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For abstract - see inside back cover.

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EQUIVALENT SAFETY CONCEPT FOR THE MARINE TRANSPORT OF MATERIALS

Report of the
5 Panel on Equivalent Safety Concept
of the Committee on Maritime Hazardous Materials
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The report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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ABSTRACT

A methodology, termed the Equivalent Safety Concept (ESC), to determine the relative hazards associated with vessels carrying hazardous materials into ports by establishing hazard indexes for the cargo, the ship, and the port was proposed by Danahy and Gathy in 1973. The ESC was intended to provide a systematic framework for use by the Captain of the Port in his daily activities.

The panel reviewed the Danahy and Gathy approach and other related literature to determine whether use of a numerical equivalent safety methodology was feasible. It concluded that it was and decided to proceed by modifying the Danahy and Gathy approach. Formulations are presented for a vessel safety index and for a cargo hazard index addressing the risk due to flammability and inhalation toxicity on accidental release of the cargo. An initial approach to formulating a port hazard index also is presented but the panel recommends that this index be refined by the Coast Guard and that it be used in its present form only as a guide for local authorities.

The vessel safety index and the port hazard index need to be tested using information acquired from accident investigations.

PREFACE

The water transportation of hazardous materials poses a certain degree of risk. To minimize the risk, the U.S. Coast Guard (USCG) is charged with the responsibility of ensuring that cargo movement is performed in a safe manner.

Decisions on the significance of a range of factors are required to determine the minimum requirements for moving hazardous materials safely. These factors include the properties of the commodity being transported, the capabilities of the ship, and the port and its characteristics. The problem of developing minimum requirements is difficult because of the large number and wide variety of hazardous materials, ship types, and port features and the need for safety regulations applicable to present situations as well as providing for future developments in new materials, ships, and ports.

To handle a complex situation in a consistent and meaningful manner a methodology, the Equivalent Safety Concept (ESC), was developed by P. J. Danahy and B. S. Gathy (see Appendix A). This methodology was designed to provide the Captain of the Port (COTP) with a systematic framework for determining the relative hazards associated with vessels carrying hazardous materials into a U.S. port by establishing hazard indexes for the cargo, the ship, and the port. The ESC methodology has not been applied to decision-making within the USCG but a relative ranking system for hazards is justifiable because the USCG has flexibility within Title 46 CFR to permit "equivalents" (i.e., if an alternative proposal can be shown to give a degree of safety consistent with that provided by existing regulations, it will be considered as providing equivalent safety).

In order to ascertain whether the original ESC or some modification of this approach had merit, the U.S. Coast Guard contracted with the National Academy of Sciences' National Materials Advisory Board to form a panel to evaluate the feasibility of such an approach. The Panel on Equivalent Safety, composed of individuals possessing expertise in chemistry, naval architecture and marine engineering, shipping practices, port procedures, toxicology, combustion phenomena and safety research, was formed. Its charge was to determine whether the ESC approach of Danahy and Gathy should be accepted or modified or whether an entirely new method should be developed. The resulting methodology was to be validated by applying it to liquefied gases currently in commerce and to other bulk liquids, as appropriate.

The goal was to develop a methodology that could be applied by the COTP to every ship carrying hazardous cargo each time it enters a port. Its application would assist the COTP in deciding whether a particular ship could enter a port with no restrictions or whether it required additional operational controls (e.g., one-way traffic in certain areas of the port, or extra tugboats). Since, in certain ports, this evaluation of safety might be made many times per day, the methodology needs to be relatively simple to use and understand.

Hyla Napadensky, Chairman

PANEL ON EQUIVALENT SAFETY CONCEPT

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Chapter 1

SUMMARY

1.1 BACKGROUND

In 1973 P. J. Danahy and B. S. Gathy presented a paper (see Appendix A) describing a methodology, the Equivalent Safety Concept (ESC), for assessing hazards and safety requirements in the marine transport of hazardous materials. Ratings are assigned to both the commodity shipped and to the transporting vessel based on the relative hazard of the former and the relative safety provided by design, operation, etc., of the latter. A combined index of these two figures, the transportation safety rating, then is developed. The port area is also assigned a numerical safety rating based on various factors and this rating is compared with the transportation safety rating to determine whether the Coast Guard is willing to take the risk of letting the vessel operate in the port.

1.2 OBJECTIVE OF THE STUDY

The Panel on Equivalent Safety Concept was to determine the feasibility of application of the ESC and to make recommendations for modifications or new approaches. The recommended concept was to be validated by one or more case studies using materials such as liquefied natural gas or other bulk liquids. The objective was to provide the Captain of the Port (COTP) with a reasonably quantitative scheme that would guide him in the management of harbor traffic so as to prevent large releases of hazardous materials that could harm people well beyond the immediate vicinity of the vessel (e.g., flammable or toxic vapor clouds).

1.3 RESULTS AND FINDINGS OF THE STUDY

After reviewing the Danahy and Gathy approach and other literature on the subject, the panel concluded that a numerical equivalent safety methodology is feasible and that the Danahy-Gathy formulation should be modified. Following the lead of Danahy and Gathy, the panel subdivided the problem into three parts:

1. By formulating a cargo hazard index (CHI) based on the physical or toxicological properties of the cargo.

2. By formulating a vessel safety index (VSI) based on ship design features that determine the quantity, location, and distribution of the cargo in the hull; the ability of a ship to avoid an accident; and the ability of a ship to maintain the integrity of the containment structure should an accident occur.

3. By developing a port hazard index (PHI) based on harbor properties that determine the likelihood of accidents and, in case of rupture of a ship's containment system, the likelihood of human casualties resulting from a toxic or flammable vapor cloud.

The panel's version of the ESC methodology was purposely kept simple to establish a framework to which sophistication could be introduced later. Until the procedure is refined, the numerical results reported here for the CHI and VSI could be clustered into broader groups labelled, for example, very dangerous, moderately dangerous, etc. For convenience, the panel restricted its assessment to seagoing ships and to the hazards of flammability and inhalation toxicity. Thus, this report presents an interim version rather than the final system. This statement must be remembered especially when considering the PHI and the V_4 term of the VSI which concerns the onboard information and control system of the vessel. The quality of the indices differs; the CHI is based on extensive experimentation and principles of physics whereas the VSI and the PHI are of lesser quality based more on the panel's experience and judgment. Further refinement of the PHI is needed, and the USCG population vulnerability model* could be used for this purpose. Given this need for further work, the complete equivalent safety methodology has not been validated by the use of case studies. Despite the incompleteness of the PHI the proposed approach, in the meantime, can be used by U.S. Coast Guard Headquarters to forewarn the COTP of potential problems when, for example, a ship with a low VSI laden with a cargo of high CHI approaches his port. The action he takes to ensure safe passage of the vessel will be based on his experience supplemented by the guidelines within a developed PHI.

The panel's work on the three indexes is summarized below.

1.3.1 Cargo Hazard Index (CHI)

The proposed simple formulation of the CHI is limited to cargoes of relatively high vapor pressure that can form a toxic or flammable cloud rapidly.

The CHI was developed from first principles in that the potential threat to the onshore population is determined solely by the area the vapor cloud can cover before it is diluted to below either its lower flammability limit or its LC_{50} (lethal concentration required to kill 50 percent of test animals). No arbitrary constants are employed to bring the toxic potential in line with the flammable potential.

The threat posed by equal quantities of toxic cargoes generally is greater than that from flammable cargoes because much lower concentrations are needed for toxic damage compared to the concentrations necessary to reach the lower flammable limit.

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*A risk analysis technique developed for the Coast Guard through their Office of Research and Development for evaluating the cost to society for a given cargo release.

Multiple hazards of both toxicity and flammability are not additive. (The victim can only be killed once.) Therefore, those cargoes having both flammable and toxic characteristics were rated based upon the worst characteristic (generally the toxic capability).

The CHI by itself is independent of the VSI and PHI and can be used to rank cargoes according to their relative toxic or flammable threat.

The greatest current limitation to the proposed CHI is the lack of comparable toxicity data for all cargoes. The use of various types of toxicity data (threshold limit values (TLV)*, LC_{50} measured for different exposure periods, etc.) lead to major discrepancies between the ranking of cargoes by the CHI and the implicit groupings of cargoes by USCG and United Nations' Intergovernmental Consultative Organization (IMCO) regulations. When rating toxic cargoes, a consistent method of weighting toxicity should be used. Danahy and Gathy (see Appendix A) used available TLV values for all cargoes for consistency. The USCG should select one toxicity criterion and apply it consistently for all cargoes. The LC_{50} is suggested as the toxicity criterion, but if something other than LC_{50} is chosen, arbitrary constants may be required.

The CHI formula can be modified and made as complex as necessary since the value for the CHI can be determined at USCG Headquarters and need not be calculated in the field. Once determined by a given formula that value is fixed for a particular cargo and is independent of the quantity of the cargo since the latter factor is included in the VSI.

1.3.2 Vessel Safety Index (VSI)

Because the functional relationships between the constituent factors chosen for inclusion in the VSI and the probability of an accident and its consequences are unknown, a linear relationship was adopted as the simplest means for expressing the VSI.

The expression for the VSI does not contain the human factor but its inclusion could be accommodated if so desired.

The proposed expression for the VSI, unlike that of Danahy and Gathy, does include the vessel's onboard information and control system but presently assigns it a constant value for all ships.**

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* For definitions of TLVs refer to: TLVs, Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment with Intended Changes for 1982, American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1982.

**If, sometime in the future, differences in effectiveness of various onboard information and control systems can be quantified on a relative (or other) basis, this constant could be changed to an appropriate variable.

The VSI like the CHI can be calculated by the USCG Headquarters and is generally constant for a given ship (so long as the vessel is maintained in an "as-designed and as-built" condition).

The weighting factors for the four terms of the VSI are based on judgment and reflect the consensus of the panel.

The VSI is independent of the hazardous nature of the cargo carried and depends solely on the characteristics of the vessel (including size, cargo subdivision, manueverability, and survivability).

The manueverability factor could be part of the PHI but was by consensus judged to be more appropriate to the VSI.

Because of gaps in knowledge and the lack of adequate information the VSI, unlike the CHI, is not founded on principles of physics and extensive testing but rather on the experience and judgment of the panel.

1.3.3 Port Hazard Index (PHI)

The PHI is not intended to be determined by any but local authority familiar with local conditions.

The PHI is not a fixed formulation that can be calculated once for any port.

The PHI suggested by the panel is only a guide for use by a local authority in its evaluation of various sectors within a port area and is expected to improve consistency.

The PHI is not complete. Certain vulnerability variables might be evaluated using the USCG population vulnerability model.

Despite the incomplete nature of the PHI, the COTP should consider the use of the proposed scheme to characterize various segments of a port on a relative basis and to identify the more vulnerable areas of the port.

Chapter 2

FEASIBILITY OF DEVELOPING AN APPROPRIATE METHODOLOGY

A literature search was carried out to determine whether there existed other work, besides that of Danahy and Gathy (1972), in which a relative ranking system was used to assess safety. The search also sought studies dealing with the risks from water transportation of hazardous materials. The panel also sought to identify analogous studies, not necessarily those dealing with the marine mode, in which equivalence of safety concepts were used.

As was anticipated by the panel, those studies dealing with risk analysis were not applicable to this study. The risk analysis studies could be divided roughly into two categories: those that were concerned with a specific commodity, type of ship, and port (e.g, LNG entering Boston Harbor), and those of a general nature that characterized ship accidents from a probabilistic point of view. The first type of study was judged to be too detailed and not appropriate for application to the wide range of ships and cargoes that enter U.S. ports. The probabilistic studies were too general to be of use in the present study, either as suggestive of an approach or in providing useful data.

One paper (Roggenburg 1975) considered certain ship and cargo factors but not port features. Two publications (Jones 1977-78, U.S. Environmental Protection Agency 1975) summarizing hazard classification systems were devoted solely to materials.

The panel considered two studies involving a ranking system in some detail. Although these studies did not involve maritime activities, they were concerned with safety and had been applied to real problems. One model, developed by the National Bureau of Standards (NBS), was described by Nelson and Shibe (1978) as follows:

> A quantitative evaluation for grading health care facilities in terms of fire safety is described. The system can be used to determine how combinations of widely accepted fire safety equipment and building construction features may provide a level of safety equivalent to that required by the widely accepted Life Safety Code of the National Fire Protection Association (NFPA). The system will provide flexibility to both the designer of new facilities and to the renovator of existing health care facilities. In this system, equivalency is judged to exist when the total impact of the occupancy risk factors and the compensating building safety features produce a level of safety equal to or greater than that achieved by rigid conformance to the explicit requirements of the NFPA Life Safety Code. In this evaluation, safety performance is gauged both in terms of overall safety impact and depth of redundance.

Although the NBS fire safety application is quite different from the hazardous materials shipping problem, the panel believed that some features of the NBS approach were relevant to its problem.

The second study (Kinney and Wiruth 1976) proposed a method for handling quantitative or qualitative information. A nomograph is developed and the factors considered are likelihood of an accident, exposure factors that deal with quantity of material or frequency of exposure, and possible consequences of an exposure. With information on these three factors a "risk score" is determined. The risk score can be quantitative or qualitative, depending upon the input data. The Naval Weapons Center has had good experience using this nomograph-risk score methodology, but the panel did not believe that it was applicable to its task.

After reviewing the existing literature as well as NBS's successful application of its equivalent safety model to health care facilities, the panel gained confidence that such numerical systems were both feasible and practical. The panel then decided to proceed by modifying the general framework of the original Danahy and Gathy (1973) concept. Changes in the formulation of the three input factors--the cargo, the ship, and the port--were made. These changes are described in Chapter 3 of this report.

Chapter 3

THE EQUIVALENT SAFETY CONCEPT

3.1 BACKGROUND

Three factors were considered to be important in formulating a concept that would provide for equivalent safety: the cargo, the vessel, and the port. Human factors such as crew training were not included because ships' masters are already licensed under a set of standards that is intended to provide a high level of competence.

The CHI is intended to provide a comparison of the hazards of various commodities based only on differences in the properties of the cargoes. The hazards considered are those that have an immediate impact on the public. Long-term public exposure and crew exposure are not considered because they can be controlled through suitable action following a release of the hazardous material. Therefore, exposure to fire and toxic vapors are the primary factors in the CHI.

The VSI includes those factors that are properties of the vessel only. The cargo containment system, the capacity of the system, ship controllability, and the onboard information and control system are considered. These factors reflect the ability of the vessel (and its human crew) to detect potentially hazardous situations and to avoid them or to resist the consequences (i.e., cargo loss) under a given set of environmental conditions.

The PHI reflects the environment through which the vessel must travel. It includes parameters such as channel width, turn radius, navigational aids, current and wind forces, and vessel traffic control. These factors are specific for each port and may change when improvements are made in the port or when weather conditions change.

The PHI is determined locally, whereas the VSI depends only on vessel properties and the CHI depends only on cargo properties. Further, the indexes are defined in such a way that a high value for a hazard index, such as the CHI, is bad and a high value for a safety index, such as the VSI, is good. The ratio of VSI to CHI could be used (in the manner described in Appendix A, sections A5 and A7) to judge whether or not additional restrictions may be needed to provide adequate public safety during the movement of hazardous cargoes into a specific port.

3.2 CARGO HAZARD INDEX

A cargo hazard may range from short term to long term, and its effects may be either immediate or delayed. The hazard may be to a human population, to buildings and equipment, or to the environment. If all these factors were to be considered the CHI would become very complicated and information not readily available would be required. One rational approach is to base the CHI on the short term, or acute, potential for fatalities to the general public (loss of a crew and ship is less significant) if a cargo of hazardous materials is released.

The two major hazards immediately following a cargo spill are toxicity and flammability. If the cargo remains in the liquid or solid phase following a spill, there usually will not be an immediate public danger. However, if the cargo vaporizes and a vapor cloud drifts or is blown away from the spill location, an immediate danger occurs. Regardless of whether the spilled cargo is toxic or flammable, the immediate danger is related to the concentration of the commodity in the atmosphere.

Following a spill, there may be many other long-term problems (e.g., substantial damage to the environment, considerable inconvenience to the public, and costly cleanup) without substantial potential for immediate fatalities. There may be long-term toxicity potential for a crew if small but constantly inhaled quantities of a cargo can cause long-term health effects. There also may be potential for abnormal corrosion from long-term use of a vessel carrying particular cargoes. However, despite the importance of these long-term problems and effects, they are not included for the sake of simplicity in the methodology presented in this report, although they cannot be neglected in regulation development. Only the immediate flammable and acute inhalation toxic threat to the public is considered.

3.2.1 Development of a Model

Having made the choice that the CHI should be based on the immediate potential for public fatalities, it is apparent that the farther the potential danger can reach from the cargo release point, the greater will be the potential for public danger. Thus, the primary immediate concern for public safety can be related to the flammability or toxicity of the vapor cloud emanating from a cargo release.

An estimate is needed of the distance from the spill area to the point where the cloud of flammable or toxic vapor is dispersed to a concentration below a chosen toxic or flammable level. The simplest approach is to assume a Gaussian distribution of vapor downwind of the spill area. Then:

$$c = M/u\sigma_y\sigma_z\pi \qquad (1)$$

where c is the concentration of hazardous material in the vapor cloud at water level on the plume centerline, M is the total rate of vapor release to the atmosphere, u is the average wind velocity, σ_y is the cloud standard deviation in the crosswind direction, and σ_z is the cloud standard deviation in the vertical direction.

Eq. 1 includes the tacit assumption that an equal quantity of cargo is spilled in each case. That assumption is necessary if the CHI is to be a property of the commodity only. The effect of cargo size on transportation safety is included in the vessel safety index (section 3.3). The units for the factors in Eq. 1 must be consistent. For this development, the units are chosen so that c is given as a mole fraction or volume fraction.

The values of σ_y and σ_z usually are written as a function of distance from the source. Furthermore, if logarithmic plots of data for σ_y and σ_z are made as a function of distance from the source, a linear relationship frequently results, particularly for the relatively short distances under consideration. Thus:

$$\sigma_y \propto X^a \tag{2}$$

$$\sigma_z \propto X^b \tag{3}$$

and

$$\sigma_y \sigma_z \propto X^n \tag{4}$$

where X is the distance from the location of the spill and n is the sum of the constants a and b.

The average wind velocity also affects vapor concentrations, but it is not related to cargo properties. Rather it is related to the weather at the spill location and therefore should be considered in evaluating the port-dependent hazards. The vapor concentration at any point can be written as:

$$c \propto M/X^n. \tag{5}$$

The value of the exponent n is a function of atmospheric stability and is usually in the range of 1.5 to 2 (Slade 1968). For present purposes (which are comparative rather than absolute) the value $n = 2$ can be used without serious error. The distance from the spill point to a given concentration therefore is:

$$X \propto (M/c)^{1/2}. \tag{6}$$

The rate of cargo vaporization depends on the size of the liquid pool floating on the water surface. Assuming an equal volume of cargo spilled, the area covered by the floating liquid will vary with the cargo density. Fannelop and Waldman (1972) showed that liquid spread over a water surface could be approximated by:

$$\frac{X_{\ell e}}{L_c} = 1.14\left(\frac{g(\rho_w - \rho_\ell)}{\rho_w L}\right)^{1/4} t^{1/2} \tag{7}$$

when gravity and inertial forces predominate, and

$$\frac{X_{\ell e}}{L_c} = 0.98\left(\frac{g^2(\rho_w - \rho_\ell)}{\rho_w \mu_w}\right)^{1/12} t^{1/4} \tag{8}$$

when gravity and viscous forces predominate. In Equations 7 and 8, $X_{\ell e}$ is the distance to the leading edge of the liquid, L_c is a characteristic length, g is the gravitational acceleration, ρ_ℓ is the spreading liquid density, ρ_w is the water density, μ_w is the water viscosity, and t is time.

The area covered by the liquid pool is proportional to $X_{\ell e}^2$ so the total rate of vapor production is:

$$M \propto X_{\ell e}^2 m, \tag{9}$$

where m is the rate of vapor production per unit area of the spilled cargo. Thus:

$$M \; \alpha \left[\frac{\rho_w - \rho_\ell}{\rho_w}\right]^2 m \tag{10}$$

In deriving Equation 10, it is assumed that the gravity-inertial regime is most important for determing the spread of spilled cargo. The choice is made because the gravity-inertial regime applies to the early stages of the spill when spreading is most rapid.

The rate of vapor release is the rate at which cargo is either released directly as a gas or the rate at which a liquid or solid cargo vaporizes. The primary interest is in the liquid cargoes because solid cargoes generally vaporize very slowly and gaseous cargoes usually are not carried in bulk. Liquefied gases are considered to be liquids.

If spilled on water, two vapor-production situations can occur. If the liquid has a boiling point lower than the ambient water temperature, the cargo will boil on contact with water and the vapor production rate per unit area will be proportional to the heat transfer rate between the water and the cargo. Thus:

$$m \propto (T_a - T_b), \tag{11}$$

where T_a is the absolute ambient temperature and T_b is the absolute boiling point of the cargo (Reid and Smith 1978). Laboratory tests have shown that the boil-off rate decreases as a function of time following the spill of liquid on a confined surface because of ice formation. However, it is expected that the boiling rate will remain nearly constant when a cargo is spilled on open water where ice is less likely to form on the water surface.

If the liquid has a boiling point higher than the ambient water temperature, the vapor production rate will depend on the evaporation rate. The evaporation rate per unit area can be estimated from:

$$m = k(P_v/P), \tag{12}$$

where k is the mass-transfer coefficient, P_v is the vapor pressure at T_a, and P is the atmospheric pressure.

The mass-transfer coefficient depends on the wind velocity, the pool size, the molecular diffusivity of the cargo vapor in air, and some ambient air properties. Correlations of evaporation rate data (Perry 1950) show that:

$$k \propto D_v^{\;2/3}, \tag{13}$$

where D_v is the molecular diffusivity at T_a. In Eq. 13 all the factors not directly related to cargo properties are omitted. The evaporation rate per unit area then becomes:

$$m \propto (P_v/P)D_v^{2/3} \tag{14}$$

if the boiling point of the cargo is higher than the ambient water temperature.

Since there are two different techniques for evaluating m, a basis must be chosen for making the two equal at a convenient reference point. The reference point is chosen as the ambient temperature and, at that point, the relationships for m are made unitless so that data from different sources can be used more conveniently. Thus, the final expression for m for cargoes with boiling points below ambient is:

$$m \propto (2T_a - T_b)/T_a \tag{15}$$

For cargoes with boiling points above ambient:

$$m \propto (P_v/P)(D_v/D_{vb})^{2/3} \tag{16}$$

D_{vb} is the diffusivity at the boiling point and is included to make the equation nondimensional. Note that if the cargo boiling point equals the ambient temperature, m is unity for either method.

The CHI is to be a measure of the potential for immediate fatalities from a cargo release. The method of estimating such a potential is to determine the distance X reached by the hazardous vapor cloud generated when the cargo evaporates. Thus, assume that:

$$\mathrm{CHI} \propto X \qquad (17)$$

or

$$\mathrm{CHI} \propto (M/c)^{1/2}. \qquad (18)$$

One further choice must be made. The vapor concentration must be chosen to represent a specific hazard level depending on whether the cargo vapor is flammable or toxic (some cargoes may be both). To make such a choice requires a judgment concerning the relative hazard from a flammable cloud as compared to a toxic cloud.

If people are caught in a flammable cloud that subsequently ignites, some will be killed. Some smaller number of people outside the cloud also may be killed by radiation from the fire. In defining the CHI for flammable cargoes, it is assumed that all the persons inside the flammable cloud are killed and that none outside the cloud are killed. The lower flammability limit (LFL) concentration represents the minimum vapor concentration in air that will sustain a self-propagating flame. The CHI for flammability will therefore be based on the vapor concentration being at the LFL. The choice is quite conservative for two reasons: not everyone inside the cloud would be killed if ignition occurs and ignition is likely to occur before the cloud reaches the maximum possible distance from the spill. It is assumed that people within the portion of the cloud where the concentration is greater than the LFL will die and that people outside this region will survive.

People within a toxic cloud have a chance of survival that varies with concentration. Assuming the results of animal tests can be extrapolated to humans then, at a concentration corresponding to the LC_{50}, there will be an equal chance for death or survival and the number of deaths due to cargo toxicity will have a smoother distribution than those due to fire.

LC_{50} data were chosen for use in Eq. 10 rather than the threshold limit value (TLV) because the TLV can show only relative levels of toxicity between chemicals and does not express absolute fatalities as does the LC_{50}. In this sense LC_{50} data are more comparable to LFL data; therefore, a toxic CHI may be directly compared to a flammable CHI.

If vapor concentrations are provided in the same units, the results for toxicity hazard or flammability hazard should be directly comparable without artificial compensation. Further, the units chosen should be dimensionless. The LC_{50} and LFL units are therefore expressed in terms of mole fractions.

3.2.2 Resulting Equations

The result is a set of four equations, of which two may apply to a given cargo.

For flammable cargoes with $T_b \geq T_a$:

$$\mathrm{CHI} = \left[(P_v/P)(D_v/D_{vb})^{2/3} \left(\frac{\rho_w - \rho_\ell}{\rho_w} \right)^{1/2} (1/\mathrm{LFL}) \right]^{1/2} . \qquad (19)$$

For flammable cargoes with $T_b \leq T_a$:

$$\mathrm{CHI} = \left[\left(\frac{2T_a - T_b}{T_a} \right) \left(\frac{\rho_w - \rho_\ell}{\rho_w} \right)^{1/2} (1/\mathrm{LFL}) \right]^{1/2} . \qquad (20)$$

For toxic cargoes with $T_b \geq T_a$:

$$\mathrm{CHI} = \left[(P_v/P)(D_v/D_{vb})^{2/3} \left(\frac{\rho_w - \rho_\ell}{\rho_w} \right)^{1/2} (1/\mathrm{LC}_{50}) \right]^{1/2} . \qquad (21)$$

For toxic cargoes with $T_b \leq T_a$:

$$\mathrm{CHI} = \left[\left(\frac{2T_a - T_b}{T_a} \right) \left(\frac{\rho_w - \rho_\ell}{\rho_w} \right)^{1/2} (1/\mathrm{LC}_{50}) \right]^{1/2} . \qquad (22)$$

(Note that the comparable equations for flammable and toxic cargoes have an identical factor and differ only in whether that factor is multiplied by $(1/\mathrm{LFL})^{1/2}$ or $(1/\mathrm{LC}_{50})^{1/2}$.)

3.2.3 CHI for Various Chemicals

The data required to evaluate the CHI for a given commodity should be chosen with a consistent basis. For ease of use, P_v, D_v, ρ_ℓ, ρ_w, and LFL are all chosen at ambient temperature, T_a, of 20°C. The LC_{50} should be measured following the Interagency Regulatory Liaison Group's (IRLG) "Guidelines for Acute Inhalation Tests in Rats" (draft copy, June 6, 1979). Unfortunately, not all present LC_{50} data follow the guidelines; therefore, calculations of CHI must be made using the available data, some of which were measured using other procedures, and some of which are not LC_{50} data.

Table 1 summarizes the data and CHI values calculated for a group of hazardous chemicals. Some of the results have been included even though the cargoes do not strictly reflect the assumptions made in developing Eq. 19 through 22.

TABLE 1 Summary of Selected Hazardous Materials Properties and Cargo Hazard Indexes

Chemical	T_b (°C)	P_v @20°C (mm H_g)	D_v/D_{vb}	1 (g/cm³)	LFL (%)	LC_{50} (ppm)	CHI Flammable	CHI Toxic
Acetaldehyde	21.1	749	0.993	0.783	4.0	4,000(L)	3.4	11
Acetone	56	185	0.816	0.791	2.6	126,600	1.9	0.88
Acrolein	51.6	220	0.836	0.841	2.8	8	1.9	110
Acrylonitrile	77.2	84	0.732	0.806	3.0	5,000	1.2	2.8
Allyl chloride	45	294	0.867	0.938	2.9	3,000(H)	1.7	5.4
Ammonia (anhydrous)	-33.3			0.771	16.0	7,300	1.9	8.8
Benzene	80	75	0.722	0.879	1.3	16,000	1.5	1.3
Butadiene	-4.4			0.621	2.0	250,000	5.8	1.6
Butane	-0.6			0.601	1.9	282,000	6.0	1.6
Butene (butylene)	-6.1			0.595	1.6		6.6	
Carbon disulfide	46.1	298	0.861	1.263	1.3	4,000(L)	5.2	9.4
Carbon tetrachloride	76.5	91	0.735	1.594		24,000[b]		2.0
Chlorine	-33.8			1.56		293[c]		64
Cyclohexane	81.9	78	0.715	0.777	1.3		1.7	
Decane	173.9	0.9	0.478	0.73	0.8		0.2	
Dimethylamine	7.2			0.680	2.8	2,000(I)	4.6	17
Epichlorohydrin	115	15	0.612	1.2	3.8	500	0.6	5.3
Ethane	-88.9			0.509	3.0		5.7	
Ethylamine	16.7			0.683	3.5	3,000(L)	4.0	14
Ethylene	-103.9			0.384	2.7		6.4	
Ethylene oxide	10.6			0.882	3.6	1,462	3.1	16
Ethyl ether	35	440	0.916	0.718	1.9	64,000	3.9	2.1
Ethyleneimine	55.6	160	0.818	0.832	3.6	2,500	1.5	5.5
Hexane	68.9	121	0.763	0.660	1.1		2.7	
Hydrazine	113.3	10.5	0.617	1.101	4.7	570	0.5	4.2
Hydrogen	-253			0.071	4.0		6.8	
Hydrogen chloride	- 84.8			1.19		5,666[b]		16
Hydrogen fluoride	19.7			0.987		1,276[c]		9.5
Methane	-161.7			0.423	5.0		5.0	
Methyl alcohol	63.9	97	0.783	0.791	6.7	174,000	0.9	0.5
Methyl bromide	4.4			1.676	10.0	2,312[c]	3.2	21
Methyl chloride	- 23.9			0.916	10.7	20,000(L)	1.8	4.1
Nitrogen dioxide	21	720	0.994	1.491		315		55
Phenol	181.1	0.2	0.465	1.072		33,000[b](L)		0.07
Phosgene	7.6			1.381		75[b]		120
Phosphorus trichloride	-162			1.574		140		110
Propane	- 42.2			0.585	2.2		6.0	
Propylene	- 47.2			0.519	2.0		6.5	
Sulfur dioxide	- 10.0			1.434		611(L)		43
Vinyl chloride	- 13.9			0.911	3.6	6,000(L)	3.0	7.4
Vinyl ethyl ether	35.5	426	0.914	0.759	1.7		3.9	

NOTE: (H) = Human TLV (threshold limit values)
(I) = IDLH (immediately dangerous to life or health)
(L) = LCLO (lowest lethal concentration published)

[a] Unless otherwise indicated, values are tests of 4 h duration.
[b] 30 minutes
[c] 1 hour

The flammability properties shown in Table 1 were largely taken from the National Materials Advisory Board Matrix of Combustion-Relevant Properties and Classifications of Gases, Vapors, and Selected Solids (1979) and the National Fire Protection's Association's (NFPA) Fire Protection Handbook (1976). Toxicity data were taken from a variety of sources including the International Technical Information Institute's Toxic and Hazardous Industrial Chemicals Safety Manual (1975) and Sax's Dangerous Properties of Industrial Materials (1979) and USCG computer printouts. Toxicity data were not always determined or reported consistently; therefore CHI values based on toxicity must be recognized as being less quantitatively consistent than those based on flammability. Molecular diffusivity data and vapor pressures were estimated using the techniques outlined by Reid, Prausnitz, and Sherwood (1977).

In the Danahy and Gathy paper (1973) where the equivalent safety concept was first presented, the CHI was calculated on a different basis. Danahy and Gathy used, among other factors, the TLV as the basis for judging toxicity and both upper and lower flammability limits for judging flammability. Table 2 compares Danahy's rankings of a number of chemicals with the present rankings. The agreement between the rankings is not particularly good.

The rankings shown in Table 2 show the rather large differences that can occur when different bases are used for judging relative hazard. The CHI values proposed by Danahy and Gathy included some terms selected qualitatively to provide limits on CHI values and to make CHI values for toxic materials somewhat larger than those for flammable materials. The proposed method of determining CHI, as given by Eq. 19 through 22, does not require adjustment because the hazard basis was chosen in such a way as to be consistent. The choice of assuming hazard to be equal at the point where vapor concentrations decrease to LC_{50} or LFL values is logical based on the approximate fatality-producing potential.

Table 3 shows a list of selected chemicals ranked according to their CHI. The first 16 of the chemicals are toxic materials, a result to be expected because toxicity can occur at much lower concentrations than those at which ignition normally occurs (e.g., 10 to 100 ppm for toxic materials versus 10,000 to 100,000 ppm for flammable materials). The chemicals with the highest rankings because of flammability are the liquefied gases; those with lower LFL values have higher rankings than those with lower boiling points.

The Coast Guard and the International Maritime Consultative Organization* (IMCO) regulations for containment of bulk cargoes implicitly categorize the potential hazard of chemicals into three broad groups. The reason for this is that three degrees of physical protection for the cargoes were developed because damage from collision, ramming, or grounding could lead to uncontrolled release of cargo. The degrees or "ship types" define the location of the cargo with respect to the ship's side and bottom and the extent to which a ship should be capable of remaining afloat after damage.

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*During the course of this study IMCO was renamed IMO (International Maritime Organization).

TABLE 2 Comparison of Ranking by Danahy and Gathy and Proposed Method

Comparative Rank[a]			Cargo Hazard Index[b]	
Danahy and Gathy	Proposed	Chemical	Danahy and Gathy	Proposed
1	1	Chlorine	50.2 Tox	64 Tox
2	16	Allyl chloride	21.4 Tox	5.4 Tox
3	6	Hydrogen fluoride	19.6 Tox	9.5 Tox
4	4	Hydrogen chloride	18.5 Tox	16 Tox
5	15	Ethyleneimine	15.5 Tox	5.5 Tox
6	2	Ethylene oxide	12.7 Flam	16 Tox
7	3	Dimethylamine	11.8 Tox	17 Tox
8	7	Carbon disulfide	11.4 Flam	9.4 Tox
9	19	Ethyl ether	8.0 Flam	3.9 Tox
10	5	Acetaldehyde	6.2 Flam	11 Tox
11	11	Ethylene	5.6 Flam	6.4 Flam
12	9	Vinyl chloride	4.6 Flam	7.4 Tox
13	14	Butadiene	4.5 Flam	5.8 Flam
14	10	Propylene	4.4 Flam	6.5 Flam
15	18	Methyl chloride	4.0 Tox	4.1 Tox
16	13	Butane	4.0 Flam	6.0 Flam
17	12	Propane	3.7 Flam	6.0 Flam
18	8	Ammonia	3.6 Tox	8.8 Tox
19	17	Methane	2.7 Flam	5.0 Flam
20	22	Benzene	1.3 Tox	1.5 Flam
21	21	Acetone	1.2 Flam	1.9 Tox
22	20	Acrylonitrile	1.2 Tox	2.8 Tox

[a] The rankings in this table are based only on the 22 cargoes presented in the paper by Danahy and Gathy, 1973, and not on all the cargoes listed in Table 1.

[b] The CHI chosen is the larger of the toxic (Tox) or flammable (Flam) values.

TABLE 3 Ranking of Selected Hazardous Chemicals

Rank	Chemical	CHI[a]	Toxic or Flammable
1	Phosgene	120	Tox
2	Acrolein	110	Tox
3	Phosphorous trichloride	110	Tox
4	Chlorine	64	Tox
5	Nitrogen dioxide	55	Tox
6	Sulfur dioxide	43	Tox
7	Methyl bromide	21	Tox
8	Dimethylamine	17	Tox
9	Ethylene oxide	16	Tox
10	Hydrogen chloride	16	Tox
11	Ethylamine	14	Tox
12	Acetaldehyde	11	Tox
13	Hydrogen fluoride	9.5	Tox
14	Carbon disulfide	9.4	Tox
15	Ammonia (anhydrous)	8.8	Tox
16	Vinyl chloride	7.4	Tox
17	Hydrogen	6.8	Flam
18	Butene (butylene)	6.6	Flam
19	Propylene	6.5	Flam
20	Ethylene	6.4	Flam
21	Propane	6.0	Flam
22	Butane	6.0	Flam
23	Butadiene	5.8	Flam
24	Ethane	5.7	Flam
25	Ethyleneimine	5.5	Tox
26	Allyl chloride	5.4	Tox
27	Epichlorohydrin	5.3	Tox
28	Methane	5.0	Flam
29	Hydrazine	4.2	Tox
30	Methyl chloride	4.1	Tox
31	Ethyl ether	3.9	Flam
32	Vinyl ethyl ether	3.9	Flam
33	Acrylonitrile	2.8	Tox
34	Hexane	2.7	Flam
35	Carbon tetrachloride	2.0	Tox
36	Acetone	1.9	Flam
37	Cyclohexane	1.7	Flam
38	Benzene	1.5	Flam
39	Methyl alcohol	0.9	Flam
40	Decane	0.2	Flam
41	Phenol	0.07	Tox

[a] The CHI chosen is the larger of the toxic (Tox) or flammable (Flam) values.

The highest standard of physical protection, Ship Type I, is required for those substances considered to have the greatest hazard; that is, on release would have wide-reaching effects. Ship Type II is required for those cargoes with significant hazard but whose release does not have as wide-reaching effects. Ship Type III is prescribed for products having still lesser hazards and is similar in concept to normal tankships, although increased survivability is required.

The regulations were developed on this basis, that the three broad degrees of hazard were balanced by three degrees of protection and survivability to provide equivalent safety.

CHI values estimated by the panel (see Table 3) may be considered to fall roughly into three broad groups as follows:

Cargoes of the:	CHI	Ship Type
Greatest overall hazard	>15	I or IG
Progressively lesser hazard	> 2.8 to 15	II or IIG
Still lesser hazard	≤ 2.8	III

Chemicals that are exceptions to this broad categorization include ten which are not permitted to be shipped in bulk in manned vessels (see page 21). These are the chemicals ranked 1 through 5, 10, 13, 17, 25, and 29 in Table 3. Other exceptions are:

1. Dimethylamine, rated 17 by the panel and (11.8 by Danahy and Gathy) and requiring type IIG ships by regulations.

2. Allyl chloride and epichlorohydrin rated 5.4 and 5.3 respectively, by the panel (Danahy and Gathy rated allyl chloride as 21.4) and requiring type I ships by regulations; saturated hydrocarbons such as propane and butane, and unsaturated hydrocarbons such as ethylene and propylene regulated by Subchapter D which covers normal tankships (i.e., type III hull).

3. Phenol rated 0.07 by the panel and requiring a type II ship by IMCO and approved by the U.S. Coast Guard for Barge Type I with double skin.

3.2.4 Limitations

There are shortcomings in the proposed technique. The greatest is the lack of toxicity data for all chemicals. The available toxicity data were taken under a variety of conditions using different animal species and improved data are required for better ranking of chemicals. Flammability data, which are based on physical properties of the chemicals, are likely to be more reproducible and easier to obtain than biological data requiring toxicity testing of animals. The testing procedures for animal tests should be similar to avoid differences in results.

In many cases, LC_{50} data measured by the IRLG guidelines were not available for calculating CHI by Eq. 21 and 22. In some cases, other LC_{50}

data were used. If no LC_{50} data were available, lowest lethal concentration (LCLO) published data or other data (see notes to Table 1) were used. The lack of reliable LC_{50} data is one of the most serious shortcomings of the proposed method. LC_{50} data provide a better basis for a hazard index rating because they are less subjective than TLV data.

Concentrations immediately dangerous to life or health (IDLH) might also have been used for the basis of toxicity in the CHI. However, IDLH concentrations have some of the same disadvantages as TLV concentrations: they are more qualitative in nature and they require an arbitrary factor to be applied to make their CHIs consistent with those of flammable cargoes.

The CHI values proposed do not include credit for the ability of people to escape from the hazard. In terms of toxic exposure, there may be a substantial reduction in hazard potential if escape is assumed to be possible. For flammable exposure, people inside buildings would likely escape with little or no injury, thus reducing the hazard potential. In addition, once ignition occurs, the flammable hazard lasts only a short time, and the spread of the flammable cloud is terminated, thus precluding further exposure. Toxic clouds would continue to spread. Some of these effects are partially offsetting; therefore, the toxic and flammable CHI values should be a reasonable method for use in judging relative cargo hazard.

3.2.5 Factors Not Included

Several additional material properties have some effect on the degree of hazard presented by a cargo and might be included in the cargo index. These properties are listed below with a brief explanation of why they were not included.

3.2.5.1 Cargo Solubility

For the short-term hazard chosen as the basis for the CHI, water-soluble cargoes would present less danger because the cargo would dissolve in water and reduce the amount that could vaporize into the atmosphere. If cargo solubility were to be included, it would require much more information than is now available. Even if data on rate of dissolution were available and partition functions for mutual solubility were known, the amount of water available is so large compared to the amount of cargo that can be spilled that all the soluble cargo that does not evaporate eventually will dissolve. To obtain conservative results, the fraction dissolved is assumed to be zero, and Eq. 19 through 22 are used as though the cargoes were not soluble. In actual cases of large, rapid spills, the spreading and evaporation may be so rapid that little dissolution takes place and the CHI will be sufficiently accurate for first estimates.

A second aspect of cargo solubility is the potential for ingestion if spilled into fresh water that is later used for potable water. Environmental damage also can occur and may be more likely than ingestion because the spilled cargo cannot be removed from the water. Potable water supply systems may be shut off until dissolved cargo has been diluted to safe levels or flows away.

3.2.5.2 Cargo Density

If a cargo is denser than water, it will not float on the water surface, but will sink below the surface. If the boiling point of the cargo is higher than ambient, vaporization will be suppressed and the cargo will not be released to the atmosphere in large quantities. Thus the immediate hazard may be reduced. However, in calculating the CHI for cargoes with $\rho_\ell > \rho_w$, the term $(\rho_w - \rho_\ell)/\rho_w$ was assumed to be unity. This choice maximizes the calculated value of the CHI and therefore gives a conservative result. This assumption should be remembered when using the CHI because the cargoes with $\rho_\ell > \rho_w$ actually may be less hazardous than is apparent from the CHI value shown in Table 1.

3.2.5.3 Ignition Energy and Temperature

Commonly occurring ignition sources (pilot lights, cigarettes, matches) will have both sufficient energy and a high enough temperature to ignite a vapor cloud if the concentration is in the flammable range. Therefore, ignition energy and ignition temperature are not very important to the cargo index.

3.2.5.4 Ingestion and Contact Toxicity

Ingestion of toxic cargoes or contact by toxic cargoes will be an infrequent problem following a cargo spill. Ingestion can occur only if water is used to supply potable water systems, and sufficient warning should be available to prevent contaminated water from being used. Contact toxicity is not likely because of limited use of raw water from navigable streams by the public and the warning time available after a spill occurs.

3.2.5.5 Vapor Density

Vapors heavier than air will tend to layer and may spread in a pattern different from that implied by Eq. 1. The spreading of heavier-than-air clouds has not been studied extensively; however, there is some evidence that the denser cloud will not travel as far as a neutrally buoyant cloud, but the heavier cloud is broader so that the ground area covered by both clouds is roughly the same. If so, the hazard is probably about the same. In any event, vapor density must be omitted until its effects on vapor dispersion are better known.

3.2.5.6 Flame Speed

The flame speed is useful in estimating whether detonation may occur. However, the assumed fatality levels are not strongly dependent on whether detonation occurs. All persons inside the flammable portion of the cloud are assumed to be killed. Detonation effects will not be felt for long distances outside the cloud; therefore, the hazard is localized to the cloud and the flame speed is not important in the CHI.

3.2.5.7 Radiation Flux

The differences in radiation fluxes among the various cargoes considered here are not expected to be very large. The CHI also is based on the premise that no fatalities occur outside the cloud; therefore, the radiation flux need not be included in the CHI.

3.2.5.8 Molecular Weight

The molecular weight is manifested through the boiling point, vapor pressure, and molecular diffusivity of a material, all of which are included in the CHI. Vapor density is related to molecular weight; however, as explained above, vapor density is not included.

3.2.5.9 Upper Flammable Limit

The portion of the vapor cloud that is above the upper flammable limit (UFL) cannot be ignited directly. However, once the cloud has been ignited, the portion above the UFL will burn as a diffusion flame. Unless all the spilled liquid has evaporated, the fire will burn back to the liquid pool. The entire cloud already has been considered as part of the hazard area so nothing would be gained by adding the UFL to the CHI.

3.2.6 Cargoes Not Approved for Shipping in Bulk

There is a tendency to define a CHI above which a cargo would not be approved for shipping. Of the commodities for which a CHI was calculated, the following are not approved by USCG regulations:

Commodity	CHI	
Hydrazine	4.2	Tox
Ethyleneimine	5.5	Tox
Hydrogen	6.8	Flam
Anhydrous hydrogen fluoride	9.5	Tox
Anydrous hydrogen chloride	16	Tox
Nitrogen dioxide	55	Tox
Chlorine*	64	Tox
Phosphorus trichloride	110	Tox
Acrolein	110	Tox
Phosgene	120	Tox

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*Not approved on manned vessels but approved on unmanned barges. Status subject to change as appropriate safety procedures are developed.

If all cargoes with a CHI greater than the lowest CHI of the nonapproved cargoes also were not approved for shipping, most of the cargoes in Table 1 would be unacceptable. This points out the great utility of the equivalent safety concept: cargoes, vessels, and ports must all be considered in the final decision. Finally, cargoes may not be approved for reasons other than those considered in the CHI (e.g., the long-term effects of a toxic vapor to the crew).

3.3 VESSEL SAFETY INDEX

The vessel safety index as originally proposed by Danahy and Gathy (1973) was mathematically described as follows:

$$\mathrm{VSI} = KF_1/F_2F_3, \qquad (23)$$

where K is a constant; F_1 is a measure of the ability to contain the cargo given an accident; F_2 is a measure of the cargo capacity or potential for damage if cargo is released as a result of an accident; and F_3 is a measure of a number of other factors such as the ability to accelerate, the ability to turn, the kinetic energy (i.e., variables that influence the likelihood of an accident). All are calculated in a relative sense to a so-called base ship rather than absolute numbers.

The mathematical description of the VSI (Equation 23) chosen by Danahy and Gathy is arbitrary. Although presented in a form resembling a risk approach (which in a broad sense is a multiplicative combination of the probability of accident and the resultant consequences) the F_1 and F_2 terms themselves contain arbitrary linear combinations of other factors summing up the credit given for certain vessel features (see Appendix A, page 46).

The panel was faced with the same problem of determining a proper expression for the VSI. Because the functional relationships between the constituent factors chosen for inclusion in the VSI and the probability of an accident and its consequences are unknown, the following linear relationship was adopted as the simplest means for expressing the VSI.

$$Y = a_0 + a_1X_1 + a_2X_2 + \dots + a_nX_n, \qquad (24)$$

where the dependent variable Y is related to accident occurence and consequence, the coefficient a_n is a weighting factor, and X_n is a term that includes characteristics of the cargo-laden vessel that influence safety. The calculation of Y yields an arbitrary number that can be used to rank vessels in terms of safety in lieu of the difficult task of estimating the probability of an accident and its resulting consequence.

Using a linear expression for VSI of the form given above segregates, in a simple manner, each of the components that make up the VSI. This is important for two reasons: First, it is highly probable that the VSI does not vary in proportion to any one of its components. Second, it permits one to look at each of the individual factors separately and to see readily how vessels attain their VSI. Thus, for example, if the controllability factor in the VSI were weak, one might want to consider the employment of tugboats or if the cargo capacity factor were high, one might have to control traffic or employ isolated terminals.

3.3.1 Factors and Limitations

For a given hazardous commodity being transported within a given port with its unique hazards and vulnerability, the VSI is intended to measure the ship's susceptibility to accident involvement and, given an accident, the ship's vulnerability to releasing its cargo and the amount of that cargo release. It is implicit in all three factors (F_1, F_2, F_3) which constitute the VSI that the term "accident" refers to collisions, groundings, and rammings only. (A collision is defined to be a ship-to-ship impact whereas a ramming is defined to be a ship-to-nonship impact such as striking a bridge or pier.) In other words, only those accidents in which the ship is interacting with the port environment and not those integral to the ship (e.g., fires and explosions) are considered.

The ship's probability of having an accident in a given port under a given set of circumstances (i.e., wind, visibility, current, traffic, etc.) depends on the operator's perception of such inputs as navigation, position, or traffic. The operator translates these inputs into control actions on the ship which, in turn, responds to the manipulations according to the combined interactive effects of the ship's own inherent maneuvering characteristics and the external environmental disturbances. The resultant output motion of the ship is then fed back either directly or through displays to the operator. Thus, given a range of competent operators, the ship's susceptibility to accident involvement varies according to perceived information, control mechanisms, and the inherent maneuverability of the ship or the response of the ship to those control inputs. Since the operating situation variables (site, time, and operationally dependent) will be accounted for when considering the port in section 3.4, insofar as accident susceptibility is concerned, the controllability of the ship as expressed in the VSI is some combination of the human operator, the input information and output control systems provided the operator, and the inherent maneuvering characteristics of the ship.

Danahy and Gathy (1973) did not include any variable for either the man or the information and control systems in their F_3 term. It does not appear feasible or desirable at this time to include the human factor. The primary reason for this judgment is the present inability to differentiate among operator performances or to assign quantitative measures to them. However, inclusion of the human factor in the future could be accommodated in the expression for VSI if so desired and when deemed feasible by the USCG.

On the other hand, the differences in information and control systems from one ship to the next can and should be included since they have a distinct impact upon accident susceptibility. One should not and cannot assume that all ships are equal from the onboard information and control system point of view, especially since the emergence of more and more sophisticated systems (such as highly accurate shipboard navigation systems for use in restricted channels).

3.3.2 A Reformulation of VSI

The expression for the VSI would be improved if it included a factor for information and control systems and was expressed in a linear form as follows:

$$\mathrm{VSI} = a_0 + a_1V_1 + a_2V_2 + a_3V_3 + a_4V_4 \qquad (25)$$

where the variable V has been substituted for the variable F to distinguish it from the Danahy and Gathy expression and where the a's are constants. V_1 is the cargo containment system term (i.e., corresponding to F_1). V_2 is the capacity term describing the potential for damage (i.e., corresponding to F_2). V_3 is a term describing the acceleration, turn, and kinetic energy factors or, more generally, the controllability of the vessel (i.e., corresponding to F_3), and V_4 is an onboard information and control system term which was not considered by Danahy and Gathy (1973).

The four individual factors should be expressed such that the VSI increases (i.e., increased safety) inversely to the cargo capacity term and directly with the cargo protection term, the controllability term, and the information and control term. Thus, to maximize the VSI or vessel safety, the cargo capacity term is minimized and the cargo protection, controllability, and information and control terms are maximized. As in the case of the original formulation, the four factors should be handled from a reference point of view, one for a base ship and another for a base barge since it does not appear feasible to combine the two. For the purposes of this report, only the ship case is discussed.

3.3.3 The Base Ship

The base ship is taken to be a Type III single-hull vessel with no pressure vessel or independent tanks. It has a conventional single-screw, single-rudder design with no auxiliary propulsion devices such as lateral thrusters. It is assumed that its information systems (including the navigation and collision avoidance subsystems) are no more than that required by current regulations for tank vessels as contained in 46 CFR Title 33 (i.e., LORAN-C, RDF, UHF voice communications, depth sounders, etc.) and that the control systems (including direct bridge control of machinery and rudder control) are in conformance with existing regulations and current marine practices.

For the purposes of this report, the base ship is considered to be a 10,000 DWT liquid bulk carrier capable of carrying such substances as benzene, a regulated flammable and toxic cargo. The ship has the following characteristics:

Deadweight	10,000 tons
Draft (max.)	25.0 ft
Length	428.0 ft
Beam	58.0 ft
Depth	30.5 ft
Horsepower	4,500 shp
Largest cargo tank	1,000 tons
No. center cargo tanks	5
No. wing cargo tanks	10
No. wing ballast tanks	0
Volumetric cargo capacity	81,500 bbls

3.3.4 The V Factors

Given the base ship, a formulation of the four factors (V_1, V_2, V_3, and V_4) was undertaken by the panel. The formulation was predicated on the assumption that, for the base ship, each of the factors should equal unity. The panel began with the formulations proposed by Danahy and Gathy (1973), adapted them to the linear form of the expression for the VSI, and made some changes that were deemed, by a consensus of the panel, to be an improvement on the original expressions for the individual factors.

3.3.4.1 V_1

Danahy and Gathy (1973) proposed that the cargo containment factor V_1 is a function of the presence of protective double bottoms and protective double sides or wing tanks, whether the tank is a pressure vessel tank, the strength of the cargo tank, and whether the ship's hull is Type I or Type II. For the purposes of the panel, it was assumed that the primary protection afforded a cargo tank is its location relative to the outer hull; the issue of protection afforded by other terms, if meaningful, can be incorporated at a later date to define this factor further. Although an oversimplification, the degree of protection offered by cargo tank location can be determined by considering the location of the cargo tank boundaries (sides and bottom) relative to the outer hull of the ship. In other words, if the outer hull forms the outer boundaries of the cargo tanks, there is no more protection afforded the cargo tank than is the case for the base ship. If, on the other hand, those boundaries are moved vertically upward from the ship's bottom and transversely inboard from the ship's sides, some additional degree of protection is provided to maintain the integrity of the cargo tanks after a collision, grounding, or ramming depending on the distances to which the tank boundaries are moved away from the outer hull.

This location protection may be said to result from the presence of a double bottom and/or double sides within the ship. Accordingly, the following expression for the V_1 factor results:

$$V_1 = D, \qquad (26)$$

where D is the numerical credit attributed to protecting the cargo tanks in the event of a collision, grounding, or ramming due to the presence of some combination of a double bottom and double sides. In the case of the base ship, there is neither a double bottom nor double sides (i.e., the outer hull forms the outer boundaries of the cargo tanks) so that D = 1 and thus:

$$V_1 = 1. \qquad (27)$$

A double bottom was considered to be 90 percent effective in the case of groundings (which make up approximately 44 percent of the spill events in port); double sides were considered to be 20 percent effective in the case of collisions (which make up approximately 34 percent of the spill events in port) and 90 percent effective in the case of rammings (which make up the remaining 22 percent of the spill events in port). Thus, the presence of a double bottom by itself gives a D value of 1.65 and the presence of double sides by themselves gives a D value of 1.36. The presence of a double bottom and double sides together gives a D value of 2.96.*

3.3.4.2 V_2

The following expression is used to calculate V_2:

$$V_2 = \frac{K}{[(C/S) + T]^{2/3}} \qquad (28)$$

where C is the total cargo capacity in tons, S is the number of cargo tanks, T is the tonnage of the single largest cargo tank, and K is a constant to be derived from the base ship. The two-thirds power to which the denominator is raised stems from the notion that the potential for damage is a function of the area (ft^2) over which the cargo will be spread upon release and the total volume (ft^3) released.

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*For example, given 100 spill events (i.e., on average 44, 34, and 22 events due to groundings, collisions, and rammings, respectively), if the ships had had double sides the spill events on average would be reduced to 44, 27.2, and 2.2 because double sides are 20 percent and 90 percent effective against spills during collisions and rammings, respectively, and ineffectual during groundings. The total spill events are now 0.734 (or 73.4 percent) of their former value. Taking the reciprocal of this gives a value for D of 1.36.

In the case of the base ship:

$$V_2 = \frac{141}{[10{,}000/15 + 1{,}000]^{2/3}} = 1 \tag{29}$$

where the value 141 is a constant selected so that V_2 for the base ship is unity.

3.3.4.3 V_3

The expression for V_3 was reformulated from Danahy and Gathy (1973) as follows:

$$V_3 = \frac{2f_A}{f_R + f_E} \tag{30}$$

where f_A, f_R, and f_E are the acceleration, turning, and kinetic energy functions, respectively; $f_A = (K_1 \times SHP/W)^{1/2}$; $f_R = (L/428)^{1/2}$; $f_E = K_2WV^2 \times 10^{-5}$; SHP is the shaft horsepower; W is the total displacement in tons; L is the length of the ship in feet; V is the speed in knots; and K_1 and K_2 are constants derived for the base ship.

For the base ship, $K_1 = 2.9$ and $K_2 = 0.12$; therefore:

$$V_3 = \frac{2[2.9(4{,}500)/13{,}000]^{1/2}}{(428/428)^{1/2} + 0.12(13{,}000)(8)^2 \times 10^{-5}} = 1 \tag{31}$$

The various constants were selected so that V_3 for the base ship equals one at an assumed maneuvering speed (V) of 8 knots.

3.3.4.4 V_4

The human factor term, V_4, was simply assigned a value of 1 until such time that other values could be assigned with justification. This factor when formulated could also include the previous safety record of a vessel.

3.3.5 Expression for the VSI

The overall expression for the VSI becomes:

$$\begin{aligned} VSI = a_0 + a_1D &+ \frac{141\ a_2}{[(C/S) + T]^{2/3}} \\ &+ 2\ a_3 \frac{(2.9\ SHP/W)^{1/2}}{(L/428)^{1/2} + 0.12\ WV^2 \times 10^{-5}} + a_4 \end{aligned} \tag{32}$$

In the case of the base ship:

$$VSI = a_0 + a_1 + a_2 + a_3 + a_4. \tag{33}$$

The values of the coefficients, a_1, a_2, a_3 and a_4, describe the relative strength of each of the four factors within the equation and a_0 is a constant that, as previously indicated, was inserted to follow the format of a general linear equation. For the purposes of the panel, the constant a_0 is assumed equal to zero, and the relative values assigned by the panel (after much debate) to a_1, a_2, a_3, and a_4 are 1.0, 1.0, 0.5, and 0.5, respectively. After normalizing the coefficients one obtains:

$$VSI = 0.333V_1 + 0.333V_2 + 0.167V_3 + 0.167V_4. \tag{34}$$

The VSI is equal to unity for the base ship since $V_1 = V_2 = V_3 = V_4 = 1$. With the foregoing formula as a basis, the individual factors can be modified to include new material. Alternatively, additional factors can be applied on a case-by-case basis.

3.3.6 Additional Factors as Applied to VSI

In general, if a single additional factor v_i impacts on any one of the four factors constituting the expression for VSI, the increased individual additional factor for any one of the four factors may be said to be $(1 + v_i)$ and, generally, $v_i < 1$. For example, a factor, v_1, applied to the factor V_1 would give the following:

$$V_1' = V_1 (1 + v_1). \tag{35}$$

If there are two additional factors, v_1 and v_2, to be applied simultaneously to V_1, then the new value for V_1, V_1'', is:

$$\begin{aligned} V_1'' &= V_1(1 + v_1) + (V_1')(v_2) \\ &= V_1(1 + v_1) + [V_1(1 + v_1)]v_2 \\ &= V_1(1 + v_1)(1 + v_2). \end{aligned} \tag{36}$$

This result may be generalized for n additional factors to:

$$V_1^{(n)} = V_1 \prod_{i=1}^{n} (1 + v_i). \tag{37}$$

If this notion is applied to each of the four factors of Eq. 34, the following results:

$$\begin{aligned} VSI = {} & a_1V_v \prod_{i=1}^{n}(1 + v_{1i}) + a_2V_2 \prod_{i=1}^{n}(1 + v_{2i}) \\ & + a_3V_3 \prod_{i=1}^{n}(1 + v_{3i}) + a_4V_4 \prod_{i=1}^{n}(1 + v_{4i}). \end{aligned} \tag{38}$$

This format permits, in a general sense, the application of any number of additional factors among ships above those contained within the expression for the four individual factors, V_1, V_2, V_3, and V_4. The user may apply special or peculiar factors on a case-by-case basis as deemed appropriate to the overall assessment of equivalent safety.

3.3.7 Application of the VSI

Using the suggested form for the VSI and not applying any additional factors, a series of 28 chemical and liquefied flammable gas carriers (including the base ship) was analyzed to determine the VSI values. In addition, four conventional oil tankers were included to expand the range of values for VSI.

The 32 ships were selected at random and include: 20 liquefied gas carriers ranging from a 1,625 m^3 LPG carrier to a 131,000 m^3 LNG carrier, 7 chemical and special product carriers ranging in size from 3,900 m^3 to 31,000 m^3, 4 oil tankers ranging in size from 20,500 DWT to 216,000 DWT, and the base ship. The ships and their values for the various input elements, C, S, T, D, SHP, W, L and V (assumed to be 8 knots in all cases), are listed in Table B-1 of Appendix B.

The VSI values were calculated from Eq. 34. These results are given in Table B-2 of Appendix B along with values for a_1V_1, a_2V_2, a_3V_3, and a_4V_4.

As seen in Table B-2, the VSI values range from 0.547 (for the 216,000 DWT oil tanker) to 1.94 for the 1,625 m^3 LPG carrier. If the four oil tankers were disregarded, the range would extend from 0.856 (for the 6,000 DWT sulfur carrier) to 1.94.

The cargo containment term, a_1V_1, has only three discrete values throughout the entire range of the 32 ships: 0.333 for single hull ships, 0.549 for those ships having a double bottom only, and 0.976 for those ships having both a double bottom and double sides. (No ships within the sample had double sides only.)

The capacity term, a_2V_2, ranges from 0.037 (for the 216,000 DWT oil tanker) to 0.928 (for the 3,900 m^3 chemical carrier). If the oil tankers were disregarded, the lower end of the range would be 0.055 for both the 126,500 and 131,000 m^3 LNG carriers.

The controllabilty term, a_3V_3, varies from 0.010 for the 216,000 DWT oil tanker to 0.319 for the 1,625 m^3 LPG carrier. If the oil tankers were disregarded, the lower end of the range would be 0.036 for the 101,000 m^3 LPG carrier.

The information and control term, a_4V_4, is constant at 0.167 since no expression for the V_4 factor was devised. This does not necessarily mean that it is not important but rather that, because of data limitations, it was assumed to be constant.

3.3.8 Conclusions and Recommendations

Table B-2 indicates clearly that the VSI is strongly dependent on V_1. In any ship fitted with a double bottom and double side, a_1V_1 constitutes an absolute value of 0.976 of the total value of the VSI; therefore, as other factors (i.e., capacity, controllability, etc.) diminish in value the VSI for these ships will always be about 1 or on a par with the base ship.

Another observation concerns the highest VSI value--the value of 1.94 for the 1,625 m^3 LPG carrier. The V_2 factor for this particular ship is one of the better ones despite the ship's having only two tanks because the overall capacity is so small. The value of V_1 is a maximum due to the presence of the double bottom and double sides as previously discussed. The high V_3 factor reflects a good horsepower-to-displacement ratio and small values of length and kinetic energy. The VSI value for this ship is neither surprising nor inconsistent with the formulation of the VSI; however, it is likely that on such a small ship the amount of damage stability and survivability is significantly less than on any of the larger ships and the risk of the ship's capsizing or sinking is therefore present. Whether or not a resultant sinking of the vessel in port should be somehow incorporated in the concept of equivalent safety is not clear at this time.

The present formulation of the VSI cannot accommodate a combination of different cargoes (i.e., it is predicated on a single commodity or cargo being transported in a given arrangement and capacity of cargo tanks with the V_2 or cargo capacity factor), but many ships in the bulk chemical trade carry a multiplicity of cargoes during a single voyage. One way of accounting for multiple cargoes is to develop V_2, the cargo capacity factor, for each cargo (by average tank size and maximum tank size for that cargo) and, thus, generate a series of VSI values for the one ship. It then would be necessary to divide each of those VSI values by the respective CHI values to identify the combination that gives the lowest value (i.e., the greatest hazard or "worst case" analysis). A large number of calculations may be required to determine what actually is the worst combination; however, some limiting values of cargo tank size and CHI may be so small that they can be ignored. An alternative method for dealing with multiple cargoes would be to determine somehow an average VSI to CHI ratio for all the cargoes and their respective tanks. In any case, although the present formulation does not account for multiple cargoes, some method for calculating a "worst case" or "average value" for such a chemical carrier could be developed.

Other intuitive or perceived inconsistencies within the present formulation for VSI include the following:

1. No variation is given within either V_1 or V_2 to account for the location of tanks along the length of the ship.

2. No variation is given within the V_1 factor to account for double side width and double bottom depth although damage statistics tend to indicate that extents of damage or depths of penetration are correlated to ship size (IMCO 1960, Robertson et al. 1974).

3. No variation appears in the V_2 factor for ships that differ in size by a factor of, for example, 10, if the number of tanks on the larger ship is 10 times as many as on the smaller ship.

Despite these inconsistencies, the VSI formulation shows some reasonable variation in relative safety from one ship to the next. Moreover, this formulation is conducive to the inclusion of other factors affecting safety and to the refinement of the factors presently defined.

The formulation of the VSI presented here is not to be construed as a final version. The panel attempted to make the formulation simple at the start by not introducing an inordinately large number of factors. Other variations for the VSI are possible. For example, the V_3 term that describes the vessel's ability to avoid an accident by virtue of its maneuverability and controllability characteristics could be placed alternatively in the PHI rather than the VSI. In addition, the V_4 term descriptive of human factors may not be necessary.

The base ship chosen is arbitrary and only serves to determine the reference point for placing the various ship types in relative order of safety. That is, the use of another base ship would not change the relative rankings, but only the range of values for the VSI. The actual magnitude of the numbers could be adjusted by the Coast Guard either by choosing a different base ship or by modifying the weighting of the independent coefficients in the VSI expression. Another possible reformulation of the VSI would be to have separate indexes for each accident type (collisions, groundings, rammings).

It should be noted that the 32 ships chosen for calculating values of VSI were for illustrative purposes only. The ships were selected at random, the data were typical values and not always exact, and the examples did not include barges.

To determine more objectively the functional relationship between the variables, to reevaluate the relative weighting of the coefficients, and to consider the inclusion of additional factors one would need, as a first step, an extensive evaluation of the existing data base of accidents. Inasmuch as the data in the individual accident files were not developed with an analysis of the equivalent safety type in mind, the shortcomings in the available information should become apparent. It is recommended that the Coast Guard carefully review its current accident reporting system and modify it so as to be able to acquire data of the type required to improve the VSI and the PHI. A model reporting system currently used by the National Transportation Safety Board (NTSB) (1979) in investigating hazardous materials spills is recommended. The NTSB report states that accident reports are written in a narrative form and are "seldom useful for upgrading emergency response planning or operations". Instead, NTSB has developed hazardous materials accident spill maps that report in a standardized format the observed behaviour of materials in an accident. The spill maps feature a time-sequenced display of dispersion patterns and ranges, weather at the times reported, injury/fatality exposure locations, and a synopsis of the accident scenario (Chemical and Engineering News 1980).

Simulation studies of maritime accidents may be another means to accumulate accident experience, particularly the role of human factors.

Because of gaps in knowledge and the lack of adequate information the VSI, unlike the CHI, is not founded on principles of physics and extensive testing but rather on the experience and judgment of the panel.

3.4 PORT HAZARD INDEX

The CHI and the VSI need be calculated only once for each commodity and each vessel, but the evaluation of the port is more complicated. The variety of port parameters may be significant and some of these parameters may vary in magnitude (and perhaps even from positive to negative--good to bad) seasonally, daily, and, sometimes, even hourly. An effort to quantify rigorously each port parameter is impractical for the near future.

Although the CHI and VSI can be calculated by USCG Headquarters for use by the COTP, only the officer with the responsibility on-scene should make the final evaluation of the overall safety situation locally. Thus, this section presents only some guidelines to assist the COTP in evaluating his port and in identifying dangerous and/or vulnerable regions in the port in a manner that will improve consistency among the various ports. The intent is not to preempt judgment of the the local authority but rather to aid the local authority.

An approach for evaluating port hazards and vulnerability was suggested by Danahy and Gathy (1973). Table A-1 of Appendix A lists some significant parameters that would either increase or decrease accident probability and Table A-2 lists some vulnerability considerations (i.e., those items to consider when evaluating potential damages to the port population and property in the event a serious accident occurred).

The panel did not believe it had the expertise necessary to devise a rigorous rating scheme for the port area; therefore, it decided merely to identify port factors considered significant and to use a binary approach to note qualitatively good and bad features. The goal was to aid the COTP in analyzing and evaluating his port areas for relative hazards and relative vulnerability and in flagging problem areas when advised that a ship with low VSI/CHI ratio was entering or leaving port.

A hypothetical port based on the averages of data from six real ports was developed. The appropriate variables are tabulated in Tables 4, 5, and 6 and a suggested method for relating these factors is described below.

TABLE 4 Port Hazard Variables and Symbols

Site Dependent (SD_1)		Time Dependent (TD_1)		Operational Dependent (OD_1)	
O	Obstructions	L	Line of sight	N	Day/night navigation
W	Channel width	C	Current force/ direction	E	Tugs
D	Channel depth	W	Wind force/ direction	VTS	Traffic control
b	Bottom type	T	Traffic	S	Speed
R	Turn radius	B/L	Background lights	CG	USCG escort
J	Channel junctions	I	Ice		
A	Aids to navigation				

The port should be divided into segments, beginning at the sea buoy, and each segment should be evaluated independently. The objective is to identify the weak links along the route the vessel intends to travel. The weakest link, or segment having the greatest hazard potential, then would be the primary controlling item for safety decisions, but other weak links also would be identified thereby assisting in secondary safety planning.

In dividing the port into segments it is suggested that the following approach would be appropriate. The channel segments should be broken down into straightaways, bends, channel junctions, and major obstructions (i.e., bridge abutments, locks, jetties, etc.). The straightaway segments should not exceed 5 miles in length; bends should include the 1/2 mile before and after the bend; channel junctions should include 1 mile of channel on either side of the junction; and the obstruction segments should include 1 mile of channel before and after the obstruction.

An example of the segmented approach is illustrated in Figure 1.

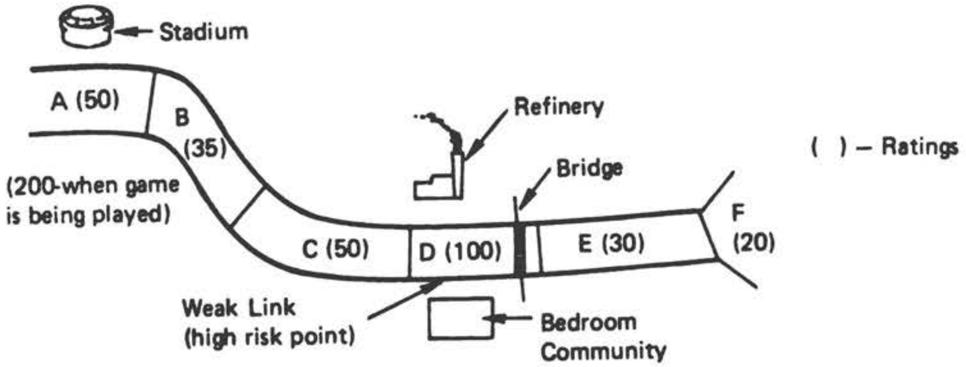

FIGURE 1 Schematic diagram of a port area segmented along the vessel route.

TABLE 5 Binary Values of Port Hazard Variables

Hazard Variable	Hypothetical or Average Port	Panel's Recommendations
Site Dependent		
Obstructions	1	0 - No obstructions 1 - Obstruction present
Minimum channel width	460 ft	(Rule of thumb: width = 4 x ship's beam) 0 - if > 4 x beam 1 - if < 4 x beam
Minimum channel depth	41 ft	(Minimum CLR to be determined by USCG, suggest 2 ft) 0 - if > 2 ft CLR 1 - if < 2 ft CLR
Bottom type	soft	0 - if soft 1 - if hard
Turn radius	Min. 2000 ft Average 4200 ft	(Rule of thumb radius: = 5 x ship's length) 0 - if radius >5 x length 1 - if radius <5 x length
Junctions	5	0 - if none 1 - if some
Aids to navigation	2 per mile	0 - if aids at 2/mile 1 - if aids > 2/mile
Time Dependent		
Line of sight (visibility)	Reference 1 mile visibility or line of sight—whichever is less	0 - if > reference 1 - if < reference
Current force/direction	2-1/2 knot average max.	≤ 2-1/2 knots > 2-1/2 knots force: 0 1 direction: vs 1 0 with 0 1 cross 1 1
Wind force/direction	8 knots average	≤ 10 knots > 10 knots force: 0 1 direction: vs 0 0 with 0 0 cross 0 1
Traffic	Not determined	0 - nonpeak period 1 - peak period
Background lights	Not determined	0 - not confusing 1 - potentially confusing
Ice	Not typically found in most U.S. ports	0 - not present 1 - present
Operational Dependent		
Daylight/nighttime navigation	Daylight vs nighttime can be argued both ways depending upon circumstances[a]	
Tug	-	1 - if tugs present 0 - if no tugs
Traffic control	-	1 - if adequate 0 - if inadequate or unrestricted
Speed	-	This is considered part of traffic contr
USCG escort	-	1 - if used 0 - if not used
Mitigation capability	b	1 - if considered effective in short reaction time and for cargo of concern

[a] Daylight vs nighttime navigation requires local evaluation considering changes in traffic density, traffic patterns, proximity of bedroom communities, etc.

[b] Mitigation capability should consider such items as fireboats on immediate standby, possibility and feasibility of igniting any flammable clouds to protect life and property ashore before such cloud reached vulnerable areas ashore.

TABLE 6 Port Vulnerability Variables and Symbols

Site Dependent (SD_2)		Time Dependent (TD_2)		Operational Dependent (OD_2)	
RA	Residential apartments	CH	Churches	CD	Close down operations
RH	Residential homes	SC	Schools	EA	Evacuate area
B	Business		Recreation Sites:	DP	Divert people
M	Manufacturer	RT	Theater		Mitigation:
C	Commercial	RS	Stadium, etc.	MA	Action
TC	Transportation center (airport, train station)	OT	Other	MD	Devices
H	Highways	W	Wind force and direction		
TU	Tunnel	ND	Military/national defense facilities, mobile		
TO	Topographic liabilities				
ND	Military/national defense facilities				

The numerical development of the PHI would be in accordance with the following relationship:

$$PHI = SD_1 + TD_1 - OD_1 + SD_2 + TD_2 - OD_2 \qquad (39)$$

where the port hazard variables (Table 4) SD_1, TD_1, and OD_1 are given by:

$$SD_1 = b_1\Sigma(O + W + D + b + R + J + A + \ldots),$$

$$TD_1 = b_2\Sigma(L + C + W + T + (B/L) + I + \ldots),$$

$$OD_1 = b_3\Sigma(N + E + VTS + S + CG + \ldots),$$

and values for the weighting factors b_1, b_2, and b_3 are taken from Table 7 and binary values for each variable identified in Table 4 are found in Table 5.

The port vulnerability parameters (Table 6) SD_2, TD_2, and OD_2 are given by:

$$SD_2 = b_4\Sigma(RA + RH + B + \ldots)^{0\text{-}1 \text{ mile}} + b_4\Sigma(RA + RH + B + \ldots)^{1\text{-}5 \text{ miles}} + b_4\Sigma(RA + RH + B + \ldots)^{5\text{-}25 \text{ miles}}$$

$$TD_2 = b_5\Sigma(CH + SC + \ldots)^{0\text{-}1 \text{ mile}} + b_5\Sigma(CH + SC + \ldots)^{1\text{-}5 \text{ miles}} + \ldots$$

and

$$OD_2 = b_6\Sigma(CD + EA + \ldots) + \ldots,$$

where values for the weighting factors b_4, b_5, and b_6 are taken from Table 8. The appropriate variables are selected from Table 6; however, the panel was not able to devise a means for assigning values to these variables. The vulnerablity model developed by the USCG could be used to formulate these values and result in another table, similar to Table 6, but having appropriate weights for the port vulnerability variables.

Physically, the PHI is equivalent to the degree of hazard represented by the configuration of the port and the degree of vulnerability influenced by people and property in the vicinity. Although these factors may raise the PHI, the safety actions (i.e., the operationally dependent actions that the USCG can institute) can regulate and reduce the final value for the PHI.

The operationally dependent variables OD_1 and OD_2 listed in Tables 4 and 6 represent actions that can be taken to improve the safety or lessen the risk (i.e., actions that the COTP can initiate to control the situation

TABLE 7 Values of Weighting Factors: b_1, b_2, b_3

Port Hazard Variables		Nonrestricted Waterway	Restricted Straightaway	Bend
Site Dependent (SD_1)	$b_1 =$	0	1	2
Time Dependent (TD_1)	$b_2 =$	1	2	3
Operational Dependent (OD_1)	$b_3 =$	0	1	3/2

TABLE 8 Values of Weighting Factors: b_4, b_5, b_6

Port Vulnerability Variables		Distance from Channel		
		0-1 Mile	1-5 Miles	5-25 Miles
Site Dependent (SD_2)	$b_4 =$	3	2	1
Time Dependent (TD_2)	$b_5 =$	2	1	0
Operational Dependent (OD_2)	$b_6 =$	1	0	0

and provide equivalent safety). Numerically, these operationally dependent variables reduce the PHI so that it is not out of proportion to the VSI/CHI ratio.

To utilize this scheme it is suggested that the COTP first evaluate the PHI assuming that there are no operationally dependent variables. If it appears that the resulting PHI value is unsuitable for a particular vessel expected to transit the port area with its hazardous cargo, by proper selection of the operationally dependent variables (from either Table 4 or 6), the COTP could judge the effect of these actions. The actions could include closing down certain operations, employing tugboats, utilizing the vessel traffic system, and escort by Coast Guard vessels. The advantage of this approach is that it identifies the need for additional operational actions on the part of the Coast Guard, the ship operators, or the people in the port. It avoids unnecessarily stringent actions, offers a choice of operations while showing their relative effect, and justifies the need for additional operational requirements. Although these lists are reasonably complete, other operational variables could be included when necessary (e.g., port characteristics that would lead to operational actions unique to that port).

Finally, since the panel has only suggested an approach for determining the PHI and was not able to complete its formulation, it urges that the Coast Guard continue the effort. This can be accomplished using the Coast Guard population vulnerability model, a list of port factors developed for a survey by the panel, and a study by Ecker (1978).

In its survey the panel compiled 65 factors grouped in nine categories that can affect the safe transit of vessels carrying hazardous materials. The nine categories are:

1. Existing regulatory considerations
2. Facilities or services provided by the port
3. Hydrography--channel configuration
4. Hydrography--depths and heights
5. Port activity
6. Short-term variables
7. Seasonal factors
8. Temporary restrictions to navigation
9. Weather

Information on the relative importance of the factors in each of the nine categories was solicited from individuals at six ports: New Orleans, Portland, Houston, Philadelphia, Los Angeles, and Long Beach. The results of the survey, in cases where checking was possible, did not agree with accident experience. Since there was real concern about the validity of the responses, the results were not used in the formulation of the PHI, but some of the information may be useful in conjunction with the results presented by Ecker (1978). He utilized a statistical approach to rank several ports and compared the results with an earlier Coast Guard analysis. Ecker's paper includes many data that give some useful insight into vessel casualties in U.S. ports. This information should be particularly useful to the COTPs of those areas covered in Ecker's study, but other COTPs will find it useful for purposes of comparison with their own data and to gain additional insight into the distribution of various types of vessel casualties. This background information should assist the COTP in assessing potential trouble areas within his zone.

3.5 NOTATION

a_i	$i = 1, 2, 3, 4$; weighting factors in the expression for VSI
b_i	$i = 1, 2, 3, 4, 5, 6$; weighting factors in the expression for PHI
c	concentration of hazardous material in the vapor cloud
C	total cargo capacity, tons
CHI	cargo hazard index
D	credit for double bottom and/or double sides
D_v	molecular diffusivity at T_a
D_{vb}	molecular diffusivity at T_b
f_A	acceleration function
f_E	kinetic energy function
f_R	turning function
g	gravitational acceleration
IDLH	(concentration) immediately dangerous to life or health
k	mass-transfer coefficient
K	constant
L	ship length, feet
L_c	characteristic length
LC_{50}	lethal concentration required to kill 50 percent of the test animals
LCLO	lowest lethal concentration
LFL	lower flammability limit
m	rate of vapor production per unit area of spilled cargo
M	total rate of vapor release to the atmosphere
OD_i	$i = 1, 2$; operational dependent port hazard variable and vulnerability parameters
P	atmospheric pressure
PHI	port hazard index
P_v	vapor pressure at T_a
S	number of cargo tanks
SD_i	$i = 1, 2$; site dependent port hazard variable and vulnerability parameters
SHP	shaft horsepower
t	time
T	tonnage of single largest cargo tank
T_a	absolute ambient temperature
T_b	absolute boiling point
TD_i	$i = 1, 2$; time dependent port hazard variable and vulnerability parameters
TLV	threshold limit value

u	average wind velocity
V	ship speed, knots
V_1	cargo containment term
V_2	cargo capacity or potential for damage term
V_3	controllability of the vessel term
V_4	onboard information and control system term
VSI	vessel safety index
v_i	additional factors
W	total ship displacement, tons
X	distance from location of the spill
$X_{\ell e}$	distance to leading edge of spilled liquid pool
ρ_ℓ	spreading liquid density
ρ_w	water density
σ_y	cloud standard deviation in crosswind direction
σ_z	cloud standard deviation in vertical direction
μ_w	water viscosity

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Appendix A

ABRIDGED VERSION OF "EQUIVALENT SAFETY AND HAZARDOUS MATERIALS TRANSPORTATION" BY PHILIP J. DANAHY AND BRUCE S. GATHY

(Originally presented as ASME Paper 73-ICT-86 at the
Intersociety Conference on Transportation,
Denver, Colorado, September 1973)

A.1 ABSTRACT

This paper proposes a methodology to assess hazards, safety, and safety requirements in the marine transportation of hazardous materials. The basic approach is to quantify on a relative basis rather than on some absolute scale. The authors suggest that each hazardous commodity can be graded on a numerical scale for relative safety provided by the design, operation, etc. By combining the commodity relative hazard rating with the vessel relative safety rating an overall transportation safety rating may be obtained. Different commodities carried in vessels of different design could have the same transportation safety rating if equivalent safety had been obtained. The paper also suggests a method to quantify, on a relative basis, the safety requirements for waterways (including ports and terminals). By relating the transportation safety rating to the port safety requirement, one can determine what vessel design features are required to transport a specific hazardous commodity to a specific terminal over a specific water route.

A.2 BACKGROUND

Risk analysis offers the regulator considerable hope for quantifying equivalent safety in the future. At present, the models available seem too sophisticated for the input data available, and the result is merely extensive documentation of the complexities involved. Therefore, a somewhat simplified approach to the Coast Guard's portion of the problem is proposed. Future refinements of this approach can provide a gradual expansion into a more sophisticated system as needs develop and knowledge permits.

Our objective is to facilitate the regulation of hazardous materials transportation in the marine mode by requiring safety equivalent to a minimum standard. Our method is to:

1. Divide the problem into three areas--the cargo, the vessel and the port/terminal waterway;

2. Quantify, on a relative basis, the significant factors in those three areas; and

3. Determine a suitable interrelationship between the areas.

It is hoped that quantifying the contribution toward safety by the significant variables will permit the planner in industry to be more free to determine what is the best solution to his unique transportation problems. The actual method used to quantify the significant factors will be subject to criticism and improvement and may otherwise be refined in the future. The quantification methods, the principles involved, the advantages of the approach, and how the approach can be used by government and industry are discussed below.

A.3 CARGO INDEX

All hazardous materials have one thing in common, the capability of causing damage. However, they do not all have equally damaging effects. If materials are compared carefully with one another, a sequential arrangement with the worst material at the top of the list and the mildest at the bottom will result. Numbers can be assigned to the commodities so listed and numerical gaps can be provided between commodities to indicate the degree of difference between commodities.

This is not the first effort to assign a number to a commodity based on its relative hazard potential. The (RSMA) publication, "Handling Guide for Potentially Hazardous Commodities", assigns what are called "priority risk rating" numbers on a scale of 0 to 25 with the highest number creating the most concern. One intended use of the RSMA guide is to indicate to salvage crews which rail cars involved in a train accident should be attended to first.

The National Fire Protection Association, in its 704M system, grades hazards on a relative basis from 0 to 4 in each of three hazard categories--fire, health, and reactivity. The National Academy of Sciences' Committee on Hazardous Materials, which advises the USCG, has developed a hazard profile system that is somewhat of an expanded version of NFPA 704M. The hazards are graded from 0 to 4 in each of 10 categories. The health and reactivity categories are each subdivided into three categories and water pollution effects are considered by three more categories. The problem of using a 0 to 4 rating is that widespread differences in destructive capability are essentially masked by the apparent equivalency of commodities assigned the same number. This is particularly true of those commodities graded as 4 (e.g., a science fiction type material such as the Andromeda Strain would merely get a 4 rating).

The initial development of a quasiscientific method for determining the relative hazard of any commodity proposed for shipment by water is described below. This relative hazard rating will be called the cargo index (CI). The higher the numerical value of the CI, the greater the relative hazard. This number is essentially a fixed value for each cargo until or unless the cargo's hazard assessment changes.

In developing the CI, K_1 is a relative vaporizing value taken from $K_1 = 3(1 - e^{-Pv/20})$ where Pv = Reid vapor pressure, K_2 is a relative ignition hazard value where K_2 is $1 + (e^{500/T}/10)$ and T = autoignition temperature (°F), UEL is the upper explosive limit (%), LEL is the lower explosive limit (%), TLV is the threshold limit value (ppm), ρ_V is the vapor density (air = 1), and T_{BP} is the boiling point of cargo, (°R).

This initial development considers the potential dangers due to large toxic vapor clouds and to large flammable vapor clouds. For toxic clouds:

$$CI = 10K_1(\rho_v/TLV)^{1/2}. \qquad (A-1)$$

For flammable clouds,

$$CI = K_1K_2/2[(UEL - LEL)\rho_v/LEL]^{1/2}. \qquad (A-2)$$

The value to be used for CI is the larger of the values determined by either the toxic or flammable approach (see Table 2 of this report for results). For cargoes having a boiling point below 0°F there is a vapor density correction factor equal to $(500/T_{BP})^{1/2}$. This results in the following equations for cryogenic cargoes:

$$CI = 10K_1(500\rho_v/T_{BP}\ TLV)^{1/2}, \qquad (A-3)$$

and

$$CI = K_1K_2/2[(UEL - LEL)500\,\rho_v/T_{BP}]^{1/2}. \qquad (A-4)$$

An obvious weakness of Eq. A-1 is the use of TLV for the significant controlling variable for toxic clouds. There are several other useful toxicity standards including LC_{50}, LD_{50}, PEL, and STL; however, TLV was used since it is readily available for nearly all materials shipped in bulk and facilitates the demonstration of a method to quantify the relative hazard potential of toxic commodities. The use of LC_{50} probably would be the preferable parameter, but even this has weaknesses (e.g., the variety of animals used, the exposure interval used, and the reliability of extrapolation of test results to the expected damage effects upon humans).

A.4 VESSEL INDEX

The overall safety of the transportation system depends on the significant contributions by the vessel carrying the hazardous materials. There are many characteristics of the transporting vessel that influence how safe the operation will be. Vessel capacity indicates the relative potential for destruction and/or damage. The spillage of 5 gallons is inconvenient, but the spillage of 5,000 gallons is bad and of 500,000 gallons, a major event. Despite the effect of size there can be compensating, or offsetting, features provided in the design. Offsetting the effect of the total size is the fact that the vessel is subdivided into many tanks. The probability of all tanks releasing all cargo is not as likely as the release from one tank. Further safety may result from the provision of non-cargo-carrying wing tanks and/or double-bottom tanks. In this way, a minor hull penetration from collision or grounding will not penetrate the cargo containment portion of the vessel.

Many other design features can be provided by the designer to enhance transportation safety. This method depends on quantification of the relative contribution of such design features to determine a vessel safety rating called the vessel index (VI). The VI is a direct indication of the degree of safety offered by the vessel. A vessel with the greatest apparent safety will have the highest value for the VI. The initial development of a method for determining the VI is described below. Note that the VI need not remain at one fixed value for one specific vessel (e.g., a tank ship designed with wing tanks could elect not to carry cargo in the wing tanks under certain circumstances and when the wing tanks are empty, the tank ship would have a higher value for VI).

In developing the VI, Δc is the total cargo capacity (tons), Δt is the largest cargo tank capacity (tons), Δs is the vessel displacement (tons), V is the vessel speed (knots), L is the vessel length (feet), N is the number of barges in tow, S is the number of cargo tanks, SHP is the shaft horsepower, MAWP is the maximum assigned working pressure, P_v is the cargo vapor pressure at 110°F, and K is a constant for future refinement.

The expression for the vessel index is,

$$VI = K\, F_1/F_2F_3 \qquad \text{(A-5)}$$

where $K = 100$, $F_1 = f_B + f_W + f_P + f_T + (f_I \text{ or } f_{II})$, $F_2 = f_C$, and $F_3 = -f_A + f_R + f_E + f_L + f_S + f_N$.

For F_1, f_B = double bottom credit = 2, f_W = wing tank credit = 3, f_P = pressure vessel tank = 1.5, f_T = tank strength credit = $MAWP/P_v$, f_I = Type I hull credit = 5, f_{II} = Type II hull credit = 2.

For F_2, f_c = capacity factor = $[(\Delta c/s) + \Delta t]^{2/3}/100$.

For F_3, f_A = acceleration factor = $(10\ SHP/\Delta s)^{1/2}$, f_R = turning factor = $(L/300)^{1/2}$, f_E = kinetic energy = $\Delta s V^2/10^5$, f_L = lead barge factor = 2, f_S = barge side vulnerability factor = 1 (each exposed side), and f_N = barge quantity factor = $N^{1/2}$.

Eq. A-5 indicates the relative safety of the vessel to contain the cargo and avoid damage to the public. It has been arrived at by first identifying those characteristics considered to have an important influence on vessel safety and then organizing them into one of three categories: resistance to release of cargo in the event of an accident (F_1), potential for damage if cargo is released (F_2), likelihood of causing an accident (F_3). The next steps involve evaluating the relative influence of each variable and determining a logical interrelationship.

Where appropriate, the effect was compared to a reference point or base line. For example, net acceleration capability was assumed to be a function of the square root of shaft basepower divided by vessel displacement tonnage. This was compared to a reference vessel of 10,000 tons and 1,000 SHP--i.e.,

$$F_A = (10\ \mathrm{SHP}\Delta s)^{1/2}.$$

Such comparisons or ratios had the advantage of making all magnification factors (f_A, f_C, etc.) dimensionless. The reference values used were: $L = 300$ ft; $\mathrm{SHP} = 1{,}000$; $\Delta S = 10{,}000$; $(\Delta c/s) + \Delta T = 1000$.

A.5 TRANSPORTATION SAFETY INDEX

After the relative hazard potential of the cargo (CI) and the relative safety capability of the vessel (VI) have been determined, they can be combined to indicate the relative safety of a particular vessel carrying a particular commodity. This combined rating will be called the transportation safety index (TSI) and is expressed as:

$$\mathrm{TSI} = \mathrm{VI}/\mathrm{CI}. \qquad \text{(A-6)}$$

Greater apparent safety will be reflected by a higher value for TSI.

A.6 PORT SAFETY INDEX

The next important component to be considered in the transportation system is the water route (i.e., port, waterway, and terminal area). Each port is different and undergoes many changes daily, seasonally, etc. Transiting port A generally may be considered easier and safer than transiting port B; however, under certain conditions (e.g., fog, ice, tides, traffic density, winds), the reverse might be true. An accident in port A might endanger more people or facilities than a similar accident in port B. Similarly, variations affecting safe access to various terminals within a port may be expected to exist. A waterway such as a river, canal, or bay may be considered to be a network connecting ports and terminals and may present a rather complicated case for safety assessment. The proposed method suggests that the port, waterway, or terminal areas be assigned numerical ratings, indicating the degree of relative safety requirements that must be met by a vessel carrying hazardous materials if it intends to transit the area. This numerical relative rating will be called the port safety index (PSI). The initial development of a method for determining the PSI is described below. A larger value for PSI indicates that the port requires greater safety consideration.

In attempting to arrive at a relative rating of the port safety requirements, we have considered two families of influencing variables. The first is a collection of those characteristics of the port or waterway that might contribute to the occurrence of a marine accident. The second is a collection of those characteristics on the shore that could indicate the degree of damage expected for an assumed release of hazardous cargo. The first group is listed in Table A-1 and, when combined in Eq. A-7 below, represents the probability of an accident occurring. The second group is listed in Table A-2 and, when combined in Eq. A-7 below, represents the degree of impact possible should the accident and release of cargo occur.

The expression for the PSI follows with the terms defined in Tables A-1 and A-2:

$$\begin{aligned} PSI = T \times 10^{-6}[((4P_1 + 2P_2 + P_3 + P_4)/5000) + A + C] \\ \times [(1/S) + (100/W) + (500/R) + (10/d) + n^3 + (V_k^2 \sin\Theta)/5]^{1/2} \end{aligned} \quad \text{(A-7)}$$

TABLE A-1

Waterway Variables	Symbol	Contribution to Accident Probability
Unobstructed line of sight, measured in miles from mid-channel to mid-channel	S	Decreases
Channel width, measured in feet at minimum point	W	Decreases
Radius of turn in channel	R	Decreases
Solid obstruction, distance in feet from side of channel	d	Decreases
Channel junctions and river crossings, quantity	n	Increases
Water current, velocity in knots at maximum current	V_k	Increases
Direction of current, angle in degrees measured from axis of channel	Θ	Increases
Vessel traffic density, in tonnage per month	T	Increases

TABLE A-2

Shoreside Variables	Symbol
Population density (fixed) people per $mile^2$	
a - within 1 mile of channel	P_1
b - between 1 and 3 miles of channel	P_2
c - between 3 and 9 miles of channel	P_3
Population density (mobile)	P_4
Roadway traffic density within two miles of channel, vehicles/mile	
Public/commercial activities within 2 miles, (i.e., office buildings, theatres, stadiums, schools, etc.)	A
Industrial complications within 2 miles (i.e., refineries, tank farms, warehouses, munitions plants)	C

Again an effort has been made to remove the effect of dimensions by using dimensionless ratios. For example, the variable S is compared to 1 mile, W is compared to 100 feet, etc.

The variables A and C are arbitrary determinations that take into account special conditions and they may not always be weighted to the same degree. For example, a large stadium might significantly increase the population density locally for several hours of the week. Such special conditions require evaluation by the local authorities although they could be based on guidelines determined at a central location.

One of the variables that determines the value of PSI is the marine traffic flow. For two ports that are otherwise equally safe, the port with significantly denser marine traffic would be assigned a higher PSI. This might have the effect of causing some traffic to shift to the other port and tend to readjust the PSI rating of both ports. More important, however, the real significance of the traffic flow is that it is a variable that is readily controllable by the Coast Guard. Other controls include providing a Coast Guard escort, requiring tug boats to be standing by or on call, temporarily stopping traffic or making it oneway, and limiting port entry to daylight hours with good visibility only. The point is that operational controls can change the apparent values of TSI or PSI.

Another aspect of the PSI is that it should help the USCG and local port authorities identify potential problem areas and guide the development of remedial actions. The installation of the Vessel Traffic Systems (VTS) being developed by the Coast Guard will contribute to greater safety in port operations. The rating of PSI will aid in determinations of priorities for the establishment of VTS facilities.

A.7 APPLICATION

If the safety provided by the vessel for its cargo of hazardous material meets or exceeds the safety requirements of the port concerned, the vessel may be permitted to enter. That is, if TSI $\geq$ PSI, the situation is acceptable.

For example, assume that a cargo is rated at 200 for CI, the vessel is rated at 900 for VI, and the port is rated at 5 for PSI. The TSI = VI/CI = 900/200 = 4.5, which is less than the 5 PSI. This situation would not be permitted without some further corrective action. On the other hand, the same vessel carrying cargo rated at 150 would yield a TSI of 6 and therefore could enter port. For a vessel transiting a long waterway (e.g., a barge tow going from Vicksburg on the lower Mississippi River to Cincinnati on the Ohio River), the controlling condition would be that area with the highest safety requirement.

The advantages of the concept are numerous and valuable to the Coast Guard, the industry, and the public. The Coast Guard will have promoted consistency and stability and demoted emotion and personal bias. Industry will have greater flexibility in managing the transportation of hazardous materials by knowing where the trade-offs are and what they mean. The public will be assured that its interests have been considered and that it will have the protection of equivalent safety whatever the cargo authorized for carriage by any vessel into any port.

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Appendix B

INPUT AND OUTPUT DATA USED IN ANALYSIS OF VSI

TABLE B-1 Input Data

Example No.	Ship	C Total Cargo (tons)	S No. of Cargo Tanks	T Largest Cargo Tank (tons)	D Double Side/ Bottom Factor	SHP Shaft Horsepower	W Ship Displacement (tons)	L Length (ft)	V Speed (knots)
1	Base Ship	10,000	15	1,000	1.0	4,500	13,000	428	8
2	101,000 m^3 LPG	60,800	8	7,600	2.93	21,000	85,000	786	8
3	40,200 m^3 NH_3	27,478	3	9,159	2.93	12,500	37,500	597	8
4	78,000 m^3 LPG	46,940	5	9,388	2.93	23,500	63,000	709	8
5	75,000 m^3 LNG	35,550	5	7,710	2.93	20,800	55,000	759	8
6	7,400 m^3 ethylene	4,230	6	705	2.93	7,500	9,000	377	8
7	11,750 m^3 NH_3	8,030	3	2,677	2.93	7,000	15,000	430	8
8	22,000 m^3 LPG	13,250	18	1,100	2.93	6,000	24,000	585	8
9	29,600 m^3 LNG	14,025	4	3,506	2.93	20,000	25,000	561	8
10	131,000 m^3 LNG	62,210	5	12,442	2.93	45,000	95,000	875	8
11	126,500 m^3 LNG	59,980	6	14,600	2.93	40,600	92,000	905	8
12	87,600 m^3 LNG	41,520	5	8,304	2.93	30,000	64,000	777	8
13	53,400 m^3 LPG	32,150	4	8,038	2.93	19,000	41,000	636	8
14	29,400 m^3 LNG	13,930	4	3,483	2.93	19,000	25,000	562	8
15	12,300 m^3 vinyl chloride	11,900	4	2,975	2.93	12,500	20,000	628	8
16	7,750 m^3 LPG	4,660	5	932	2.93	4,000	9,500	392	8
17	126,300 m^3 LNG	59,850	6	9,975	2.93	40,000	92,000	923	8

8	1,625 m^3 LPG	975	2	488	2.93	1,900	5,000	218	8
9	19,300 m^3 NH_3	13,200	4	3,300	2.93	10,000	28,000	505	8
0	50,000 m^3 LNG	23,700	6	3,950	2.93	16,000	39,000	695	8
1	6,200 m^3 vinyl chloride	5,924	2	2,977	2.93	5,000	12,000	351	8
2	17,000 m^3 chemical	16,500	33	750	1.65	10,000	27,000	526	8
3	3,900 m^3 chemical	3,500	26	225	1.65	3,600	8,000	355	8
4	31,000 m^3 chemical	30,800	46	2,570	2.93	16,000	41,000	556	8
5	20,500 m^3 petrochemical	20,200	33	1,122	1.0	8,000	30,000	579	8
6	6,600 m^3 chemical	6,500	26	406	1.0	3,750	12,500	334	8
7	17,900 m^3 chemical	17,600	24	1,100	2.93	8,200	26,000	500	8
8	20,500 DWT oil	20,500	33	955	1.0	7,000	28,000	530	8
9	216,600 DWT oil	216,600	12	27,075	1.0	30,000	245,000	1,017	8
0	67,750 DWT oil	65,750	13	6,575	1.0	20,000	80,800	748	8
1	105,000 DWT oil	105,000	11	17,500	1.0	22,000	124,000	804	8
2	6,000 DWT sulfur	6,000	2	3,000	1.0	3,200	13,000	297	8

TABLE B-2 Output Data

Example No.	Ship	a_1V_1 Cargo Containment	a_2V_2 Cargo Capacity	a_3V_3 Controllability	a_4V_4 Information and Control	VSI
1	Base Ship	0.333	0.333	0.167	0.167	1.00
2	101,000 m^3 LPG	0.976	0.076	0.036	0.167	1.26
3	40,200 m^3 NH_3	0.976	0.067	0.081	0.167	1.29
4	78,000 m^3 LPG	0.976	0.066	0.057	0.167	1.26_5
5	75,000 m^3 LNG	0.976	0.080	0.063	0.167	1.29
6	7,400 m^3 ethylene	0.976	0.373	0.318	0.167	1.83
7	11,750 m^3 NH_3	0.976	0.153	0.181	0.167	1.48
8	22,000 m^3 LPG	0.976	0.313	0.283	0.167	1.55
9	29,600 m^3 LNG	0.976	0.128	0.166	0.167	1.44
10	131,000 m^3 LNG	0.976	0.055	0.045	0.167	1.24
11	126,500 m^3 LNG	0.976	0.055	0.044	0.167	1.24
12	87,600 m^3 LNG	0.976	0.072	0.062	0.167	1.28
13	53,400 m^3 LPG	0.976	0.074	0.089	0.167	1.30_5
14	29,400 m^3 LNG	0.976	0.128	0.162	0.167	1.43
15	12,300 m^3 vinyl chloride	0.976	0.143	0.164	0.167	1.45
16	7,750 m^3 LPG	0.976	0.310	0.218	0.167	1.67
17	126,300 m^3 LNG	0.976	0.064	0.044	0.167	1.25

18	1,625 m^3 LPG	0.976	0.477	0.319	0.167	1.94
19	19,300 m^3 NH_3	0.976	0.133	0.105	0.167	1.38
20	50,000 m^3 LNG	0.976	0.118	0.085	0.167	1.35
21	6,200 m^3 vinyl chloride	0.976	0.143	0.201	0.167	1.49
22	17,000 m^3 chemical	0.549	0.404	0.109	0.167	1.23
23	3,900 m^3 chemical	0.549	0.928	0.255	0.167	1.90
24	31,000 m^3 chemical	0.976	0.214	0.083	0.167	1.44
25	20,500 m^3 petrochemical	0.333	0.325	0.085	0.167	0.910
26	6,500 m^3 chemical	0.333	0.621	0.170	0.167	1.29
27	17,900 m^3 chemical	0.976	0.313	0.249	0.167	1.70_5
28	20,500 DWT oil	0.333	0.346	0.087	0.167	0.933
29	216,600 DWT oil	0.333	0.037	0.010	0.167	0.547
30	65,750 DWT oil	0.333	0.091	0.038	0.167	0.629
31	105,000 DWT oil	0.333	0.052	0.022	0.167	0.574
32	6,000 DWT sulfur	0.333	0.202	0.154	0.167	0.856

Appendix C
BIOGRAPHICAL SKETCHES OF PANEL MEMBERS

HYLA NAPADENSKY received B.S. and M.S. degrees in mathematics from the University of Chicago. She holds the joint positions of senior engineering advisor and manager of Fire and Explosion Research at IIT Research Institute.

GEORGE ALTVATER received a B.B.A. degree from Northwestern University. He worked for the Waherman Steamship Company, the Port of Mobile, and the Port of New Orleans. Mr. Altvater was director of the Ports of Baton Rouge and Houston until his retirement.

GEORGE W. FELDMANN received A.B., B.S., and Ch.E. degrees from Columbia University. After forty years with E. I. du Pont de Nemours and Co. he retired and became a consultant. His expertise is in rubber chemicals, flourine and titanium process development, marine engineering, and movement of bulk dangerous products by barge and vessel.

JAMES P. FLYNN received a B.S. from Bucknell University and a Ph.D. in chemistry from Iowa State University. Since graduation he has been employed by The Dow Chemical Company and is presently a research associate. His technical expertise encompasses the evaluation of chemical hazards, hazardous waste disposal, and health and environmental regulations.

WALLACE A. HAYES received an A.B. degree from Emory University and M.S. and Ph.D. degrees in biochemistry from Auburn University. Following post-doctoral work at Vanderbilt University, he held professorships at the University of Alabama and the University of Mississippi. He now is employed by Rohm and Haas Corporation as director of Toxicology.

KEVIN MOSER graduated from the U.S. Coast Guard Academy. He served as skipper of several Coast Guard vessels before becoming chief of Port Safety and Law Enforcement at Coast Guard Headquarters. He also served as the head of the U.S. Delegation of the United Nation's Intergovernmental Consultative Organization (IMCO). Capt. Moser is now retired.

JOSEPH D. PORRICELLI received a B.S. degree from the U.S. Coast Guard Academy and an M.Sc. degree in engineering at the University of Michigan. He worked for the Coast Guard in the Merchant Marine Technical Division until he cofounded and became managing principal of engineering at Computer Optecnomics, Inc.

J. REED WELKER received B.S. and M.S. degrees from the University of Idaho and a Ph.D. in chemical engineering from the University of Oklahoma. He was employed by the Research Institute of the University of Oklahoma and later became a vice president at University Engineers, Inc. He currently is president of Applied Technology Corporation.

RAYMOND A. YAGLE received B.S.E. and M.S.E. degrees from the University of Michigan. After working as a research engineer at Frederic Flader, Inc., he joined the faculty of the University of Michigan as a professor of Marine Engineering. He has served as chairman of the National Research Council's Ship Research Committee.

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16. Abstracts

A methodology, termed the Equivalent Safety Concept (ESC), to determine the relative hazards associated with vessels carrying hazardous materials into ports by establishing hazard indexes for the cargo, the ship, and the port was proposed by Danahy and Gathy in 1973. The ESC was intended to provide a systematic framework for use by the Captain of the Port in his daily activities.

The panel reviewed the Danahy and Gathy approach and other related literature to determine whether use of a numerical equivalent methodology was feasible. It concluded that it was and decided to proceed by modifying the Danahy and Gathy approach. Formulations are presented for a vessel safety index and for a cargo hazard index addressing the risk due to flammability and inhalation toxicity on accidental release of the cargo. An initial approach to formulating a port hazard index also is presented but the panel recommends that this index be refined by the Coast Guard and that it be used in its present form only as a guide for local authorities.

The vessel safety index and the port hazard index need to be testing using information acquired from accident investigations.

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