in large part as a result of the incorporation of the many diverse data bases into comprehensive files. Many of the data bases are not intended as tanker spill files. Rather, they document factors related to vessel safety or sources of pollution. In these cases tanker spills are often included, but are not the object of the collection procedure. The more specifically applicable data bases are often concerned with vessel or tanker safety, and document casualties and other significant incidents. In these cases, very few spills of an operational nature are included. Incident verification methods were thus relatively ineffective for these operational spills. It was felt that they should therefore not be included in the principal spill file. The separation of casualty and operational spills is also supported by the results

of earlier risk analyses. Numerous studies have shown a distinction between these two sets of tanker spills in both their spill frequency and spill volume characteristics. Indeed, there is no basis for the belief that operational and casualty spills would demonstrate the same risk relationships. It would therefore be invalid to combine these two groups during the analysis, even were they comparable in reliability. Operational spills have been collected separately, without the requirement of cross-referencing, and used as a separate information source, with the understanding that the data have not been verified as completely as the casualty data file.

The result of this effort is thus two distinct files documenting tanker spills. The Casualty Spill File includes spills which involve a breach of vessel integrity. Thus, a hull or tank rupture would be included, and a hose rupture or valve failure would not, unless a subsequent event (e.g., fire or explosion) resulted in further damage. Entries in this file have been carefully cross-checked and verified.

Thirteen different sources were used in the development of the Casualty Spill File. Discrepancies between two reports of a given incident were resolved through the prioritizing of the sources, based on the consistency of the information they contain. When more than two reports of an incident are found, and discrepancies occur, agreement between any two of the sources might support the use of that agreed information if they represent independently reported information. That is, certain baseline sources such as Lloyd's Weekly Casualty List are assimilated into more than one of the sources used. Thus, agreement between reports could simply be repetition, rather than verification. Acceptance of such repetitions as confirmation of details is avoided whenever this problem is known to occur.

The following descriptions of the sources are presented in order of priority, based upon the quality of information contained as evaluated via the methods discussed above. In some cases, there are varying degrees of confidence based upon different types of entries. These are discussed for the individual cases. All sources provide worldwide coverage unless otherwise noted.

- 1) International Chamber of Shipping (ICS). Tanker Casualty Bulletins, 1975 - 1979, annual summaries, unpublished (43).

The ICS reports proved to be the most consistent and comprehensive of any source found for the years 1976-1979. They represent a compilation by Lloyd's Register of Shipping for ICS of casualty reports published by Lloyd's of London Press Ltd. in "Lloyd's List." The relative completeness of this source makes it invaluable in verifying the occurrence of a casualty reported elsewhere, although the preliminary nature of many of the casualty reports does limit the amount of information available in many instances. Specifically, should subsequent reports indicate spillage, this may not have been included in ICS. Details which have been provided, however, regarding ship and casualty characteristics are consistently accurate. Because of this, unverified spill reports from this source have been included in the data base.

Information provided in a casualty report is divided into three groups: ship, voyage, and casualty details. Ship details include name, machinery, type, deadweight tonnage, year built, and flag. Voyage details include cargo, cargo condition (in ballast, laden, etc.), date, and position. Casualty details include casualty category, damage assessment, numbers of dead and injured, reported spillage, and a description of the incident. Information provided in the casualty section of incident reports is occasionally sparse, due again to the preliminary nature of the reports.

In 1979, ICS expanded the individual incident reports to include environmental location (port, open sea, etc.), weather, and type of material spilt. Many of the entries in these new categories were blank, especially weather and type of material spilt. This again relates to the amount of detail available about the incident itself.

2) International Tanker Owners Pollution Federation Limited (TOVALOP), computerized data base, 1974-1980 (44).

The TOVALOP data base consists of voluntary reports by member tanker owners of oil spillage. As it is voluntary, confidentiality of reporting members is provided. In order to protect this confidentiality, names and other vessel identifiers were excluded from the file TOVALOP provided. In the spirit of this protection, descriptions of methods used to incorporate this data are not provided. It is sufficient to state that satisfactory methods of incident identification were found which were consistent with the approach used for other sources.

TOVALOP provides extensive reportage of tanker oil spillage, although individual reports provide only limited information. Details provided include: date of incident; country and port of occurrence; deadweight and gross tonnage of vessel; age of vessel; and codes for operation in progress, cause of spill, and quantity spilt. A numerical value for quantity spilt is occasionally provided.

- 3) Det Norske Veritas (DNV), from Ship Accidents data base, 1965-1980 (46).

The DNV data base was developed for analytical use in the study of ship safety. The version supplied to OIW documents casualties involving tankers. The information contained regarding an incident is quite detailed and in a convenient format. The data base is not as extensive as others, with 182 incidents in the entire file.

Incidents are divided into two entries: vessel characteristics and accident characteristics. Under vessel characteristics are included name, flag, gross and deadweight tonnage, year built, cargo, and classification society. Accident characteristics include date, casualty sequence and narrative text, location, environmental location, weather, number of deaths, damage, and spillage.

- 4) Center for Short-Lived Phenomena (CSLP), Major Oil Spills Involving Tankers, © 1972-1978; International Summary of 1979 Spills, © 1979 (40).

The CSLP directory "details major oil spills involving tankers It provides information on the tanker name, DWT, location, type of oil spilled, amount spilled, and cause The primary sources used were the CSLP data files, U.S. Coast Guard casualty record, and Lloyd's Weekly Casualty Reports. In the event of conflicting data, the CSLP adhered to the following priorities: for spills within U.S. territorial waters - U.S. Coast Guard, CSLP, and Lloyd's; and for spills outside U.S. territorial waters - Lloyd's, CSLP, and U.S. Coast Guard (40)."

The CSLP summary documents spills of over 20,000 gallons (approximately 70 tons) of oil. Information provided for each report includes name and deadweight tonnage of the tanker, date and location of spill, cause of spill, and type of oil.

5) Maritime Data Network, Ltd. (MARDATA), 1978-1979 (38).

MARDATA is a computerized information service which provides information on tanker incidents to subscribers. Two years of data were obtained through the U.S. Coast Guard, documenting all tanker incidents in the data base for those years. Unfortunately, the copy provided OIW had several gaps of information, apparently due to a physical processing error. This problem, while raised in telephone conversations and progress reports, was never resolved.

MARDATA provides entries for each ship for which a major incident was reported. All such incidents are placed in this single entry. Ship characteristics provided include current vessel name, deadweight tonnage, year built, number of incidents in complete file, flag, and owner. Incident characteristics are not provided, simply a casualty category and narrative text. This format is not conducive to analytical use, and incidents are often described in insufficient detail for the extraction of information needed for such use. Cross-referencing minimized this problem.

6) U.S. Coast Guard, Tanker Casualty File (TCF) computerized data base, 1969-1977 (37).

TCF was divided into two distinct sections: 1969-1973 and 1974-1977. Each has a different format and different amounts of information about an incident. TCF was assigned an equal priority with MARDATA, the need for which in 1978 and 1979 was due primarily to the delinquency of data for these later years in TCF.

Information in TCF was compiled from six sources: Lloyd's Weekly Casualty Reports; Coast Guard Situation Reports; Coast Guard Marine Commercial Vessel Casualty Files; Coast Guard Operations Summaries; Lloyd's Register Quarterly Casualty Returns; and data from the U.S. Salvage Association, Incorporated. It documents casualties, and includes, among others, all such for which spillage occurred.

For the years 1969-1973, TCF documented spills with the following information: name, flag, gross and deadweight tonnage of vessel; year of construction; cargo; maneuverability factor; casualty type; month and year of casualty; quantity spilt and method of determination; damage; region of casualty; and further casualty details. With a format revision in 1974, reports were

expanded to also include: location of casualty; subsequent events in casualty sequence; complete date of casualty; and further details of casualty.

The format of TCF in these later years was very concise yet complete. A variation of this format was used in the OIW Casualty Spill File. This will be described below in greater detail.

TCF was actually assigned several different levels of priority, dependent upon the quality of information contained therein. This relates primarily to two categories, pollution assessment and method of determining outflow.

Pollution Assessment indicates whether or not pollution occurred. Many polluting incidents were reported as unknown or not polluting in TCF. This may indicate a lack of follow-up on reports, similar to ICS above. The verification methods described above allowed for such incidents to be included if reported as spill incidents elsewhere. For incidents for which TCF did report oil spillage in the years for which verification took place, virtually all were substantiated elsewhere. Because of this confidence in spill reports, TCF reported spills were included without verification when none could be found. This totalled seven spills for 1976 and 1977.

The Method of Determining Outflow was undoubtedly the weakest feature of TCF. It consisted of a code describing how the amount of outflow was determined. In most cases, this was via reporting or estimation. Coding instructions do not include a way to report an unknown amount of spillage. Rather, they instruct that the size of such a spill should be approximated using "calculated values based on the median spill size, using reported and estimated spill sizes, for four size class groups" (37). Such an approach, from an analytical perspective, has negative value, for the information is not only useless, but raises speculation as to the objectivity of the file, and the possible existence of similar, but unwritten, rules or guidelines. This is particularly true as tanker size is the primary potential exposure variable to be addressed in this study.

In establishing priorities, spill information for which volumes were listed as "reported" was accepted. Spill information for "estimated" spills was accepted only if no other source of information was found, and no spill-related information was accepted for "calculated" spills, beyond the fact that spillage did occur.

7) French Petroleum Institute (IFP) data base, 1955-1980 (45).

The IFP data base documents tanker accidents which result in spill volume of over 500 metric tons. Sources used by IFP are: Lloyd's Quarterly Statistics; MARDATA; the Center for Short-Lived Phenomena; and technical and general literature. Each entry in the data base includes tanker name, flag, age, and deadweight tonnage; year, location, and cause of casualty; amount spilt; cargo type; and occasionally weather.

An interesting feature of IFP is the inclusion of spill volumes via estimation methods. Unlike the TCF method, IFP provides estimations in very specific instances based upon sound physical criteria. For cases having no reported amount of spillage (generally sinkings of empty tankers), a conservative estimate of bunker fuel on board is made by determining the minimum amount of bunker fuel needed for the voyage and using an average consumption rate. In addition, the amount of solid petroleum wastes adhering to tank walls is estimated based upon tanker size and type of oil carried. In cases of partial damage, tank size estimates can also be made based upon IMCO standards, and the above methods applied. Such estimates by IFP have been accepted as valid in cases of litigation.

A serious problem of IFP is one of verification. In numerous instances, an incident was included in multiple entries. The errors occurred as a result of tanker name changes. In particular, MARDATA reports only the most recent name of a tanker, while most other sources use the name at time of occurrence. For example, two groundings in New Jersey in 1976 were reported involving the vessels Oswego Hope and Richard C. Sauer. Both are in fact the same incident, as the Richard C. Sauer was renamed Oswego Hope in 1978. The discovery of this flaw in IFP via OIW verification methods lends confidence in these methods, and also points out the need for such methods.

8) Environmental Protection Service (Canada)/Canadian Coast Guard, Eastern Canada Traffic Regulation System (ECAREG), tanker spill data, 1973-1980 (47).

The ECAREG file documents tanker spills in Eastern Canada (St. Lawrence Waterway and coast). The brief summary information includes fiscal year, vessel name, gross tonnage, year built, and amount and type spilled. While a

limited number of spills are included, the careful compilation allows for great confidence in the occurrence as reported for those incidents included.

- 9) U.S. Coast Guard, Pollution Incident Reporting System (PIRS), computerized data base, 1973-1979 (39).

PIRS includes polluting incidents of all kinds which affect or threaten water bodies in the U.S. The breadth of incidents thus covered has led to a form ill-suited for a tanker analysis. Virtually no tanker characteristics are provided, and the tanker identification provided is not conducive to actually identifying the vessel reported.

A preliminary comparison of PIRS and TCF reports of U.S. incidents indicated that some 60% of each was represented in the others, with about 40% of each representing independent entries. In the case of PIRS, a large number of the events appeared to be coded incorrectly, as very few of those not in TCF were verified in other data bases. A large number of the TCF spills which did not appear in PIRS were coastal spills, suggesting a gap in PIRS' information there.

For these reasons, little use was found for the PIRS data in this analysis. Some verification did take place as a result of preliminary examinations of the data contained.

- 10) U.S. Environmental Protection Agency (EPA), Oil Spills and Spills of Hazardous Substances report, 1967-1977 (41).

EPA reports in narrative fashion significant spill incidents. Many of these are the results of tanker accidents. The descriptions of the incidents and subsequent effects and clean-up operations were extremely informative. Unfortunately, only a few incidents were reported in this manner. The usefulness of this file lies in its provision of otherwise undiscovered details.

- 11) Spill Technology Newsletter (STN), The 35 Largest Oil Spills, 1942-1978 spill summary; World Eagle, Where the Oil Was Spilled, 1962 to early 1980 (TOV), spill summary; and the Republic of Liberia (LIB), Oil Spillage Attributed to Liberian Tankers 1978-1979 (48,49,42).

All three summaries consist of brief listings of tankers involved in oil spillage. These were used for verification purposes and, rarely, as information sources.

Once an incident has been selected for inclusion, all that remains is the structuring of information into an accessible format. The format used in this case is a variation of that used by the U.S. Coast Guard for the Tanker Casualty File (37).

In TCF, each entry contains more characters than could be held in a single record (line) on the computer system used by OIW. TCF also documents information not relevant to the current study. The format was therefore condensed to allow a one entry/one record format. The result is an entry of up to 135 characters. The format description (see Appendix B) is largely U.S. Coast Guard text, with some modification.

Once the Casualty Spill File was established for the years 1969-1979, a second modification took place. For the years 1976-1979, for which the Tanker Register (see below) was computerized, more detailed and accurate vessel characteristics were provided. The result of this is a file with consistent tanker characteristics for use in subsequent analysis. The new items are shown in Appendix B.

The Casualty Spill File, while complicated in its formation, provides ready accessibility for analytical purposes. The file contains 190 spills for the four year period 1976-1979, and 739 for the 1969-1979 period. Only the 1976-1979 spills are well verified, however, due to the coverage of the sources used. Thus, the number of spills and quality of information varies dramatically for 1969-1975 and for 1976-1979.

Port call data and tanker characteristics cover only the latter four years. Thus, no relationships between spill occurrence and exposure variables can be made for the earlier years. This relegates data from the years 1969-1975 to a supplementary role in assessing general tanker spill trends.

3.2 TANKER REGISTER

The purpose of the Tanker Register is the documentation of tank vessel characteristics for the world tanker fleet. This data base would provide a basis for comparison with a sample of this fleet, namely those tankers involved in oil spillage incidents. The file also would provide for vessel identification, as few tanker identifiers are absolute.

The Tanker Register is a compilation of data on the world fleet of oil carriers from Lloyd's Register of Ships, and covers the years 1976-1979 (33). Published annually, the Register of Ships contains the names, classes, and general information concerning all known ocean-going merchant ships of 100 or more gross tons. This information is derived from member societies, government agencies, and, if necessary, vessel owners. Information from outside sources is often incomplete and of questionable accuracy. Thus, no guarantee of the accuracy of that information is made.

The Register of Ships appears to be the best single source of information on the world fleet. Entries contained up to 60-plus discrete items of information on each vessel. This extensive amount of information includes much which is not useful in a statistical analysis. Thus, an a priori elimination of many details took place. These include owner, builder, equipment manufacturer, classification society, and many structural and equipment details. Chosen for inclusion in the data base were 15 details. These were computerized in a systematic format. Subsequently, information concerning the laid-up status of vessels and numbers of port calls were provided from other sources. The format and items included are shown in Appendix B.

The development of the data base was accomplished by successively incorporating five editions of the Lloyd's Register of Ships. This was done by using the earliest edition included, 1976-1977, to establish the bulk of the file. For this first year, all tankers of greater than 5,000 deadweight tons (2,500 gross tons if deadweight was unavailable) were incorporated into the data base. The resulting file documents tankers active in 1976.

For 1977 tankers, the 1977-1978 edition of the Register of Ships was used. In this case, it was only necessary to note deletions or additions from the previous year. A deletion could mean that a tanker had either been removed from service or had undergone a name change. Similarly, a new entry could mean either a new vessel entering the fleet, or a new name for a vessel already included. The Lloyd's number, which remains constant for the vessel regardless of other changes, provided the link between these two sets of changes. If the same Lloyd's number appeared in each list, this would identify those entries as name changes. The vessel status codes shown in the format description were used to denote the status of new listings.

The years 1978 and 1979 were incorporated via the same method, using the 1978-1979 and 1979-1980 Register of Ships, respectively. An additional step was also taken for 1979. The 1980-1981 edition was used to ensure that all

1979 construction vessels would be included as new entries for that year. This was necessary due to the imperfect correspondence between year of construction and year of inclusion in the Register of Ships. Similarly, new vessels in earlier years were attributed to their year of construction, not the year of incorporation into the file.

Following the completion of the data collection, the selection of the tanker fleet to be used in the analysis was made. For this purpose, two sets of tankers have been excluded from consideration: communist flag vessels and combination carriers. Communist flag vessels have been excluded due to poor reportage of tanker activity. The nations excluded are: Bulgaria; Cuba; the Democratic People's Republic of Korea; the German Democratic Republic; the People's Republic of China; Poland; Rumania; the Soviet Union; and Vietnam.

Combination carriers were found to have ship characteristics drastically different from strictly oil carriers. The inclusion of combination carriers would thus distort any analysis based upon those characteristics.

Following the collection of data, procedures were developed to account for missing values in the data base. Of particular concern were missing deadweight tonnages. Additionally, length and draft values were on occasion missing. Discussion with consultants and review of methods used by other researchers led to methods for estimating these missing values when needed for analysis. These are presented in Appendix C.

The final steps in the documentation of the world tanker fleet were the inclusion of information derived from Lloyd's Monthly List of Laid-up Vessels and the Lloyd's Vessel Movement File (50,29). This information was used to improve the documentation of the activity level of the tanker fleet.

For each year of the file, the January and July issues were used to document the laid-up status of tankers. To facilitate the inclusion of this information, each issue was assumed to be representative of a six-month period. This assumption does not necessarily portray the status of an individual tanker accurately for short periods of time. It does allow the consideration of tanker activity to extend beyond merely whether or not a tanker is in existence. The number of port calls made by each tanker in each year was also included in the file.

The resulting data base consists of entries for 4,055 distinct tankers. The information contained in each entry provides the necessary background of tanker characteristics for the analysis of their relationships to tanker safety.

3.3 LLOYD'S PORT CALL DATA

The relationship between tanker characteristics and tanker spillage is at best incomplete without the consideration of activity levels. For example, in assembling the OIW Tanker Register, some vessels were found to be laid-up for the entire period 1976-1979 (50). One active vessel, on the other hand, had over 900 port calls during the same period (29). It seems extremely questionable that this vessel experienced the same risk of spillage as the laid-up vessels. Similarly, the a priori equation of this vessel with one which makes fewer than 20 port calls each year seems equally dubious. Thus, it is necessary to examine various measures of tanker activity to determine if, and how, they are related to risk.

One measure of tanker activity, albeit a crude one, has already been presented. This is simply the number of years which the tanker was in existence. This can be extended to include only those periods it was not laid-up. The resulting measure of tanker years is a rather simple refinement of the tanker fleet documentation. It helps to account for the worldwide excess of tanker tonnage and the resulting inactivity of a significant percentage of the world fleet by excluding a laid-up ship from consideration. Inherent in this method is the assumption that laid-up vessels differ significantly from active vessels in their exposure to spill risk. Unfortunately, excluding laid-up vessels fails to account for any risk to those vessels, which is not necessarily valid. With the data currently available, however, it is not possible to document a separate level of risk for tankers with laid-up status. A more detailed measure of tanker activity, and a potential exposure variable, would be one already mentioned, port calls. This information is available from only one source: Lloyd's Vessel Movement File (29). This file is computerized for the years 1976-1979, and a condensed form has been purchased from Lloyd's for these years.

In the form obtained for this study, the Vessel Movement File identifies each port of call made by all oil tankers over 4,000 deadweight tons in the world fleet for each year. The format of these data is straightforward: for each entry, the name and Lloyd's number of the vessel are provided, and the name and port code of the port visited. This format allows for the analysis, after data reduction, of spill risk from two perspectives. The activity levels of tankers as measured by port calls could prove to be a valuable

exposure variable for assessing spill risk to a particular tanker or group of tankers. Similarly, the tanker activity within a given port or port system can be used to assess risk for a port, based upon the characteristics of that port.

The availability of port call data also allows for the development of other potential exposure variables. For example, the incorporation of information from the Tanker Register could be used to measure tonnage throughput by tankers, tanker groups, ports or port systems. While this does not provide the volume of oil transported, it may nonetheless be a valuable exposure variable. Additionally, the distance travelled within a port system has been shown to be related to oil spillage of tankers while in transit (51,52,53). Given that a distance travelled within the port system, from port entry to berthing, could be determined, this variable could be developed from the port call data. Similarly, ton-miles travelled could also be documented. Unfortunately, neither of these have proven feasible for this study.

One shortcoming of the port call data is that it does not provide origin-destination pairs. Thus, it does not allow the consideration of total distance travelled (not just within ports) as an exposure variable. A previous study of the Vessel Movement File indicates that the accuracy of the file breaks down at this level, the validity of such an analysis would in any case be suspect (28).

In reducing the port call data into useful form, several steps were taken. Port calls to be included for analysis were limited to those by tankers included in the Tanker Register. Thus, combination carriers, Communist flag vessels, and vessels of less than 5,000 deadweight tons were not included. Additionally, port calls made to Communist ports were excluded. Nations excluded were: U.S.S.R.; Poland; the German Democratic Republic; Bulgaria; Rumania; Vietnam; the People's Republic of China; the Democratic People's Republic of Korea; and Cuba. As previously discussed, this is due to the questionable public reporting practices of these nations, regarding both port calls and spill incidents.

Further reduction of the data base involved collecting multiple port calls under a single entry. That is, a given tanker/port pairing is entered only once, with the number of occurrences included. The resulting data base includes over 350,000 port calls to 1,707 different ports by 3,511 tankers.

3.4 PORT CHARACTERISTICS FILE

In order to address the possible relationship between spillage within a port and the characteristics of that port, a data base was established documenting available port characteristics for the most active tanker ports worldwide. For this purpose, a port was defined as a terminus. Thus, neither the Panama Canal nor the Strait of Gibraltar would qualify. Similarly, Berry Head, U.K., which is simply a lightering point with no land facilities, was also excluded (54). The ports were chosen based upon the number of port calls reported in the Lloyd's Vessel Movement File for the years 1976-1979.

The port characteristics file was initially intended to include a variety of physical characteristics for consideration in subsequent analysis, in addition to tanker activity information. For this purpose, the Guide to Port Entry, 1979-1980, a comprehensive source of port information, was obtained (55,56). Unfortunately, this source, like all others discovered, did not document physical characteristics in a consistent or systematic manner. Indeed, the only characteristic provided with any reliability was the number of oil tanker berths at the port. Another source, the International Petroleum Encyclopedia, 1980, provides an estimation of maximum size of vessels which can call at the world's major oil ports (57,58). This information relates poorly to actual vessels calling at the ports, however. In many cases, the vessel size varied by factors of five or more from the maximum size vessels to have actually called. Thus, the information was of little value as a port characteristic.

As an alternative to documenting physical characteristics, efforts were also made to define perceived safety levels for the ports addressed, based upon industry-provided data. In this case, several oil companies involved in tanker operation were contacted in the hope of obtaining port information. Information was requested on preventive measures taken in specific ports. It also was hoped that a questionnaire would be distributed to masters of vessels for their evaluation of the relative risk of port systems. One company responded, however, that this would not prove worthwhile as their masters would typically classify as safe all ports at which they call. Additionally, it is uncommon for a single master to be knowledgeable on a large number of worldwide ports (59). Thus, despite efforts to document both physical characteristics and perceived risks, the resulting file is essentially limited to documenting port activity.

The use of individual ports was considered for developing subsequent relationships to oil spills. This was found to be infeasible due to imprecise identification of casualty spill location. In many cases spills within a bay or other enclosed waterway could not be satisfactorily identified with a specific port. Further, many spills were identified as being located at or near a specific port (e.g., "near Lisbon" or "approaching Singapore") when any of several nearby ports could have been chosen. For this reason, the use of port systems was found to be the preferred alternative.

For each major port, a port system was identified based upon proximity. The selection was facilitated through the use of Lloyd's port codes, which lists a limited number of ports in a given area, and proved to be straightforward in many cases. For example, for restricted waters such as the Delaware River, ports included were easily selected from the Lloyd's List of Port Codes (60). In this case, Philadelphia, Morrisville and Gloucester (New Jersey) are the only ports identified distinctly by Lloyd's. For others, such as Camden, port calls are included under an identified port name, such as Philadelphia. Similarly, the port code for New York encompasses the entire New York Harbor area.

In the case of each port system, an attempt was made to identify a separation point between open and restricted waters. In many cases, the sparsity of ports identified by Lloyd's made the separation obvious. In others, the decision became subjective. For island groups, such as the Bahamas or Netherlands Antilles, the entire island group was chosen, primarily due to the vagueness of reported spill positions. It will be seen in Subsection 4.3 that the model developed conforms well to all of the port groups, including the island groups.

Sixty port systems were identified, which contained the seventy-three most active oil ports in the world, based upon number of port calls made. The reason for the choice of sixty port systems rather than some other number is based upon where Greater Puget Sound falls among them.

For each port system, characteristics relating to the port system and to the most active individual port were recorded. These characteristics were: number of port calls; tonnage throughput; maximum size and draft of vessels having called; estimated maximum vessel size (individual port only); variance of tanker size (port system only); number of spills (port system only); volume of spills; and number of berths. The number of berths includes all berths

identified as oil berths in the Guide to Port Entry, including offshore terminals.

The port systems chosen are described below. The Lloyd's port codes assigned to each port system define the area covered by each system and the major oil ports which fall within them. The order is based on number of port calls at the largest major oil port within the port system.

<u>OIW Defined Port System</u>	<u>Lloyd's Port Codes Included (60)</u>	<u>Most Active Port(s) Identified by Lloyd's (29)</u>
1. Ras Tanura	06-370	Ras Tanura
2. New York	12-240	New York ¹
3. Singapore	06-1610 <u>to</u> 06-1640	Singapore, Pulau Bukum
4. Mississippi River	11-2445 <u>and</u> 11-2460 <u>to</u> 11-2800	New Orleans
5. Delaware River	12-223 <u>to</u> 12-237	Philadelphia
6. Cape Town, S.A.	05-1390 <u>to</u> 05-1410	Table Bay
7. Netherlands Antilles	11-1600 <u>to</u> 11-1670	Aruba, Curacao, Bonaire
8. Kharg Island, Iran	06-670	Kharg Island
9. Rotterdam	02-670 <u>to</u> 02-687	Europort, Rotterdam
10. Los Angeles	08-890 <u>to</u> 08-903	Los Angeles
11. San Francisco	08-765 <u>to</u> 08-780	San Francisco
12. Dubai, United Arab Emirates	06-225 <u>and</u> 06-240	Dubai
13. Milford Haven, U.K.	00-1150	Milford Haven
14. Neches/Sabine, Texas	11-2370 <u>to</u> 11-2430	Port Arthur, Beaumont
15. Galveston Bay	11-2330 <u>to</u> 11-2360	Houston, Galveston
16. Tokyo Bay	06-5220 <u>to</u> 06-5340	Yokohama, Chiba
17. Sea of Marmara	04-2650 <u>to</u> 04-2690 <u>and</u> 04-3090 <u>to</u> 04-3180	Istanbul
18. Canary Islands	05-175 <u>to</u> 05-230	Las Palmas, Tenerife
19. Corpus Christi	11-2260 <u>to</u> 11-2290	Corpus Christi
20. Massachusetts Bay	12-645 <u>to</u> 12-660	Boston

OIW Defined Port System	Lloyd's Port Codes Included (60)	Most Active Port(s) Identified by Lloyd's (29)
21. Sardinia	04-456 <u>to</u> 04-530	Sarroch
22. Piraeus, Greece	04-2240 <u>to</u> 04-2310	Piraeus
23. Genoa, Italy	04-560 <u>to</u> 04-570	Genoa
24. Le Havre, France	02-1745 <u>to</u> 02-1830	Le Havre
25. The Bahamas	11-1295 <u>to</u> 11-1355	Freeport
26. Marseilles, France	04-320 <u>to</u> 04-340	Fos, Port de Bouc
27. Fawley, U.K.	00-420 <u>to</u> 00-540	Fawley
28. Augusta, Sicily	04-970 <u>to</u> 04-980	Augusta
29. Tees, U.K.	00-3190 <u>to</u> 00-3200	Tees
30. Jebel Dhanna, Abu Dhabi	06-280	Jebel Dhanna
31. Chesapeake Bay	12-190 <u>to</u> 12-220	Hampton Roads, Baltimore
32. Virgin Islands	11-309 <u>to</u> 11-370	Hovic
33. Hamburg, W. Germany	02-10 <u>to</u> 02-110	Hamburg
34. Antwerp, Belgium	02-1140 <u>to</u> 02-1160 <u>and</u> 02-1164 <u>to</u> 02-1580	Antwerp
35. Mina Al Ahmadi, Kuwait	06-440 <u>to</u> 06-470	Mina Al Ahmadi, Shuaiba
36. Trinidad	11-10 <u>to</u> 11-100	Pointe a Pierre
37. Dumai, Indonesia	06-1760	Dumai
38. Bahrain, Bahrain	06-340	Bahrain
39. Bandar Mahshahr, Iran	06-610 <u>to</u> 06-630	Bandar Mahshahr
40. Wilhelmshaven, W. Germany	02-260	Wilhelmshaven
41. River Thames, U.K.	00-8 <u>to</u> 00-290	London, Isle of Grain, Shell Haven
42. Lisbon, Portugal	03-550 <u>to</u> 03-555	Lisbon
43. Valdez, Alaska ²	08-125 <u>to</u> 08-160	Valdez
44. Puerto Mexico, Mexico	11-2200	Coatzacoalcas
45. Das Island, U.A.E.	06-290	Das Island
46. Bombay, India	06-890	Bombay
47. Miami, Florida	12-10 <u>to</u> 12-30	Port Everglades
48. Bilbao, Spain	03-310	Bilbao
49. River Humber, U.K.	00-3245 <u>to</u> 00-3470	Immingham

OIW Defined <u>Port System</u>	Lloyd's Port Codes <u>Included</u> (60)	Most Active Port(s) Identified <u>by Lloyd's</u> (29)
50. Trieste, Italy	04-1240 <u>to</u> 04-1254 <u>and</u> 04-1260 <u>to</u> 04-1270	Trieste
51. Mina al Fahal, Oman	06-160	Mina al Fahal
52. Karachi, Pakistan	06-780	Karachi
53. Shatt-al-Arab, Iraq	06-500 <u>to</u> 06-550 <u>and</u> 06-560 <u>to</u> 06-590	Khor al Amaya
54. Liverpool, U.K.	00-1330 <u>to</u> 00-1660	Eastham
55. Jeddah, Saudi Arabia	06-40	Jeddah
56. Ras es Sider, Libya	04-3940	Ras es Sider
57. Puerto la Cruz, Venezuela	11-1510 <u>to</u> 11-1550	Puerto la Cruz
58. Bonny, Nigeria	05-820 <u>to</u> 05-860	Bonny
59. Corncake Inlet, N. Carolina	12-170	Wilmington
60. Greater Puget Sound, Washington	08-530 <u>to</u> 08-640 <u>and</u> 08-380 <u>to</u> 08-460	Bellingham ³

¹ "New York" encompasses the jurisdictional area of the Port Authority of New York and New Jersey

² Included due to heavy tanker activity, even though not operating for the entire period 1976-1979

³ Bellingham as identified by Lloyd's includes the Ferndale and Cherry Point refineries.

The order of port systems based upon port calls within the entire port system varies significantly from this list. For example, the Thames River is the eighth most active port system, and there are twenty systems with fewer port calls than Greater Puget Sound. Once the sixty port systems were selected, the systems were grouped according to several different criteria. This is described in Subsection 4.3.

3.5 OPERATIONAL SPILLS

While many data bases were located describing the circumstances surrounding the occurrence of tanker spills, only one of these data bases appears to describe the occurrence and volume of operational oil spills worldwide, defined in this study as all non-casualty tanker spills. This is the data provided by the International Tanker Owners Pollution Federation Limited (TOVALOP) (44). These data consist of voluntary reports by member owners and therefore the confidentiality of the information was a required stipulation when the data were provided to OIW. Specifically, the names of vessels were excluded from the data.

These data have provided a computerized record of the occurrence of all types of spills between 1974 and 1980. The record for each spill incident contained a mixture of explicit values (for the date, the size and age of the tanker, and sometimes a value for the spill volume) and coded values. The coded information indicated the cause of the spill, the operation in progress, the country and port nearest the spill and the volume spilled. The coded volume spilled only indicated that the amount of oil spilled fell within a certain range of values (e.g. 5 to 50 barrels). In the spirit of the confidentiality of this data, detailed descriptions of the data fields are not provided in this report. However, the general methods used by OIW to obtain estimates of the frequency and volumes of oil spilled will be presented.

In order to construct a data base describing the operational spills of the studied fleet for the same time period described by the port call data, the TOVALOP data were first searched for spills occurring during the inclusive years 1976 through 1979. Those spills with codes which indicated that the circumstances surrounding the spill were strandings, groundings or collisions were excluded. In order to ensure that only operational spills of the world fleet were included, the recorded characteristics of the spilling vessels were compared with those of the studied fleet. The correlation of the characteristics of a spilling tanker with those of a tanker in the studied fleet resulted in the inclusion of that spill in the data base. Thus, if a tanker was not in the studied world fleet, it would be possible for any of its operational spills to be included in the analysis if its physical characteristics exactly matched a vessel in the world fleet. Also, if there were any coding errors on the TOVALOP tape, or if the characteristics were incorrectly related

to TOVALOP, the analysis would not have selected those spills as belonging to the studied fleet. Finally, any spills that took place in Communist countries (U.S.S.R., The Democratic Peoples Republic of Korea, Bulgaria, Rumania, Vietnam, Cuba, Poland, The German Democratic Republic or The People's Republic of China) were excluded. This selection process resulted in the accumulation of 1,735 operational spills with a combination of explicitly stated spill volumes and coded volumes in spill ranges.

In order to determine the volume spilled from the TOVALOP data, the coded spill volumes were treated in the following manner. All spills reported as having between a trace of oil spilled and 5 barrels were encoded as being one ton. (One ton equals approximately 7.3 barrels.) (58) For those spills greater than 5 barrels, if no explicit volume was reported, the volume was defined as the midpoint of the range. For example, for spills encoded as being between 5 and 50 barrels, the volume was defined as 27.5 barrels, and calculated to be 4 tons. For the largest spills, only a lower limit was given for the range: 5,000 barrels. For this one range, the volume to be substituted was defined as the average of all spills in the data base with volumes explicitly reported, and greater than 5,000 barrels. This mean value was a simple arithmetic average, and is the best estimate of the expected volume of these spills. Even though the distribution of all operational spill volumes is accepted to be lognormal (14), the expected volume is the mean value. This value was only used in 5 substitutions.

SECTION 4. STATISTICAL ANALYSES AND RESULTS

4.1 BASIC PREMISES

This study was a statistical analysis of historical data which established and studied relationships among risk indicators and exposure variables. Before beginning the presentation of the many different approaches, methods and results, it is vitally important to understand the assumptions underlying these analyses. This subsection might have been placed in an earlier section concerned with the general approach, but it is most important that the concerns presented in this section be fully understood before the results of the study are presented. Therefore, the following paragraphs in this section will address:

- The completeness of the data base
- The results as hindcasts and not predictions
- The completeness of potential exposure variables
- The non-causal nature of statistically determined relationships
- The assumption that similar tankers and port systems have similar spill histories.

OIW gathered oil spill data from thirteen different sources around the world and then merged the data into one data base. Because of the extensive data gathering and data verification efforts, the data used in these analyses are the most highly verified description of casualty related tanker oil spillage to date. However, some spills are probably not reported to any agency or group and in turn, these spills would not be in OIW's data base. Since it is most likely that these unreported spills had relatively small volumes, their "omission" should not significantly affect any results. Furthermore, standard statistical techniques indicate the natural variability within the data and one can therefore discuss the average amount of oil spilled under a given set of circumstances with some assurance. Since it is reasonable to assume that the vast majority of all large spills have been reported and that most of the vessel owners are reporting spills to the various governments as required by law, and to the tanker owners/operators groups as requested, one can gain some assurance that the statistics generated during this analysis are valid.

The analyses were based upon historical data. OIW studied the spilling history of tankers and not the spilling future of tankers. These studies used four years of experience and have determined relationships between the risks and parameters describing tanker operations and ports. It is not OIW's intent to suggest that these relationships will hold for all time. It is reasonable to assume that studying what has happened can help plan for the future, but only when conditions do not change significantly. This is a very practical stand, as it provides a basis for planning future actions upon the basis of experience and not just assumption. However, OIW's results were determined from historical data and strictly speaking, they are hindcasts, not forecasts.

The analyses were concerned with determining relationships using quantified data. Not all aspects of tanker operations are recorded and available for study. For example, tanker speed at the time of a casualty was not documented in the data bases. The efforts had to be directed toward those operations which were quantified and recorded by various groups. OIW looked at a long list of possible exposure variables, based upon years of experience in the field of oil spills and tanker risks, and proposed as many variables as possible. Many variables proposed by other investigators have also been included in this study (9-27). While other possible exposure variables exist, these analyses considered more statistical variables than in previous studies.

This study established a number of relationships among the various exposure variables and risk indicators. These are empirical relationships, and do not necessarily imply cause and effect. The possible exposure variables were proposed, in many cases, because they might have a relationship with oil spills; nevertheless, the results that are to be presented are not to be interpreted as causal relationships. The utility of these empirical relationships should not be questioned simply because a cause and effect relationship has not been determined. Even if a very strong heuristic argument could be advanced supporting the idea of a causal relationship, it was not the intent of this study to try to support such arguments. These empirical relationships, derived from a statistical analysis of historical data, are valid representations of the frequency and volume of oil spills.

Finally, this study of tanker oil spills is based upon an assumption that the occurrence and volume of oil spills can be expressed as some function of the physical characteristics of tankers and/or of the activity level of ports or tankers. This assumption carries the implicit interpretation that tankers

of similar characteristics or ports of similar characteristics will have similar spill histories. This assumption has been verified by the results of this and many previous studies, which have discovered relationships between the frequency of spills and vessel size, port calls, and other exposure variables, and between the volume spilled and the size of tankers (9-27). So there is good and sufficient reason for one to base an analysis upon that assumption. But this effectively rules out the possibility of finding that a particular tanker has an unsafe characteristic, different from all tankers of similar size, power, age, or activity. For example, both the U.S. and Canadian Coast Guard keep records of spills by tankers, and this information is available when the tanker attempts to enter a port. Based upon the tanker's spill history, action can then be taken to mitigate the tendency of specific vessels to incur spillage (62,63,64). But studying particular tankers was not the intent of this study; this analysis presumes that groups of similar vessels or ports with similar activity levels will have similar spill histories.

4.2 COMPARISON OF THE SPILLING TANKERS AND ALL TANKERS

This study focused on determining relationships among the various exposure variables and risk indicators, namely the frequency of spills and the volume of spillage. For several obvious reasons, it was necessary to verify that the tankers responsible for spills during the 1976-1979 period did not differ to any significant degree from those tankers having no spills. First of all, any relationships uncovered using only the spilling fleet, such as a deadweight tonnage-volume relationship, would not be applicable to the world fleet if the two fleets differed substantially. Secondly, the consistency of the two fleets is necessary since the frequency analysis is as dependent on the behavior of non-spilling tankers as on the behavior of spilling tankers.

Those tankers that had spills - 181 tankers, including 9 tankers responsible for 2 spills each - were compared to their counterparts in the studied fleet containing 4,055 tankers. Perhaps spilling tankers were on the average underpowered, or perhaps disproportionately older, or perhaps making disproportionately more port calls. Or were the tankers responsible for spills just a representative subset from the 4,055 vessels in the world tanker fleet with no unique characteristics?

First of all, the World Fleet File was plotted as a function of deadweight tonnage (DWT). Figure 4-1 shows the number of tankers in each range of 20,000 DWT (but since the file only includes tankers greater than 5,000 DWT, the lowest range effectively includes only a 15,000 ton range of data). The data are highly skewed with a relatively large percentage of the tankers in the small end of the distribution. Over seventy-two percent of all tankers are less than 100,000 DWT; only 9.5% are between 100,000 and 200,000 DWT; 15.3% are between 200,000 and 300,000 DWT; and the remaining 2.7% are greater than 300,000 DWT. In addition to the skewness, there is a range of some 40,000 DWT, between 160,000 and 200,000 DWT where there are very few tankers. This range of sizes almost seems to have been skipped by the ship builders.

Figure 4-2 shows the distribution of tankers by age. The values plotted are the number of tanker years during the period 1976 through 1979. In addition to showing the distribution of ages for the World Fleet, the subdistributions of certain ranges of sizes of tankers (5,000 to 49,999 DWT; 50,000 to 99,999 DWT; and greater than or equal to 200,000 DWT) are also shown. There are two very obvious peaks in the distribution of the world fleet tankers. The first is for the approximately 19 year old tankers and is comprised almost entirely of tankers less than 50,000 DWT in size. A second peak in the world fleet distribution is seen near four years old and is comprised of a mixture of tankers of all sizes. Notice that the peak at four years old is also seen in each of the three ranges of sizes. It appears as though ship building has dropped off in the last few years and relatively few new tankers are entering the fleet.

Figure 4-2 also shows a trend with time to build larger and larger vessels. Twenty years ago, almost all of the vessels were less than 50,000 DWT. Then production of 50,000 to 99,999 DWT tankers began to pick up and peaked about 12 years ago. Production once again picked up and then peaked a second time about four years ago. Although it was not included on this figure (for clarity), the production of 100,000 to 199,999 DWT tankers began about 15 years ago and peaked about 8 years ago. The first tankers of more than 200,000 DWT are now about 13 years old and their production peaked about four years ago.

Figure 4-3 shows the percentage of tankers in the spilling fleet as a function of deadweight tonnage for the two periods 1969 through 1979 and for 1976 through 1979. The relative percentages of spills by those tankers less

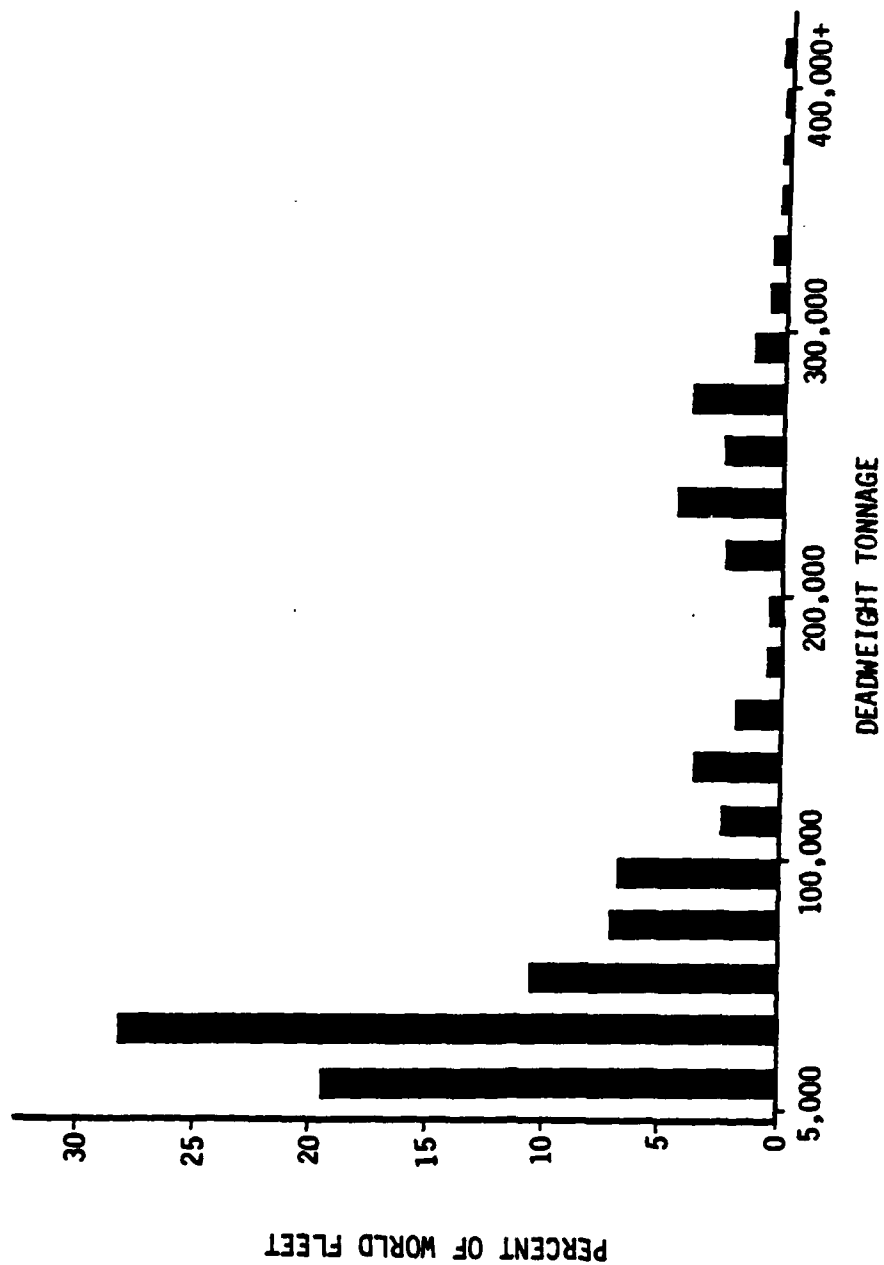


FIGURE 4-1. SIZE DISTRIBUTION OF TANKERS IN WORLD FLEET (TOTAL = 4,055).



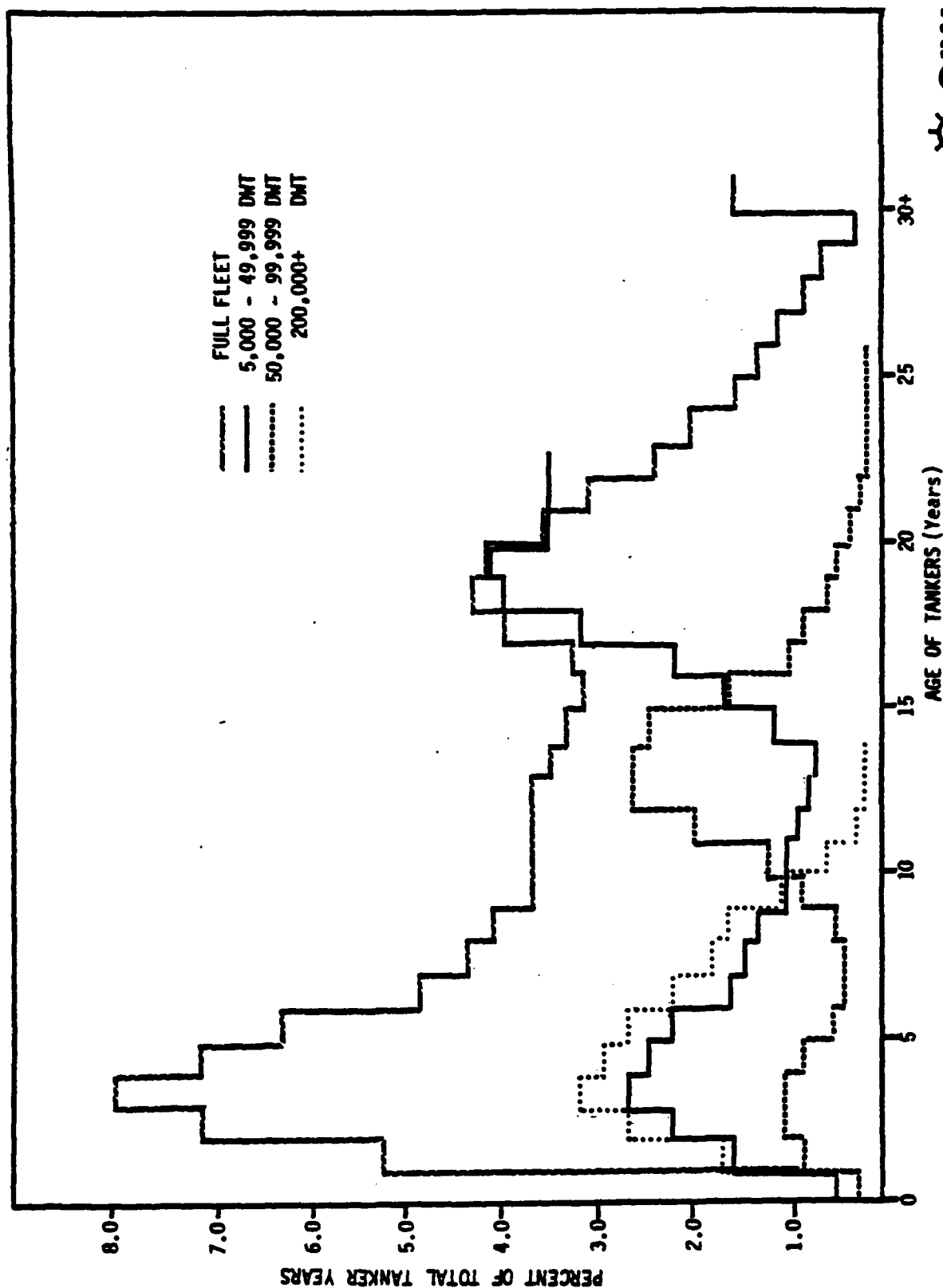


FIGURE 4-2. DISTRIBUTION OF THE AGE OF WORLD FLEET.

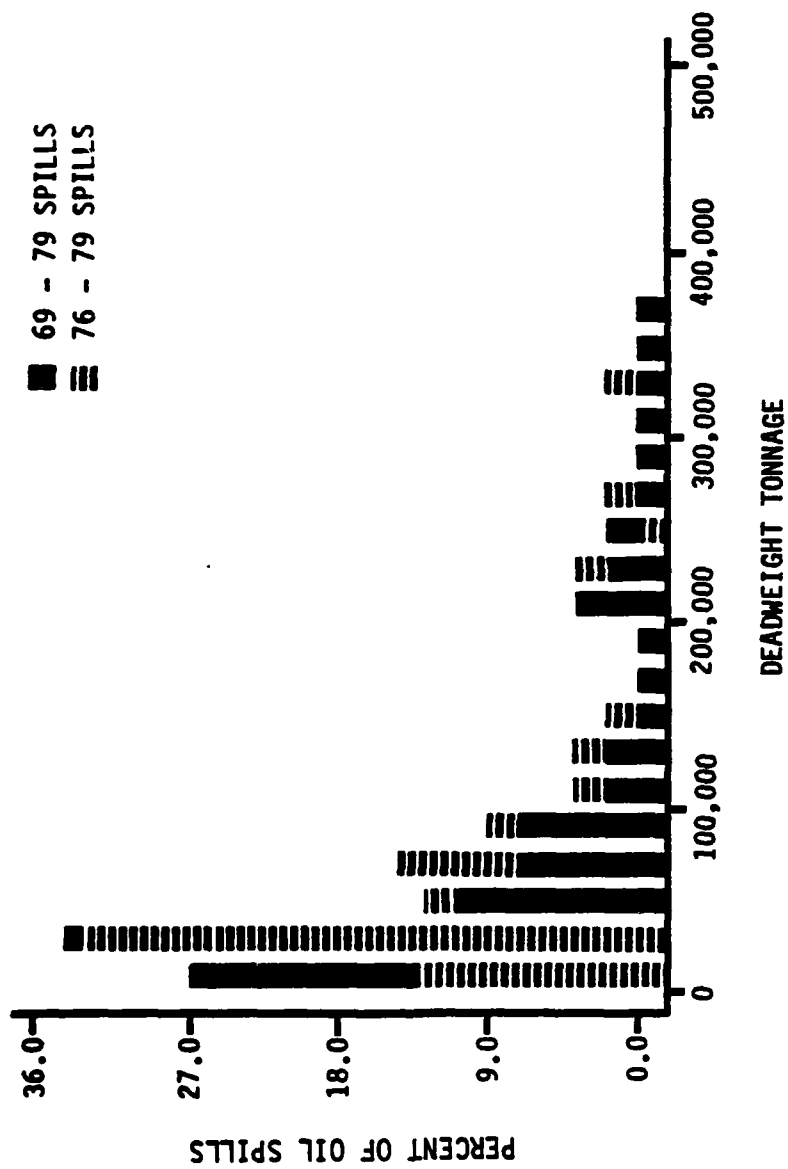


FIGURE 4-3. COMPARISON OF CASUALTY OIL SPILLS DURING THE PERIODS 1969-1979 AND 1976-1979.



OIW

than 160,000 DWT has changed significantly between these two periods. Between 1969 and 1979, tankers less than 40,000 DWT accounted for nearly 58% of all spills. Between 1976 and 1979 they accounted for less than 44% of all spills. Those tankers between 40,000 and 160,000 DWT accounted for more than 44% of the spills between 1976 and 1979 but for less than 32% between 1969 and 1979. When one considers that the 1976 through 1979 data is a subset of the other data, it is quite obvious that the distribution of sizes of spilling tankers has changed dramatically during the last eleven years. Figure 4-2 shows that the distribution of tankers is now markedly different than the distribution of tankers 11 years ago. This provides an additional rationale for limiting the analysis to the years 1976-1979.

The spilling vessel fleet and the world fleet, containing both spilling and non-spilling vessels, were compared by looking at their (1) ages, (2) deadweight tonnages, (3) throughput tonnages, (4) number of port calls, and (5) horsepower.

Grouping the world tanker fleet into ranges based on some criterion allows one to compare the characteristics of spilling tankers with the characteristics of non-spilling tankers. Three unique grouping schemes were utilized in order that this could be accomplished. The first scheme involved dividing the world tanker fleet based on the criterion of deadweight tonnage (Subsection 4.3 on deadweight tonnage). The 4,055 tankers in the world fleet were divided among 20 deadweight tonnage ranges, resulting in an approximately equal number of tankers in each range. The second criterion used for dividing the tanker fleet was age. The 4,055 tankers were distributed among fifteen 2-year age categories and one category for vessels 30 years old or older (see Subsection 4.3 on age). The third method for apportioning the world fleet tankers was based on the number of port calls made by a tanker. Tankers making a similar number of port calls per year were grouped into twenty categories, with the number of port calls ranging from 0 to over 300 per year (see Subsection 4.3 on port calls). Using these three approaches, the five characteristics of the spilling fleet listed above could be compared with the five characteristics of the world fleet.

An average age for each of the categories based on deadweight tonnage and number of port calls was calculated for both fleets, spilling and world. The

correlation between the average ages of the spilling fleet and the average ages of the world fleet, using the deadweight ranges, was 0.94 (see Figure 4-4). However, small spilling tankers, 5,000 DWT to 18,900 DWT, tended to be older than tankers of the world fleet of the same deadweight tonnage by approximately four years. The overall average age of all 4,055 vessels in the world fleet was 10.75, while the overall average age for the spilling tankers was 11.64, less than a year difference. The average ages based on the port call ranges varied more than the average ages based on the deadweight ranges, but not to any substantial degree.

The average deadweight tonnages of the spilling fleet were consistent with the average deadweight tonnages of the world fleet. The average deadweight tonnages for spilling tankers were extremely consistent with those average tonnages for the world fleet, based on the age categories ($r = 0.98$) (See Figure 4-5).

While still relatively consistent, spilling tankers that made the fewest number of port calls, 0 to 13.50 port calls per year were somewhat larger than tankers of the world fleet making the same number of port calls. The overall average deadweight tonnage for all 4,055 tankers was 91,112 DWT, while the overall average deadweight for spilling tankers was 80,279 DWT, a difference of 13%.

The consistency between the throughput (defined as the sum of deadweight tonnage times the number of port calls, not the quantity of oil transported) of spilling tankers and the throughput of the world fleet is not as substantial as it was for age and deadweight tonnage, but is still significant. The following correlation coefficients resulted from comparing the throughput tonnages of the spill fleet with the throughput tonnages of the world fleet:

$r = 0.54$ based on the twenty DWT intervals

$r = 0.86$ based on the sixteen age intervals

$r = 0.74$ based on the twenty port call intervals

See Figure 4-6 for a graphical representation of the relationship between the average throughput tonnages of the two fleets according to deadweight tonnage intervals.

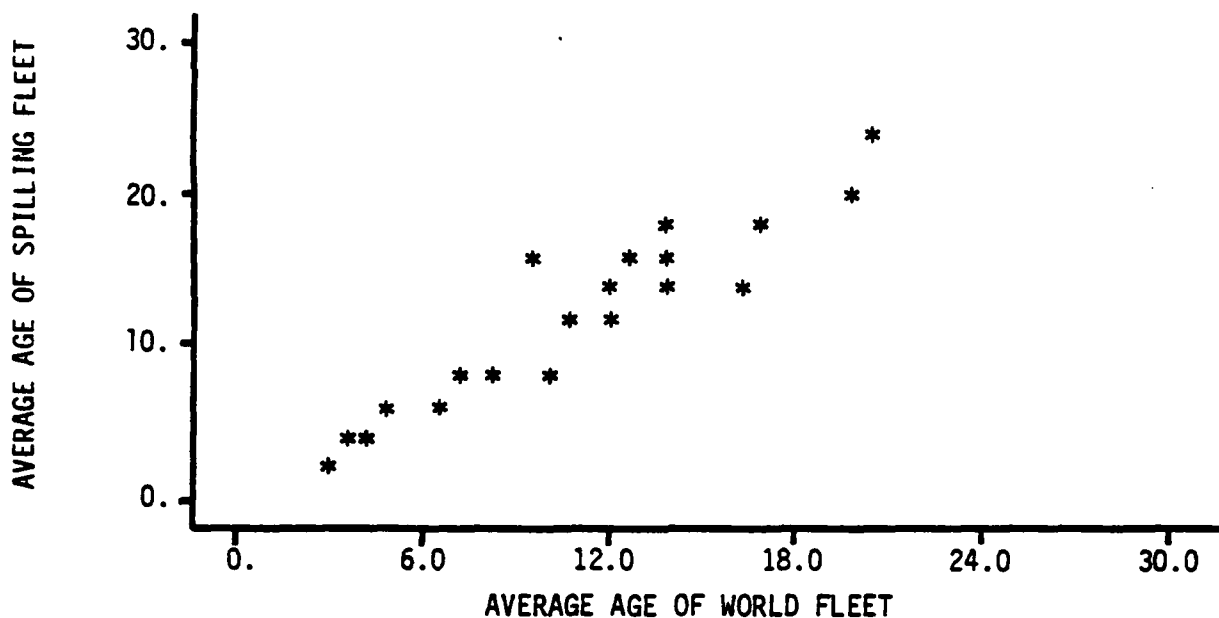


FIGURE 4-4. RELATIONSHIP BETWEEN AVERAGE AGES IN SPILLING AND WORLD FLEETS
(Based upon DWT Ranges).

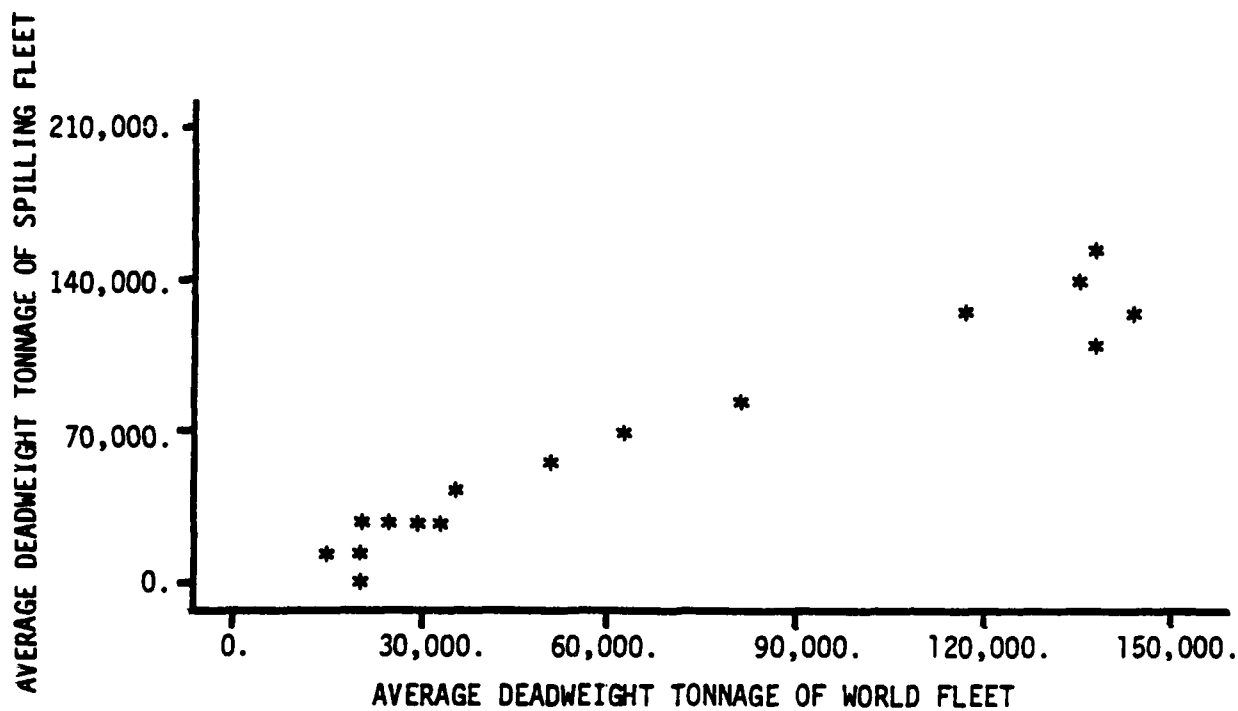
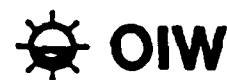


FIGURE 4-5. RELATIONSHIP BETWEEN AVERAGE DEADWEIGHT TONNAGES IN
SPILLING AND WORLD FLEETS
(Based upon Age Ranges).



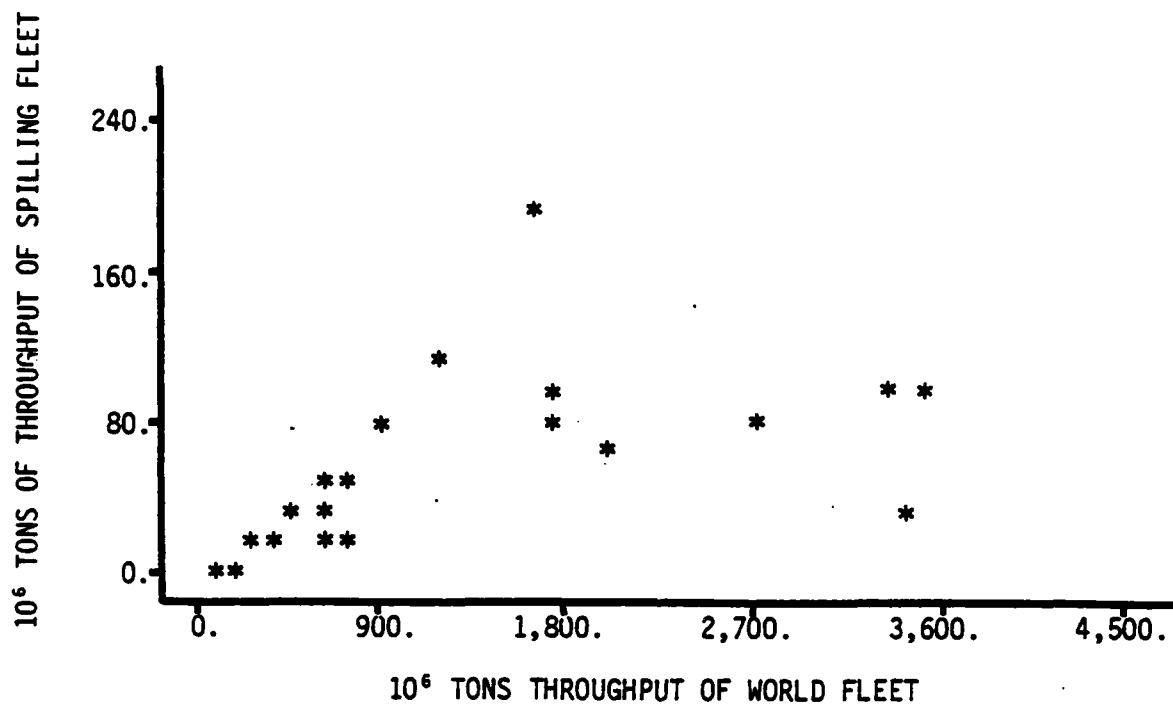


FIGURE 4-6. RELATIONSHIP BETWEEN TONNAGE THROUGHPUT IN SPILLING AND WORLD FLEETS.

(Based upon DWT Ranges).

Vessels in the spill fleet made 18,305 of the total 350,237 port calls, or 5% of the total. A correlation of 0.85 resulted when the number of port calls made by the spilling fleet was compared to the number of port calls made by the world fleet, based on deadweight ranges. (See Figure 4-7) The same comparison based on the age categories produced a correlation of 0.90. It was found that tankers of the world fleet were active 79% of the time while tankers in the spilling fleet were active 84% of the time. In other words, the percentage of active time reflects the amount of time a tanker was not in a laid-up state while in existence during the 1976-1979 period. Furthermore, the average number of port calls per tanker year for world tankers was 27.4 and 30.2 for spilling tankers.

The same high degree of consistency that existed between average deadweight tonnages of the spilling fleet and the world fleet exists for horsepower. One would expect this result since deadweight tonnage and horsepower are so highly correlated ($r = 0.96$). The average horsepower of a vessel in the spilling fleet is 13,079 while the average horsepower of a vessel in the world fleet is 13,594. The following correlations were obtained by comparing the average horsepower values of the spilling fleet and the world fleet:

$r = 0.99$ based on the twenty deadweight tonnage intervals

$r = 0.94$ based the sixteen on age intervals

$r = 0.79$ based on the twenty port call intervals

Figure 4-8 shows the horsepower relationships on the basis of deadweight tonnage intervals.

In conclusion, there is no reason to believe the tankers that have had spills behave any differently from those that have not been responsible for spills. Spilling tankers do not tend to be larger or smaller, overpowered or underpowered, older or younger, or less active or more active than tankers in the world fleet. Those tankers in the spilling fleet can thus be considered a representative subset of the world tanker study fleet.

4.3 ANALYSES OF WORLD FLEET SPILL CHARACTERISTICS

This subsection of the report describes the results of OIW's analysis of relationships between the studied world fleet and the frequency and volume of

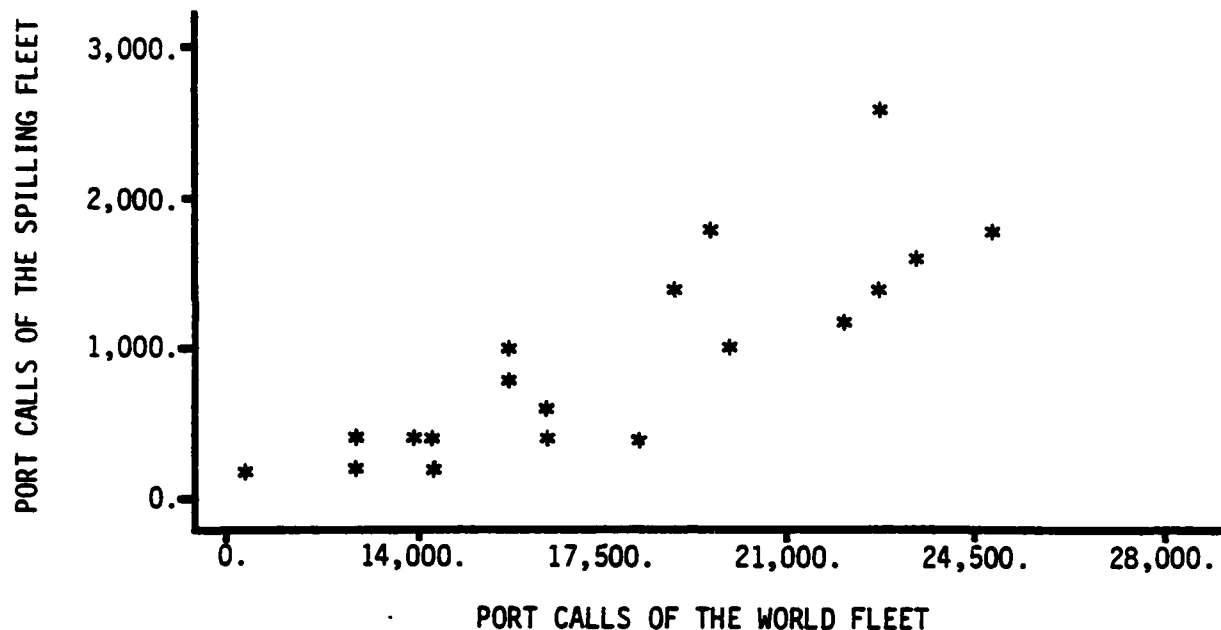


FIGURE 4-7. RELATIONSHIP BETWEEN NUMBER OF PORT CALLS IN SPILLING AND WORLD FLEETS.

(Based upon DWT Ranges).

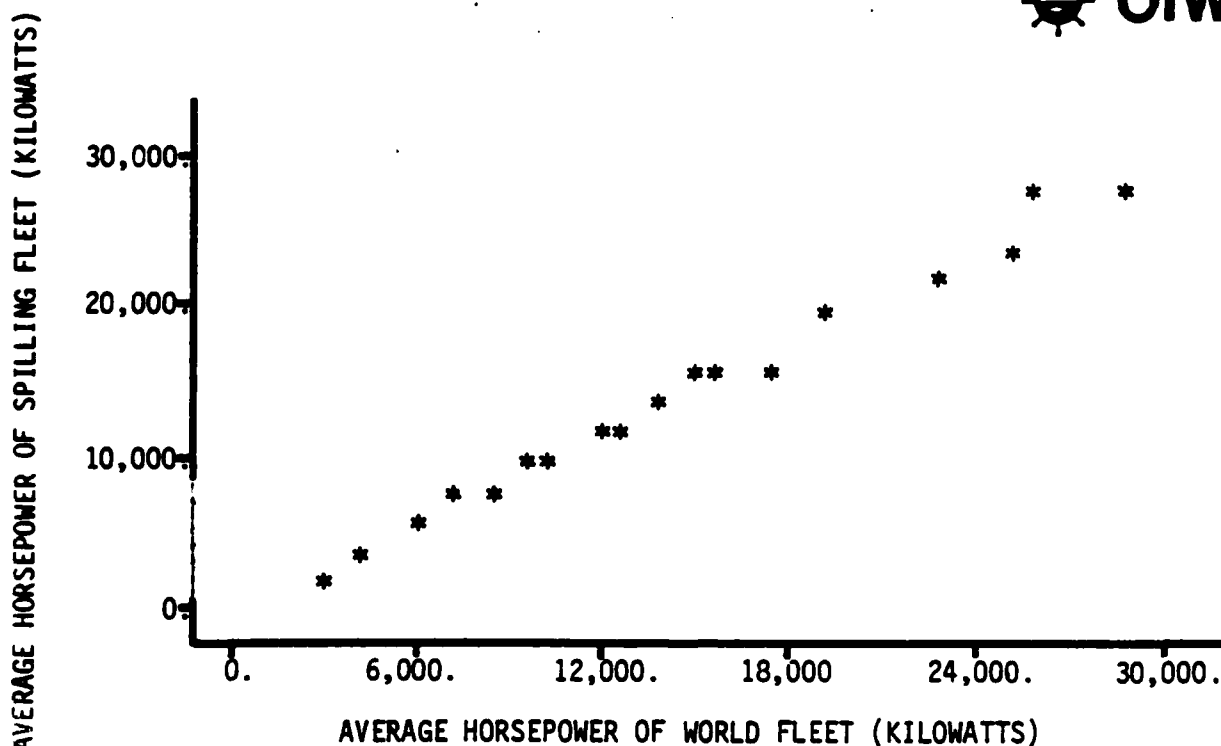


FIGURE 4-8. RELATIONSHIP BETWEEN HORSEPOWER AVERAGES IN SPILLING AND WORLD FLEETS.

(Based upon DWT Ranges).



oil spills. In the previous subsection, certain characteristics of the world fleet and of the spilling fleet were presented and found to be similar. That is, no significant differences were found in the average age, size, number of port calls and so on for the spilling fleet and the world fleet. For example, while old tankers have had many spills, there are many old tankers, and no relationship was determined. (See Subsection 4.2 of this report for a more complete analysis of this point.) Since there was no one characteristic of spilling tankers which separated them from the studied world fleet tankers, the analysis concentrated upon determining relationships involving the world fleet by assuming that the spilling population was representative.

The simplest approach to this portion of the analysis would have been to take each vessel in the fleet; describe its physical characteristics and level of activity; add the number, volume and circumstances of all oil spills; add the ports at which it called, and then perform every conceivable correlation and regression among all of the variables. However, only 190 spills were attributable to hull rupture, for example, so the above methods would have to be applied to a data base with 3,874 ships having zero spills, 172 ships having one spill each, and 9 ships having 2 spills each over the four year period. The data base would be very sparse. This type of analysis also does not take into account the fact that 3,874 tankers have not had a hull rupture spill, or that vessels with characteristics similar to a spilling vessel have not had spills. Finally, if a particular vessel (of a given size or age) has had a spill, it would not necessarily be valid to conclude that the age or size were the important parameters without considering how many other vessels of similar size and age existed. Thus, it becomes readily apparent that one must group similar vessels according to their similar characteristics and then determine if any one group or set of groups have different spill histories.

The controversy surrounding the spilling history of tankers has been due, in large part, to determining the proper grouping scheme of vessel characteristics. Some analyses have divided the fleet into groups of deadweight tonnages (such as 0-50,000; 50,001-160,000; and greater than 160,000 DWT), and then determined the volume and number of spills for one particular characteristic, such as port calls. Other investigators have pointed out that this only describes a portion of the spill history, and since different sized tankers have to make different numbers of port calls, the more important parameter is tons of throughput. Other investigators will maintain that the

activity level of port systems can relate the frequency of tanker spills more accurately than any physical characteristic of the tankers themselves. In order to resolve this controversy, it is necessary to try to relate all of these different exposure variables to the various risk indicators by using a number of different groupings.

This study was designed to resolve the controversy over which groupings were proper and which exposure variables were the most important, by studying many different exposure variables and risk indicators, and by studying their relationships when the data had been grouped according to a number of different schema, including the deadweight tonnage of the vessels, vessel age, the activity level of the tankers in terms of the number of port calls per year, and finally grouped by port systems.

For most of the analyses, the data were sorted and placed in approximately 20 different ranges for each of the four different grouping schema. It is well known that information tends to be "lost" by sorting the data into too few groups. The most obvious case of this is sorting the data into only one group and determining the mean value. In this case, the entire data set is reduced to one number. For this study, the problem was the necessity of aggregating the data (since there are many tankers without any casualty spills) without losing too much information in the process. Briefly, it was discovered that placing 5% of the tankers into each deadweight tonnage range would result in each bin having at least two spills. Furthermore, Sturges' Rule (65) indicates that for a frequency analysis of 4,055 points, there should be 13 groups of data in order to minimize the variance without losing too much information. Choosing more than 13 intervals reduces the amount of information lost. As OIW wanted to retain as much detail as possible, each sorting schema ordered the data and then aggregated it into approximately 20 intervals. Further discussion of the criteria used is presented where appropriate.

Analysis From Deadweight Tonnage Perspective

One of the main emphases of this study was a detailed examination of the relation of tanker size to the frequency and volume of an oil spill. For this study, deadweight tonnage was chosen as the variable to characterize the size of the tanker as it most closely relates to the amount of oil which can be

carried by the tanker. The remainder of this Subsection describes in detail the methodology and results of the investigation of oil spill risk when the data have been sorted by the deadweight tonnages of the vessels and aggregated into 20 ranges of values.

The possible values of deadweight tonnage of the oil tankers in our analysis varies from a defined minimum of 5,000 DWT to a maximum of 555,031 for tankers in the world fleet. Since there are 4,055 distinct tankers in the world fleet in the period from 1976 through 1979, and only 190 casualty spills, it is clear that most of the values of possible deadweight tonnage of oil tankers are not utilized. Only about 0.7% of all possible values of deadweight tonnage are realized in the world fleet, and less than half as many are realized in the spill data (operational and casualty). Any analysis which attempts to treat each integer value of deadweight tonnage would find that most of the values would be zero; more than 99.3% of the values of deadweight tonnage in the world fleet would have zero vessels of that size.

Therefore, a methodology was developed for dividing the possible values of deadweight tonnage into a small number of ranges. In this manner, all of the vessels in a specified range would be placed in an interval and then treated as though they were examples of a similar type of vessel. If the assumption that groups of vessels of similar characteristics will exhibit similar behavior is not true, it will be demonstrated when correlations are calculated for the groups of vessels and the risk indicators. For example, if there is a poor correlation between the size of the vessel and the frequency of spillage, then this might indicate that similar sized vessels do not exhibit similar spillage frequencies.

In addition to resolving the questions about how to deal with a distribution where most of the possible values are zeros, grouping the data can allow an investigator some influence over the variance of the resulting grouped data. That is, by properly selecting the upper and lower limits of the intervals, an investigator can control the variance to some extent by requiring that each interval has the same number of data points. Since only one factor (such as number of spills, number of tankers in the world fleet or deadweight tonnage) can be used as the selection criterion, it is important to demonstrate that the method which was finally chosen does control the variance better than the other suggested methods.

Two final considerations must be borne in mind during this process. First, the fewer intervals that are created, the higher the percentage of data that will be in each interval and, relatively, the lower the variance. However, if only a few intervals are created, then a large amount of information is effectively averaged together to get a "mean" value. Information about the finer scales of the distribution is lost. Thus, there must be a trade-off when selecting the number of intervals. Second, if one divides the data into a large number of intervals, the manipulation of the large amount of data can become a problem.

Since it appears to be necessary to organize the deadweight tonnage data into ranges, the question becomes how to do this. Clearly, the method must not be biased either for or against any class of vessel and, if possible, it should help to control the variance among the ranges.

Three methods were developed and considered. The following paragraphs describe each method.

(1) Equal Intervals of Deadweight Tonnage - This is the relatively common methodology of dividing the values into bins of a constant amount when producing histograms. That is, by selecting the value of 20,000 DWT, the fleet is divided into bins from 0 to 20,000; 20,001 to 40,000 and so on up to 540,001 to 560,000.

(2) Equal Number of Spills - This method seeks to minimize the variance by requiring that each range of deadweight tonnage has experienced the same number of spills. In order to determine the ranges, one sorts the spill data into groups. For example, if the data are sorted (by the deadweight tonnage of the tanker) into groups of 8 spills, then the upper limit (of deadweight tonnage of the tanker spilling the oil) of each group can be defined to be the upper limit of a deadweight tonnage range. When calculating the number of spills per exposure variable, there would then always be 8 spills in each group.

(3) Equal Number of Tankers (or tanker years) - This method seeks to minimize the variance by requiring that each range of deadweight tonnage contains the same number of tankers. Since the tankers are the source of the oil, this method effectively requires that the same number of samples/subjects be in each group.

The method selected for use is primarily method number (3): Equal Number of Tankers. This methodology appears to give us the most flexibility in reducing the variance.

The method involving equal intervals of deadweight tonnage can be dismissed due to the skewness of the distribution (Figure 4-1). There is a large aggregation of tankers in the lower portion of the distribution and very few tankers in the higher portion. Some intervals larger than 250,000 DWT have no tankers in them at all.

Of the other two choices, (3) is better than (2) for a variety of reasons. For example, if the estimates of spill rate (number of spilling tankers in the interval/number of tankers in the interval) from each interval are taken together, and the mean spill rate computed, the following is observed:

(2) yields an average spill rate of .061 (standard deviation = .037)

(3) yields an average spill rate of .045 (standard deviation = .024)

The overall spill rate is

$$\frac{\text{total number of spilling tankers}}{\text{total number of tankers}} = \frac{181}{4055} = 0.045$$

Thus, method (3) yields an average spill rate the same as the overall rate. Additionally, the standard deviation from (3) is lower than that of (2).

There is another reason for using method (3). It is easy to think of many kinds of statistical analyses where each tanker would be considered as an experimental unit. In that case, keeping an equal number of tankers (an equal number of experimental units) in each interval is necessary to maintain equal (or nearly equal) estimates of variance of spill rates.

This phenomenon is illustrated by considering a comparison of variance estimates attached to spill rates computed for each interval for the two methods. For method (2), the variance estimates¹ range from 0.0000 to 0.0041. For method (3), the variance estimates range from 0.0000 to 0.0006, a much smaller span. This would indicate that method (3) gives more consistent variance estimates than does (2).

¹ Variance (of proportion p) = $\frac{p(1-p)}{n}$, where

p = observed spill rate for that interval

n = number of tankers in the interval

A final reason for choosing method (3) is that in addition to giving a consistent variance estimate per tanker, the method gives relatively constant variance estimates per tanker year. An analysis of the spill rates per tanker year was performed following the methodology just presented for analyzing the spill rates per tanker and found similar results. Admittedly, there are more variations among the ranges (about 18%) but these were not considered significant.

Thus, it was decided to set the limits of approximately 20 ranges of deadweight tonnage by sorting the world fleet into intervals with approximately 203 tankers in each interval. In several instances, there were a number of tankers of a specific size and this size happened to be the dividing line between two ranges. Therefore it was not possible to put 203 tankers in each group. Furthermore, these dividing lines were initially calculated to the exact ton and give the improper impression of being "magical" numbers. To avoid giving this impression, it was decided to round the numbers to the nearest 100 tons.

The number of tankers in each of these new rounded intervals was determined and the differences between the nominal number of tankers (203) in each group and the actual number of tankers were studied. For the ranges determined by using the numbers rounded to the nearest 100 tons, there were 19 ranges with non-zero differences, which ranged from -8 to +8 with a mean of zero and a standard deviation of 4.4. These slight variations will not adversely affect our variance estimates nor our statistics as described earlier.

Analysis of Casualty Spills

Once the ranges for the deadweight tonnage sorting had been determined, the data concerning the tanker characteristics, casualty spills and operational spills were sorted and added to the ranges. Specifically, a number of characteristics (both exposure variables and risk indicators) were determined. These characteristics included the following:

- | | |
|---|---|
| ● midpoint of the range | ● mean deadweight tonnage within each range |
| ● number of tanker years | ● number of casualty spills |
| ● number of tankers | ● total volume of oil from casualty spills |
| ● number of casualty spills with a known volume | |

- average volume spilled per incident
- age
- number of operational spills
- total amount of oil spilled during operational spills
- number and volume of casualty spills occurring in coastal areas and ports
- number of port calls
- average horsepower
- total throughput
- number of operational spills with known volumes
- average volume spilled during an operational spill incident

The following additional exposure variables of the spilling fleet were calculated and included in the data base:

- average age
- horsepower
- deadweight tonnage
- port calls
- number of tankers
- number of tanker years
- throughput

Furthermore, many nonlinear forms of these terms were also included in the data base, such as the square, square root, inverse and inverse square root of deadweight tonnage, the inverse of port calls and age, number and volume of spills per port call, number and volume of spills per tanker year, and number and volume of spills per throughput. The last three nonlinear terms were calculated for both operational spills and for casualty spills.

During the analysis of relationships among these variables, simple linear and multivariate regression techniques were employed. For a description of the statistical techniques, consult Appendix D. When regression equations are provided, a number of descriptive statistics can be found in Appendix E, in addition to those provided in the text.

Many of the averages calculated for each of the ranges were based on the number of years that the tanker was in the fleet during the period of analysis, 1976 through 1979. For example, when calculating the age in a given range, the individual tanker ages were included for each year and then the sum

was divided by the number of tanker years in that range. Thus, when a tanker was either added to or deleted from the fleet during the period of analysis, its age was only averaged into the data base for the proper number of years. Since the exact month of construction of each vessel was not known, all ages were calculated as an integer. However, when calculating the number of tanker years for tankers zero years old (e.g., for the age of a tanker in 1976 when it was constructed some time in 1976), it would have been inappropriate to count that tanker as having been in the fleet for a full year. The tanker may have been in the fleet from 1 to 365 days. Therefore, for those cases of zero age, this was only considered to be a net of one half a tanker year.

Table 4-1 lists the number of tankers in each range, the number of tankers having casualty spills, and the number of tanker years for both fleets. As described previously, the number of tankers in each range is near 203 and the variations among the ranges do not significantly affect the statement that the number of tankers (experimental units) is constant. Even with the limits rounded to the nearest 100 tons, the number of tankers only changes by ± 8 ($\pm 5\%$). Similarly, while the number of tanker years varies from 526 to 732, the relative change compared to the nominal value of 639 tanker years per range is less than 18%. The analysis presented earlier in this section showed that the spill rate by tanker years was very consistent and that the number of tanker years is relatively constant among the ranges. Figure 4-9 shows the plot of the number of tankers and the number of tanker years as a function of deadweight tonnage.

In addition to the observation that no obvious trends are seen in the figure, regressions between number of tankers and tanker years against deadweight tonnage revealed that the constant term is highly significant (at the 99% level) but that the slope term is not significant even at the 50% level. The correlation between tanker years in a range and the deadweight tonnage of the range is only 0.13. No evidence of a linear relationship was found.

Table 4-2 lists the number, total volume and average volume of casualty spills. As can be observed from the varying number of spills in each group and in Figure 4-10, the number of spills is not constant. The number of spills per tanker appears to have a relative maxima near 65,301 to 80,100 DWT. From the figure and from the correlation between the number of hull rupture spills and the deadweight tonnage of 0.21, it is apparent that there is no significant linear relationship between the two.

TABLE 4-1
DESCRIPTION OF TANKERS AND TANKER YEARS BY TANKER SIZE

DEADWEIGHT TONNAGE LIMITS	<u>NUMBER OF TANKERS</u>		<u>TANKER YEARS</u>	
	WORLD FLEET	SPILLING FLEET	WORLD FLEET	SPILLING FLEET
5,000- 7,300	207	7	732.0	27
7,301- 15,800	211	3	710.5	11
15,801- 18,800	205	4	542.5	13
18,801- 20,200	196	6	526.0	17.5
21,201- 21,700	201	9	634.0	34
21,701- 26,800	198	12	662.0	42
26,801- 30,600	200	14	650.5	45
30,601- 34,100	208	12	630.0	37
34,101- 37,500	200	5	582.0	15
37,501- 44,900	201	5	564.5	9.5
44,901- 53,400	205	15	606.0	52.5
53,401- 65,300	208	12	619.0	40.5
65,301- 80,100	207	22	690.0	77
80,101- 93,500	205	11	677.25	38.5
93,501-123,100	206	15	676.00	51
123,101-155,300	206	7	622.50	22.5
155,301-227,300	198	6	635.75	20.5
227,301-254,300	203	6	723.0	22.5
254,301-276,300	200	2	702.25	8
276,301-560,000	190	8	593.25	25
ENTIRE FLEET	4,055	181	12,779.0	609



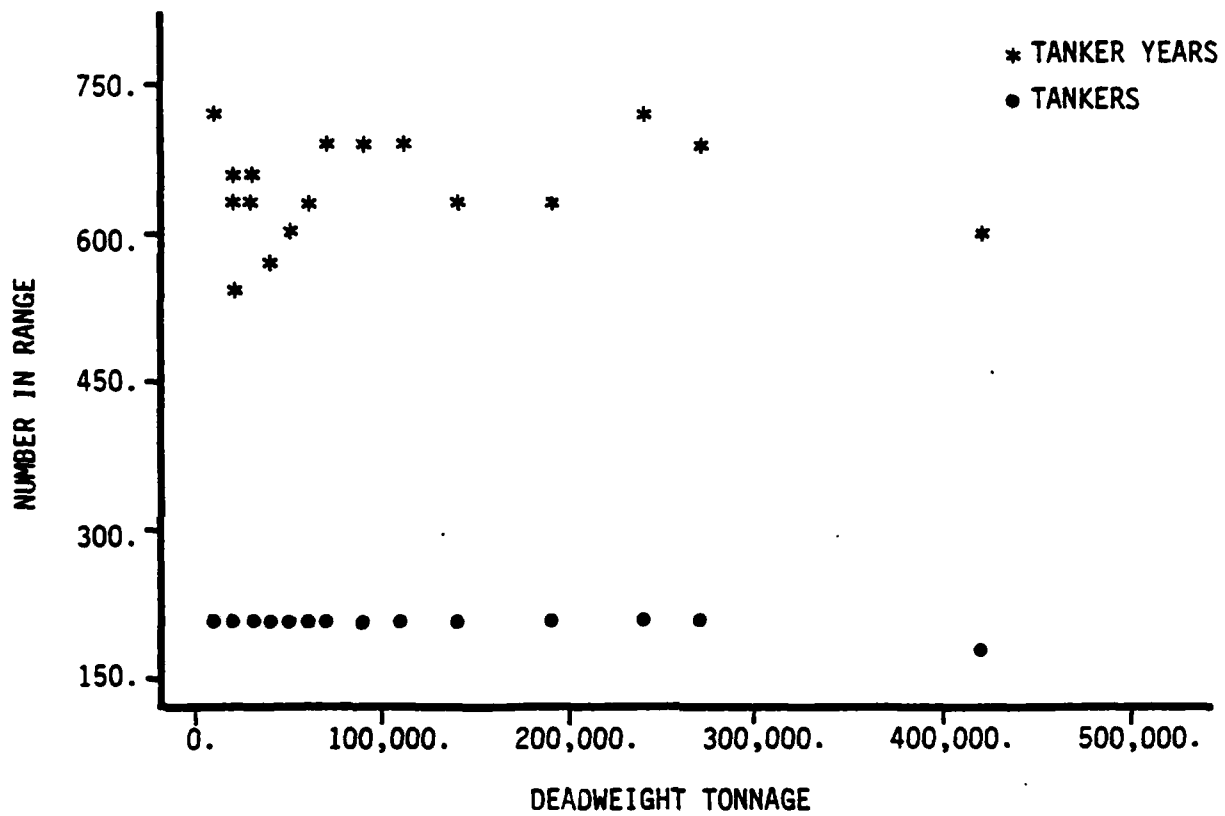


FIGURE 4-9. DISTRIBUTION OF TANKERS AND TANKER YEARS WITH TANKER SIZE.

TABLE 4-2

DESCRIPTION OF CASUALTY OIL SPILL CHARACTERISTICS (1976-1979)

DEADWEIGHT TONNAGE LIMITS	NO. OF SPILLS	NO. OF SPILLS W/KNOWN VOLUME	TOTAL VOLUME (Tons)	AVERAGE VOLUME (Tons)
5,000- 7,300	7	7	11,631	1,662
7,301- 15,800	3	2	51	26
15,801- 18,800	4	3	2,020	673
18,801- 20,200	7	5	19,304	3,861
20,201- 21,700	9	8	4,189	524
21,701- 26,800	13	12	28,729	2,394
26,801- 30,600	15	14	69,768	4,983
30,601- 34,100	12	12	126,553	10,546
34,101- 37,500	5	5	36,746	7,349
37,501- 44,900	6	6	7,339	1,223
44,901- 53,400	17	16	16,291	1,018
53,401- 65,300	13	11	110,828	10,075
65,301- 80,100	22	18	17,379	966
80,101- 93,500	12	11	20,407	1,855
93,501-123,100	15	15	261,167	17,411
123,101-155,300	7	7	51,306	7,329
155,301-227,300	6	6	68,151	11,359
227,301-254,300	6	6	230,751	38,459
254,301-276,300	2	2	1,004	502
276,301-560,000	9	9	345,043	38,338
ENTIRE FLEET	190	175	1,428,657	8,164



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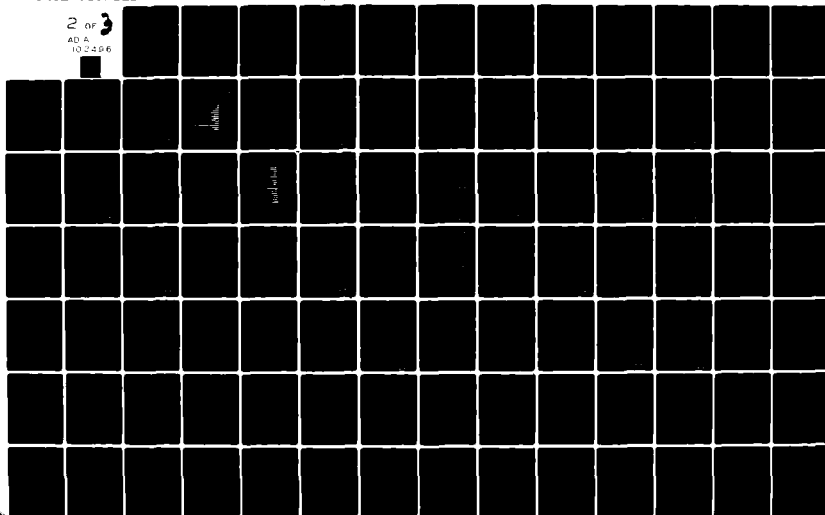
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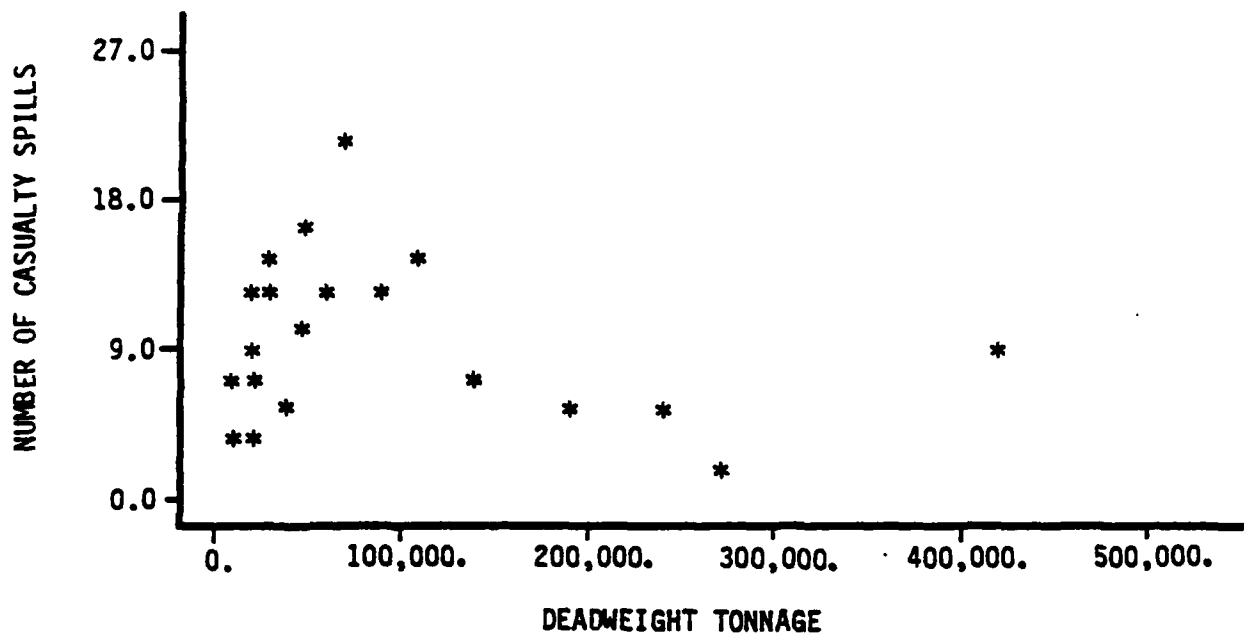


FIGURE 4-10. DISTRIBUTION OF CASUALTY SPILLS WITH TANKER SIZE.

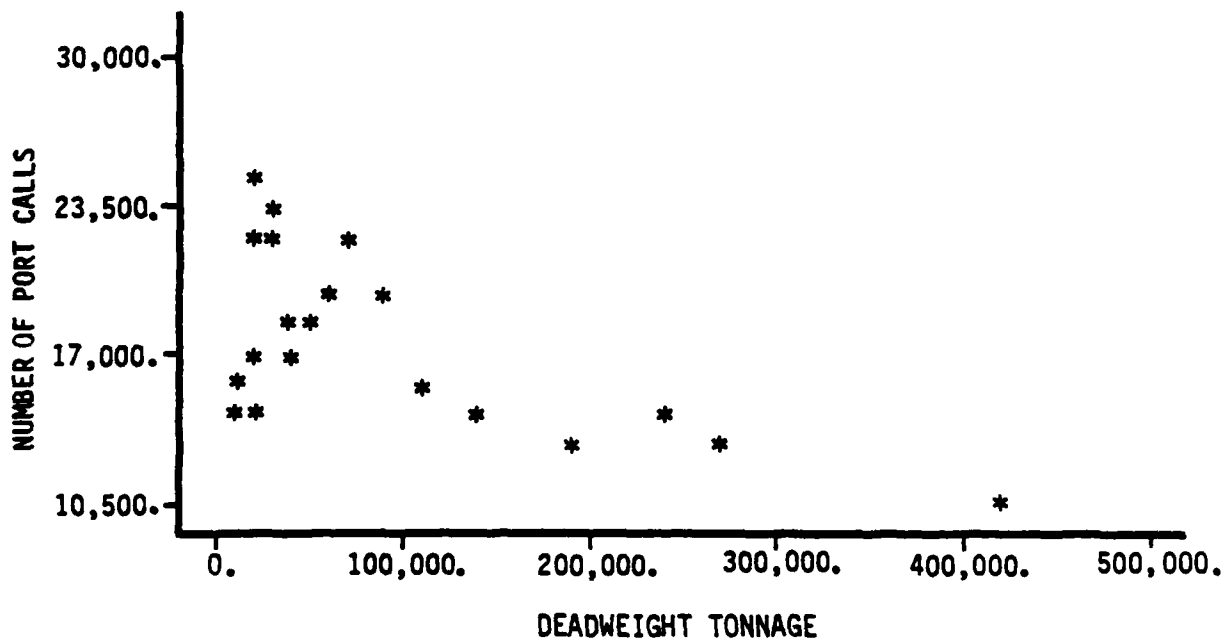


FIGURE 4-11. DISTRIBUTION OF PORT CALLS WITH TANKER SIZE.



From the shape of the curve on Figure 4-10, it would appear to be possible to fit a higher order equation in deadweight tonnage to the number of spills per tanker. This was tried, and it was found that a quadratic equation did not fit the data any better than a linear equation. The multiple correlation was very low and the regression coefficient for the squared term in deadweight tonnage was not significantly different from zero. The exposure variable which had the strongest correlation with the number of spills was the number of port calls; this variable also shows the same peak in its distribution near 70,000 DWT. (See Table 4-3 for a listing of the port calls in each range and Figure 4-11 for a plot of port calls versus deadweight tonnage). The peak in the number of port calls can apparently account for the peak in the number of spills.

The number of tankers in each range does not take into account how long each tanker has been in the fleet, nor does it account for any tankers which may be laid up or otherwise not in service. In order to properly consider these factors, a comparison should be made between the number of spills and the number of tanker years in each range. Figure 4-12 shows the frequency of casualty spills per tanker year for each group as a function of the size of the tankers. This figure shows a result very similar to that of Figure 4-11 for the number of spills per tanker. It suggests that port calls would fit the spill data better than deadweight tonnage.

Figure 4-13 shows the relationship of spills per deadweight tonnage throughput of the vessel plotted as a function of deadweight tonnage. Again, throughput is defined as the sum of the deadweight tonnage times the number of tanker port calls, not the quantity of oil transported. This figure shows a completely different type of relationship than was seen in Figure 4-12. For throughput, the number of spills shows a peak at the smallest tankers which decreases with size, and levels out for all vessels roughly greater than 70,000 DWT. This type of hyperbolic curve might indicate that there was an inverse relationship with deadweight tonnage, but in the ratio of spills per ton of throughput, the throughput values are completely dominant. While the number of spills can vary from 2 to 18 (a factor of 9) the throughput values vary from less than 100,000,000 tons to more than 3,000,000,000 tons: a factor of 30. The correlation between spills per throughput and the inverse of throughput is 0.93.

TABLE 4-3

DESCRIPTION OF PORT CALLS AND THROUGHPUT BY TANKER SIZE

DEADWEIGHT TONNAGE LIMITS	NUMBER OF PORT CALLS		THROUGHPUT	
	WORLD FLEET	SPILLING FLEET	WORLD FLEET (Tons)	SPILLING FLEET (Tons)
5,000 - 7,300	15,718	740	93,403,446	4,762,288
7,301 - 15,800	14,456	285	167,965,046	4,217,544
15,801 - 18,800	13,899	481	242,008,196	8,678,743
18,801 - 20,200	16,552	685	324,326,176	13,355,702
20,201 - 21,700	22,027	1,239	461,651,313	25,565,532
21,701 - 26,800	24,732	1,836	611,651,919	46,389,693
26,801 - 30,600	22,692	1,353	659,121,255	38,428,254
30,601 - 34,100	23,377*	1,659	745,752,840	51,680,576
34,101 - 37,500	16,463	363	589,594,612	12,619,019
37,501 - 44,900	18,138	300	738,111,453	12,830,165
44,901 - 53,400	18,750	1,477	931,467,657	73,261,111
53,401 - 65,300	19,551	1,833	1,149,189,093	111,140,437
65,301 - 80,100	22,802	2,565	1,664,810,925	190,300,317
80,101 - 93,500	20,031	1,001	1,738,353,735	86,950,818
93,501 - 123,100	15,854	904	1,692,881,408	94,081,141
123,101-155,300	14,299*	450	1,965,248,252	62,606,288
155,301-227,300	13,082*	403	2,710,666,917	84,945,088
227,301-254,300	13,970	415	3,327,777,370	99,578,015
254,301-276,300	12,975	138	3,441,808,751	36,694,170
276,301-560,000	10,869*	283	3,551,392,733	95,462,220
ENTIRE FLEET	350,237	18,410	26,807,183,097	1,153,547,121

*: -1 year old tanker port calls included



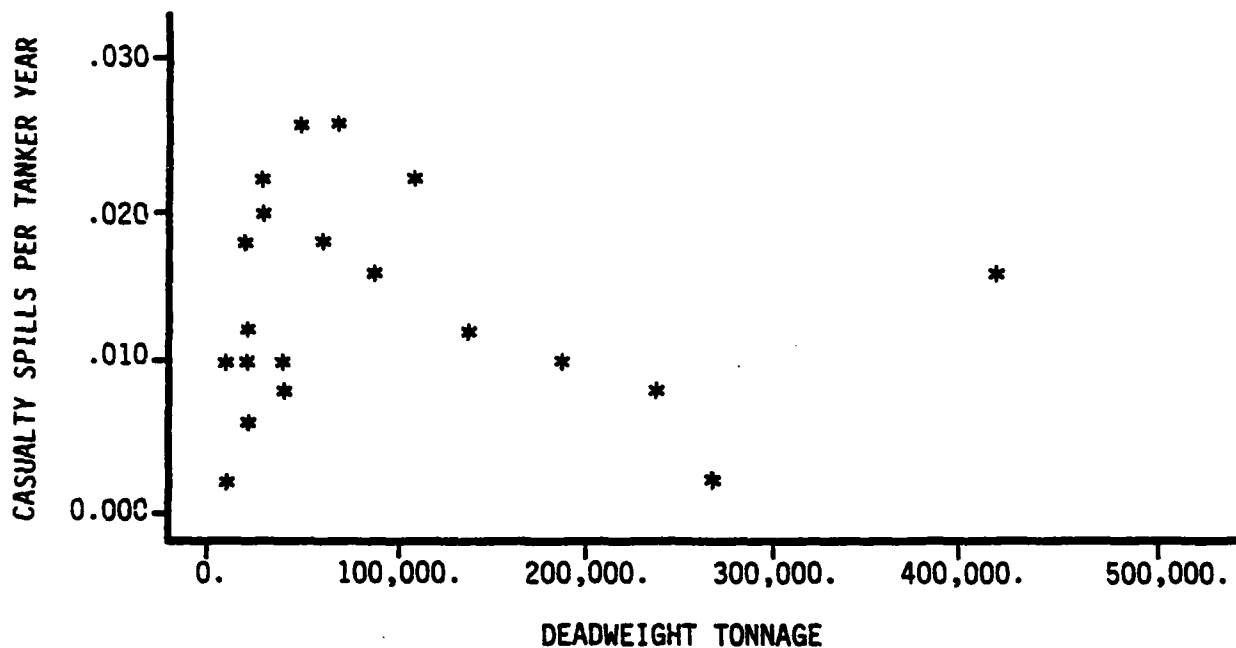


FIGURE 4-12. DISTRIBUTION OF CASUALTY SPILLS PER TANKER YEAR WITH TANKER SIZE.

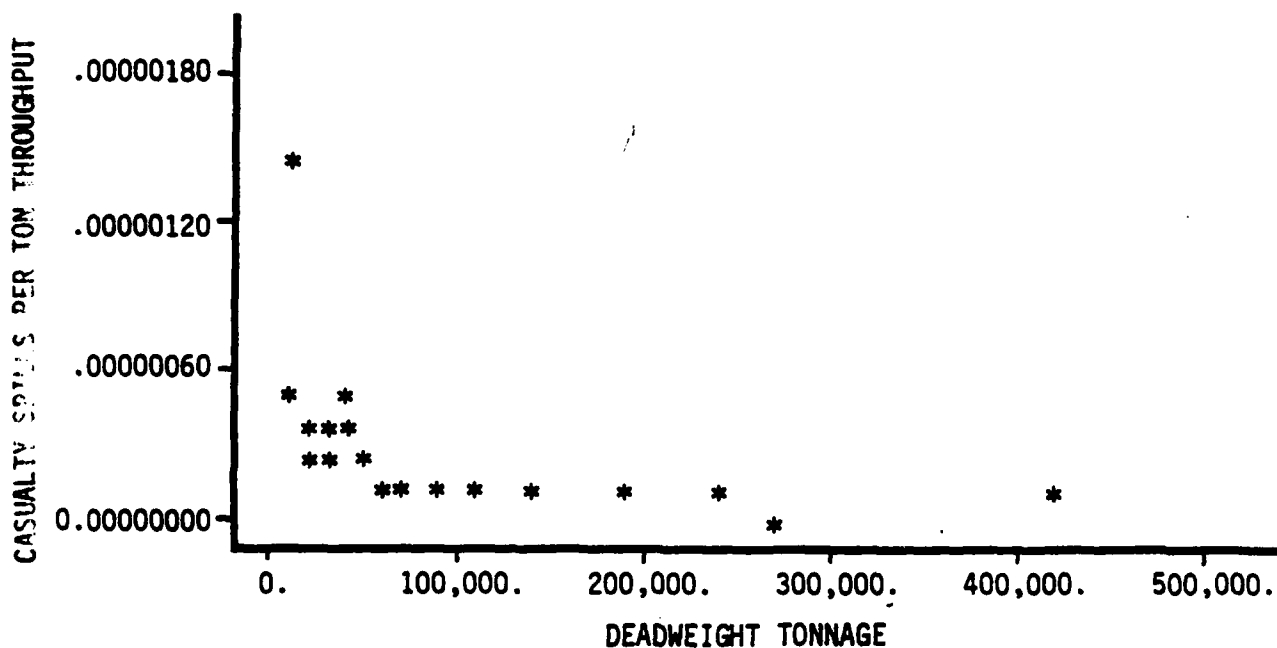


FIGURE 4-13. DISTRIBUTION OF CASUALTY SPILLS PER TON THROUGHPUT WITH TANKER SIZE.



The only parameter that consistently had a coefficient significantly different from zero at the 95% level was port calls. Of all the linear regressions and plots of parameters versus number of spills, and of all the combinations of parameters including nonlinear terms (such as inverses, square roots, squares, products of parameters and ratios of parameters), only one showed a relationship ($r = 0.67$) with the number of spills. Since the data are sorted by deadweight tonnage, it may be that port calls, deadweight tonnage and combinations of these two terms are the important factors in hindcasting the frequency of casualty oil spills.

The net result of this portion of the analysis showed simply that port calls are linearly related to the number of spills in ranges of deadweight tonnage. The equation was

$$\text{SPILLS (Casualty)} = -5.573 + 8.607 \times 10^{-04} * (\text{PC}) \quad (1)$$

where

SPILLS = number of casualty spills in a deadweight tonnage interval.

PC = number of port calls in the interval

For the range of port calls for which the relationship is valid (10,869 to 24,732 in four years), the number of spills increases at a rate of 0.086% of the number of port calls. For each increase of approximately 1,162 port calls the number of casualty spills increases by one. The constant was not significantly different from zero at the 95% level.

Having established a functional relationship for the frequency of casualty spills, the next discussion addresses the question of volume spilled from these spills. An initial look at the correlations between pairs of variables and at the plots of volume spilled and each of the variables would indicate that deadweight tonnage, age, and perhaps throughput and horsepower might be related to volume spilled. (Average ages of the ranges are listed in Table 4-4; average horsepower is listed in Table 4-5).

However, both average horsepower and throughput are highly correlated with deadweight tonnage ($r=0.92$ and $r=0.94$, respectively), and as a result, neither contributed significantly to any relationship with volume spilled. In all of the numerous combinations of variables and combinations of nonlinear functions of the variables, the only term which was consistently important in

TABLE 4-4

DESCRIPTION OF AVERAGE DEADWEIGHT TONNAGE AND AGE BY TANKER SIZE

DEADWEIGHT TONNAGE LIMITS	<u>AVERAGE DEADWEIGHT TONNAGE</u>		<u>AVERAGE AGE</u>	
	WORLD FLEET (DWT)	SPILLING FLEET (DWT)	WORLD FLEET	SPILLING FLEET
5,000- 7,300	5,939.1	6,039.2	9.695	15.704
7,301- 15,800	11,488.2	13,072.6	13.753	16.455
15,801- 18,800	17,275.6	17,968.0	20.373	24.769
18,801- 20,200	19,568.3	19,511.1	19.899	19.400
20,201- 21,700	20,930.6	20,657.6	16.764	18.941
21,701- 26,800	24,522.5	25,292.3	11.756	11.607
26,801- 30,600	28,941.2	28,679.7	12.861	15.144
30,601- 34,100	32,052.3	31,510.4	10.314	7.905
34,101- 37,500	35,735.9	34,770.3	13.973	13.733
37,501- 44,900	40,764.2	42,149.5	13.764	18.316
44,901- 53,400	49,777.4	49,353.8	15.924	14.552
53,401- 65,300	58,948.0	61,171.3	12.090	13.235
65,301- 80,100	73,135.0	74,252.3	10.901	11.006
80,101- 93,500	86,804.5	87,009.2	6.686	6.909
93,501-123,100	106,515.0	105,351.1	8.292	8.765
123,101-155,300	137,121.5	138,277.9	4.459	3.644
155,301-227,300	206,785.6	211,358.9	7.061	8.171
227,301-254,300	238,240.5	240,119.9	4.613	5.622
254,301-276,300	265,360.1	266,735.0	3.612	3.500
276,301-560,000	331,186.7	335,021.0	3.207	2.840
ENTIRE FLEET	91,111.5	80,278.9	10.751	11.638



TABLE 4-5

DESCRIPTION OF AVERAGE HORSEPOWER BY TANKER SIZE

DEADWEIGHT TONNAGE LIMITS	<u>AVERAGE HORSEPOWER</u>	
	WORLD FLEET (Kilowatts)	SPILLING FLEET (Kilowatts)
5,000- 7,300	2,902.1	2,450.6
7,301- 15,800	3,933.9	4,815.5
15,801- 18,800	5,784.9	5,359.4
18,801- 20,200	5,958.4	5,702.4
20,201- 21,700	6,195.9	5,880.7
21,701- 26,800	7,089.4	7,564.7
26,801- 30,600	8,669.2	8,009.6
30,601- 34,100	9,715.0	9,347.2
34,101- 37,500	10,371.2	10,468.9
37,501- 44,900	12,108.3	11,502.4
44,901- 53,400	12,747.3	12,129.9
53,401- 65,300	13,519.6	13,633.3
65,301- 80,100	14,839.0	15,178.1
80,101- 93,500	15,860.9	16,110.7
93,501-123,100	17,455.4	16,223.3
123,101-155,300	19,453.5	19,371.5
155,301-227,300	22,663.4	21,761.4
227,301-254,300	25,191.3	24,100.7
254,301-276,300	25,936.1	27,826.0
276,301-560,000	28,547.8	28,558.0
ENTIRE FLEET	13,594.4	13,079.2



the equations (i.e., had a coefficient which was significantly different from zero) was deadweight tonnage. Of all the variables tested, only the size of the vessel related significantly to the volume of oil spilled. The correlation between the total amount of oil spilled and deadweight tonnage was found to be 0.61. Since the relationship appears to be linear, and since averaging data tends to smooth the data, it was not surprising to find that deadweight tonnage had a somewhat higher correlation with the average volume spilled in a range ($r=0.71$). For average volume spilled, the least squares equation was determined and found to be:

$$VOL = 521 + 0.08383*(DWT) \quad (2)$$

where

VOL = average volume for casualty spills in a deadweight tonnage interval.

DWT = the average of the deadweight tonnage interval

The constant term in the equation was not significantly different from zero. The equation means that the estimate of the average volume of a casualty spill is 521 tons plus about 8.4% of the deadweight tonnage of the spilling tankers.

However, the least squares regression technique requires that the variance of the dependent variable be constant (34). As can be seen in Figure 4-14, the variance is not constant but increases with increasing deadweight tonnage. This "complication" requires that slightly more sophisticated techniques be used to establish a relationship between deadweight tonnage and volume spilled. Since the problem of increasing variance with the independent variable has been observed before, the solution only requires the application of an existing technique.

The usual result of a least squares regression equation is of the form $y = k*x + b$. But if the variance of "y" increases with "x," the least squares minimization is not a valid technique to employ. However, if the standard deviation can be shown to increase linearly with "x," then it is valid to use the method on the variables "y/x" and "1/x" (34,36). This results in an equation of the form: $y/x = k + b/x$. Then, by simply multiplying this regression equation by "x," the result is a final equation of the form: $y = k*x + b$.

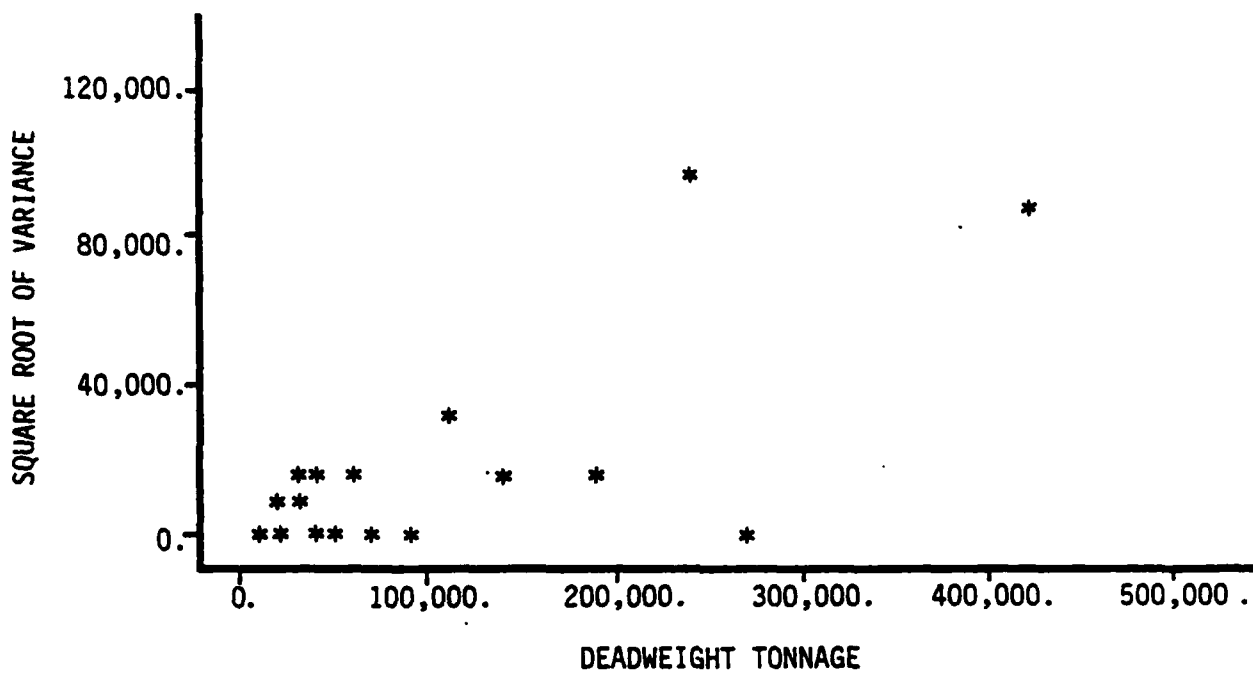


FIGURE 4-14. DISTRIBUTION OF THE VARIANCE OF AVERAGE SPILL VOLUME WITH TANKER SIZE.

In order to employ this technique, it was only necessary to show that a linear model relating the standard deviation and deadweight tonnage is preferable to one of constant standard deviation. The standard deviations for each of the 20 ranges were calculated and found to have a correlation of 0.75 with deadweight tonnage. Furthermore, the slope of the regression line between the standard deviation and deadweight tonnage was significantly different from zero, indicating that the standard deviation is not simply a constant. Therefore, it is permissible to employ the technique to obtain the proper equation. Regressing the variables "average volume/DWT" against "1.0/DWT" and then multiplying the resulting equation by "DWT" results in the equation

$$VOL = 791 + 0.07986 * (DWT) \quad (3)$$

where

VOL = average volume of casualty spills in a deadweight tonnage interval

DWT = the midpoint of the deadweight tonnage interval

Thus the estimate of the average volume spilled in an interval is roughly equal to 8% of the deadweight tonnage plus 791 tons. The constant is barely significant (different from zero) at the 90% level and is not significant at the 95% level. It may simply be a fortuitous result, or an example of the robustness of the least squares method, that simply regressing volume and deadweight tonnage gives an equation which is not significantly different from that determined by regression techniques which account for the increase in standard deviation with deadweight tonnage. The constants from the two techniques were 521 and 791, and neither was significantly different from zero at the 95% level. The two values for the slope were 0.08323 and 0.07986 (a relative difference of 4%).

In addition to determining a relationship between the volume of oil spilled and deadweight tonnage for all casualty spills, it was also necessary to determine the relationship for those spills occurring in coastal areas and harbors. There are heuristic arguments suggesting that almost all of the very large spills occurred at sea, and therefore the volume spilled nearshore would be much smaller. An analysis similar to that performed for all casualty spills was repeated for the nearshore spills and the results were similar. For these nearshore spills, the "best" estimate of the volume was:

$$VOL = 348 + (0.06523) * (DWT) \quad (4)$$

where

VOL = average volume spilled in a deadweight tonnage interval
from casualty spills in nearshore areas

DWT = the midpoint of the deadweight tonnage interval

Notice that the relative percentage of volume spilled per deadweight ton for nearshore spills (6.5%) is similar to that for all casualty spills (7.999). The constant is not significantly different from zero even at the 50% level.

Analysis of Operational Spills

Table 4-6 lists the characteristics of operational spills that have occurred to tankers in the world fleet. The number of spills, the number of spills with known volumes, the total amount of oil spilled and the average volume spilled are presented for each range and for the fleet as an average. Since it was considered plausible that the characteristics relating to the frequency and occurrence of operational spills would be different than those relating to the frequency and occurrence of hull rupture spills, the two different types of spills were analyzed separately.

Comparing the various characteristics of the world fleet with the number of operational spills revealed that the only parameter which appeared to have any consistent relationship was port calls. The correlation between port calls and number of spills was only 0.53 but the slope term in the regression equation was significantly different from zero at the 95% level. None of the other terms in these analyses showed any obvious relationship in a plot of the parameter versus number of spills, nor did any term have a significant correlation with the number of spills. The only relationship determined for the frequency of operational oil spills was

$$SPILLS \text{ (Operational)} = 13.3 + 0.0042 * (PC) \quad (5)$$

where

SPILLS = number of operational spills in a deadweight tonnage interval

PC = number of port calls in a deadweight tonnage interval

TABLE 4-6

DESCRIPTION OF OPERATIONAL OIL SPILL CHARACTERISTICS (1976-1979)

DEADWEIGHT TONNAGE LIMITS	NO. OF SPILLS	NO. OF SPILLS W/KNOWN VOLUME	TOTAL VOLUME (Tons)	AVERAGE VOLUME (Tons)
5,000- 7,300	20	15	706	47.07
7,301- 15,800	33	23	1415	61.52
15,801- 18,800	58	37	406	10.97
18,801- 20,200	68	44	1852	42.09
20,201- 21,700	105	76	858	11.29
21,701- 26,800	122	82	219	2.67
26,801- 30,600	99	66	46,573	705.65
30,601- 34,100	107	77	7,108	92.31
34,101- 37,500	78	46	35,346	768.39
37,501- 44,900	84	52	772	14.85
44,901- 53,400	108	79	2,070	26.20
53,401- 65,300	92	60	455	7.58
65,301- 80,100	146	92	53,683	583.51
80,101- 93,500	87	45	17,763	394.73
93,501-123,100	108	60	13,267	221.12
123,101-155,300	42	26	33	1.27
155,301-227,300	122	79	48,760	617.22
227,301-254,300	113	78	556	7.13
254,301-276,300	69	52	2,015	38.75
276,301-560,000	74	46	19,824	430.96
ENTIRE FLEET	1,735	1,135	253,681	223.51



Thus the estimated number of operational spills will increase by one for every increase of 238 port calls whereas the estimate of the number of casualty spills increased by one for an increase of 1,162 port calls. The constant in this equation was not significantly different from zero even at the 50% level, while the slope coefficient was significant at the 95% level.

It is interesting and informative to compare this equation with the average rate of spills per port call derived from the data base. Since the equation does not depend upon the size of the vessels, it should be possible to determine the relationship between spills and port calls when the data have not been sorted into ranges of deadweight tonnage. This procedure is equivalent to forcing the equation through the origin and it is realized that this would result in a biased estimate of the number of spills. However, since the constant term was not significant, the mean rate equation was derived. The equation is:

$$\text{SPILLS (operational)} = 0.00495 * \text{PC} \quad (6)$$

where

SPILLS = number of operational spills in a deadweight tonnage range
PC = number of port calls in that interval

The estimate of the number of spills increases one for an increase of roughly 200 port calls.

This latter equation is not statistically different from the previous equation and both compare very favorably with rates derived by OIW in previous studies for the rate of spills in the U.S.: 0.00498 spills per port call (2-7). Equation (6) was used in subsequent analyses. While it is recognized that this introduces bias with regard to the relationship of operational spills to deadweight tonnage groups, it is more appropriately used when applied to other groupings, such as by port system. This is due to the widely varying numbers of port calls, and the knowledge that no port calls would result in no operational spills, rather than 13.3 as given by equation (5).

An alternative would be to use the rate defined in equation (5) as the spill rate, rather than that found in equation (6). This would be undesirable as it would result in a consistent underestimation of number of spills. Thus when the casualty spills and operational spills are considered together, the relative weight of operational spills would be lower than actual experience would indicate.

The analysis of factors relating to the volume of operational spills did not find any terms with significant correlations or with obvious relationships on the plots. In the attempted regressions between the individual parameters and volume spilled, the only significant term was the constant in the equation. On the basis of this analysis, the only result derived is that:

$$VOL = 224$$

where

VOL = average volume spilled during an operational spill

Analysis from Age Perspective

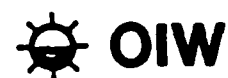
The age of a tanker was another perspective used for looking at the relationships between the number of spills and the volume of spills, and the various tanker characteristics. The 4,055 oil tankers that have been included in the study were grouped according to sixteen age categories, the first group being 0 and 1 year old tankers, the second group being 2 and 3 year old tankers, and so on, with the last group being tankers 30 or more years old. This procedure for grouping the world fleet tankers did not produce an equivalent number, or approximately equivalent number, of tankers or tanker years in each category as did the grouping technique based on deadweight tonnage described in the previous section. The age group containing the greatest number of tanker years was the 2 and 3 year old category, representing 15% of the total number of tanker years. The age category containing the fewest number of tanker years was the 26 and 27 year old category, representing less than 1% of the total number of tanker years of the world fleet.

As shown in Table 4-7, the age category responsible for the greatest number of casualty-caused spills during the 1976-1979 period, representing 13% of the total number of spills, was the category containing those tankers 18 and 19 years old, while the age category responsible for the most oil spilt was the category with tankers 4 and 5 years old. Only tankers 28 and 29 years old had no spills during the four year period. The frequency of spills by tankers stayed relatively constant until tankers reached 22 or 23 years old, at which point the frequency of spills dropped significantly, from an average of 16 spills to an average of 2 spills for each 2-year age category over the four year period. See Figure 4-15 for the relative distribution of spills and volume spilt by age groups.

TABLE 4-7

DESCRIPTION OF CASUALTY SPILLS AND TANKER YEARS BY AGE

TANKER AGE (Years)	NO. OF SPILLS	NO. OF SPILLS W/KNOWN VOLUME	TOTAL VOLUME (Tons)	TANKER YEARS	
				WORLD FLEET	SPILLING FLEET
0 to 1	13	13	16,019	930.5	25.5
2 to 3	12	12	153,930	1,875.5	61.5
4 to 5	23	22	4,059	1,648.0	69.5
6 to 7	10	10	86,291	1,152.5	48.0
8 to 9	9	8	51,808	929.0	35.0
10 to 11	21	20	62,377	879.0	61.0
12 to 13	15	14	118,838	833.5	60.0
14 to 15	21	16	58,170	759.5	50.5
16 to 17	13	12	66,645	854.5	54.0
18 to 19	24	21	95,684	1,025.0	66.5
20 to 21	18	16	97,505	748.0	40.5
22 to 23	5	5	75,050	448.5	19.0
24 to 25	2	2	1,260	265.0	9.0
26 to 27	2	2	2,000	154.0	3.0
28 to 29	0	0	0	70.5	0.0
30 & over	2	2	21	206.0	6.0
ENTIRE FLEET	190	175	1,428,657	12,779.0	609.0



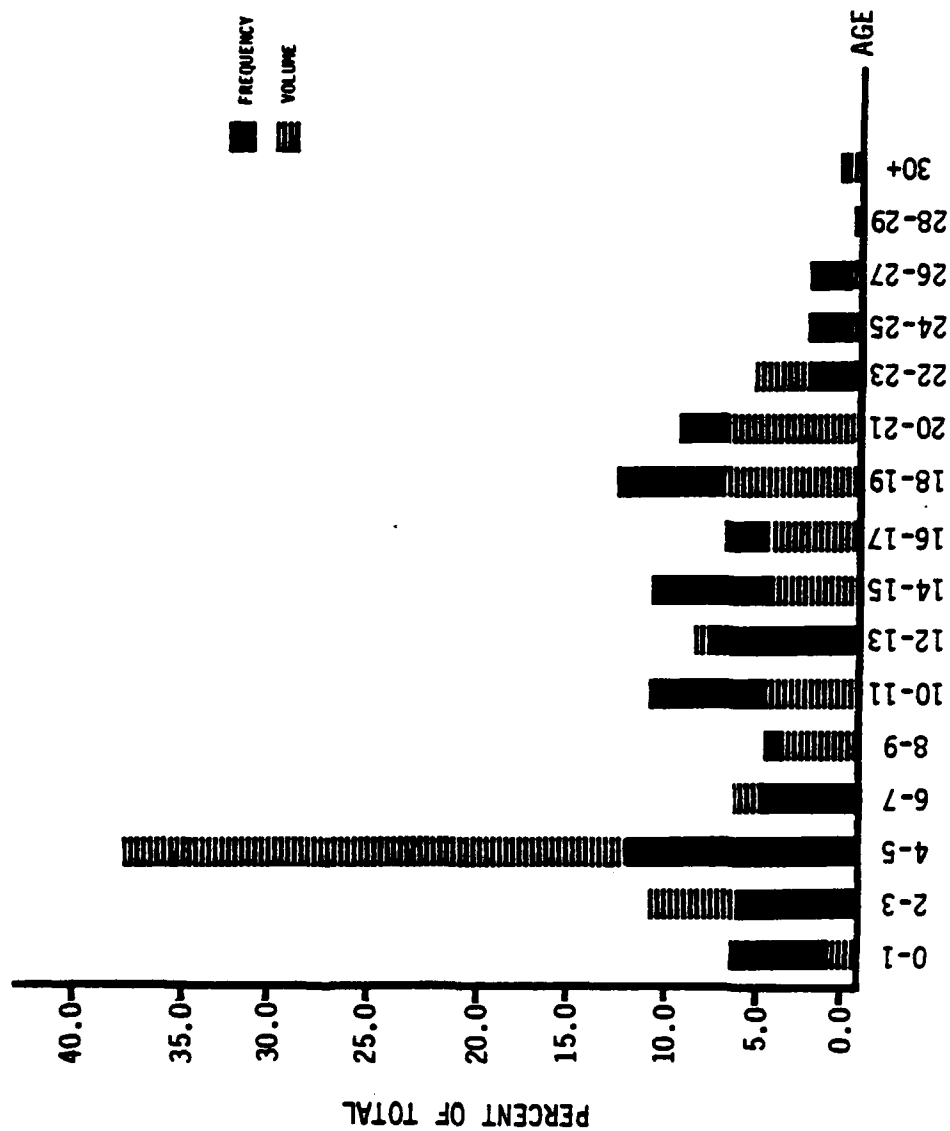


FIGURE 4-15. DISTRIBUTION OF SPILLS AND VOLUME ACCORDING TO AGE INTERVALS.

As mentioned above, the sixteen categories based on age exhibit varying numbers of tanker years. Based on the a priori assumption that those categories with the most tanker years would be the categories with the greatest number of spills, one would not expect the frequency of spills to remain constant with age. Therefore, a normalizing factor was necessary in order that the relationship between spill frequency, spill volume and age could indeed be analyzed. By looking at spills per tanker year, spills per port call and spills per ton of throughput, the problem of unequal units in each age category was addressed.

The 12,779 tanker years, defined to be the sum of the years the tankers in the world fleet were active during the 1976-1979 period, were distributed according to the age categories. Similarly, the total throughput for the four year period, 26,807,183,097 tons, and the total number of port calls for the four year period, 350,237, were apportioned according to the sixteen age groups. The linear and nonlinear relationships between spills per tanker year and age, spills per port call and age, and spills per ton of throughput and age were examined.

The first frequency rate, spills per tanker year, appeared to have a definite relationship with the age of the tanker. The frequency of spills tended to increase with age until tankers reached the age of 14 or 15 years old, after which the frequency of spills steadily decreased with age. Tankers producing the highest frequency, 2.8 spills per 100 tanker years, were those tankers in the 14 and 15 year old range.

Graphically, the frequency of spills exhibits a convincing dependency on age; however, statistically, the frequency-age dependency becomes less obvious (See Figure 4-16). The spill rates of 2 year old tankers and 14 year old tankers, or any age tanker do not differ statistically, due to the variance of the spill rates. The relationship between spills per tanker year and age is "best" described by the following quadratic regression equation:

$$\text{SPILLS PER 100 TANKER YEARS} = -0.0064 \cdot \text{AGE}^2 + 0.185 \text{AGE} + 0.611 \quad (7)$$

whose maximum occurs at 14.45 years, which is verified by the data.

The quadratic model relating spill frequency to age produced a correlation of $r=0.66$; in other words, 44% ($100\% \times 0.66^2$) of the variation in the spill rates can be accounted for by the frequency-age relationship.

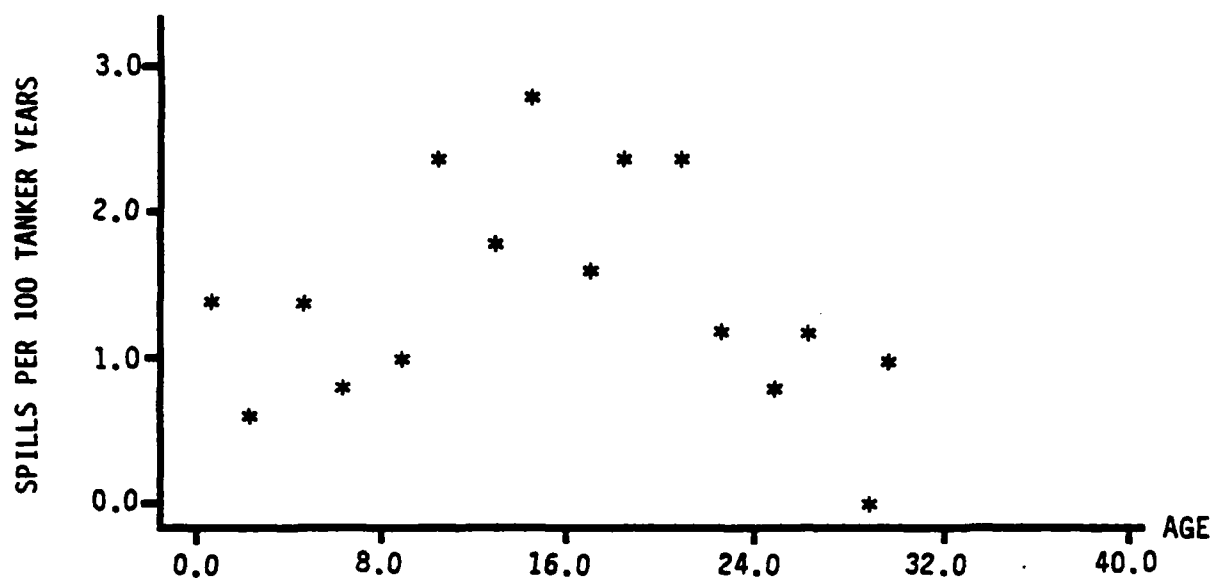


FIGURE 4-16. SPILLS PER 100 TANKER YEARS BY AGE.

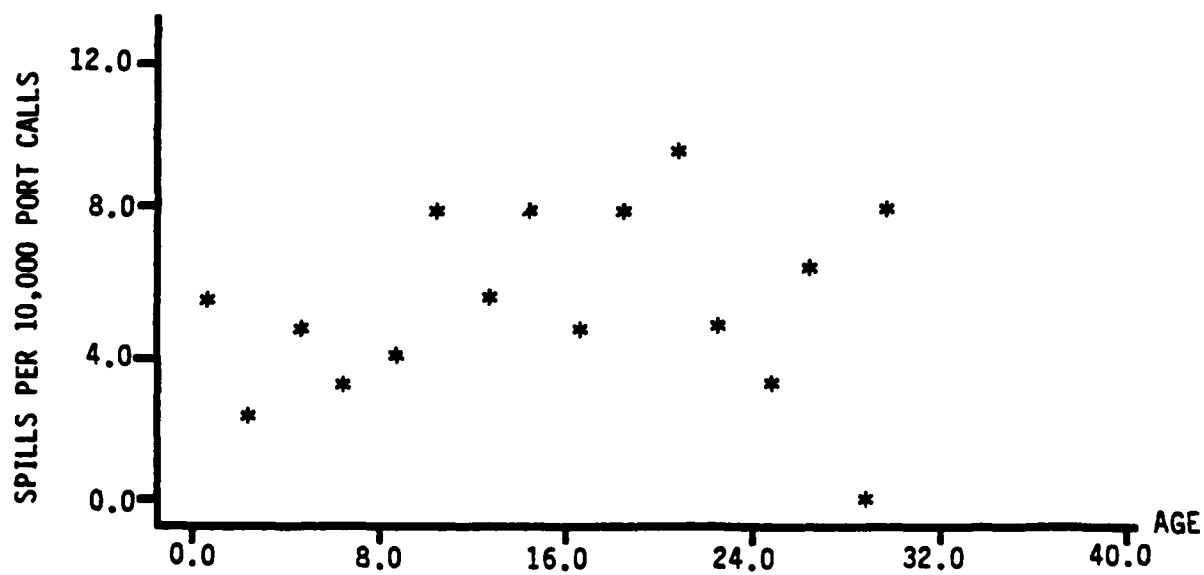


FIGURE 4-17. SPILLS PER 10,000 PORT CALLS BY AGE.



The second rate used to analyze the frequency-age relationship was spills per port call. Statistically, spills per port call did not have any consistent pattern with age, but rather the rates seemed to be quite random with age. Graphically, the frequency of spills tended to increase with age until tankers reached 20 or 21 years old, after which the spill rate remained relatively constant (See Figure 4-17).

As with the preceding spill rate, spills per tanker year, spills per port calls for any age tanker is not statistically distinguishable from any other rate for another age category. In other words, age is not a "good" predictor of spill frequency, using port calls as the normalizing factor. Using a linear model to describe the frequency-age relation yielded a correlation of 0.12, whereas, a quadratic model yielded a correlation of 0.36. In other words, 13% of the variation in the spill rates can be explained by the quadratic function; 87% remained unexplained.

The third spill rate, spills per ton of throughput, generally increased with age, with the exception of the 28 to 29 year old category, which had a rate of 0 since no spills occurred in this age group (See Figure 4-18). A linear model relating spills per ton of throughput and age resulted in a correlation of 0.66; in other words, 44% of the variation of the sixteen spill rates can be explained by age.

In a similar fashion, the volume spilled for each age category was normalized by the number of spills, tanker years, port calls and tonnage throughput and then analyzed with age.

The average volume spilled per casualty-caused incident decreased with age overall, with the maximum average occurring in the 4 and 5 year old category (See Figure 4-19 and Table 4-8). The large average found within this age category is a result of two very large spills by four year old tankers which accounted for approximately 35% of the total oil spilled during the 1976-1979 period. Another mean volume which deviates from the general downward trend of average volumes was exhibited by tankers 22 to 23 years old, possibly a point at which tankers begin to wear out. A correlation of -0.48 is obtained from the linear relationship between spills per ton of throughput and age; in other words, 23% of the variation in spill rates is explained by the average volume-age relationship.

The remainder of the age analysis focused on relating age to the various tanker characteristics: horsepower, deadweight tonnage, number of port calls

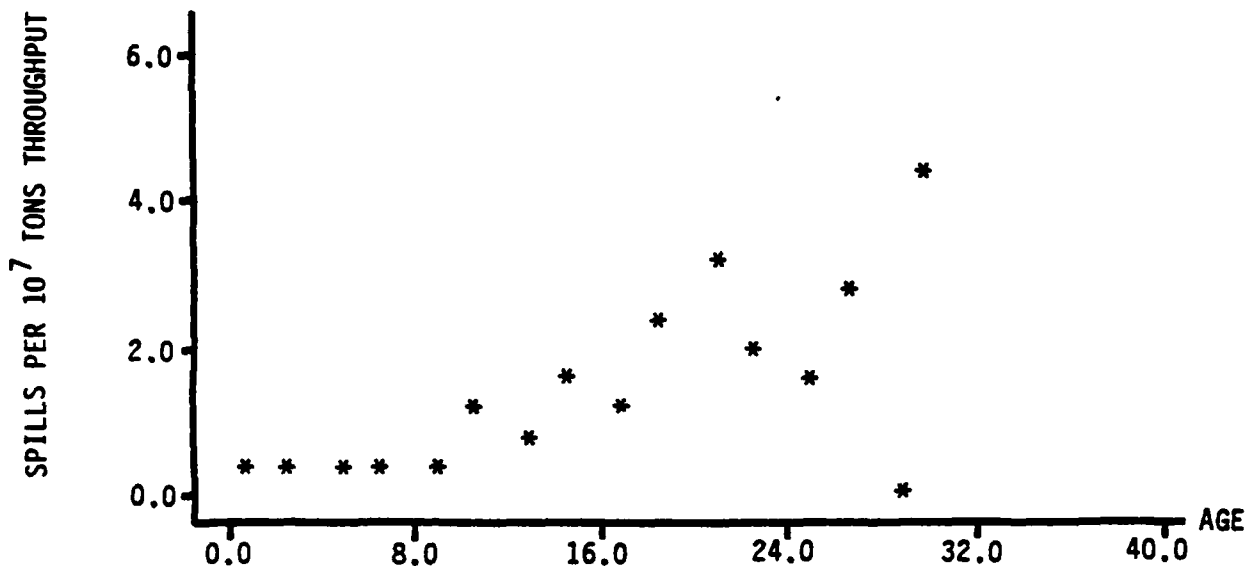


FIGURE 4-18. SPILLS PER 10^7 TONS THROUGHPUT BY AGE.

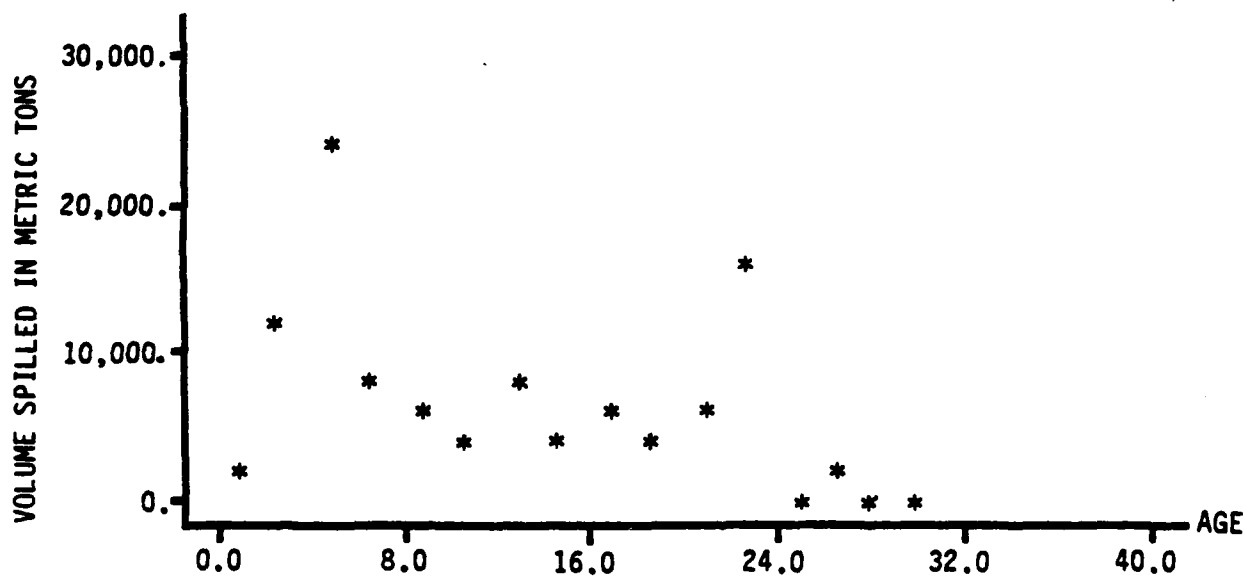


FIGURE 4-19. AVERAGE VOLUME SPILLED BY AGE.

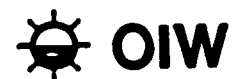


TABLE 4-8

DESCRIPTION OF AVERAGE VOLUME SPILLED AND
AVERAGE DEADWEIGHT TONNAGE BY AGE

TANKER AGE (Years)	AVERAGE VOLUME (Tons)	<u>AVERAGE DEADWEIGHT TONNAGE</u>	
		WORLD FLEET (DWT)	SPILLING FLEET (DWT)
0 to 1	1,232	139,155.48	147,566.61
2 to 3	12,828	143,511.78	132,480.26
4 to 5	24,685	137,699.72	116,236.49
6 to 7	8,629	135,507.68	134,449.10
8 to 9	6,476	117,058.29	127,949.11
10 to 11	3,119	81,472.24	89,178.89
12 to 13	8,488	64,415.97	66,801.43
14 to 15	3,636	50,403.58	51,305.67
16 to 17	5,554	37,218.83	36,198.29
18 to 19	4,556	32,102.13	32,567.47
20 to 21	6,094	28,522.58	26,386.43
22 to 23	15,010	23,984.15	22,038.00
24 to 25	630	22,120.84	20,978.22
26 to 27	1,000	21,322.66	22,678.33
28 to 29	--	21,188.12	--
30 & over	11	13,584.42	10,931.50
ENTIRE FLEET	8,164	91,111.5	80,278.90



and tonnage throughput. All four tanker characteristics exhibited a strong connection with age, and all decreased with age.

The average age and deadweight tonnage for each of the sixteen age groups were highly correlated ($r = -0.95$) and as one would expect, deadweight tonnage decreased with age (See Figure 4-20). As discussed in the previous section on deadweight tonnage, supertankers are relatively new additions to the tanker fleet, which tends to increase the average size of young tankers. The average deadweight tonnage of a tanker 8 or 9 years old is more than double that of a tanker 14 or 15 years old (age is calculated for the period of 1976-1979), while tankers between 16 and 30 years old maintained a relatively constant average deadweight tonnage.

Furthermore, average horsepower (See Table 4-9) and throughput exhibited a downward trend as age increased (See Figures 4-21 and 4-22). Since deadweight, horsepower and throughput maintain a substantial amount of multicollinearity, all three vessel characteristics demonstrate similar relationships with age.

The number of port calls for the sixteen age groups had less consistency with age than either the horsepower or the average deadweight tonnage (See Figure 4-23 and Table 4-10). The number of port calls made by tankers 2 and 3 years old was more than twice that of the number of port calls made by tankers 8 and 9 years old, while the number of tanker years in each age category differed by 20%.

Other studies have shown age to be an important factor when looking at the frequency of spills, a relationship that cannot be dismissed without irrefutable evidence (11,12,14,15). This study has produced no such irrefutable evidence. However, the analysis of the data in this study has not shown age to be a significant indicator (or as significant as other indicators) of spill frequency. This may be due to the use of improved data bases, and in particular of actual port call data. Past studies, when considering tanker activity, have had to approximate numbers of port calls, based typically upon tanker size. Another possible explanation might be the selection of two-year age intervals, while some studies have used as large as five-year intervals. In such cases, the general trend reflected in equation (7) could easily produce a stronger relationship. In any case, no significant age relationship was found in this study, and thus age does not appear as a statistically significant variable in the frequency analysis.

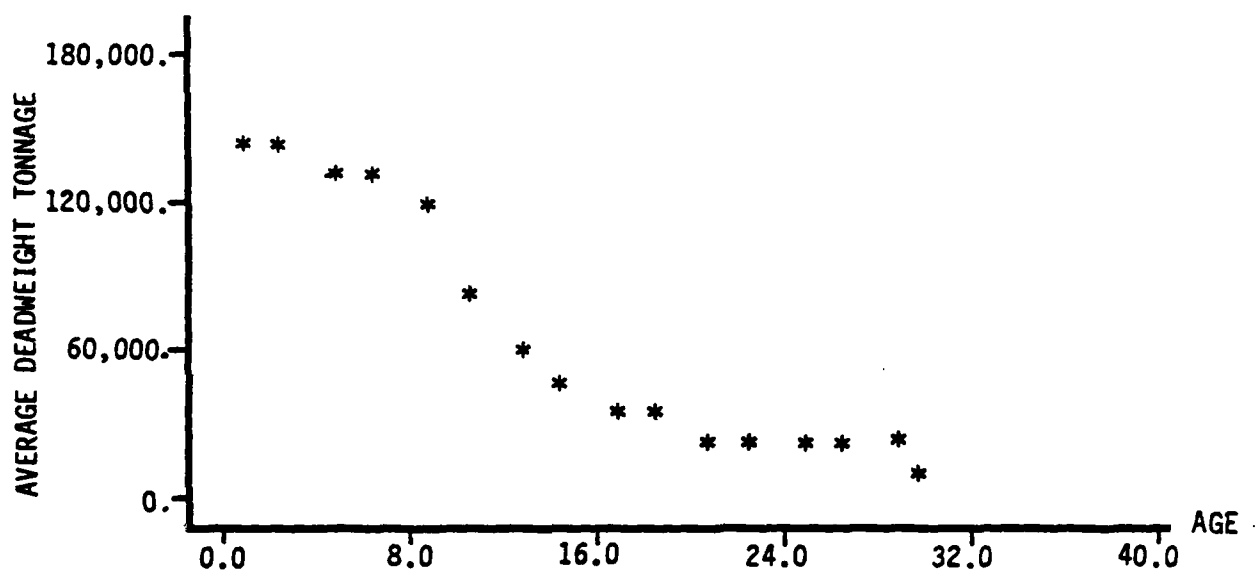


FIGURE 4-20. AVERAGE DEADWEIGHT TONNAGE BY AGE.

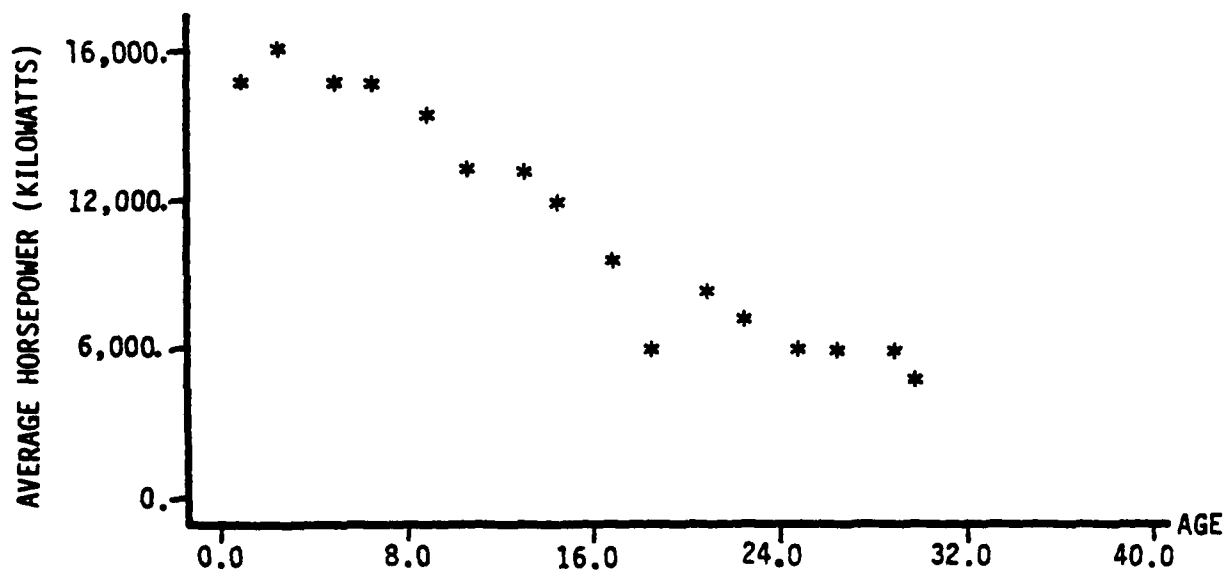


FIGURE 4-21. AVERAGE HORSEPOWER BY AGE.



TABLE 4-9

DESCRIPTION OF AVERAGE HORSEPOWER BY AGE

TANKER AGE (Years)	<u>AVERAGE HORSEPOWER</u>	
	WORLD FLEET (Kilowatts)	SPILLING FLEET (Kilowatts)
0 to 1	17,252.50	17,758.92
2 to 3	17,579.59	17,078.49
4 to 5	16,867.04	15,976.49
6 to 7	16,446.95	17,115.06
8 to 9	15,269.95	17,350.85
10 to 11	13,435.84	15,099.74
12 to 13	13,121.50	13,592.68
14 to 15	11,814.16	11,340.89
16 to 17	10,023.01	9,514.68
18 to 19	6,157.57	8,960.15
20 to 21	8,443.95	7,480.27
22 to 23	7,225.36	6,449.47
24 to 25	6,503.01	6,379.11
26 to 27	6,380.68	5,284.67
28 to 29	6,596.15	0
30 & over	4,254.91	3,167.00
ENTIRE FLEET	13,594.40	13,079.20



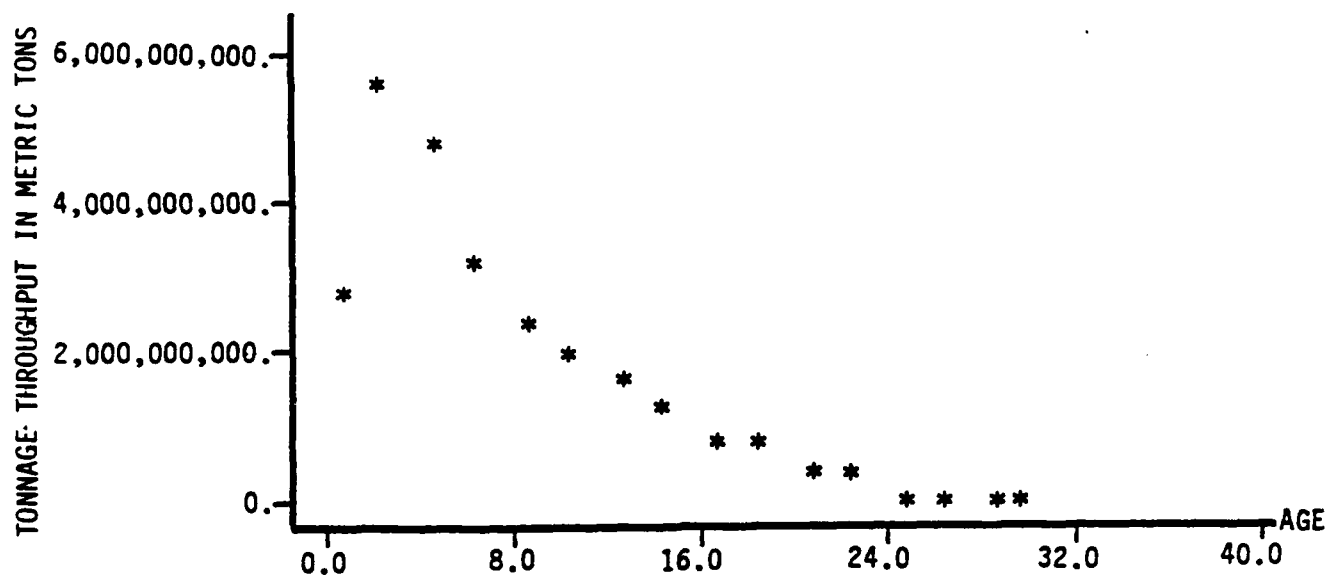


FIGURE 4-22. TONNAGE THROUGHPUT BY AGE.

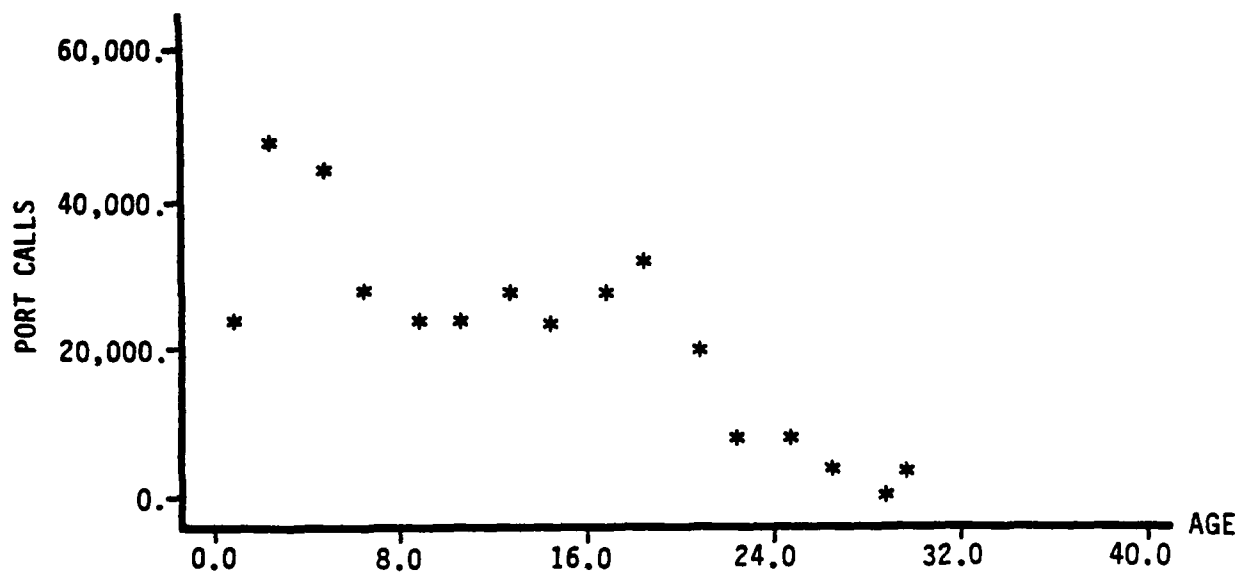


FIGURE 4-23. PORT CALLS BY AGE.



TABLE 4-10

DESCRIPTION OF PORT CALLS AND TONNAGE THROUGHPUT BY AGE

TANKER AGE (Years)	<u>PORT CALLS</u>		<u>THROUGHPUT</u>	
	WORLD FLEET	SPILLING FLEET	WORLD FLEET (Tons)	SPILLING FLEET (Tons)
0 to 1	24,136	673	2,633,105,259	64,649,995
2 to 3	49,497	1,960	5,624,061,364	152,214,688
4 to 5	44,897	2,452	4,856,879,683	167,805,468
6 to 7	29,430	1,285	3,343,250,559	122,084,280
8 to 9	24,262	988	2,577,859,374	112,143,400
10 to 11	25,748	1,710	1,914,945,881	148,371,275
12 to 13	26,603	1,799	1,644,707,833	116,315,866
14 to 15	25,856	1,669	1,215,879,114	91,997,877
16 to 17	27,422	1,764	988,871,735	70,217,253
18 to 19	30,574	2,285	958,096,290	65,087,925
20 to 21	19,166	1,177	532,391,081	29,245,760
22 to 23	9,838	337	233,746,506	7,426,486
24 to 25	6,094	146	132,685,903	3,019,199
26 to 27	3,104	68	72,654,102	1,500,996
28 to 29	1,216	0	32,750,968	0
30 & over	2,394	97	45,297,445	1,466,653
ENTIRE FLEET	350,237	18,410	26,807,183,097	1,153,547,121



Analysis from Port Call Perspective

The third approach used for analyzing the relationships between frequency of spills, volume of spills and the different tanker characteristics was from the perspective of port call activity. A logical question to ask is, does the port call activity level of a vessel have a bearing on the frequency of spills or the spill volume? Do tankers making a few port calls per year (but perhaps travelling great distances) spill less frequently than those tankers making substantially more port calls per year?

Twenty port call intervals were constructed, striving to ensure approximately equivalent numbers of tankers in each interval: the first interval consists of those tankers making 0 to .24 port calls per tanker year; the second, of those tankers making .25 to 2.99 port calls per tanker year; and so on, with the last interval consisting of those tankers making 62.00 or more port calls per tanker year. Tankers making 0 to .24 port calls per year constituted the interval with the largest number of tankers and tanker years; 545 tankers made no port calls and were not in a laid up state. (See Table 4-11).

As shown in Table 4-12, tankers making 19.00 to 20.99 port calls per tanker year were responsible for the greatest number of spills: 19 spills, or 10% of the total number of spills. Those tankers making 17.50 to 18.99 port calls per tanker year were responsible for the fewest number of spills: 4 spills, or 2% of the total number of spills. Interestingly, the port call interval with the maximum number of spills and the port call interval with the minimum number of spills are adjoining intervals. No apparent trend is exhibited by a graphical representation of the frequency-port call data. (See Figure 4-24). The relationship between the number of spills in each port call activity interval and the volume spilled in each interval is illustrated in Figure 4-26.

As mentioned before, since the number of tankers and the number of tanker years varied up to 34% from port call interval to port call interval, a normalizing factor was once again needed. Using the same method as with age, spill frequency was analyzed by looking at the relationships between port calls and the following spill rates: spills per tanker year, spills per port call, and spills per ton of throughput. A spill rate was calculated for each of the twenty port call activity categories by dividing the number of spills

TABLE 4-11

DESCRIPTION OF TANKERS, PORT CALLS AND TANKER YEARS
BY PORT CALL ACTIVITY LEVEL

PORT CALLS PER TANKER YEAR	WORLD FLEET NO. OF TANKERS	<u>PORT CALLS</u>		<u>TANKER YEARS</u>	
		WORLD FLEET	SPILLING FLEET	WORLD FLEET	SPILLING FLEET
.00 to .24	545	51	0	957.25	18.0
.25 to 2.99	180	641	25	524.50	26.0
3.00 to 7.49	192	2,589	120	509.00	21.5
7.50 to 11.49	188	5,705	245	574.25	25.0
11.50 to 13.49	158	6,110	300	474.50	23.0
13.50 to 15.49	177	8,361	356	558.00	25.0
15.50 to 17.49	214	11,921	607	705.75	36.0
17.50 to 18.99	157	10,194	291	549.25	15.5
19.00 to 20.99	228	16,170	1,289	795.50	64.0
21.00 to 22.49	179	13,772	618	620.75	28.0
22.50 to 23.99	151	12,551	615	533.25	26.0
24.00 to 26.49	207	18,123	783	706.50	31.0
26.50 to 28.99	175	17,363	970	618.50	35.0
29.00 to 31.99	172	18,573	513	603.00	17.0
32.00 to 35.99	194	23,254	1,719	678.50	50.0
36.00 to 39.99	184	25,447	990	666.50	26.0
40.00 to 44.49	187	28,583	835	669.00	20.0
44.50 to 50.49	189	32,144	1,154	673.00	24.5
50.50 to 61.99	182	36,948	2,505	662.00	45.0
62.00 and over	196	61,737	4,475	700.00	52.5
ENTIRE FLEET	4,055	350,237	18,410	12,779.00	609.0



TABLE 4-12

DESCRIPTION OF SPILLS AND VOLUME SPILLED BY
PORT CALL ACTIVITY LEVEL

SPILLS DUE TO CASUALTIES

PORT CALLS PER TANKER YEAR	NO. OF SPILLS	NO. OF SPILLS W/KNOWN VOLUME	VOLUME SPILLED (Tons)
.00 to .24	10	10	91,231
.25 to 2.99	8	8	111,140
3.00 to 7.49	10	10	48,105
7.50 to 11.49	7	7	40,505
11.50 to 13.49	8	8	393,731
13.50 to 15.49	8	6	104,606
15.50 to 17.49	11	11	63,902
17.50 to 18.99	4	4	1,142
19.00 to 20.99	19	19	329,885
21.00 to 22.49	8	8	51,258
22.50 to 23.99	8	8	18,524
24.00 to 26.49	8	7	3,813
26.50 to 28.99	11	11	11,541
29.00 to 31.99	5	4	35,762
32.00 to 35.99	14	11	5,992
36.00 to 39.99	8	6	25,762
40.00 to 44.49	7	6	14,005
44.50 to 50.49	8	7	60,986
50.50 to 61.99	13	12	11,033
62.00 and over	15	12	5,734
ENTIRE FLEET	190	175	1,428,657



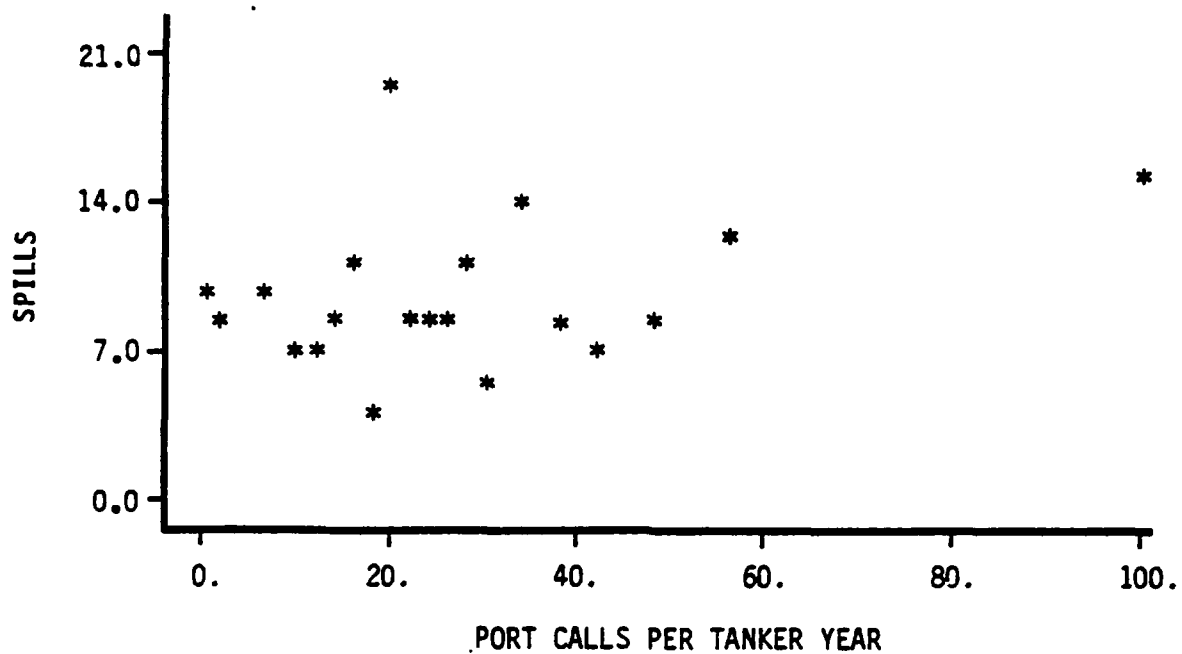


FIGURE 4-24. DISTRIBUTION OF SPILLS ACCORDING TO PORT CALL ACTIVITY.

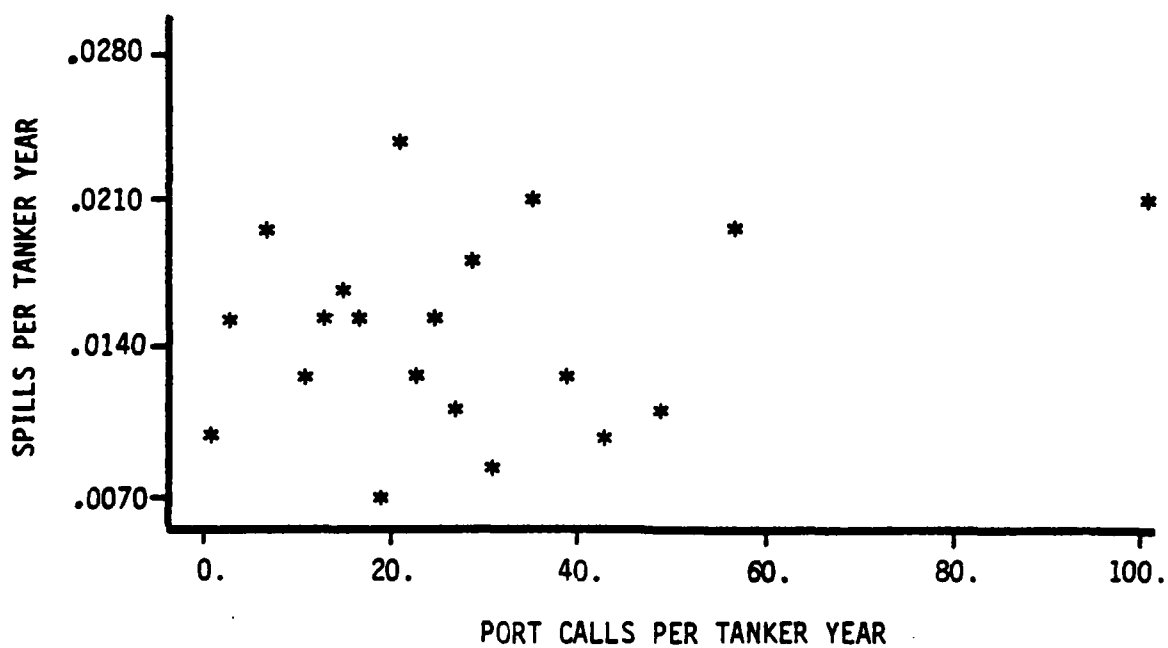
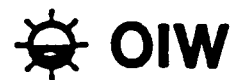


FIGURE 4-25. RELATIONSHIP BETWEEN SPILL RATE AND PORT CALL ACTIVITY.



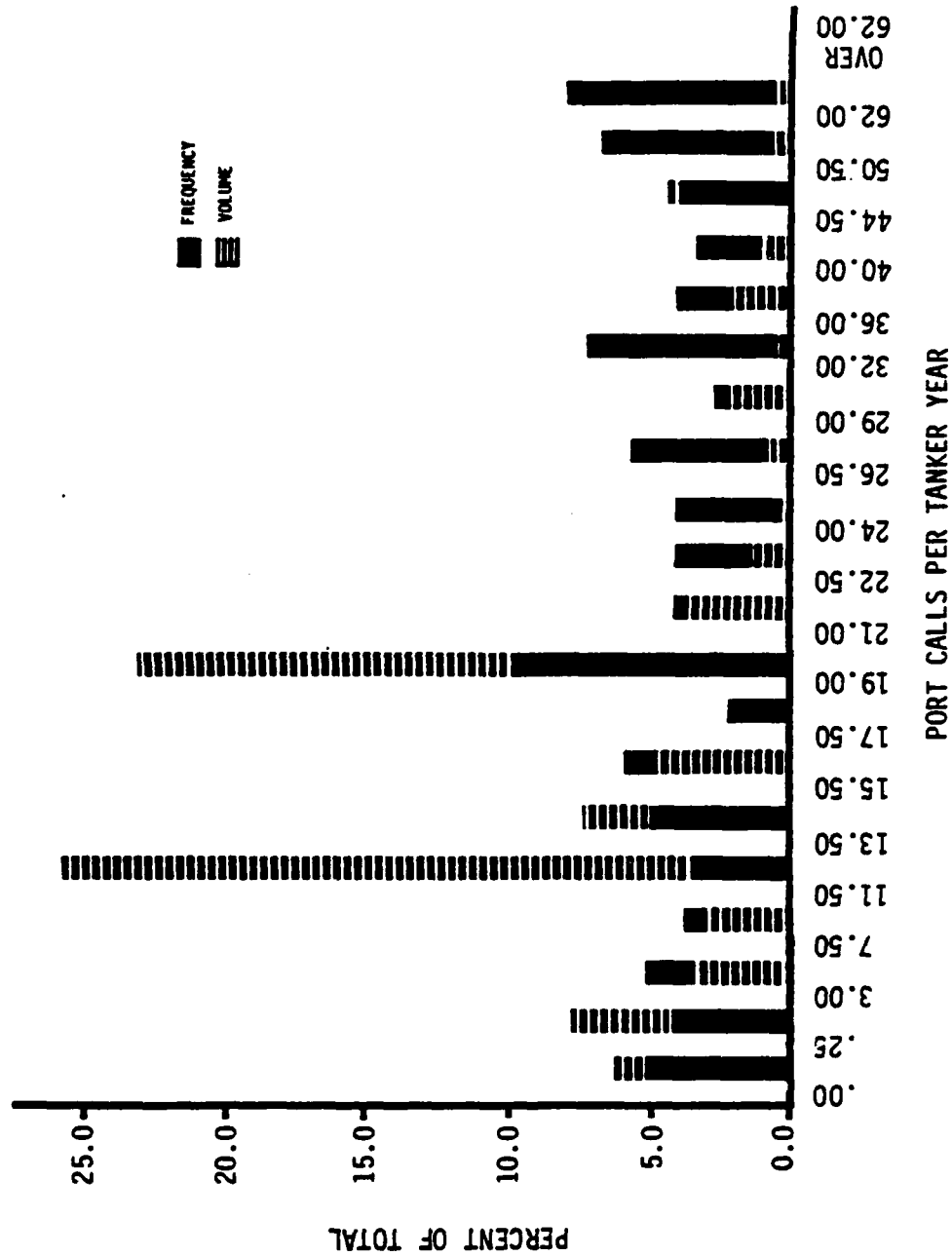


FIGURE 4-26. DISTRIBUTION OF THE FREQUENCY OF SPILLS AND VOLUME OF SPILLS ACCORDING TO PORT CALL ACTIVITY.



in each category by the number of tanker years (or port calls or tonnage throughput) in each category.

The first spill rate, spills per tanker year, showed little or no consistency with the number of port calls made by a vessel (See Figure 4-25). Those tankers making 19.00 to 20.99 port calls per year had the maximum spill rate, a rate of 2.4 spills per 100 tanker years, while those tankers making 17.50 to 18.99 port calls per year had the minimum spill rate of .7 spills per 100 tanker years. A weak linear relationship is exhibited between the spills-per-tanker-year rate and port call activity, yielding a correlation of 0.27. In other words, from the data, 7% of the variation in the spill rates is accounted for by the differences in port calls.

The second rate, spills per port call, and the third rate, spills per ton of throughput, exhibited no significant trends with port call activity. The spill rates by tankers making 3.00 port calls or more per year remained very constant as the number of port calls increased. For example, there was no statistical difference between the spill rates (both spills per port call and spills per ton of throughput) of a vessel making 4 port calls per year, or a tanker making 20 port calls per year, or a vessel making 60 port calls per year. Those vessels making 0 to .24 port calls per year had a spill rate of 19.6 spills per 100 port calls. This extreme rate is most likely due to the problem of port calls not being reported at some small ports, a problem most acute for small vessels. Various ports that are equipped only to handle coastal or intraharbor traffic often do not have the facility for reporting port calls. The port call data show no port calls by these small vessels, when in reality they could have had a sizeable number of port calls. This problem has been recognized, but no additional data are available to correct the situation.

Frequency, as defined by the three spill rates above, has not been found to be significantly linked to the port call activity of a vessel (or as significantly linked as spill rates have been to other criteria). For this reason, the categorizing technique based on the port call activity of a vessel used for analyzing the frequency of spills was not used in the final analysis.

An average spill volume for each of the twenty port call intervals was calculated in order that the question of whether the port call activity of a tanker had any significant bearing on the average amount spilled could be addressed. Graphically, there appeared to be a minimal downward trend of the

average spill volumes as the number of port calls made by a vessel increased. (Figure 4-27) Vessels which made 11.50 to 13.49 port calls per year had the largest average spill volume, 49,216 tons per incident, whereas, vessels which made 17.50 to 18.99 port calls per year had the minimum average spill volume, 286 tons per incident. Statistically, the linear model relating average volume spilled with the number of port calls made by vessels explained 12% of the variability found within the data.

The remainder of the analysis on port call activity relates the various tanker characteristics to the number of port calls made by the tankers. What relationship exists between the number of port calls made by a tanker and its deadweight tonnage, age, horsepower and tonnage throughput?

The relationship between the number of port calls made by a vessel and its deadweight tonnage follows a very definite pattern. (See Figure 4-28) The average deadweight tonnage of a vessel steadily increased as the number of port calls made by such vessels increased until vessels making more than 17.5 port calls per year were reached; at this point the average deadweight tonnage began to decrease as the number of port calls increased. This maximum average deadweight tonnage, located in the interval of vessels making 15.50 to 17.49 port calls, was 170,707 deadweight tons, while the minimum average deadweight tonnage, 25,672 deadweight tons, was found in the interval of vessels making .25 to 2.99 port calls per year. See Table 4-13 for a complete listing of average deadweight tonnages.

As previously mentioned, certain ports that deal mostly with small tanker traffic do not always report (or have the capacity to report) all port calls. As a result, the lower end on the port call scale tends to have lower deadweight tonnage averages. In other words, those tankers specified as having made no port calls are in many instances small tankers whose port calls have simply been unrecorded.

A linear relationship between the average deadweight tonnage and the number of port calls made by a tanker produced a correlation of 0.39, whereas a quadratic relationship produced a correlation of 0.43.

As mentioned before, horsepower and deadweight tonnage are highly correlated ($r=0.96$) so one can anticipate the findings based on the deadweight-port call relationship would hold for the horsepower-port call relationship. Graphically, horsepower follows the same trend as seen with deadweight: a peak occurring in the 15.50 to 17.49 port calls per year interval and a minimum

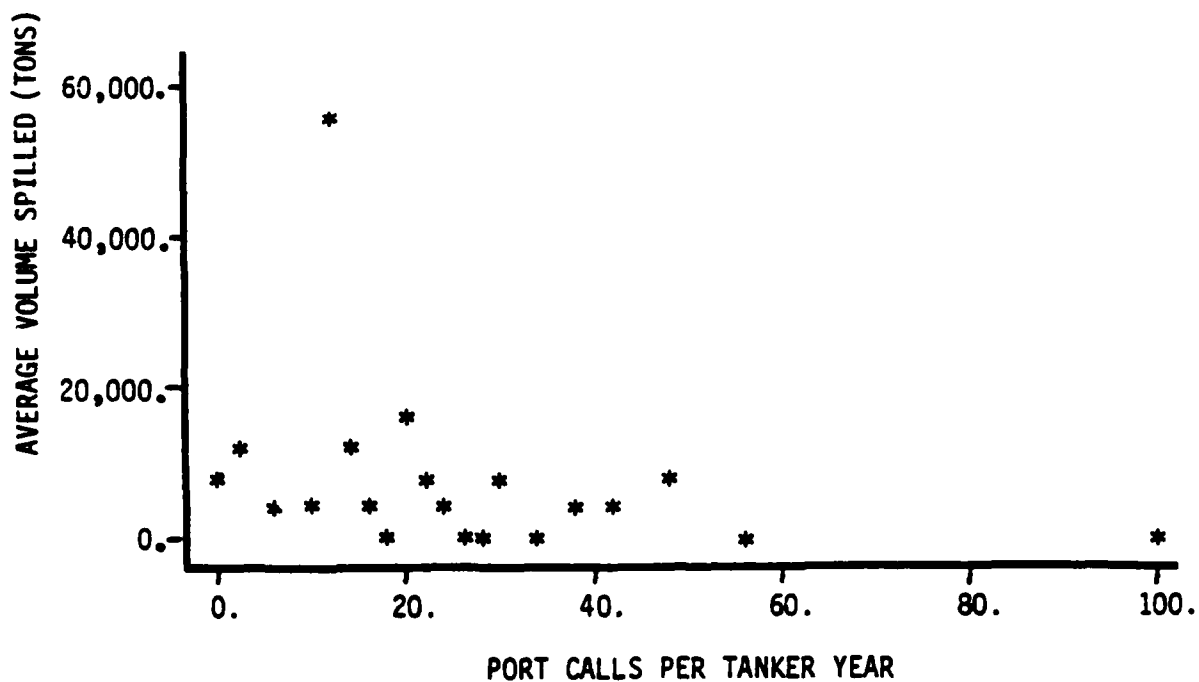


FIGURE 4-27. RELATIONSHIP BETWEEN AVERAGE VOLUME SPILLED AND PORT CALL ACTIVITY.

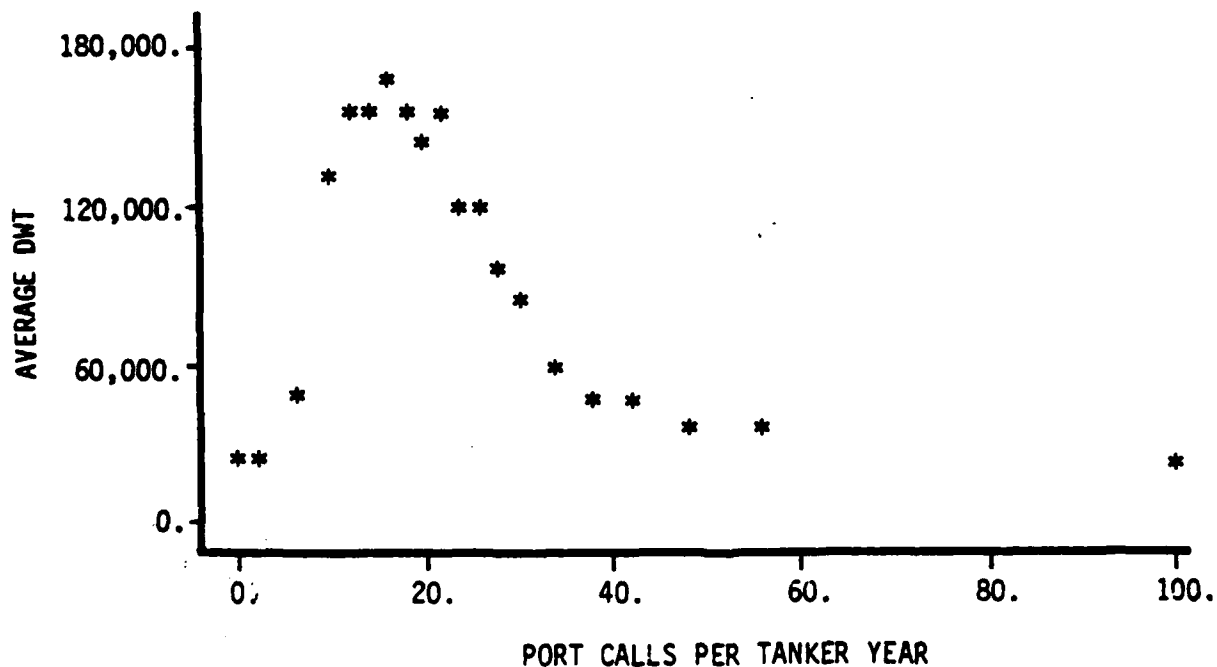
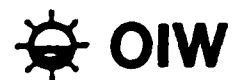


FIGURE 4-28. RELATIONSHIP BETWEEN AVERAGE DWT AND PORT CALL ACTIVITY.



TABLE 4-13

DESCRIPTION OF AVERAGE DEADWEIGHT TONNAGE AND AVERAGE HORSEPOWER
BY PORT CALL ACTIVITY LEVEL

PORT CALLS PER TANKER YEAR	<u>AVERAGE DEADWEIGHT TONNAGE</u>		<u>AVERAGE HORSEPOWER</u>	
	WORLD FLEET	SPILLING FLEET	WORLD FLEET (Kilowatts)	SPILLING FLEET (Kilowatts)
.00 to .24	29,406.67	36,374.03	7,785.10	8,973.75
.25 to 2.99	25,672.38	46,583.08	6,535.91	9,244.69
3.00 to 7.49	48,783.68	81,860.00	9,462.81	11,540.09
7.50 to 11.49	134,531.81	162,585.88	16,184.97	18,229.68
11.50 to 13.49	152,906.94	259,303.72	17,772.65	24,116.87
13.50 to 15.49	160,879.01	100,048.76	19,323.01	15,545.56
15.50 to 17.49	170,706.52	102,549.56	20,113.97	14,973.88
17.50 to 18.99	156,363.13	122,695.10	18,827.52	15,276.23
19.00 to 20.99	144,787.33	98,317.38	17,919.22	16,219.16
21.00 to 22.49	158,661.96	123,711.66	19,445.12	16,874.18
22.50 to 23.99	116,814.15	77,482.90	15,617.78	12,383.04
24.00 to 26.49	124,097.06	74,034.94	16,299.83	13,239.42
26.50 to 28.99	100,894.27	66,371.97	14,845.33	13,235.23
29.00 to 31.99	80,849.44	62,640.29	13,780.91	13,680.41
32.00 to 35.99	57,038.99	54,941.38	11,327.58	11,571.24
36.00 to 39.99	52,798.98	58,006.46	11,328.74	12,600.25
40.00 to 44.49	43,779.93	47,768.00	10,328.98	11,628.19
44.50 to 50.49	40,808.75	43,986.51	10,011.13	10,602.57
50.50 to 61.99	38,571.74	39,068.27	9,995.02	9,525.60
62.00 and over	29,945.51	31,246.95	7,789.34	7,022.80



again in the .25 to 2.99 port calls per year interval (See Table 4-13 and Figure 4-29).

The average age of the tankers in the port call categories followed a pattern that was nearly the reverse of the deadweight-port call relationship and the horsepower-port call relationship(See Figure 4-30 and Table 4-14). The youngest average age falls in the range of 15.50 to 17.49 port calls per year. As the number of port calls increased, the average age decreased until the range of 15.50 to 17.49 port calls per year was reached, after which the average age steadily increased.

The average throughput of a vessel and the number of port calls the vessel makes showed a relationship similar to the relationship found with average deadweight and port calls (See Figure 4-31). Throughput steadily increased until vessels were making 21.00 to 22.49 port calls per year. After this point the average throughput began to decrease and then level off. Vessels making 26.5 or more port calls per year roughly had the same average throughput. A linear model relating average throughput and the number of port calls yielded a correlation of 0.35; in other words, 12% of the variation in the average throughput values can be explained linearly by the number of port calls made by a tanker.

Grouping vessels according to their average number of port calls per year was not found to be the "best" scheme for the analysis of frequency of spills and volume of spills.

Analysis from Port System Perspective

The port characteristics file provides the basis for the analysis of spill frequencies and spill volumes and their relationship to port systems. In this case, it is not the individual tankers or tanker groups which are being studied, but the effects of their cumulative activity in port systems.

Potential exposure variables considered for the analysis were developed directly from the port characteristics file for each port system. These are:

- port calls
- tonnage throughput
- maximum size tanker
- maximum tanker draft

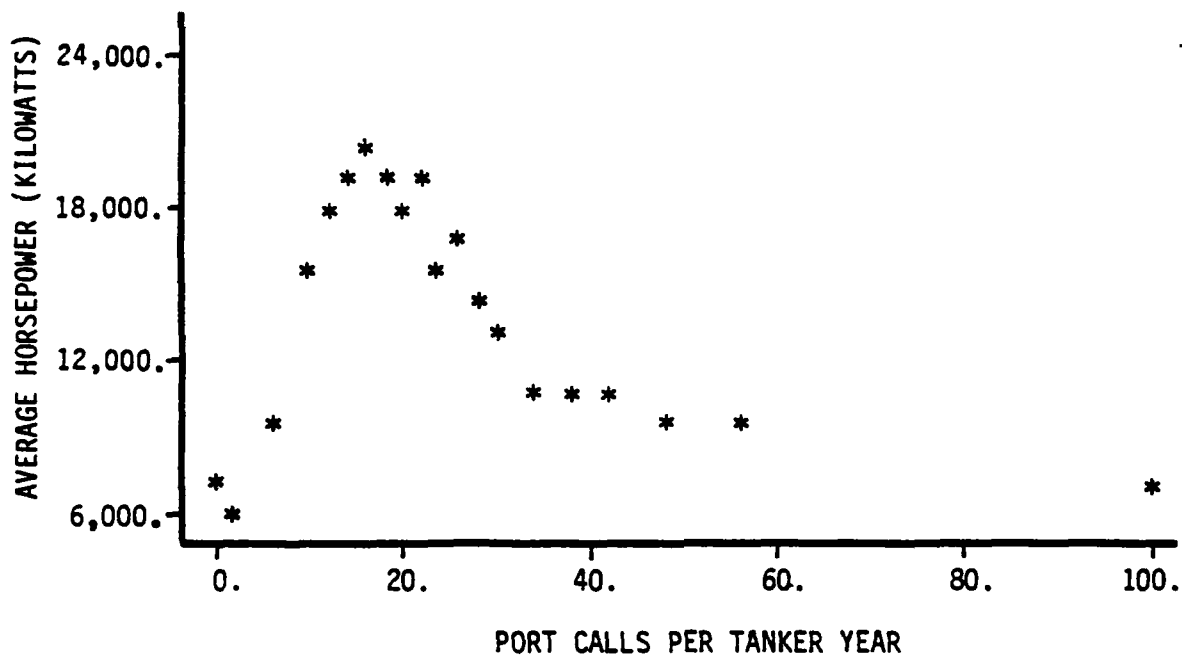


FIGURE 4-29. RELATIONSHIP BETWEEN AVERAGE HORSEPOWER AND PORT CALL ACTIVITY.

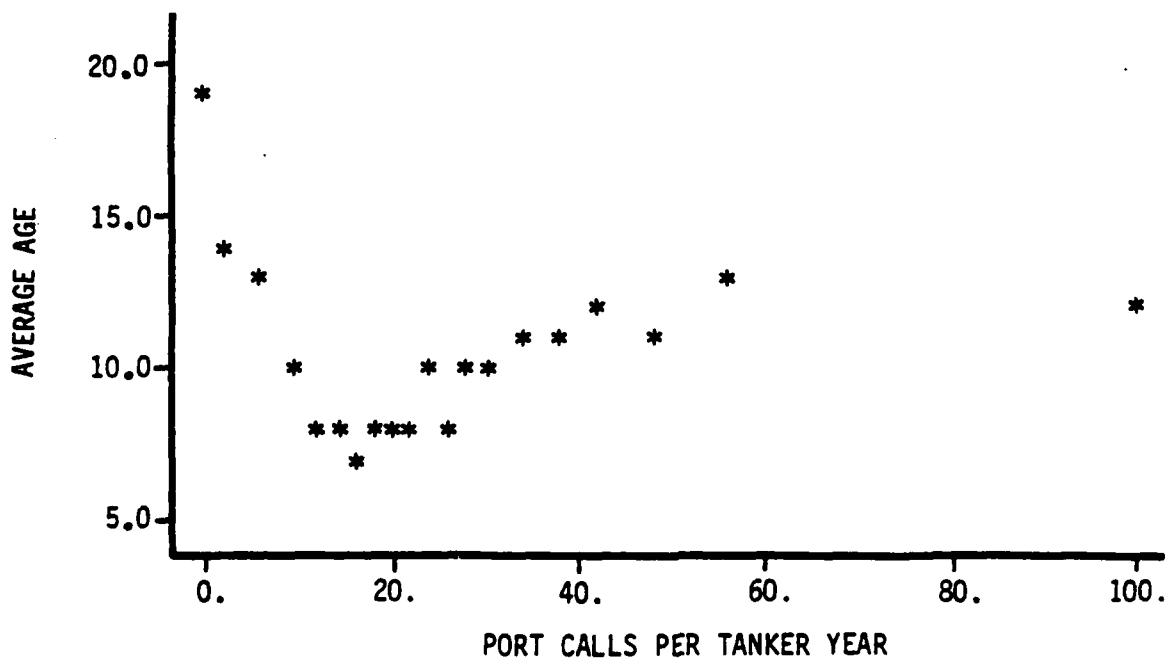


FIGURE 4-30. RELATIONSHIP BETWEEN AVERAGE AGE AND PORT CALL ACTIVITY.



TABLE 4-14

DESCRIPTION OF AVERAGE AGE AND TONNAGE THROUGHPUT
BY PORT CALL ACTIVITY LEVEL

PORT CALLS PER TANKER YEAR	<u>AVERAGE AGE</u>		<u>THROUGHPUT</u>	
	WORLD FLEET	SPILLING FLEET	WORLD FLEET (Tons)	SPILLING FLEET (Tons)
.00 to .24	19.31	15.42	5,379,208	0
.25 to 2.99	13.98	13.63	2,032,134	1,746,434
3.00 to 7.49	12.95	17.12	142,992,163	12,223,279
7.50 to 11.49	9.58	12.76	802,038,597	40,382,795
11.50 to 13.49	8.21	4.61	941,835,426	78,140,778
13.50 to 15.49	7.73	12.36	1,370,233,275	35,570,527
15.50 to 17.49	7.09	9.64	2,032,996,121	61,964,468
17.50 to 18.99	7.66	10.84	1,597,394,904	35,734,496
19.00 to 20.99	7.76	9.39	2,336,864,218	126,588,402
21.00 to 22.49	7.54	10.30	2,185,496,290	76,295,666
22.50 to 23.99	9.82	12.79	1,476,438,690	46,783,299
24.00 to 26.49	8.15	11.13	2,236,736,740	58,728,636
26.50 to 28.99	9.65	11.46	1,743,250,198	64,610,074
29.00 to 31.99	10.03	12.29	1,501,939,043	32,030,318
32.00 to 35.99	10.96	13.71	1,317,965,469	94,631,746
36.00 to 39.99	11.29	8.27	1,340,794,892	57,325,233
40.00 to 44.49	11.86	11.85	1,250,507,293	39,515,541
44.50 to 50.49	11.49	11.94	1,317,669,391	50,898,916
50.50 to 61.99	13.39	15.47	1,419,660,018	97,025,910
61.00 and over	12.41	10.20	1,766,959,027	143,350,603
ENTIRE FLEET			26,807,183,097	1,153,547,121



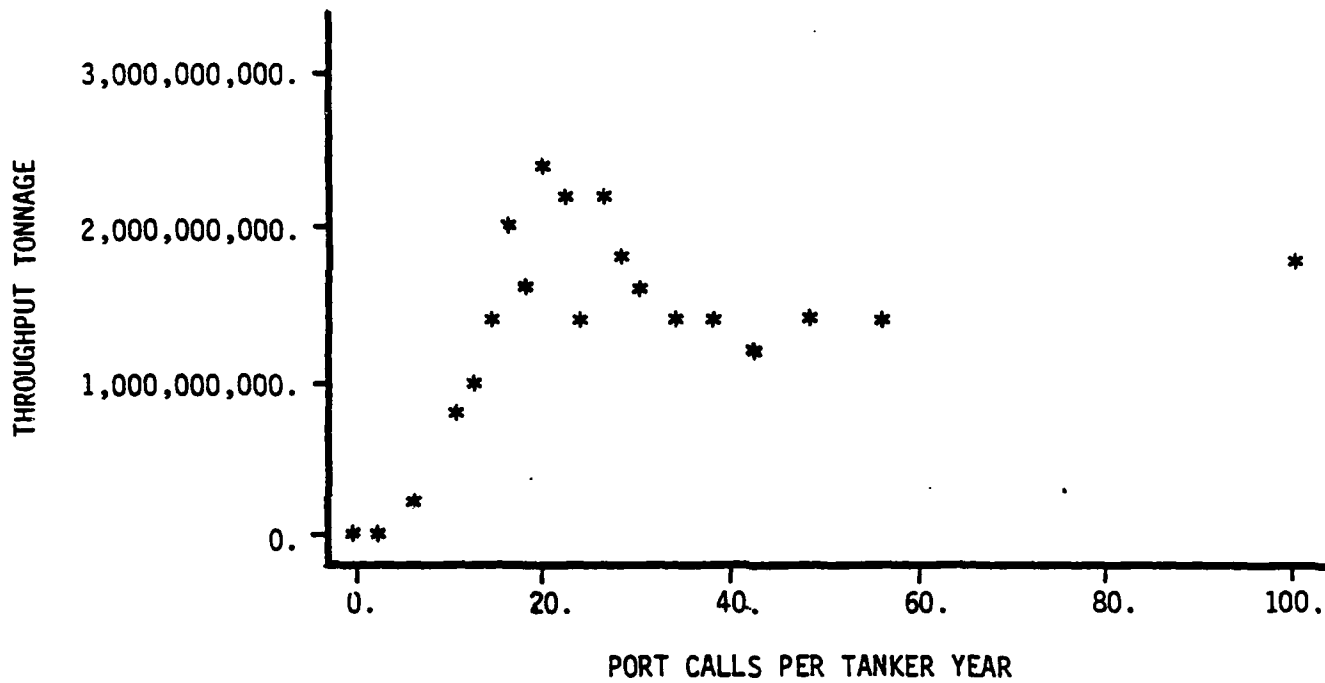
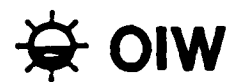


FIGURE 4-31. RELATIONSHIP BETWEEN THROUGHPUT TONNAGE AND PORT CALL ACTIVITY.



- number of berths
- average vessel size
- variance of vessel size
- number of port calls per berth (average)
- tonnage throughput per berth (average)
- percentage of total activity located at largest individual port

In addition, several functions of these exposure variables were tested when preliminary results indicated possible nonlinear relationships. It must be noted that attempts to document physical characteristics of specific ports and port systems for this analysis were unsuccessful, with the exception of number of berths. Thus, this section primarily addresses port activity rather than port characteristics. The relationships of physical port characteristics and tanker spillage in ports have therefore not been addressed.

Several measures of spill frequency were also developed for each port system. These are:

- number of casualty spills
- number of casualty spills per port call
- number of casualty spills per tonnage throughput
- number of casualty spills per berth

Following the analysis of the diversity of port systems, subsequent analysis involved identifying significant exposure variables for each of the four frequencies. This resulted in the elimination of most of the potential exposure variables as non-essential.

For frequency (number of spills), two exposure variables were found to be significant. These were port calls and tonnage throughput. Both were significant at the 99% level. No other variables were significant at the 90% level, although average tanker size was significant at the 80% level.

For spills per port call, no exposure variables were found to be significant, although the constant was highly significant (99.9%). The resulting relationship is of the form

$$\text{SPILLS/PC} = \text{CONSTANT}$$

which again indicates that port calls is a valid exposure variable for predicting spills, as was found above.

For spills per ton throughput, average tanker size was the single significant exposure variable, and was significant at the 95% level.

For spills per berth, port calls per berth was the single significant exposure variable, at the 99% level. The constant was not significant, resulting in an equation of the form

$$\text{SPILLS/BERTH} = \text{CONSTANT} \times (\text{PC/BERTH})$$

It can be seen that this again repeats the relationship between spills and port calls.

As a result of this initial analysis, two possible measures of spill frequency were found to be important, and three exposure variables were significant. The relationships developed were:

$$\text{SPILLS} = 6.199 \times 10^{-4} * (\text{PC}) - 2.515 \times 10^{-3} * (\text{THPT}) - 0.017 \quad (8)$$

$$\text{SPILLS/THPT} = -5.051 \times 10^{-5} * (\text{DWT}) + 9.889 \times 10^{-3} \quad (9)$$

where

SPILLS = number of casualty spills per year for the four year period 1976-1979

PC = number of port calls per year for the four year period 1976-1979

THPT = total tonnage throughput in MDWT per year for the four year period 1976-1979

DWT = average tanker size in KDWT for the four year period 1976-1979

The correlation for equation (8) was $r=0.64$, and the value of r^2 adjusted for the number of degrees of freedom was r^2 adjusted = 0.39. For equation (9), $r = 0.32$ and r^2 adjusted = 0.09. It can be seen that equation (8) accounts for far more variability than does equation (9).

One problem with predicting casualty spill frequencies from the port characteristics file is the relatively low rate of occurrence of spills. For sixty port systems for a four year period, sixty-eight casualty spills were recorded. Twenty-eight port systems had no casualty spills at all in this period. The low rate of occurrence for individual ports due to the limited

time frame of the data bases can account in part for the low values of correlation despite the high significance of the variables used. In an effort to overcome this, port systems were grouped according to similar port characteristics. Groups of three port systems were used, which results in twenty "port groups," a number consistent with the groupings used in other phases of the analysis. By thus effectively including twelve port years in each group, greater consistency in the predictability of spill occurrence might be expected. The port systems were grouped in four different ways, according to number of port calls, tonnage throughput, number of berths, and average tanker size.

The most significant set of results were provided by grouping according to port call activity. This is not unexpected, as number of port calls was consistently the most significant exposure variable. Results from other groupings provided similar results, but with generally lower correlations and significance. On this basis, port call groupings were chosen as the preferred method.

For port call groups, the same exposure variables were included for each measure of spill frequency, with one exception. For number of spills, average tanker size was added as a third exposure variable, significant at 99%. The resulting equation relating number of spills to port calls, tonnage throughput, and average tanker size is:

$$\begin{aligned} \text{SPILLS} = & 1.518 \times 10^{-3} * (\text{PC}) - 1.199 \times 10^{-2} * (\text{THPT}) + 7.445 \\ & \times 10^{-2} * (\text{DWT}) - 0.720 \end{aligned} \quad (10)$$

where

SPILLS = number of spills per port system per year for the years 1976-1979

PC = number of port calls per year for a port system

THPT = total tonnage throughput in MDWT per year for a port system

DWT = average tanker size in KDWT per year for a port system

The correlation for equation (10) is $r=0.92$, and r^2 adjusted = 0.82. This indicates that this model accounts for a large proportion of the total variance. The improved predictive ability, when compared to the model based upon sixty individual ports, has led to the use of equation (10) in subsequent applications. A comparison of estimated and actual spills for the twenty port groups can be seen in Figure 4-32.

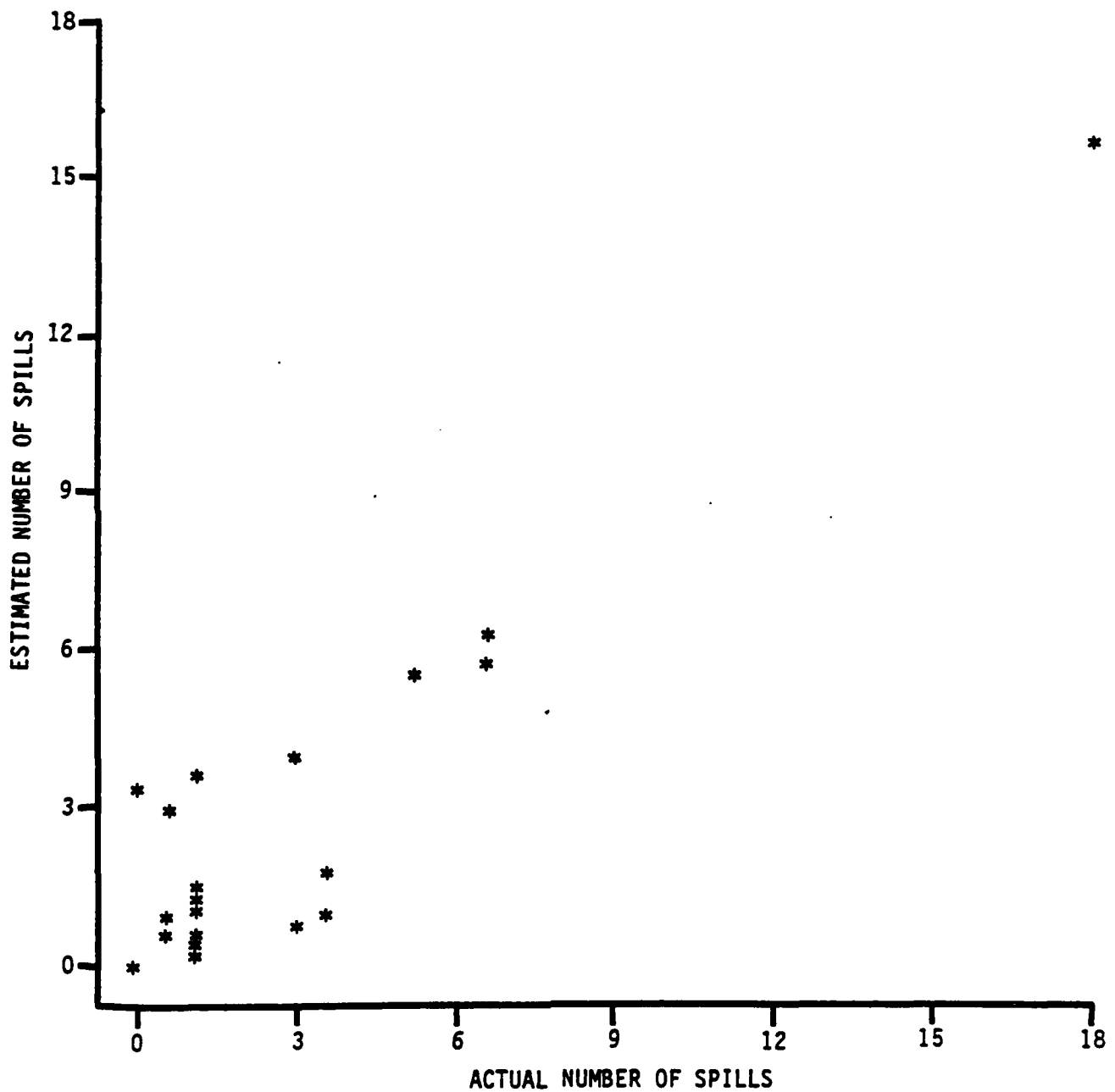


FIGURE 4-32. COMPARISON OF ACTUAL AND ESTIMATED NUMBER OF SPILLS FOR PORT GROUPS 1976-1979.



With the inclusion of average deadweight tonnage as a significant exposure variable, it is desirable to consider the variability of the size of tankers calling at the port as an additional exposure variable. One might hypothesize that variations in the fleet mix of tankers calling at a port could have a significant impact on the spill risk experienced. For example, if all tankers calling were exactly the average deadweight tonnage, this could result in a different spill risk than a broad range of tanker sizes resulting in the same size average.

In order to measure this phenomenon, the variance of the deadweight tonnage of tankers calling at each port system was developed. While the distribution of tanker sizes was not determined, the variance about the mean does provide an indication of the variability of the data. Several other derivative statistics were also developed, including the standard deviation and standard ratio. The standard ratio is the ratio of the standard deviation and average size, providing a measure of variability relative to the average size.

For the twenty port groups, several different approaches were tried and none yielded any significant improvements in the model shown in equation (9). For the sixty individual port groups, the standard ratio was not significant at the 95% level but was significant at the 90% level. The coefficient of the standard ratio was negative, initially implying that the number of spills increases as the variability of individual tanker size decreases. Since the ports all tend to have small tankers, this variability increases as the maximum size of tankers in the port increases. The risk relationship with the standard ratio may reflect the fact that large ports tend to be safer simply because they have fewer physical constraints, and not because they have larger tankers in the system. Thus, the relationship discovered for the individual port systems may be an indication that ports which can physically accommodate large tankers are safer than ports which cannot accommodate large tankers, instead of being an indication that port calls by large tankers result in safer conditions.

Equation (10) can be used to approximate spill occurrence for any scenario which is within the domain of the analysis. This domain is defined by the highest and lowest values included for each of the three exposure variables. These limits for port groups are:

	Lower Bound	Upper Bound
Port Calls/Year	269	2,718
Tonnage Throughput/Year(MDWT)	16.4	312
Average Tanker Size (KDWT)	42.3	132.7

All three of these bounds act as constraints in all cases. It should be noted that the interrelationship of these three variables will in most cases preclude the consideration of the entire ranges of one or more variables. For example, should a port system have a tonnage throughput of 25 MDWT, and an average tanker size of 50 KDWT, this means that 500 port calls were made. Should one wish to consider the case of an average size of 100 KDWT, this would imply that 250 port calls were made, which is below the lower bound for that variable and thus does not fall within the domain of the equation even though 100 KDWT is within the upper bound for average size.

In addition to these absolute endpoints of the analysis, consideration must be given to the distribution within these intervals of the three variables being addressed. In particular, the interaction of the three variables is of interest.

The number of port calls and tonnage throughput of port groups are highly related, with a correlation of $r=0.93$. The distribution can be seen in Figure 4-33. The linear relationship was expected, due to the relatively low variance of average deadweight tonnage and the relationship between the three variables:

$$THPT = PC \cdot DWT$$

The implication of the high correlation between port calls and tonnage throughput is that the analysis should not extend into regions where either of these varies greatly while the other remains fairly constant. This is indeed seen through the limits shown above, where both port calls and tonnage throughput vary by factors of ten or more, while their ratio, deadweight tonnage, varies only by a factor of three.

Also of significance is the sparsity of data points for port groups with 16,000 or more port calls (1,300 port calls/year for a port system). Should the model be used for estimating spills in this region, the reliance on very few actual data points which describe it must be noted.

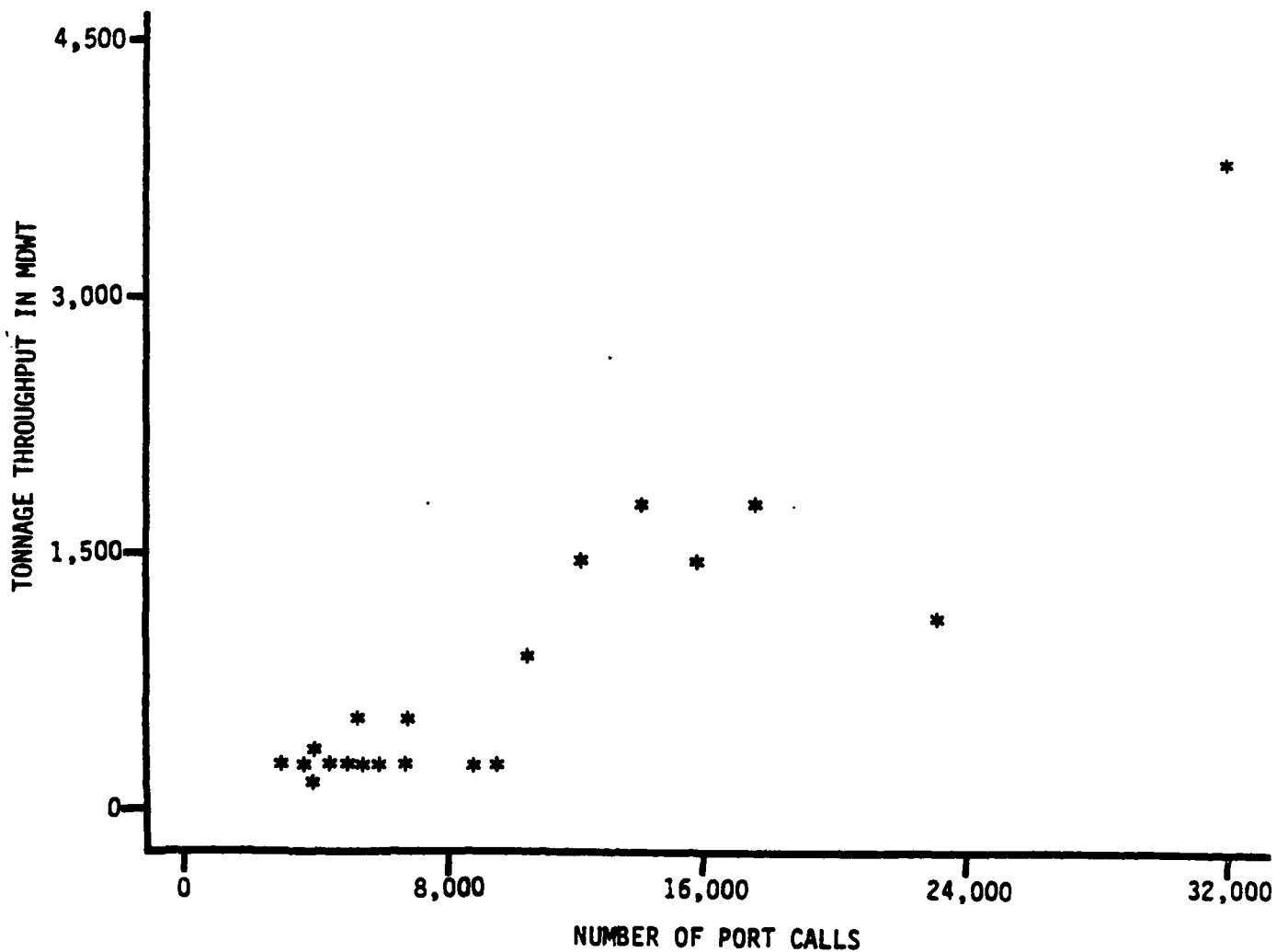


FIGURE 4-33. DISTRIBUTION OF TONNAGE THROUGHPUT WITH NUMBER OF PORT CALLS FOR PORT GROUPS 1976-1979.



The relationships between average deadweight tonnage with number of port calls and average deadweight tonnage with tonnage throughput are shown in Figures 4-34 and 4-35. The correlations are $r=0.36$ and $r=0.62$, respectively. These lower correlations indicate greater freedom in specifying deadweight tonnage, regardless of port calls and throughput. The average deadweight tonnages are well scattered, with the exception of the upper ends of the port call and tonnage throughput ranges, where sparsity of data again becomes important.

The analysis of spill volumes and port characteristics was addressed in two variables: total volume spilled in port systems and average spill volume in port systems. These were related to the various potential exposure variables developed for port systems.

No significant relationships were discovered relating spill volumes and port characteristics. No exposure variables were significantly related to either measure of spill volume, even at the 50% level. This indicates that port characteristics are not the determining factor in spill volumes, but simply in determining spill frequencies. Tanker characteristics must be analyzed to determine adequate spill volume relationships, as has already been done.

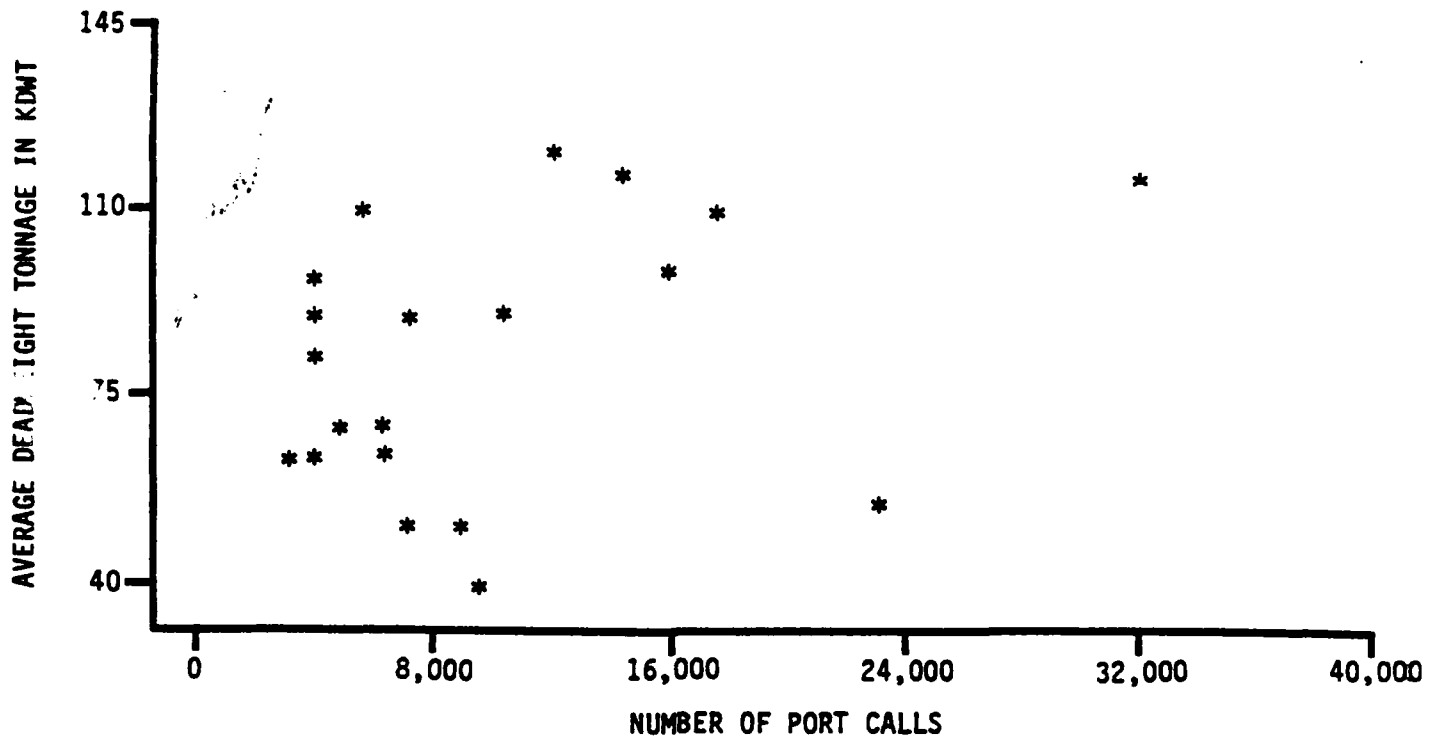


FIGURE 4-34. DISTRIBUTION OF AVERAGE DEADWEIGHT TONNAGE WITH NUMBER OF PORT CALLS FOR PORT GROUPS 1976-1979.

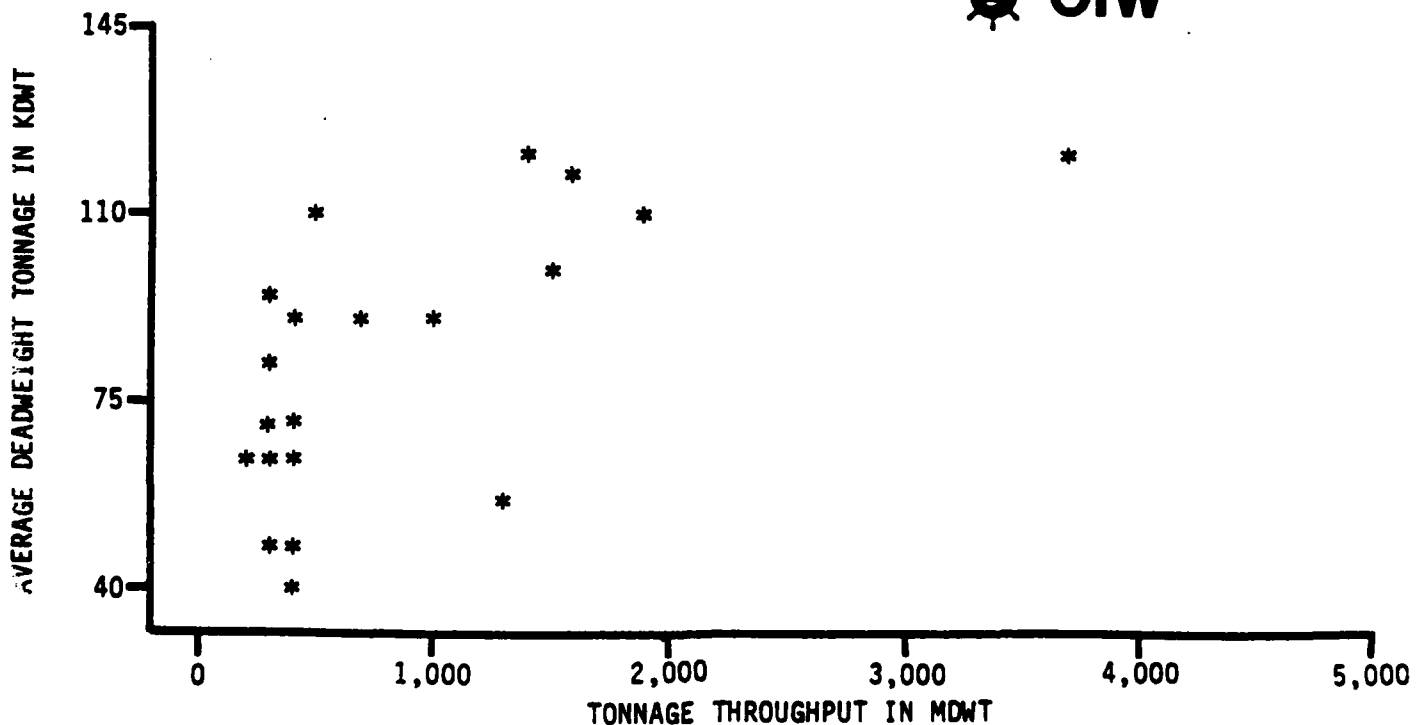


FIGURE 4-35. DISTRIBUTION OF AVERAGE DEADWEIGHT TONNAGE WITH TONNAGE THROUGHPUT FOR PORT GROUPS 1976-1979.

SECTION 5. MINIMIZATION OF RISK INDICATORS

5.1 REGRESSION EQUATIONS

The statistical analysis resulted in four equations useful in optimizing spill risk in port systems. These equations relate to the casualty spill occurrence, casualty spill volume, operational spill occurrence, and operational spill volume. The four equations are:

$$\begin{aligned} \text{SPILLS (casualty)} = & 1.518 \times 10^{-3} * (\text{PC}) - 1.188 \times 10^{-2} * (\text{THPT}) \\ & + 7.445 \times 10^{-3} * (\text{DWT}) - 0.7200 \end{aligned} \quad (1)$$

$$\text{SPILLS (operational)} = 4.95 \times 10^{-3} * (\text{PC}) \quad (2)$$

$$\text{VOL (casualty spill)} = 348 + 65.2 * (\text{DWT}^2) \quad (3)$$

$$\text{VOL (operational spill)} = 224 \quad (4)$$

where

PC = number of port calls per year in a port system in 1976-1979

THPT = tonnage throughput per year in MDWT for a port system in 1976-1979

DWT = average tanker size in KDWT in a port group in 1976-1979

DWT² = tanker size in KDWT

Ninety-five percent confidence limits for regression equations (1), (2) and (3) are shown in Figures 5-1, 5-2 and 5-3, respectively. The confidence limits for equation (1) are calculated by holding tonnage throughput constant at 25.25 million deadweight tons per year, the tonnage throughput of tankers in Puget Sound during the studied period (see Subsection 5.2). A confidence interval for the constant in equation (4) is obtained by adding and subtracting one standard deviation from 224. The resulting confidence interval for volume spilled in an operational spill is [0,2528].

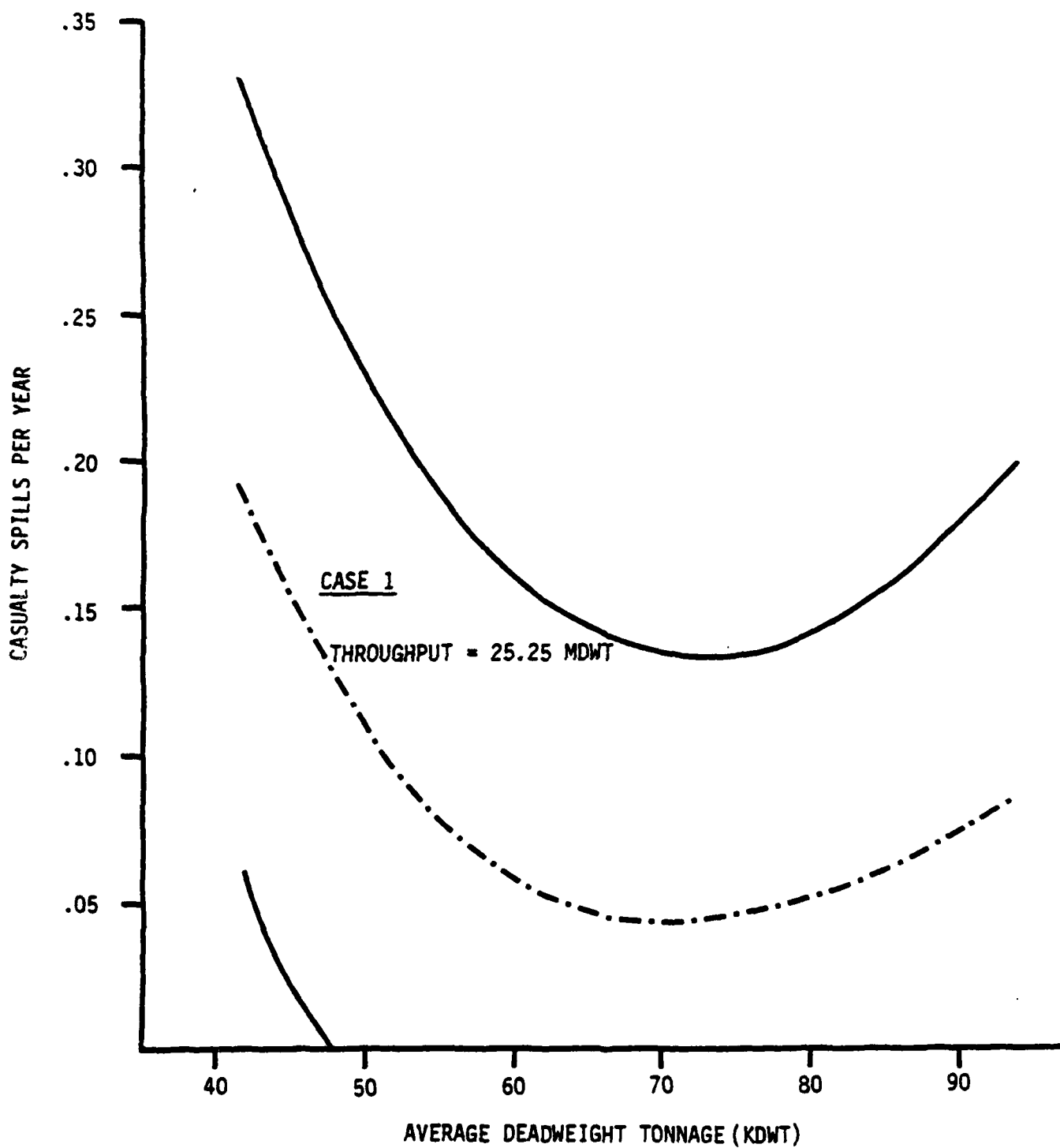


FIGURE 5-1. 95% CONFIDENCE LIMITS FOR RELATIONSHIP OF AVERAGE DEADWEIGHT TONNAGE TO NUMBER OF CASUALTY SPILLS

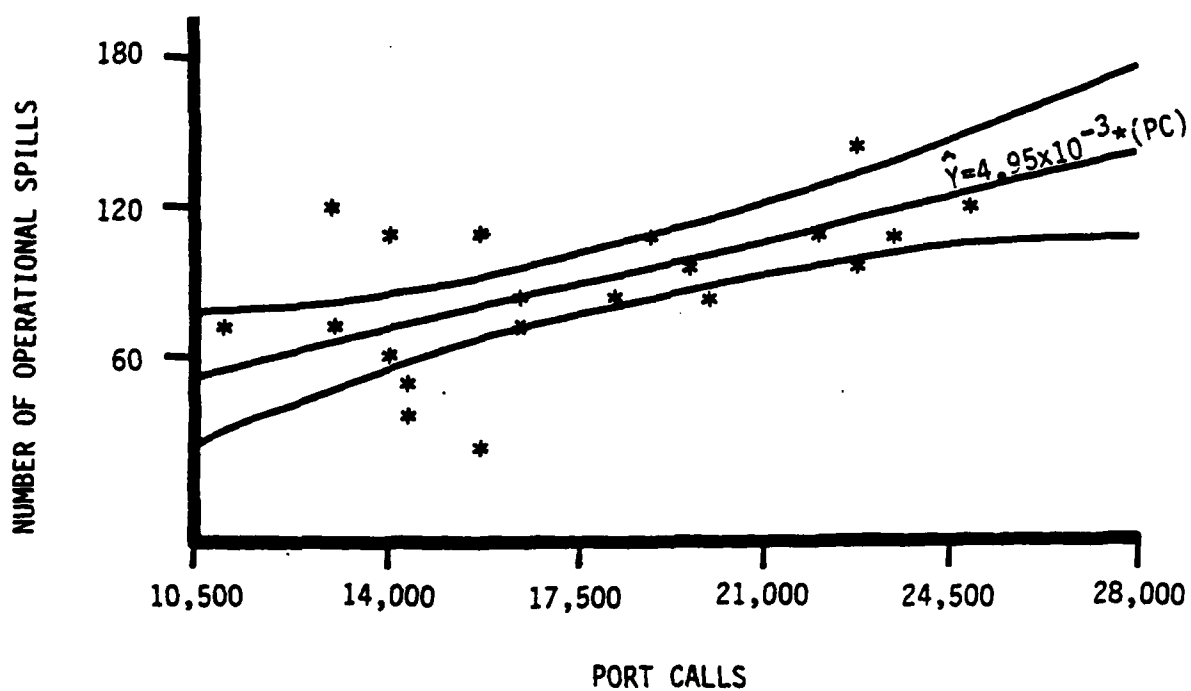


FIGURE 5-2. 95% CONFIDENCE LIMITS FOR RELATIONSHIP OF
NUMBER OF PORTS CALLS TO NUMBER OF OPERATIONAL SPILLS

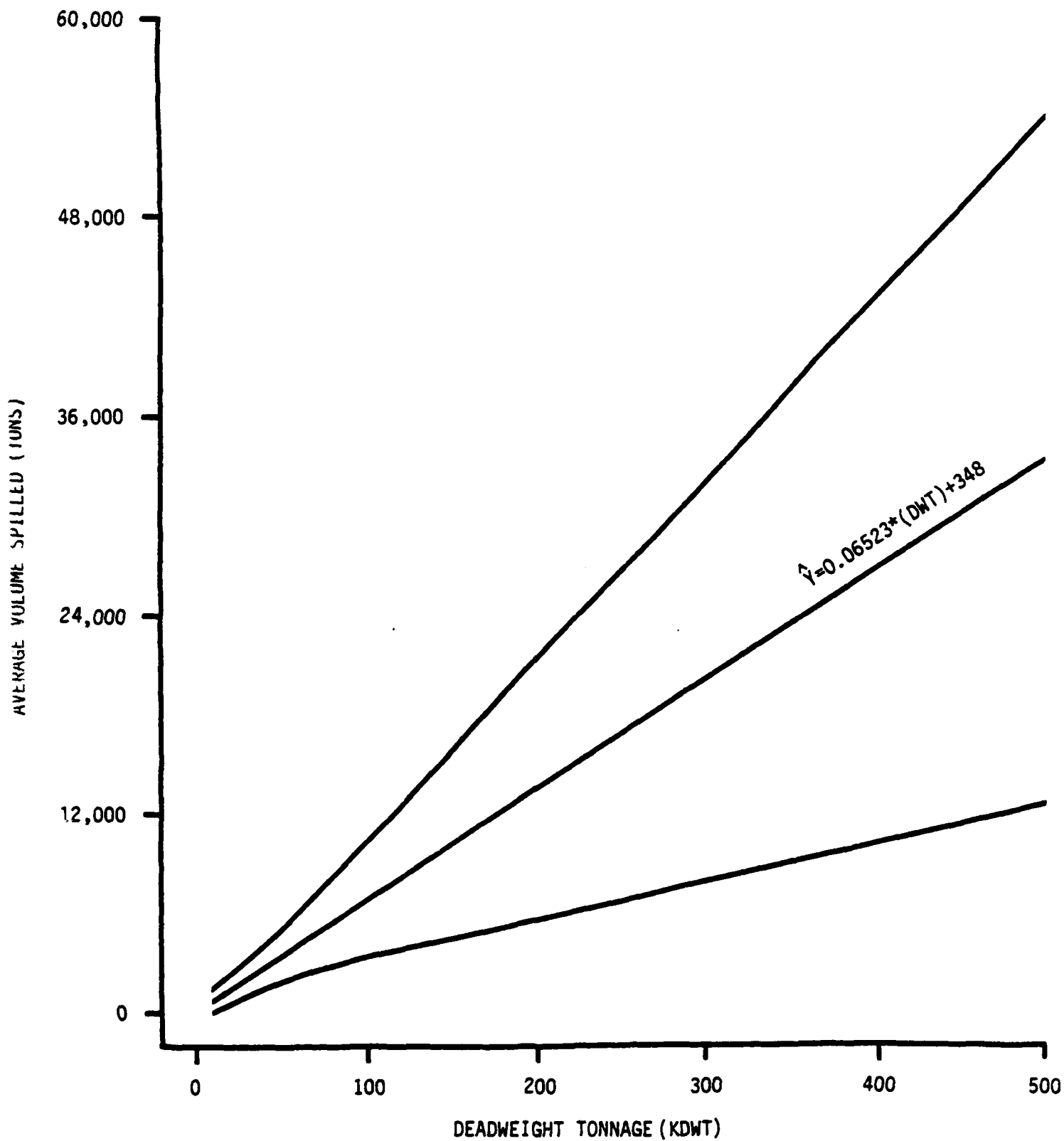


FIGURE 5-3. 95% CONFIDENCE LIMITS FOR RELATIONSHIP OF DEADWEIGHT TONNAGE TO AVERAGE VOLUME.

These equations can be used to develop several different indicators of risk. Three risk indicators are presented here which are readily available from the above equations.

Number of Casualty Spills

The number of casualty spills is defined by equation (1) above. The desirability of the use of this measure of tanker risk in subsequent optimization lies in the desire to avoid casualty spills. The variability of casualty spill sizes leads to the potential for high volume spills in individual cases, with correspondingly large impacts.

In order to simplify equation (1), the underlying relationship between port calls, average deadweight tonnage and tonnage throughput must be applied. The relationship is:

$$(\text{Tonnage Throughput}) = \sum_{\text{all vessels}} (\text{Number of Port Calls}) * (\text{Deadweight Tonnage})$$

In the present case, if THPT is Tonnage Throughput in MDWT and DWT is Average Deadweight Tonnage in KDWT, the relationship becomes:

$$\text{THPT} = (\text{PC}) * (\text{DWT}) * 10^{-3}$$

or

$$\text{PC} = (\text{THPT} / \text{DWT}) * 10^3 \quad (5)$$

Using the identity above, equation (1) can be written in terms of tonnage throughput and deadweight tonnage as follows:

$$\begin{aligned} \text{SPILLS (casualty)} = & 1.518 * (\text{THPT} / \text{DWT}) - (1.188 * 10^{-2}) * \text{THPT} \\ & + (7.445 * 10^{-3}) * (\text{DWT}) - 0.7200 \end{aligned} \quad (6)$$

Total Volume Spilled in Casualty Spills

The total volume spilled in casualty spills is often used as a risk indicator. One reason is again related to the potential for large spills.

Another reason for distinguishing between casualty and operational spills is location. Most operational spills occur at berth. Thus, the spill occurs in an area already developed and subject to pollution, and at the same time, response and clean-up equipment is frequently immediately available. Casualty spills, on the other hand, occur primarily away from the fixed facilities, often in a less developed location possibly more sensitive to environmental impacts and less accessible for response equipment.

The total volume spilled by casualty spills can be obtained for a port system through the use of equations (1) and (3). Before this is done, two preliminary notes need to be made.

First, although the analysis of port characteristics revealed a relationship between tanker size and casualty spill frequency, the analysis of tanker characteristics revealed no such valid relationship. The average size spilling tanker has been shown to be equal to the average size tanker in the world fleet. Thus, the average size tanker to call in a port system can be viewed as the best estimate of the average size tanker to spill in a port system.

Second, the relationship between average casualty spill size and tanker size is linear. This means that the average spill size for a set of tankers is equal to the spill size of an average size tanker. That is, any two groups of spilling tankers which result in the same average vessel size will exhibit the same estimated average spill volume. Therefore, it is appropriate to substitute DWT for DWT2 when considering estimated spill volumes at the port level.

The combination of these two points allows the conclusion to be drawn that any two fleet mixes of vessels resulting in the same average size will exhibit the same average spill size.

The average volume of oil spillage resulting from casualties in port groups (CASVOL) can be identified as:

$$\begin{aligned}
 \text{CASVOL} &= [\text{VOL (casualty spill)}] * [\text{SPILLS (casualty)}] \\
 &= 0.5283 * (\text{PC}) + 0.0990 * (\text{PC}) * (\text{DWT}) \\
 &\quad - [0.7746 * (\text{THPT}) + 44.35] * (\text{DWT}) + 0.4854 * (\text{DWT})^2 \\
 &\quad - [4.134 * (\text{THPT}) + 250.6]
 \end{aligned}
 \tag{7}$$

Substituting equation (5) into this risk equation yields the following:

$$\begin{aligned} \text{CASVOL} = & 528.3*(\text{THPT}/\text{DWT}) + 0.4854*(\text{DWT})^2 \\ & - [0.7746*(\text{THPT}) + 44.35]*\text{DWT} \\ & + [94.9*(\text{THPT}) - 250.6] \end{aligned} \quad (8)$$

Equation (8) did not originate as a regression equation but rather as a function of two regression equations. Therefore, no confidence limits are given for equation (8).

Total Volume Spilled from all Tanker Spills

The total volume spilled from all tanker spills is a common risk indicator. Its desirability lies in its measure of overall oil spillage. The minimization of total spillage (casualty and operational) is often identified as the goal of reducing tanker risk.

The total volume spilled can be obtained through the use of equations (1) through (4). Equations (1) and (3) have been used to determine equation (7) above. Similarly, equations (2) and (4) can be used to determine the expected volume of oil spillage resulting from operational spills (OPVOL), resulting in the equation:

$$\text{OPVOL} = 1.109*(\text{PC}) \quad (9)$$

The total volume spilled (TOTVOL) can be readily obtained from equations (7) and (9) as:

$$\begin{aligned} \text{TOTVOL} &= \text{CASVOL} + \text{OPVOL} \\ &= 1.637*(\text{PC}) + 0.0990*(\text{PC})*(\text{DWT}) \\ &\quad - [0.7746*(\text{THPT}) + 44.35]*(\text{DWT}) + 0.4854*(\text{DWT})^2 \\ &\quad - [4.134*(\text{THPT}) + 250.6] \end{aligned} \quad (10)$$

Using equation (5), the above risk equation becomes:

$$\begin{aligned} \text{TOTVOL} &= 1637*(\text{THPT}/\text{DWT}) + 0.4854*(\text{DWT})^2 \\ &\quad - [0.7746*(\text{THPT}) + 44.35]*\text{DWT} \\ &\quad + [94.9*(\text{THPT}) - 250.6] \end{aligned} \quad (11)$$

Since equation (11) was not generated as a regression equation but rather as a function of regression equations (1), (2), (3) and (4), no confidence limits are given for the total volume spilled from all tanker spills.

Sensitivity of Risk Indicators

The three risk indicators developed above provide alternate measures by which to evaluate possible scenarios. All three relationships are restricted in their applicability to within the domain of the port group analysis. The bounds of that domain, based upon groups of three port systems, or effectively 12 port years, were first presented in Subsection 4.3. They are:

	<u>Lower Bound</u>	<u>Upper Bound</u>
Port Calls/year	269	2,718
Tonnage Throughput/year	16.4	312
Average Deadweight Tonnage	42.3	132.7

The sparsity of data near the upper end of the port call and tonnage throughput ranges should again be noted.

In order to fully understand the effect each variable has on the risk indicator in the multivariate regression models, it is helpful to standardize each variable to have unit variance. When two or more variables are measured on different units (such as deadweight tons and number of port calls), standardized regression coefficients provide a vantage point from which the importance of the variables in the model can be compared. The relative impact on the risk indicator of incrementing a given variable by one standard deviation unit, while fixing the other variables, is readily conveyed by the use of standardized variables. It is important to note the standardized variables are indicated by an apostrophe (') and are not to be confused with the original variables.

The first risk indicator, as defined by equation (1), is written in standardized form (') as

$$\text{SPILLS (casualty)'} = 2.922*(\text{PC}') - 2.619*(\text{THPT}') + 0.587*(\text{DWT}') \quad (12)$$

By ranking the absolute values of the coefficients, the importance of each variable can be ascertained; the larger the coefficient of the term, the more impact the variable has on the dependent variable. The coefficient indicates that one standard deviation unit increase in the number of port calls (while holding all other variables constant) would introduce the greatest change in the number of casualty spills. In other words, the frequency of casualty spills is most responsive to variability in the number of port calls and least responsive to variability in the average deadweight tonnage.

Applying the same relationship between port calls, average deadweight and tonnage throughput, as seen in equation (5), to the standardized variables yields the following:

$$(PC') = (THPT'/DWT') \quad (13)$$

The second risk indicator, defined by equation (7), is first standardized then simplified by making the substitution in equation (13). The standardized form of the risk equation becomes:

$$CASVOL' = 2.265*(THPT') - 2.030*(DWT')*(THPT') + 0.455*(DWT')^2 \quad (14)$$

From the above equation it is apparent that tonnage throughput contributes the most significant impact on the total volume spilled in casualty spills. Holding deadweight constant and increasing tonnage throughput by a standard deviation unit would introduce a greater change in the volume spilled in casualty spills than the reverse procedure.

It must be noted that equation (14) is only approximately standardized. The risk indicator is the product of two standardized equations, but these two equations were derived from slightly different sets of data. Therefore, the mean values and variances of the deadweight tonnage term in the two equations are only approximately equal. Since the deadweight tonnage term in the risk equation has a mean value close to zero and a variance close to one, equation (14) can be considered to be approximately standardized.

The third risk indicator, defined by equation (10), can be written in standardized form as follows:

$$\text{TOTVOL}' = \text{CASVOL}' + \text{OPVOL}'$$

$$= [2.265 * (\text{THPT}') - 2.030 * (\text{DWT}') * (\text{THPT}') + 0.455 * (\text{DWT}')^2] + [0.625 * (\text{PC}')] \quad (15)$$

Again, the coefficient indicates a standard deviation unit change in tonnage throughput would have a greater impact on the risk indicator than changes in the other terms in the model.

The same situation with unequal mean values and variances that existed with the second risk indicator exists with the third risk indicator. As shown by equation (5), the port calls term in equation (9) can be written as a function of tonnage throughput and deadweight tonnage. By making the substitution, the mean values and variances of the tonnage throughput and deadweight tonnage terms found in equation (7) are only approximately equal to their counterparts found in equation (9). Therefore, while equation (15) suffices to convey the relative importance of the terms in the model, it can be regarded as only approximately standardized.

Other potential risk indicators not presented include operational spill occurrence, operational spill volume, large spill occurrence, and others. In some cases, it was felt that they would simply not be useful. In others, such as for risk of occurrence of large spills, the results obtained are not suited to those applications. In the case of large spills, individual spill volumes have not been predicted, and they cannot therefore be addressed. Additionally, there are relatively few large spills, and an analysis based upon aggregated data was not feasible. Previous studies documenting spill size distributions have done so for all spills. When considering specific tanker characteristics, the data are too sparse to develop and verify such distributions for separate groups of tankers. Thus, the results of this analysis cannot be used to address this concern.

5.2 OPTIMIZATION OF TANKER SIZE

Each of the three risk indicators developed in Subsection 5.1 can be used to determine optimal values for average tanker size and port calls as a function of tonnage throughput. For a given port system with a known tonnage

throughput, this can then be used to determine an absolute optimal value for each of the two remaining variables. Applying the underlying relationship between port calls, average deadweight tonnage, and tonnage throughput found in equation (5) to the three risk equations, they became:

$$\begin{aligned} \text{SPILLS (casualty)} = & 1.518*(\text{THPT}/\text{DWT}) - 1.188 \times 10^{-2}*(\text{THPT}) \\ & + 7.445 \times 10^{-3}*(\text{DWT}) - 0.7200 \end{aligned} \quad (6)$$

$$\begin{aligned} \text{CASVOL} = & 528.3*(\text{THPT}/\text{DWT}) + 0.4854*(\text{DWT})^2 - [0.7746*(\text{THPT}) + 44.35]*(\text{DWT}) \\ & + [94.9*(\text{THPT}) - 250.6] \end{aligned} \quad (8)$$

$$\begin{aligned} \text{TOTVOL} = & 1637*(\text{THPT}/\text{DWT}) + 0.4854*(\text{DWT})^2 - [0.7746*(\text{THPT}) + 44.35]*(\text{DWT}) \\ & + [94.9*(\text{THPT}) - 250.6] \end{aligned} \quad (11)$$

For a given throughput scenario, these equations can each be optimized using differential calculus. The solutions for each indicator provide three different means of evaluating such scenarios.

The sensitivity of the three risk indicators was examined by incrementing tonnage throughput and observing the effect these changes have on the optimal average deadweight tonnages. If the optimal deadweight tonnage is not found to vary to any significant degree with an increase in tonnage throughput, the model describing the risk indicator can be considered insensitive to small changes in tonnage throughput.

Number of Casualty Spills

The differentiation of equation (6) with respect to average deadweight tonnage, assuming tonnage throughput is a constant, yields

$$d\text{SPILLS (casualties)}/d\text{DWT} = -1.518*(\text{THPT})*(1/\text{DWT})^2 + 7.445 \times 10^{-3}$$

To optimize the original relationship, the derivative is allowed to equal zero. This yields, after some algebraic manipulation, the optimal average deadweight tonnage (DWT_{OPT}):

$$DWTOPT = 14.28 \cdot (THPT)^{1/2}$$

(16)

Consideration of the second derivative verifies that this relationship minimizes the original equation. No other local optima exist within the bounds of the analysis. Thus, this relationship provides the global optimum.

The application of these relationships to Greater Puget Sound and other port systems is straightforward. As an example, the cases of Greater Puget Sound (Case 1), a port system with twice the tonnage throughput of Greater Puget Sound (Case 2), and one of thrice the tonnage throughput (Case 3) are shown. All of these cases lie within the bounds of the analysis.

For the years 1976-1979, the tonnage throughput of tankers in Greater Puget Sound was 25.25 million deadweight tons (MDWT) per year. Thus, Case 2 yields 50.5 MDWT, and Case 3 yields 75.75 MDWT.

The selection of tonnage throughput as a constant characteristic of a port system is based upon the assumption that a given amount of oil will be transported into the port by tanker, regardless of how tanker activity might be constrained. This assumption that oil demand is external to method of delivery assumes that the cost of final petroleum products is relatively insensitive to changes in transportation costs due to policies based upon tanker size. While this may be true for small changes in fleet mix or average size, it would not be expected to hold in extreme cases.

Similarly, the assumption of constant tonnage throughput implies a constant rate of tanker utilization. Should the utilization rate increase, fewer tankers would be needed to provide the same amount of oil. As tonnage throughput measures tanker capacity, rather than the amount of oil being carried, this could result in a decrease in both number of port calls and tonnage throughput. This could be expected to reduce the risk of spill occurrence, although the effect on spill volume is undetermined.

Table 5-1 shows the optimal average deadweight tonnage and the estimated number of casualty spills, volume from casualty spills, and total volume spilled for these three optimized cases.

Figure 5-4 shows the relationship between spill frequency and average deadweight tonnage for each of the three cases. The endpoints of the curves represent the constraints of the analysis for that particular scenario. It can be seen that in each case, there is a minimum value of spill risk and a corresponding optimal average deadweight tonnage. In Case 1, with the current

TABLE 5-1

OPTIMAL AVERAGE TANKER SIZE FOR MINIMIZED NUMBER OF CASUALTY SPILLS
FOR GREATER PUGET SOUND
1976-1979

	Historical Experi- ence ¹	Estimated Level ² of Risk	CASE 1 Optimized of Puget Sound	CASE 2 Hypothetical Throughput Scenario (Twice the Current Level)	CASE 3 Hypothetical Throughput Scenario (Thrice the Current Level)
Tonnage Throughput/ Year (MDWT) ³	25.25	25.25	25.25	50.5	75.75
Optimal Average Deadweight Tonnage	51,430	51,430	71,750	101,500	124,300
Optimal Number of Port Calls/ Year	491	491	352	498	610
Spills (Casualty)/ Year ⁴	0.0	0.11	0.048	0.19	0.23
Casualty Spill Volume/Year in Tons (metric)	0	404	245	1,333	1,954
Total Spill Volume/Year in Tons (metric) ⁵	231	946	635	1,885	2,629

- 1 - Historical experience describes spills recorded in the data bases. Actual values of throughput, port calls, and vessel size.
- 2 - Estimated level of risk are values determined from the spill models.
- 3 - Defined as the sum of the deadweight tonnage times the number of port calls, not the quantity of oil transported.
- 4 - Expressions of frequency are useful indicators of future events, but caution must be taken to avoid misinterpretation of these estimated values. "One spill every 'X' years" expresses a calculated rate and does not indicate when a spill may occur.
- 5 - Includes casualty and operational spills.

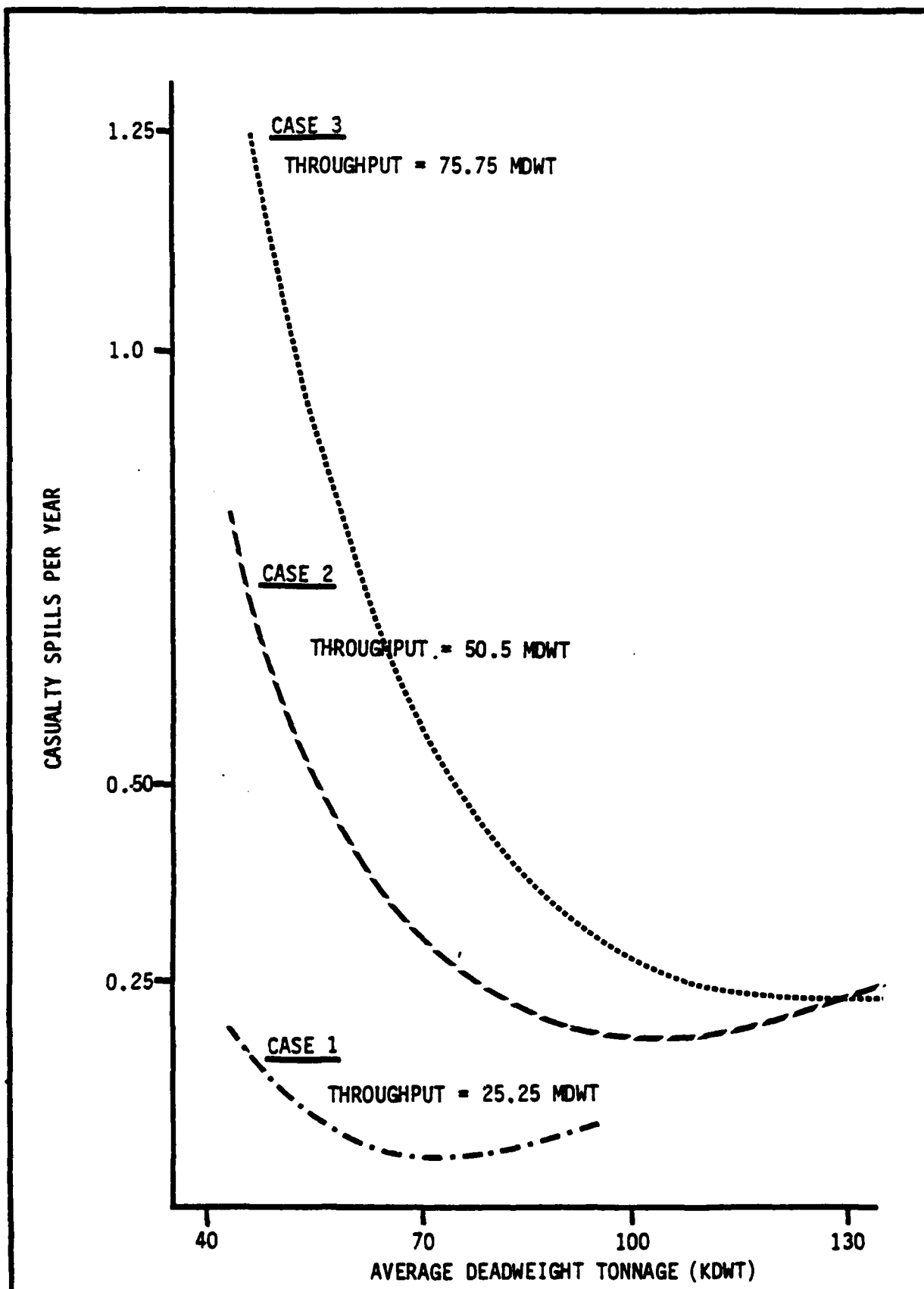


FIGURE 5-4. RELATIONSHIP OF AVERAGE DEADWEIGHT TONNAGE TO NUMBER OF CASUALTY SPILLS

throughput of Greater Puget Sound, it can be seen that this minimum occurs near 70,000 deadweight tons. A range of values can be identified with equal or lower risk of occurrence than the current level of risk. This range extends from 51,430 to approximately 100,000.

The sensitivity of equation (6) is examined by incrementing the current tonnage throughput of tankers in Greater Puget Sound (Case 1) and noting the effect the increase has on the optimal average deadweight tonnage. Increasing tonnage throughput by 10% raised the optimal average deadweight tonnage from 71,750 deadweight tons (DWT) to 75,261 DWT, an increase of less than 5%. Further incremental increases of tonnage throughput showed the optimal average deadweight tonnage increases by approximately 44% of the per cent change in tonnage throughput, or equivalently,

$$(\% \text{ increase in DWT}_{OPT}) = 0.44 * (\% \text{ increase in THPT}).$$

The increase in tonnage throughput results in a much smaller increase in the optimal solution, an indication that the model is relatively insensitive to limited variations.

Volume of Spillage from Casualties

The differentiation of equation (8) with respect to average deadweight tonnage, again with tonnage throughput held constant, yields

$$dCASVOL/dDWT = -528.3 * (THPT) / (DWT)^2 + 0.9708 * (DWT) - [0.7746 * (THPT) + 44.35]$$

Setting this equal to zero yields

$$0 = (DWT)^3 - [0.7979 * (THPT) + 45.68] * (DWT)^2 - 544.2 * (THPT) \quad (17)$$

The optimal solutions are gained in this case through determining zeroes of this cubic polynomial for specific values of THPT. Inspection of the second derivative indicates that for positive DWT, any optimum is a minimum. This implies that at most one optimum exists within the bounds of the analysis, and that it will be a minimum if it exists.

The solutions to this equation are provided in Table 5-2 for the three cases identified above. Also included are the number of casualty spills, volume of casualty spills, and total volume spilled for each of the three optimal scenarios. Figure 5-5 represents the three curves relating casualty spill volume to average deadweight tonnage for each of the three cases. The endpoints denote the bounds of the analysis. Again, a range of values with equal or lower risk than the current level has been identified, extending from 51,430 to approximately 87,000 average deadweight tons.

Increasing the current tonnage throughput in Greater Puget Sound (Case 1) by 10% in risk equation (8) results in the optimal average deadweight tonnage increasing from 68,740 deadweight tons (DWT) to 70,850 DWT, an increase of less than 3%. The approximate relationship between any per cent increase in tonnage throughput and the per cent increase in the optimal average deadweight tonnage can be illustrated mathematically by:

$$(\% \text{ increase in DWT}_{OPT}) = 0.27 * (\% \text{ increase in THPT})$$

In other words, the optimal average deadweight tonnage increases one percent when tonnage throughput is incremented by 4%. Therefore, the volume of spillage from casualty spills does not appear to be substantially sensitive to limited variability in tonnage throughput.

Total Volume Spilled

Differentiation of equation (11) with respect to average deadweight tonnage, again with tonnage throughput held constant, yields

$$dTOTVOL/dDWT = -0.7746*(THPT) + 0.9708*(DWT) - 44.35 - 1637*(THPT)*(1/DWT)^2$$

Setting this equal to zero to find local minima and maxima yields the equation

$$0 = (DWT)^3 - [0.7979*(THPT) + 45.68]*(DWT)^2 - 1686*(THPT) \quad (18)$$

The optimal solutions are found by obtaining zeroes of this cubic polynomial for specific values of THPT. Inspection of the second derivative

Table 5-2

OPTIMAL AVERAGE TANKER SIZE FOR MINIMIZED VOLUME OF SPILLAGE FROM CASUALTIES
FOR GREATER PUGET SOUND
1976-1979

			<u>CASE 1</u>	<u>CASE 2</u> Hypothetical Throughput Scenario (Twice the Current Level)	<u>CASE 3</u> Hypothetical Throughput Scenario (Thrice the Current Level)
	Historical Experi- ence ¹	Estimated Level ² of Risk	Optimized Puget Sound		
Tonnage Throughput/ Year (MDWT) ³	25.25	25.25	25.25	50.5	75.75
Optimal Average Deadweight Tonnage	51,430	51,430	68,740	89,410	109,600
Optimal Number of Port Calls/ Year	491	491	367	565	691
Spills (Casualties)/ Year ⁴	0.0	0.11	0.049	0.20	0.25
Casualty Spill Volume/ Year in Tons (metric)	0	404	240	1,258	1,842
Total Spill Volume/Year in Tons (metric) ⁵	231	946	647	1,884	2,609

- 1 - Historical experience describes spills recorded in the data bases. Actual values of throughput, port calls, and vessel size.
- 2 - Estimated level of risk are values determined from the spill models.
- 3 - Defined as the sum of the deadweight tonnage times the number of port calls, not the quantity of oil transported.
- 4 - Expressions of frequency are useful indicators of future events, but caution must be taken to avoid misinterpretation of these estimated values. "One spill every 'X' years" expresses a calculated rate and does not indicate when a spill may occur.
- 5 - Includes casualty and operational spills.

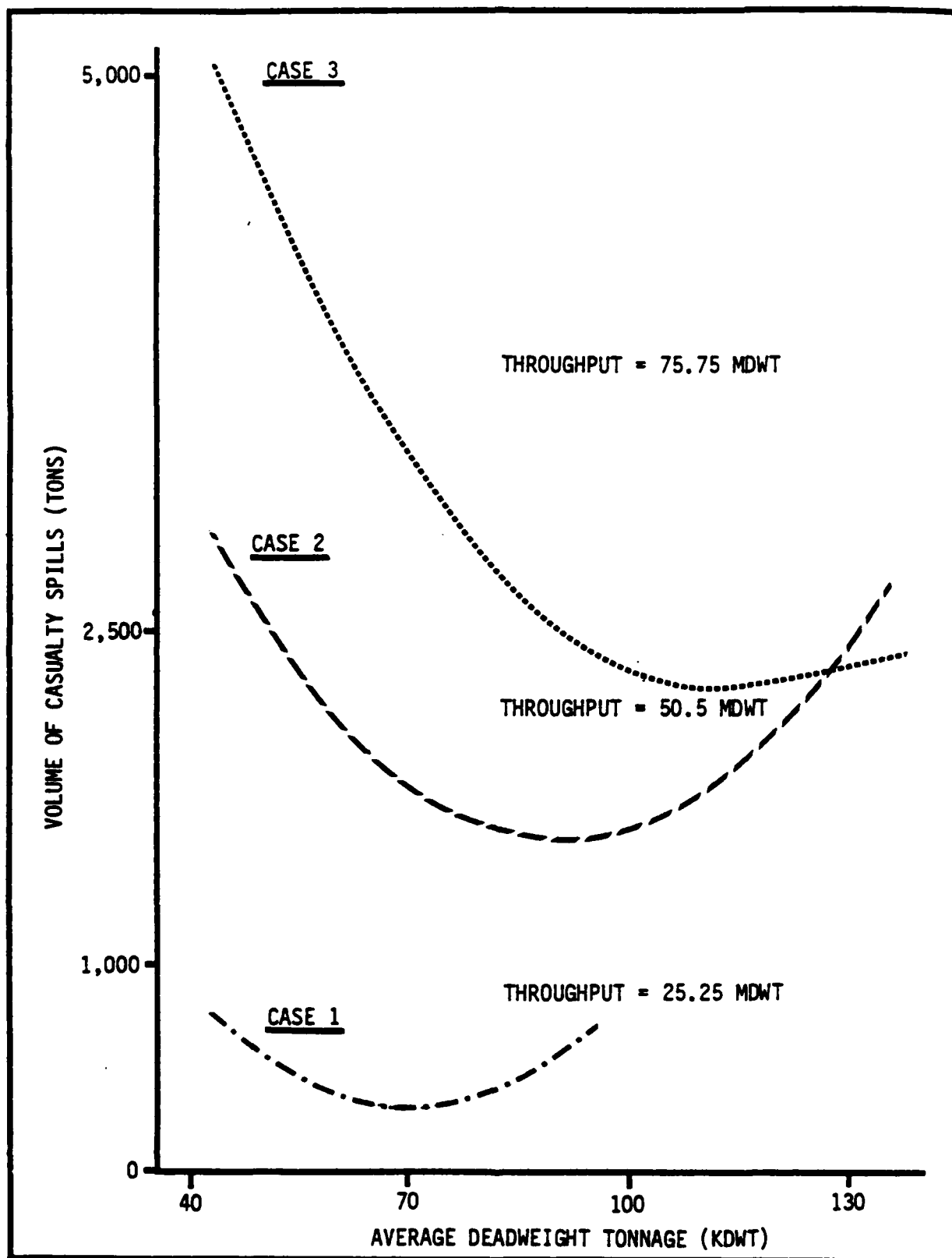


FIGURE 5-5. RELATIONSHIP OF AVERAGE DEADWEIGHT TONNAGE TO TOTAL VOLUME OF CASUALTY SPILLS.

indicates that for positive DWT, any optimum will be a minimum. This also implies that at most, one local minimum can exist within the bounds of the analysis.

The solutions of this equation for the three cases being illustrated are provided in Table 5-3, along with the corresponding values of the three risk indicators. Figure 5-6 represents the three curves relating total spill volume to average deadweight tonnage for each of the three cases. The endpoints denote the bounds of the analysis. A range of values with risk level equal to or lower than the current level extends from 51,430 to approximately 97,000.

The sensitivity of equation (11) is again examined by increasing tonnage throughput of tankers in Greater Puget Sound by 10%. This increase results in an increase of less than 3% in the optimal average deadweight tonnage, an increase from 73,670 deadweight tons (DWT) to 75,960 DWT. The approximate linear relationship between any per cent increase in tonnage throughput and the per cent change in the optimal average deadweight tonnage is as follows:

$$(\% \text{ increase in DWT}_{OPT}) = 0.29 * (\% \text{ increase in THPT})$$

Since increases in tonnage throughput are followed by much smaller increases in the optimal deadweight tonnage, the risk equation can be considered to be relatively insensitive to limited increases in tonnage throughput.

Applicability of Model to Greater Puget Sound

Many questions arise when a statistical model such as that developed here is to be applied. Foremost in this case is: What justification is there for applying this model to Greater Puget Sound? Specifically, given that Greater Puget Sound is a unique port system, how can a model based upon strikingly different port systems be used to describe estimated spill occurrence in Greater Puget Sound?

At the heart of such a concern is the definition of statistical analysis: "the collection, classification, analysis, and interpretation of numerical facts or data, and by the use of mathematical theories of probability, the imposition of order and regularity on aggregates of more or less disparate elements" (66). In short, such an analysis finds commonality among the diverse factors (or variables) presented in the problem.

Table 5-3

OPTIMAL AVERAGE TANKER SIZE FOR MINIMIZED TOTAL VOLUME SPILLAGE
FOR GREATER PUGET SOUND
1976-1979

			<u>CASE 1</u>	<u>CASE 2</u> Hypothetical Throughput Scenario (Twice the Current Level)	<u>CASE 3</u> Hypothetical Throughput Scenario (Thrice the Current Level)
	Historical Experi- ence ¹	Estimated Level ² of Risk	Optimized Puget Sound		
Tonnage Throughput/ Year (MDWT) ³	25.25	25.25	25.25	50.5	75.75
Optimal Average Deadweight Tonnage	51,430	51,430	73,670	95,340	115,700
Optimal Number of Port Calls/ Year	491	491	343	530	655
Spills (Casualties)/ Year	0.0	0.11	0.049	0.19	0.24
Casualty Spill Volume/Year in Tons (metric)	0	404	253	1,262	1,862
Total Spill Volume/Year in Tons (metric) ⁵	231	946	633	1,863	2,569

- 1 - Historical experience describes spills recorded in the data bases. Actual values of throughput, port calls, and vessel size.
- 2 - Estimated level of risk are values determined from the spill models.
- 3 - Defined as the sum of the deadweight tonnage times the number of port calls, not the quantity of oil transported.
- 4 - Expressions of frequency are useful indicators of future events, but caution must be taken to avoid misinterpretation of these estimated values. "One spill every 'X' years" expresses a calculated rate and does not indicate when a spill may occur.
- 5 - Includes casualty and operational spills.

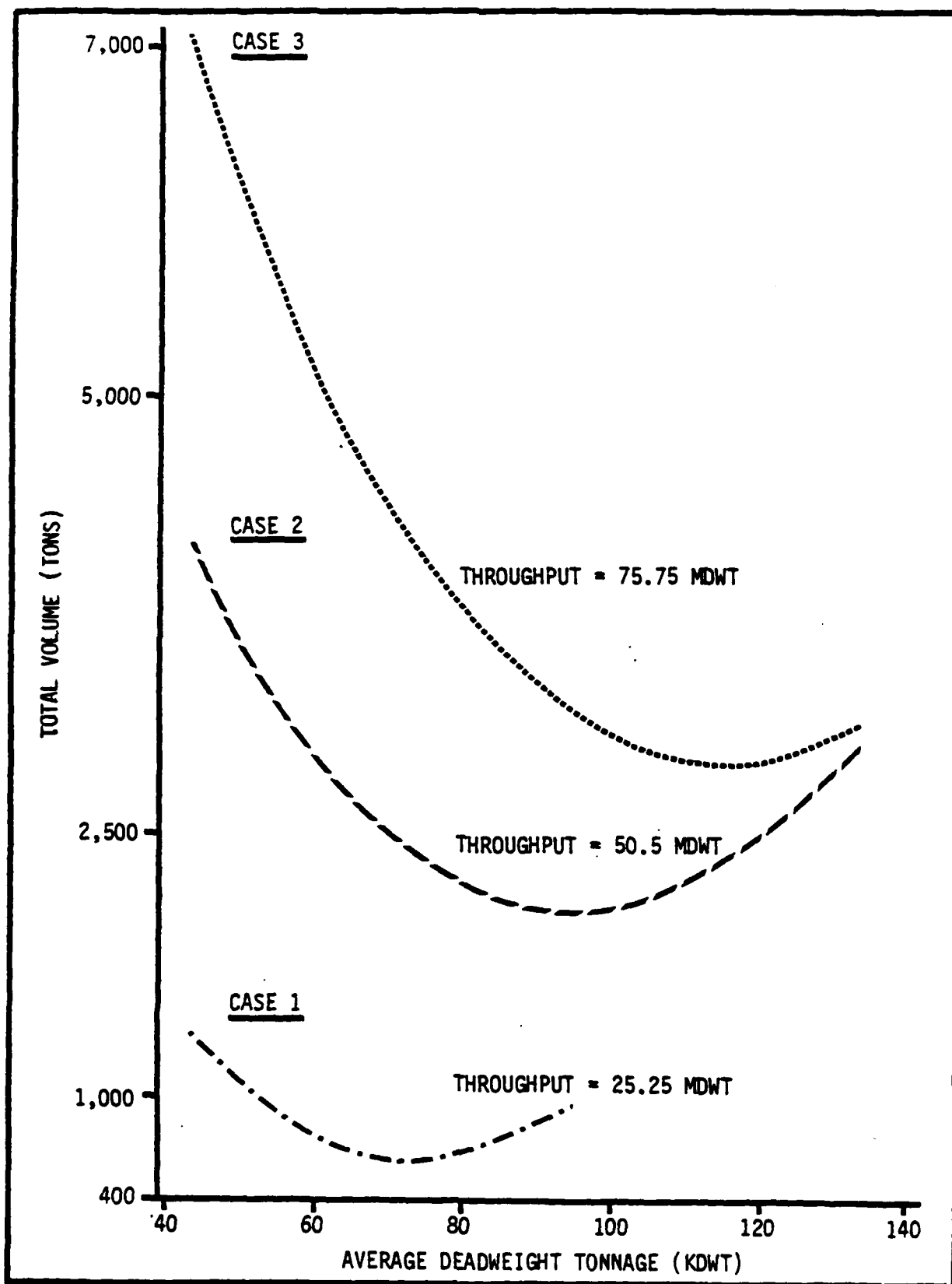


FIGURE 5-6. RELATIONSHIP OF AVERAGE DEADWEIGHT TONNAGE TO TOTAL VOLUME SPILLED.

In the present case, sixty port systems were studied. Each is unique. Some of these unique features are accounted for explicitly in the model: namely, port activity as described by number of port calls and tonnage throughput, and average tanker size. Other features are not included explicitly. These include, for example, physical port characteristics and traffic density. Some such factors are included implicitly in the model, to some degree, through other variables. For example, physical constraints limiting the maximum vessel size may be reflected in part through average deadweight tonnage. Any such implicit inclusion can only be hypothesized.

The significance of excluded variables is measured by the validity of the model. If some factor of overriding importance is excluded both explicitly and implicitly, then theoretically the accuracy of the model would be poor. This is not the case. Thus, one of three conclusions can be drawn in the present case. First, the three explicit variables may account for other important factors. Second, the three variables included are the most important variables, with all others having relatively little influence upon spill risk. Third, other important factors are not included either explicitly or implicitly, but are relatively invariable for the majority of port systems studied, and thus are not accounted for.

If either of the first two conclusions are accepted, then the validity for application to Greater Puget Sound results directly. If the third conclusion is accepted, then the applicability to Greater Puget Sound is dependent upon whether these unincorporated factors vary dramatically for Greater Puget Sound, thus reducing the accuracy of the model in that specific case.

The determination of the uniqueness of Greater Puget Sound with regard to these unincorporated, in fact unidentified, but important factors could be achieved directly based upon input data used in this study. The resulting model can be used to determine the accuracy in predicting the various risk indicators in Greater Puget Sound. This will indicate whether Greater Puget Sound is an aberration from the worldwide experience or indeed does experience similar tanker spill risk.

For the years 1976-1979, no casualty spills have been reported for Greater Puget Sound. This in itself is not unusual. In fact, twenty-eight of the sixty port systems studied had no casualty spills reported in this period. Using the model developed above, 0.44 spills were estimated for this time period. Based upon that, and assuming a Poisson distribution of spill occurrence with time, zero is the most likely number of spills to have occurred,

with a probability of 64%. Thus, the model is a reasonable predictor of actual occurrence of casualty spills in Greater Puget Sound for this period.

Past OIW studies have also noted that while Greater Puget Sound has had no casualty spills, the occurrence of casualties (non-spilling) involving tankers has been consistent with that for other U.S. ports (1). In fact, the tanker casualty rate for Greater Puget Sound has been higher than the average rate developed for eight major U.S. port systems. Fortunately, no tanker casualties have been reported as resulting in spills for the years 1976-1979.

Operational spillage in Greater Puget Sound is also comparable to that predicted from the model for the years 1976-1979. In this case, however, the reported number and volume of spills are regarded with less confidence due to the form of the operational spill data base. Specifically, precise spill locations must be interpreted from a three letter code for which no reference guide is available (67). Also, as reported earlier, spill volumes are generally reported in ranges, rather than explicit values. For Greater Puget Sound, thirteen operational spills were identified, with an estimated volume of 925 tons, for the years 1976-1979. The model estimates ten spills with a total volume of 2,240 tons for the same period.

A comparison for the developed risk indicators of recorded and estimated spill histories can be seen in Tables 5-1 through 5-3. It can be seen that the estimated spill volumes exceed the recorded historical values. This is due in large part to the absence of casualty spills during this period. Additionally, recorded operational spill volume is lower than the estimated spill volume, even though a greater number are recorded than estimated.

When predicting numbers of spills, it can be seen that the models are quite accurate for both casualty and operational spills. When total spill volumes are then determined, the estimated spill volumes are higher than the actual spill volumes. This result is not unexpected, due to the distribution of individual spill volumes. Individual tanker spill volumes have been found to follow distributions with the characteristic that most spill volumes fall below the average spill volumes (14). This is due to the infrequency of extremely large spills which have a large influence upon average spill size. Thus, in the case of relatively few spills, it is most likely that the average spill size is lower than the average spill size of the entire data base, due to the low likelihood of an extremely large spill. Such is the case in Greater Puget Sound. To ignore the possibility of such catastrophic spills,

however, would ignore the overwhelming impact that such spills have. In short, given a "long enough" time frame, the estimated spill volume would be the expected average spill volume.

Stated another way, the present level of risk inherent in this system is higher than the actual experience to date. The fact that there have been zero casualty oil spills in Greater Puget Sound during the study period, for example, does not indicate that there is zero chance of such spills in the future. The level of risk in any active operation or system is always greater than zero.

Finally, when considering the uniqueness of Greater Puget Sound, it must be noted that the single most unique feature during the years 1976-1979 was the existing 125,000 deadweight ton limit, imposed through law or regulation rather than due to physical constraints. When considering the excellent safety record of this area in the past, the possibility that it may be related, in part, to this limit cannot be discarded.

SECTION 6. CONCLUSIONS, RECOMMENDATIONS AND COMMENTS

The previous sections of the report have presented the results of this study: the acquisition of data bases, the approach, the results of the statistical analyses and finally, the optimization of the final empirical relationships. This section will offer some insights and interpretations into the use of the results of the analyses. This discussion is intended to be an overview only. It is well recognized that these numbers may be further interpreted and debated and that any potential rulemaking action will be based upon economic, social, environmental, legal and political factors.

First, the results are properly interpreted as hindcasts of the spilling history of tankers. While strong heuristic arguments can be advanced for using recent descriptions of spillage to plan for the future, such use of the information is technically outside the scope of this project. Furthermore, a very basic assumption of this study was that similar tankers and port systems would have similar spilling histories, so the identification of particular vessels and port systems with extremely poor or extremely good records are also beyond the scope of the study. These results indicate those physical characteristics of groups of tankers and port systems that are statistically related to the frequency and volume of oil spills. Thus, this study has developed the parameters which can hindcast the risks for various aggregates of tankers, not for individual tankers. Finally, since the results of this study are based upon statistical analyses involving correlations and multi-variable regressions, the relationships are not necessarily causal. Obviously, a port call does not "cause" an oil spill, but this and previous studies demonstrate that it is a reliable indicator of the frequency of such spills.

When considering the optimized conditions, it must be noted that they optimize spill risk only with regard to the variables addressed. Thus, improving tanker utilization, requiring tug assistance, or reducing demand for oil are not options addressed in the study. Also, other constraining factors, such as tanker availability or physical port constraints, which should be considered, are not a part of the optimization process. As an example, it is possible to contrive a circumstance where the optimal average size would exceed the maximum size vessel which could call in a port. Thus the results

of the optimization process must be studied for their plausibility when applied.

In Section 5, the statistically derived equations were used to determine what particular set of average tanker size, port calls and throughput would minimize the estimated number of casualty spills, the estimated volume due to casualty spills, and the average amount of oil spilled in a given port system per year. Some of these risk indicators could be optimized for casualty spills, for operational spills and for both types of spills. The net result is that there are a number of different optimal conditions and that having several "best" solutions is not a contradiction. The definition of "best" is left open for interpretation and discussion. This section will simply help to relate the numbers derived from the study to the different definitions of the "best" solution.

The analysis presented in Subsection 4.3 showed that the volume of oil spilled from casualties could range up to an average value of about 34,000 tons for the largest range. The expected volume of operational spills, on the other hand, was not found to be a function of any of the exposure variables. While the volume spilled does vary among different incidents, the volume spilled per incident is taken to be a constant (224 tons). Therefore, if one is seeking to minimize the probability of large volume spills, the most likely risk indicator to minimize would be the volume of casualty spills. Admittedly, there can be very large volume operational spills but this analysis did not find any exposure variable which related to this risk indicator.

The initial question in a discussion of large oil spills is how many tons constitutes a "large" spill? For illustrative purposes, and for this section only, consider the possibility of a spill being larger than the mean value of all hull rupture spills in the data: 8,164 tons. There is nothing magical about this number; it is simply the arithmetic average of all spills. At least 25 of the 190 spills had a volume greater than the average, so based on a very simple frequency analysis, one could say that about one spill in eight in the studied world fleet would have a volume greater than 8,164 tons (or approximately 2-1/2 million gallons).

Before proceeding to a discussion of the volume of oil which could be expected to spill in a port during a specified period, it would be useful to offer two additional facts to help put the information and qualitative analysis of the preceding paragraph in perspective. The hindcasts are indicators

of what might have been (or if one accepts the heuristic arguments, they might be interpreted as predictors). A frequency of one spill in "X" years does not mean that the event will necessarily happen in the next "X" years, or only once in the next "X" years, or any similar misinterpretation. The frequency only points out the likelihood of the event occurring in a given period of time. The spill may never happen, or it may happen twice a day for the next "X" years. The probability of these last two statements is low but finite. The second fact to be borne in mind is that the average tanker in Greater Puget Sound during the study period was 51,246 DWT and was therefore capable of spilling nearly 16 million gallons. A 125,000 DWT tanker could potentially spill more than 38 million gallons.

Operational spills appear to have an average volume and frequency related to the number of port calls. Operational spills account for approximately 25% of the total volume spilled. Using these relationships, the frequency and the expected volume of operational spills can be reduced by reducing the number of port calls. If the throughput of oil in a port system does not decrease, a reduction in the number of port calls would necessitate an increase in the tanker size. But since the size of casualty spills increases with the size of the vessel, and typically, 75% of the oil spilled is from casualty spills, the combination of decreased numbers of port calls and increased tanker size could significantly increase the estimated amount of oil spilled. Thus, minimizing the number and expected volume of operational spills alone would not seem to be the "best" way to reduce the amount of oil spilled.

The final risk indicator to be discussed is the expected amount of oil that would have been spilled in a given period of time. This indicator is effectively the product of the estimated frequency of oil spills and the mean volume of a spill. This indicator takes into account both operational spills and casualty spills. In the Greater Puget Sound port system, currently, the hindcast would indicate that the inherent level of risk is 1,013 tons per year.

As further illustration of the optimization process, consider the situation where the Greater Puget Sound port system had twice increased the amount of oil throughput during the last four years. In order to minimize the total volume spilled, the average size of the fleet should increase from 73,670 DWT to 95,340 DWT. The estimated frequency of casualty spills increases by nearly a factor of four from 0.05 spills per year to nearly 0.2 spills per year.

Furthermore, the relative percentage of casualty spilled oil would have increased from its current level of 43% to nearly 72%. Thus, more oil would be spilled and a greater percentage of that spillage would be due to casualty spills.

Conclusions

Within the constraints of this study, the following conclusions are drawn:

1. There is a quantifiable relationship between oil spill risk and tanker size. Oil spill frequency is linearly related to tanker size, port calls, and throughput. Oil spill volume is linearly related to tanker size. The relationship between tanker size and total oil spillage is thus nonlinear and multivariate.
2. Optimal average tanker sizes for port systems (about 70,000 deadweight tons for Greater Puget Sound) have been determined for three risk indicators. However, an optimal upper limit on individual tanker size (e.g., 125,000 deadweight tons) has not been determined.
3. At current throughput levels for the Greater Puget Sound port system, three optimal average tanker sizes, based upon spill frequency and volume, not including risk of damage, were found to be:
 - a. About 72,000 average deadweight tons for minimizing the number of spills which might result from tanker casualties.
 - b. About 69,000 average deadweight tons for minimizing the volume of spills which might result from tanker casualties.
 - c. About 74,000 average deadweight tons for minimizing the total volume of spills which might result from tanker casualties and operations.
4. The optimal average tanker size increases nonlinearly with throughput in a port system.

5. With the current 125,000 deadweight ton limit in effect, the average size of tankers calling in Greater Puget Sound during the study period was about 51,000 deadweight tons (or about 20,000 less than the three optimal averages determined in this study). A range of values for average deadweight tonnage has been identified for which the three risk indicators are equal to, or less than, the estimated current risk.
6. Statistically meaningful relationships were not found relating tanker age and spill risk. This does not mean that such a relationship does not exist. A general trend was observed in the data indicating a slight peak in spill frequency near 15 years of age.

Recommendations

From the results of the study, the following recommendations are made:

1. It should be determined whether risk reduction through limitations upon tanker characteristics such as size would be more beneficial than through any other risk management measures, such as improved Vessel Traffic Service.
2. If a tanker size limit rule is made final, the size selected should reflect consideration and trade-offs among additional factors, including economic, social, environmental, legal, and political concerns. This study indicates that to minimize the risk indicators discussed, the size limit selected should be greater than 70,000 deadweight tons.
3. Further investigations of tanker size and spill risk should concentrate upon three areas: the physical characteristics of ports (including weather and sea conditions); the risk of occurrence of large spills; and the risk of damage due to oil spillage.

Comments

If tanker size had been found to be an invalid exposure variable, this study would have drawn and published that conclusion. Such results could have removed any quantitative basis for the present rulemaking approach to risk

reduction through restricting tanker size. This study shows that tanker size is a proper exposure variable. Thus, there is a limited basis for this rule-making approach. It is by no means the only basis or only rulemaking approach which should be considered in the decision-making process of the Coast Guard.

Many possible courses of action are available. Although this is by no means an exhaustive list, they include:

- Maintain the current tanker size limit at 125,000 deadweight tons
- Introduce a new upper size limit on tanker size
- Introduce a lower limit on tanker size
- Remove all tanker size limitations
- Introduce limitations on other tanker characteristics or activities

Maintaining the current tanker size limit would result in the level of risk estimated for Greater Puget Sound by the models developed in this study. The purposes served by the original imposition of the limit would continue to be served at the same level of effectiveness. This effectiveness needs to be weighed against any costs incurred due to the limitation, and compared to alternative policies.

The introduction of a new upper limit on individual tanker size could result in either a higher or lower size than the current 125,000 deadweight tons. It would be expected that raising (lowering) the size limit would raise (lower) the average tanker size. In terms of spill risk, a higher limit would result in a lower overall spill risk for limited changes in average deadweight tonnage, and lowering the limit would raise the spill risk. The impact of a change in the size limit upon average size would need to be determined before the effect of a change could be quantified. For example, there are very few tankers in the range from 160,000 to 200,000 deadweight tons. Thus, varying the limit through this interval would have very little impact on vessels available to call. It should be noted that a large increase in average size could increase spill risk. Additionally, an increase in the size limit would increase the estimated average spill size due to casualties. Again, factors not addressed in this study, such as risk of environmental damage, would need to be considered.

The introduction of a lower limit on tanker size, essentially excluding tankers below a given size, would be expected to result in an increase in

average deadweight tonnage. Again, for a limited range this would result in a decreased spill risk. The impacts of an imposed lower limit upon average tanker size would need to be determined. Additionally, impacts upon industry could be expected to be large, as many sites might be excluded from tanker calls due to limited size facilities.

The imposition of a lower limit is not an exclusive option. In conjunction with such a limit, an upper size limit could also be imposed. In such a case, the impacts of the two limits would tend to offset each other to some degree. Possible advantages of such a policy would lie outside the realm of this study.

The removal of tanker size limitations would likely result in an increase in average deadweight tonnage. Depending upon the extent of that increase, the risk of spillage could go down. For a large increase, the spill risk could increase. Other risks not accounted for in this study, such as the risk of large spills, might be expected to increase.

Finally, the introduction of limitations upon tanker characteristics other than size would have no effect upon the spill risk determined in this study, except as such limitations might affect the average deadweight tonnage. The overall impacts of such possible limitations should be evaluated outside the realm of this study.

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APPENDIX A
DATA CONTACTS

ORGANIZATION

AFRICA

1. Republic of Liberia
Bureau of Maritime Affairs
New York, NY

ASIA

2. Consulate-General of Japan
Seattle, WA
3. Energy Inc.
Kent, WA
4. Maritime Safety Agency
Tokyo, Japan
5. Nihon Kainan Boshi Kyodai
Tokyo, Japan
6. The Japan Tanker Owners Association
Tokyo, Japan
7. Pusat Dokumentasi
Ilmiah Nasional
Jakarta, Indonesia

EUROPE

8. Advisory Committee on Oil Pollution of the Sea
London, England
9. British Department of Energy
Petroleum Engineering Division
London, England
10. British Department of Trade
Marine Division
Marine Pollution Control Unit
London, England
11. Chemical Industries Association Ltd.
London, England
12. Cork County Council (Bantry Bay)
Cork, Ireland

13. Det Norske Veritas
Oslo, Norway
14. Gemeentelijk Havenbedrijf/Amsterdam
Amsterdam, The Netherlands
15. Helsinki University of Technology
Helsinki, Finland
16. Institut Francais du Petrole (IFP)
Rueil-Malmaison, France
17. Inter-Governmental Maritime Consultative Organization
Maritime Safety Committee
London, England
18. International Chamber of Shipping
London, England
19. International Tanker Owners Pollution Federation, Ltd. (TOVALOP)
London, England
20. Ireland Government
21. Liverpool Polytechnic
Liverpool, England
22. Liverpool Underwriters Association
Liverpool, England
23. Lloyd's of London
London, England
24. Maritime Directorate
Oslo, Norway
25. Marseilles-Fos
France-Gare Maritime Records & Statistics
Marseille, France
26. Ministry of Transport
Directorate General of Shipping & Marine Affairs
The Hague
The Netherlands
27. Ministerie Van Sociale Zaken
Directoraat-General
Van De Arbeid
Voorburb,
The Netherlands
28. Municipal Port Authority
Rotterdam
The Netherlands

29. National Maritime Institute
Middlesex, England
30. National Ports Council
London, England
31. Nederlands Maritiem Instituut
Rotterdam
The Netherlands
32. Norsk Senter for Informatikk
Oslo, Norway
33. Port Autonome Du Havre
Le Havre, France
34. RWS-Directie
Noord Zee
Rijswijk
The Netherlands
35. Statistical Office of the European Communities
Brussels, Belgium
36. University of Warwick
Statistics Service
Warwick, England

NORTH AMERICA

37. American Institute of Merchant Shipping
38. Environment Canada
Environmental Protection Service
Dartmouth, Nova Scotia
39. Massachusetts Institute of Technology
Cambridge, MA
40. Hughes Aircraft Company
41. National Maritime Research Center
Computer Aided Operations Research and Analysis Facility
Kingspoint, NY
42. National Maritime Study Center
Kingspoint, NY
43. Tanker Advisory Center
New York, NY
44. Transport Canada
Canada Coast Guard
Dartmouth
Nova Scotia

45. Transport Canada
Termopol-Ottawa
Ottawa, Canada
46. U.S. Coast Guard
Washington, D.C.
47. U.S. Dept. of Energy
Energy Information Administration
48. U.S. Dept. of Transportation
Washington, D.C.
49. U.S. Dept. of Transportation
Transportation Systems Center
Cambridge, MA
50. Maritime Administration
Washington, D.C.
51. U.S. National Oceanic and Atmospheric Administration
52. U.S. National Transportation Safety Board
Bureau of Accident Investigation
Washington, D.C.
53. U.S. Office of Technology Assessment
Washington, D.C.
54. World Trade Information Center
New York, NY
55. Worldwide Information Systems (Center for Short-Lived Phenomena)
Cambridge, MA

APPENDIX B

DATA FILE FORMATS

CASUALTY SPILL DATA FILE

<u>Item</u>	<u>Columns</u>	<u>Explanation</u>
1. Vessel Name	1-25	If vessel name is longer than 25 characters, only the first 25 are provided.
2. Vessel Type	26-28	For this file, all entries are OIL, for oil tankers.
3. Vessel Call Sign	29-34	
4. Nation of Registry	35-36	Two letter code for flag, from attached table
5. Gross Tonnage	37-42	In metric tons.
6. Deadweight Tonnage	43-38	In metric tons.
7. Year of Construction	49-50	Last two digits of year of construction
8. Casualty Sequence and Pollution Assessment	51-62	Up to three casualty types and the corresponding pollution assessments are provided. Each casualty type consists of a three letter code, and an associated pollution assessment, a one letter code which follows immediately. The casualty types are: - BKD - Breakdown - BKM - Breaking mooring - CAP - Capsizing - COL - Collision - EXP - Explosion - FRE - Fire - GRD - Grounding - LOA - Loss of anchor - RAM - Ramming a man-made object - STF - Structural failure - WXD - Heavy weather damage

Pollution Assessment Codes are:

- Y,P - Polluting casualty
- N - Non-polluting casualty
- S - Other vessel polluted
- B - Both vessels polluted
- U - Unknown if vessel polluted

Thus, COLP would be a polluting collision, FRENEXPP a fire with subsequent polluting explosion.

<u>Item</u>	<u>Columns</u>	<u>Explanation</u>
9. Date of Casualty	63-68	Coded as MMDDYY
10. Cargo Condition	69-70	Two letter code: LO - Loaded with oil BA - Ballast OT - Chemical cargo LG - Liquefied gas ME - Empty, not gas-free GF - Empty, gas-free UN - Unknown
11. Amount of Outflow	71-76	Quantity spilt in metric tons. If less than 1, 1 is shown
12. Method of Determining Outflow	77	One letter code: R - Reported in information source E - Estimated by information source M - Slight leak or sheen C - Amount unknown. Accompanied by 0 or 1 in 11.
13. Region of Casualty	79-80	Two digit code from accompanying table
14. Specific Location	81-91	Either latitude and longitude or Lloyd's route and port codes
15. Specific Area	92	One letter code: P - Pier H - Harbor, river, canal E - Entranceway C - Coastal, within 50 miles of land S - Sea, over 50 miles from land U - Location not reported
16. Damage Assessment	93-94	Two letter code: SK - Sinking HD - Heavy damage, i.e. structural OD - Other damage ND - No damage UN - Unknown
17. Damage Location	95	One digit code for location on vessel: 1 - Bow, forward of cargo tanks 2 - Cargo tanks 3 - Ballast tank within cargo block

<u>Item</u>	<u>Columns</u>	<u>Explanation</u>
		4 - Both cargo and ballast tank within cargo block 5 - Machinery space 6 - Stern 7 - Bottom 8 - Deck 9 - Combination of above locations 0 - Not reported
18. Extent of Damage	96	One letter code: X - Damage to property off vessel exceeds damage to vessel P - Port side of vessel damaged S - Starboard side of vessel damaged C - Damage near centerline E - Entire vessel damaged U - Not reported I - Could not be determined
19. Role of Vessel	97	One letter code: S - Striking vessel H - Hit by other vessel N - No other vessel involved U - Unknown
20. Other Vessel Type	98	One letter code: T - Tanker G - Liquid gas carrier X - Other U - Unknown
21. Number of Deaths	99-100	Dead or missing
22. Number of Injuries	101-102	
23. Location of Deaths/ Injuries	103	One letter code: B - On both vessels S - On subject vessel O - On other vessel P - On pier V - Various other locations U - Unknown
24. Information Sources	104-135	Three letter codes for information sources. First source documents event as a spill; others may not. Codes used are: CAN - ECAREG (Canadian EPS/CG)

ItemColumnsExplanation

DNV - Det Norske Veritas
EPA - Environmental Protection
Agency
ICS - International Chamber of
Shipping
IFP - French Petroleum Institute
LIB - Republic of Liberia
MAR - MARDATA
PIR - USCG PIRS
STN - Spill Technology Newsletter
TCF - Tanker Casualty File
TOV - World Eagle "Where the Oil
Spilled"
TVP - TOVALOP
WWI - Center for Short-Lived
Phenomena

MODIFICATIONS TO CASUALTY SPILL FILE FORMAT

The following items replace items 1-3 previously shown. The information is obtained from the Tanker Register compiled by OIW.

<u>Item</u>	<u>Columns</u>	<u>Description</u>
a. Lloyd's Number	1-7	A seven digit number unique to a vessel, regardless of changes in name, ownership, flag, etc.
b. Length of Vessel	9-14	Extreme length in meters
c. Breadth	16-20	Extreme breadth in meters
d. Draft	21-26	Maximum summer draft amidships, in meters
e. Vessel Type	27	One digit code: 1 - Oil tanker 2 - Asphalt carrier
f. Rebuilt	28	One digit representing number of times vessel has been rebuilt
g. Power	29-33	Maximum shaft power, in kilowatts

TANKER REGISTER FORMAT

Item	Columns	Explanation
1. Lloyd's Number	1-7	A unique ship identifier regardless of changes in name, flag, owner, or classification of vessel type
2. Call Sign	8-14	Often changes when the owner of flag of registry changes
3. Official Numbers	15-21	Also changes often
4. Vessel Name	22-41	If the vessel name is longer than 20 characters, only the first 20 are provided
5. Flag of Registry	42-43	Two-letter code for flag, from attached table
6. Gross Tonnage	44-49	In metric tons
7. Deadweight Tonnage	50-55	In metric tons
8. Year of Construction	56-57	If ship has been rebuilt, the year of rebuilding is provided.
9. Length	58-63	Extreme length in meters
10. Breadth	64-69	Extreme breadth in meters
11. Draft	70-75	Maximum summer draft amidships, in meters
12. Vessel Type	76	1-digit code: 1 - Oil tanker 2 - Asphalt or oil/asphalt carrier 3 - Bulk/oil carrier 4 - Ore/oil carrier 5 - Chemical/oil carrier 6 - Ore/bulk/oil carrier 7 - Other combination carriers Chemical tankers are not included
13. Rebuilt	77	1-digit code: 0 - Never rebuilt 1,2 - Number of times rebuilt
14. Power	78-82	Maximum shaft power, in kilowatts

Item	Columns	Explanation
15. Vessel Status	83-85	1977-1979 changes, 1-digit code: 0 - No change from previous year 1 - Deleted from file in that year 2 - Name changed during that year 3 - New name of existing ship 4 - New vessel added to file in that year 5 - Intermediate name in a given year (two or more name changes in a year)
16. Laid-up Status	86-89	1976-1979 1-digit codes for laid-up vessels: 0 - Not laid-up 1 - Laid up 1/2 year 2 - Laid up entire year
17. Port Call Activity	90-101	1976-1979 3-digit numbers documenting numbers of port calls made by vessel.

APPENDIX C
METHODS FOR ESTIMATING MISSING TANKER CHARACTERISTICS

After the compilation of the data file was completed, it was found that approximately 2% of the entries reported gross tonnage but lacked deadweight tonnage. The values for the missing data were estimated by utilizing linear regression methods.

Previously, deadweight tonnage has been estimated by multiplying the gross tonnage by a factor of 1.7. This method was found to be lacking in accuracy and in need of refinement. One study, Developing Tanker Casualty and Tanker Traffic Data Bases for 1969-1977, used the following gross tonnage ranges and regression equations:

<u>GROSS TONNAGE RANGES</u>	<u>REGRESSION LINE</u>
1500 to 6500 GRT	$DWT = 1.273 \text{ GRT} + 846$
6500 to 29,999 GRT	$DWT = 1.770 \text{ GRT} - 2616$
over 30,000 GRT	$DWT = 2.107 \text{ GRT} - 13,834$

Two different approaches to the problem were implemented and the reliability of the results produced from the two methods were compared. The first method involved using gross tonnage as the predictor for deadweight tonnage. By plotting the points (x = gross tonnage, y = deadweight tonnage) for those entries reporting both tonnages, it was possible to see certain trends in the data. By partitioning gross tonnage into several ranges, instead of using the entire range, the error of estimate was reduced. The following initial ranges were chosen:

- less than 71,000 GRT
- 71,000 to 152,000 GRT
- over 152,000 GRT

All but one of the missing values fell within the first range. By obtaining a linear regression equation for this range and observing where the actual deadweight values deviated from the deadweight values calculated from the regression equation, it was possible to select ranges for further parti-

tioning. The patterns established by these deviations were utilized to produce the following ranges and regression equations:

<u>GROSS TONNAGE RANGE</u>	<u>REGRESSION LINES</u>	<u>NO. OF MISSING VALUES</u>
(1) 2,400 GRT to 6,999 GRT	DWT = 1.333 GRT+1187.215	12
(2) 7,000 GRT to 27,999 GRT	DWT = 1.815 GRT-2557.935	49
(3) 28,000 GRT to 70,999 GRT	DWT = 2.090 GRT-9154.080	17
(4) 71,000 GRT to 80,999 GRT		0
(5) 81,000 GRT to 151,999 GRT	DWT = 1.981 GRT+10451.972	1
(6) over 151,999 GRT		<u>0</u>
	TOTAL	79

By using these partitions, the average deviation was substantially reduced.

The second method for calculating deadweight tonnage is based on the assumption that deadweight can more accurately be predicted using length, breadth and draft.

Two variations of this method were examined. The first was using an equation that is often used in nautical engineering:

$$\text{DWT} = \text{length} \times \text{breadth} \times \text{draft} \times .84 \times .87$$

35 .

where .84 is the assumed block coefficient, 35 is a conversion factor and .87 is the approximate ratio of deadweight to displacement. The length used in the above equation is waterline length, which is approximately 97% of registered length, the measurement used in our data file.

The second variation involved finding a regression equation, using our data file, relating (length x breadth x draft) and deadweight. This resulted in the following equation:

$$\text{DWT} = 0.7306 * (\text{LNG} * \text{BRD} * \text{DRT}) - 6559$$

A random sample was then taken from the data file from those entries reporting deadweight, length, breadth, and draft. Deadweight tonnage was estimated for those selected, using the methods described above, and compared

to the reported deadweight tonnage. The first method, based on gross tonnage, consistently produced results closer to the actual deadweight than did the two variations based on length, breadth and draft.

It was decided to use the method for estimating deadweight based on gross tonnage rather than length, breadth and draft for several reasons. First, the length needed to accurately utilize the equation involving a block coefficient, and a ratio factor, is the waterline length, which is unavailable. Secondly, this equation is more accurate for large vessels than for small vessels. Since all but one of the missing values come from vessels less than 71,000 GRT, the equation based on length, breadth and draft does not produce the "best" results. Lastly, the random sample indicated that in 10 out of 11 cases, the deadweight tonnage estimate based on gross tonnage more closely represented the actual deadweight than did the estimate based on length, breadth and draft.

In order to estimate missing values of draft and length, the relationships between deadweight tonnage (DWT) and draft (DRT), and between deadweight tonnage (DWT) and length (LNG) were examined by making a logarithmic transformation on DWT.

Regression procedures were applied to the world tanker fleet file, containing 4,055 entries, using deadweight tonnage as the dependent variable and length and draft as the independent variables. The regression analyses resulted in the following linear equations and correlation coefficients:

REGRESSION LINES

CORRELATION COEFFICIENTS

$$DRT = 3.949 \ln(DWT) - 29.772$$

$$0.966$$

$$LNG = 61.855 \ln(DWT) - 444.189$$

$$0.986$$

For analyses which use draft and length, these linear equations will be used to supply the missing values in the file.

APPENDIX D STATISTICAL TECHNIQUES

The following ideas on simple linear regression and multivariate regression can be further examined by referring to Walpole and Myers (1978) (72), Kleinbaum and Kupper (1978) (35), and Snedecor and Cochran (1978) (34).

SIMPLE LINEAR REGRESSION

Bivariate relationships were analyzed using simple linear regression methods; this is the case where there is a single independent variable X and a single dependent variable Y . The variation of Y is observed while controlling the values of X . The general form of a bivariate linear relationship is as follows:

$$Y = \beta_0 + \beta_1 X + E. \quad (B.1)$$

As outlined in Kleinbaum and Kupper (1978) (35), the following statistical assumptions are needed for using a straight-line model:

1. The n observed Y values are statistically independent of one another.
2. The variance is constant for all X , a condition defined as homoscedasticity and written as $\sigma^2_{Y|X} = \sigma^2$.
3. For any fixed value of X , Y is normally distributed.
4. The means, $\mu_{Y|X}$, fall on a straight line.
5. The error term (E) has a mean of 0.

Least-Squares Method

The least-squares method determines the line that best fits the data by minimizing the vertical distance from the line to the data points. Therefore, by minimizing

$$SSE = \sum_{i=1}^n (Y_i - \hat{Y}_i)^2 = \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_i)^2 \quad (B.2)$$

one chooses the values for β_0 and β_1 that produce the best-fitting line based on the data. The values, $\hat{\beta}_0$ and $\hat{\beta}_1$, which minimize the sum of squares are referred to as the least squares estimates.

Minimization of the sum of squares in (B.2) produces the following parameters that define the best-fitting line:

$$\text{slope} = \beta_1 = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^n (X_i - \bar{X})^2} \quad (\text{B.3})$$

$$\text{intercept} = \beta_0 = \bar{Y} - \beta_1 \bar{X} \quad (\text{B.4})$$

$$\text{where } \bar{X} = \sum_{i=1}^n X_i / n \text{ and } \bar{Y} = \sum_{i=1}^n Y_i / n.$$

It is worth noting that the least-squares estimates, $\hat{\beta}_0$ and $\hat{\beta}_1$, define the best-fitting line for the n sample points. In all likelihood, another sample of n points would not produce the same exact estimates.

Adequacy of the Straight-Line Model

The adequacy of the linear model in describing the relationship between a single independent variable and a single dependent variable can be tested using several procedures. For further discussion of these procedures, refer to Walpole and Myers (1978) (72).

1. R^2

The square of the sample correlation coefficient is used as an indication of how well the linear model fits the observed data. R^2 indicates what proportion of the variance in Y exhibited by the data is accounted for by the postulated model. The square root of R^2 , called the correlation coefficient, ranges from -1 to 1 , with ± 1 representing a perfect linear relationship and 0 representing statistical independence. The percentage of variance in Y explained by the linear model is $R^2 \times 100\%$.

2. Significance of Slope

To test the null hypothesis H_0 that the regression is not significant, the following T-statistic can be used:

$$T = \frac{\beta_1}{S_{\beta_1} / \sqrt{n-1}} \quad (\text{B.5})$$

where $\hat{\beta}_1$ is estimated from the sample,

$$S^2_{yx} = \frac{1}{n-2} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2 = \frac{1}{n-2} \text{SSE} \quad (\text{B.6})$$

and

$$S^2_x = \frac{\sum_{i=1}^n X_i^2 - \left(\sum_{i=1}^n X_i\right)^2 / n}{n-1} \quad (\text{B.7})$$

The null hypothesis H_0 that $\beta_1 = 0$ is rejected at the α significance level when $|T| > t_{\alpha/2}$ where $t_{\alpha/2}$ is a value of the t-distribution with $n-2$ degrees of freedom.

3. Significance of Intercept

To test the null hypothesis H_0 that the intercept is not significant (i.e., the intercept does not differ significantly from 0), the following T-statistic can be used:

$$T = \frac{\hat{\beta}_0}{S_{yx} \sqrt{1/n + \bar{X}^2 / (n-1) S_x^2}} \quad (\text{B.8})$$

The null hypothesis H_0 that $\beta_0 = 0$ is rejected at the α significance level when $|T| > t_{\alpha/2}$ where $t_{\alpha/2}$ is a value of the t-distribution with $n-2$ degrees of freedom.

4. Regression Sum of Squares

The null hypothesis H_0 that the linear model is not significant can be tested by using the following F-test:

$$F = \frac{\text{SSR}/1}{\text{SSE}/(n-2)} \quad (\text{B.9})$$

The regression sum of squares, SSR, reflects the amount of variation in the Y values explained by the linear model and can be written as:

$$\text{SSR} = \text{SST} - \text{SSE}.$$

The hypothesis H_0 is rejected at the α significance level if $F > F_{\alpha}(1, n-2)$ where F_{α} is a value from the F-distribution with 1 and $n-2$ degrees of freedom. As described in Applied Regression Analysis and Other Multivariable Methods (35), the t-test and the F-test are equivalent since

$$t^2_{\alpha/2} = F_{\alpha}(1, n-2). \quad (\text{B.10})$$

CONFIDENCE LIMITS

In addition to examining the relative importance of the slope and y-intercept in the linear model, it is often important to attach a confidence interval on the mean response for various values of the independent variable. Using a prechosen confidence level, an interval can be constructed about the mean for a given $X = X_0$. Confidence limits for the regression line can be obtained by plotting several upper and lower endpoints of the intervals and sketching the curves that connect these points.

A $(1-\alpha)100\%$ confidence interval for the mean response $\mu_{Y|X}$ is given by

$$\hat{Y}_0 \pm t_{\alpha/2} s \sqrt{1/n + (X_0 - \bar{X})^2 / (n-1)S_x^2}$$

where $t_{\alpha/2}$ is a value of the t distribution with $(n-2)$ degrees of freedom, $\hat{Y}_0$ is the estimated value using the model, and s is the standard deviation of Y about the regression line.

MULTIVARIATE REGRESSION

Multivariate regression is an extension of simple linear regression. Instead of observing the change in Y by controlling a single independent variable, multivariate regression analyzes the relationship between the dependent variable Y and k independent variables, $X_1, X_2, \dots, X_k$. The general form of the multivariate regression model is given by

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + E \quad (B.11)$$

where $\beta_0, \beta_1, \beta_2, \dots, \beta_k$ are the regression coefficients.

The same basic assumptions needed for using a straight-line model are needed for a multivariate regression model but in an extended form:

1. The n observed Y values are statistically independent of one another.
2. For any fixed combination of $X_1, X_2, \dots, X_k$ the variance of Y is constant and written as $\sigma^2_{Y|X_1, X_2, \dots, X_k} = \sigma^2$.
3. For any fixed combination of $X_1, X_2, \dots, X_k$, Y is normally distributed with a mean of $\beta_0 + \beta_1 X_1 + \dots + \beta_k X_k$.

Least Squares Method

The least squares method chooses estimates of $\beta_0, \beta_1, \dots, \beta_k$ which minimize

$$SSE = \sum_{i=1}^n (Y_i - \hat{Y}_i)^2.$$

It is not worthwhile to list the solutions for the least squares estimates here. Computer algorithms are available to calculate these estimates which otherwise would take a considerable amount of time to calculate.

Adequacy of the Model

The methods used for determining the adequacy of the straight-line model are applicable to multivariate regression with some modifications.

1. $\frac{R^2}{R^2}$ indicates what proportion of the variance in Y exhibited by the data is explained by the linear combination of the k independent variables.
2. Significance of Variables in the Regression Model
The significance of any variable in the postulated model can be tested by using the following statistic:

$$T = \frac{\hat{\beta}_i}{S_{\hat{\beta}_i}} \quad (B.12)$$

where $S_{\hat{\beta}_i}$ is the sample standard deviation of the least squares estimate $\hat{\beta}_i$. The null hypothesis that β_i is not significant in the regression model is rejected if $|T| > t_{\alpha/2}$ where $t_{\alpha/2}$ is a value of the t-distribution with $(n-k-1)$ degrees of freedom.

3. Regression Sum of Squares
To test the adequacy of the model, the null hypothesis that the regression is not significant can be tested by calculating

$$F = \frac{SSR/K}{SSE/(n-k-1)} \quad (B.13)$$

The null hypothesis is rejected at the α significance level if

$$F > F_{\alpha}(k, n-k-1)$$

where F_{α} is a value from the F-distribution with k and $n-k-1$ degrees of freedom.

CONFIDENCE LIMITS

When two or more independent variables appear in the regression model, a confidence interval on the mean response can be obtained for a chosen set of values for the independent variables, $X_{10}, X_{20}, \dots, X_{k0}$. A $(1-\alpha)100\%$ confidence interval for the mean response $\mu_{Y|X_{10}, X_{20}, \dots, X_{k0}}$ is given by

$$\hat{Y}_0 \pm t_{\alpha/2} S \sqrt{X'_0 (X'X)^{-1} X_0}$$

where $t_{\alpha/2}$ is a value of the t distribution with $(n-k-1)$ degrees of freedom. The vector X_0 represents the chosen values for the independent variables and X is the sample matrix.

POLYNOMIAL REGRESSION

No indication of a "better" model is given by the lack of fit tests performed on a straight-line model. If the straight-line model is tested and found to adequately describe the variations in Y exhibited by the data, no further model need be considered. On the other hand, if the straight-line model is tested and found to be inadequate, a graph of the data points or the residuals may suggest the use of a parabolic model. The general form of a second order parabolic model is as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_1^2 + E. \quad (B.14)$$

Least Squares Method

As in the case of linear regression, the least squares method of estimation involves minimizing the distance from the data points to the fitted parabola, thereby producing the "best-fitting" parabola for the sample data. The estimates $\hat{\beta}_0$, $\hat{\beta}_1$, and $\hat{\beta}_2$ are called the least squares estimates and represent estimates of the unknown coefficients of the parabolic model.

Solving for $\hat{\beta}_0$, $\hat{\beta}_1$ and $\hat{\beta}_2$ can most easily be accomplished by utilizing available computer algorithms as the formulas to the solutions are quite complex.

Determining the Importance of X^2 in the Model

Theoretically, the addition of the second order term in the parabolic model will increase the regression sum of squares (SSR) and reduce the error sum of squares (SSE). It must be decided whether the increase in the regression sum of squares is significant; in other words, is it justifiable to include X^2 in the model?

The lack-of-fit test for a second order parabolic model uses the following F-statistic

$$F = \frac{SSR - R(\beta_1)}{SSE/(n-2-1)} \quad (B.15)$$

where SSR is the regression sum of squares with β_0 , β_1 , and β_2 in the model and $R(\beta_1)$ is the regression sum of squares without β_2 in the model.

The null hypothesis that the parabolic model is not significant is rejected at the α level of significance if $F > F_{\alpha}(1, n-2-1)$.

REGRESSION MODEL ASSUMING A NON-CONSTANT VARIANCE

The linear relationship between the average volume spilled and deadweight tonnage (see Section 4.3, Analysis from Deadweight Tonnage Perspective) violated the constant variance assumption. As deadweight tonnage increased, the variance increased. First it was necessary to show the standard deviation of Y (average volume) was statistically increasing linearly with X (deadweight tonnage). Then the model could be written as

$$Y = \beta_0 + \beta_1 * X + E * X \quad (B.16)$$

where E represents the error term with mean 0 and variance σ^2 . The variance of equation (B.16) is

$$\text{Var}(Y) = X^2 \sigma^2. \quad (B.17)$$

Therefore, for any given X the variance of Y is a function of X and not a constant.

Dividing both sides of equation (B.16) by X results in the new regression model

$$Y/X = \beta_0/X + \beta_1 + E. \quad (B.18)$$

By regressing Y/X against 1/X, the linear regression requirement of constant variance is satisfied. The dependent variable, Y/X, now has a mean of $(\beta_0/X + \beta_1)$ and variance of σ^2 ; therefore, ordinary regression methods can be employed.

For a detailed explanation of the proceeding method, see Recent Advances in Sales Ratio Analysis written by James E. Reinmuth (36).

LEVELS OF SIGNIFICANCE

1. Type I Error:

Hypothesis testing involves using sample data to test whether a statistic calculated from the sample data is significantly different from the hypothesized statistic value. The α level of significance specifies the regions of acceptance and rejection of the null hypothesis. If the sample data indicates the rejection of the null hypothesis when it is true, a type I error has been committed. The probability of type I error is most commonly referred to as the α level of significance.

2. Type II Error:

The second type of error that can be committed is accepting the null hypothesis when it is false. The probability of type II error is most commonly denoted by β .

For a further description of levels of significance, see Probability and Statistics for Engineers and Scientists by Walpole and Myers (72).

APPENDIX E

DESCRIPTIVE STATISTICS FOR REGRESSION EQUATIONS

For each regression equation found in the text, the page numbers on which the equation appears and the following descriptive statistics are given:

- R
- R^2
- R^2 adjusted for the degrees of freedom
- Standard error of estimate (SEE)
- Standard error of the regression coefficients

Pages ES-9 and 67:

$$(\text{Number of Casualty Spills}) = -5.573 + 8.607 \times 10^{-4} * (\text{Port Calls})$$

$$R = 0.67$$

$$R^2 = 0.45$$

$$R^2 \text{ adjusted} = 0.42$$

$$\text{SEE} = 3.972$$

Standard error of the regression coefficients:

Variable:	Standard Error:
Port calls	0.0002
(constant)	4.039

Page 70:

$$(\text{Average Volume Spilled}) = 521 + 0.08383 * (\text{Deadweight Tonnage})$$

$$R = 0.71$$

$$R^2 = 0.50$$

$$R^2 \text{ adjusted} = 0.47$$

$$\text{SEE} = 8,299.25$$

Standard error of the regression coefficients:

Variable:	Standard Error:
Deadweight Tonnage	0.020
(constant)	2,570

Pages ES-9, ES-11 and 73:

$$(\text{Average Volume Spilled}) = 348 + 0.06523 * (\text{Deadweight Tonnage})$$

$$R = 0.78$$

$$R^2 = 0.60$$

$$R^2 \text{ adjusted} = 0.58$$

$$\text{SEE} = 7,420$$

Standard error of the regression coefficients:

Variable:	Standard Error:
Deadweight Tonnage	0.01575
(constant)	2,218

Pages ES-10, ES-11 and 75:

$$(\text{Number of Operational Spills}) = 4.95 \times 10^{-3} * (\text{Port Calls})$$

$$\left. \begin{array}{l} R = \\ R^2 = \\ R^2 \text{ adjusted} = \end{array} \right\} *$$

$$\text{SEE} = 27.412$$

Standard error of the regression coefficients:

Variable:	Standard Error:
Port Calls	0.0003

* The statistical package used does not provide these values for equations forced through the origin. However, these values should be approximately equal to those values obtained from the corresponding equation that was not forced through the origin (see page E-4).

Pages ES-10 and 79:

$$(\text{Spills}/100 \text{ Tanker Years}) = -0.0064*(\text{AGE})^2 + 0.185*(\text{AGE}) + 0.611$$

$$R = 0.66$$

$$R^2 = 0.44$$

$$R^2 \text{ adjusted} = 0.35$$

$$\text{SEE} = 0.612$$

Standard error of the regression coefficients:

Variable:	Standard Error:
AGE^2	0.0021
AGE	0.0659
(constant)	0.4364

Pages ES-10, ES-11 and 104:

(Number of Casualty Spills/Year)

$$= 1.518 \times 10^{-3} * (\text{Port Calls/Year})$$

$$- 1.188 \times 10^{-2} * (\text{Tonnage Throughput in MDWT/Year})$$

$$+ 7.445 \times 10^{-3} * (\text{Average Deadweight Tonnage in KDWT})$$

$$- 0.720$$

$$R = 0.92$$

$$R^2 = 0.85$$

$$R^2 \text{ adjusted} = 0.83$$

$$\text{SEE} = 1.63$$

Standard error of the regression coefficients:

Variable:	Standard Error:
Port Calls	0.0002
Tonnage Throughput	0.0019
Average Deadweight	
Tonnage	0.0019
(constant)	2.0830

Pages ES-11 and 76:

$$\text{VOL (Operational Spill)} = 224$$

$R =$	}	not applicable
$R^2 =$		
$R^2 \text{ adjusted} =$		
$\text{SEE} =$		

Standard error of the regression coefficients:

Variable:	Standard Error:
(constant)	2,304.3

Page 72:

$$\text{VOL} = 791 + 0.0799 * (\text{DWT})$$

$R = 0.74$
 $R^2 = 0.55$
 $R^2 \text{ adjusted} = 0.52$
 $\text{SEE} = 7,861$

Standard error of the regression coefficients:

Variable:	Standard Error:
DWT	0.0167
(constant)	2,350

Page 73:

$$\text{SPILLS (Operational)} = 13.3 + 0.0042 * (\text{PC})$$

$R = 0.53$
 $R^2 = 0.28$
 $R^2 \text{ adjusted} = 0.24$
 $\text{SEE} = 27.99$

Standard error of the regression coefficients:

Variable:	Standard Error:
PC	0.0016
(constant)	28.46

Page 103:

$$\text{SPILLS} = 6.199 \times 10^{-4} * (\text{PC}) - 2.515 \times 10^{-3} * (\text{THPT}) - 0.017$$

$$R = 0.64$$

$$R^2 = 0.41$$

$$R^2 \text{ adjusted} = 0.39$$

$$\text{SEE} = 1.33$$

Standard error of the regression coefficients:

Variable:	Standard Error:
PC	0.0001
THPT	0.0007
(constant)	0.2890

Page 103:

$$\text{SPILLS/THPT} = -5.051 \times 10^{-5} * (\text{DWT}) + 9.889 \times 10^{-3}$$

$$R = 0.32$$

$$R^2 = 0.10$$

$$R^2 \text{ adjusted} = 0.09$$

$$\text{SEE} = 0.0078$$

Standard error of the regression coefficients:

Variable:	Standard Error:
DWT	0.0195
(constant)	0.0019

**DATA
FILM**