A Risk Analysis Framework for Maritime Transport of Packaged Dangerous Goods – A Validating Demonstration

VOLUME II

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ABSTRACT

Volume II of the thesis presents the results of the validating demonstration of the risk analysis framework presented in Chapter 5, Volume I. For a number of interrelated reasons, including enhancing external validity, ensuring data and methodology triangulations, and filling gaps and extending the data, the risk analysis framework is step-by-step demonstrated in practice based on combination of the qualitative and quantitative empirical data and data analysis methods. The main datasets included: a) a representative marine accident case history; and b) the statistical incident data collected from the two largest U.S.' hazmat (hazardous materials) incident databases. In this study, considerable efforts have been made to enhance understanding of dangerous goods risks. Given the size and uniqueness of the empirical data, this study might be one of the largest of its kind, and some of the results might not be found elsewhere. Based on understanding and the results of the risk analysis, detailed recommendations for improving human safety and health, and the protection of the marine environment and property are provided. The validating demonstration showed that the risk analysis framework satisfy both validity and reliability conditions. The results of the risk analysis replicated the framework. This study contributes to both communities - academics and practitioners alike. Given the representativeness, the large size and the diversity of the data, and the universal properties of the systems and risks studied, many results and recommendations are also valid for other systems and risks in other locations, countries or regions, including the countries of the Baltic Sea Region. Some results will assist relevant organisations or institutions to predict and explain phenomena. They may serve as the basis for further study and development of risk evaluation criteria in the field. The risk analysis framework contains many specific and detailed guidelines and firsthand experiences that will assist, but not guarantee, risk analysts to prepare and perform risk analyses and projects, including identification, selection and collection of relevant risk-related data and data analysis methods and techniques, and generation and presentation of detailed, valid, reliable as well as transparent results in a more efficient and effective manner.

SUMMARY

Human safety and health, the protection of the environment and property, and security concerning the dangerous goods supply chain have become increasingly important issues for many organisations, industries, governmental authorities and the general public. Such concerns stem mainly from production, transport and use of large and still increasing amounts of different types of dangerous goods, severe consequences that could result from unintentional accidents and deliberate acts, and the general belief that risks should be better managed. For example, it is estimated that over 300 million tons of different types of dangerous goods are transported and handled annually in the BSR (Baltic Sea Region). The literature study showed that many risk studies have largely been confined to the risks of individual systems or activities of the supply chain and a few bulk dangerous cargoes carried by water, in particular large oil spills.

The risk analysis is a rigorous process that is facilitated by specific risk analysis frameworks and techniques. The literature study showed that, in recent years, many risk assessment frameworks and techniques have been developed in many industries and sectors, including the shipping industry. Thus, the FSA (Formal Safety Assessment), which may be one of the most “authoritative” frameworks in the shipping industry, is a generic framework that is not intended for application in all circumstances (IMO, 2002). The FSA is tested or applied in several maritime-related systems or issues concerning safety or risks, which are not necessarily related to the risks of maritime transport of packaged dangerous goods. The FSA and many frameworks and techniques that have been studied, evaluated and presented in Chapter 3, Vol. I and Mullai, 2006b, are not readily applicable for the risk analysis concerning maritime transport of packaged dangerous goods. They lack some essential concepts representing the system and risks of dangerous goods in general and packaged dangerous goods in particular. Therefore, on the basis of understanding gained from the literature study of some of the world’s best frameworks and techniques, guidelines and practices in the shipping and other industries and sectors, and the analysis of large amounts of the empirical data, a risk analysis framework has been developed for readily application in the maritime transport system of PDG. The framework is presented in Chapter 5, Vol. I, and Mullai, 2004.

Furthermore, in many domains of science, it is a common procedure to test, validate or demonstrate models, including frameworks, techniques and methods, on the basis of other datasets on the same or other systems, phenomena or settings of interest than those used or considered in the development of models. Therefore, it has been equally important and necessary to demonstrate the risk analysis framework presented in Chapter 5, Vol. I.

Given the above context, the twin objectives of this study are to: a) *demonstrate the application of the risk analysis framework* presented in Chapter 5, Vol. I; and thereby b) *enhance understanding of the dangerous goods risks, and provide recommendations for improving human safety and health and the protection of the marine environment*

and property. For a number of interrelated reasons, including enhancing external validity of the study, ensuring data and methodology triangulations, filling gaps and extending the data, the risk analysis framework is step-by-step demonstrated in practice based on the combination of qualitative and quantitative data and data analysis methods. The main datasets included: a) a representative marine accident case history (i.e. the m/v “Santa Clara I” accident case); and b) statistical incident data collected from the U.S. Hazardous Material Information System (HMIS, 1993-2004) database (ca. 186,000 incidents) and the U.S. National Response Center (NRC, 1990-2004) database (ca. 454,000 incidents). The extensive literature study showed that, given the diversity and the amount of the empirical data used, this study might be one of largest studies of its kind, including the studies cited in both volumes of this thesis, and some of the results might not be found elsewhere.

The following some findings from the statistical data analysis. The data showed that, since 1983, hazmat transport incidents, which accounted for approximately 42% of all hazmat supply chain incidents reported in the U.S., have increased significantly (2.5 fold). After road transport (58.4%), the water transport mode is the second largest contributor (18%) to the total number of transport incidents. Vessel incidents have shown the highest increase (+81%) in transport incidents. Approximately 38% of all types of ships/facilities involved in vessel incidents (1990-2004) were cargo/military ships, including ships carrying PDG, such as dry cargo ships (6.9%), container ships (6.5%), military ships (20.5%) and barges (46.5%). Incidents are attributed to a wide range of causes and contributing factors, including these main categories human, technical, managerial, operational, environmental and other factors. The results of comparisons suggest that the U.S. economy (GDP) (has increased 2.6 fold since 1970) and transport performance characteristics (in value, tons and ton-miles) may have considerable influencing powers on the trends or patterns of supply chain incidents, including all transport modes combined and vessel incidents. They may have offset or diminished the effects of the preventive risk management strategies and measures. The majority of dangerous goods transport incidents (76%) are surprisingly reported during cargo handling operations, respectively during unloading (59.2%) and loading (16.8%). But, because of weather or sea hazards, it is no surprise that 64% of vessel incidents were reported during the voyage or en route phase of transport. The top three weakest and/or the most vulnerable packaging components are reported to be the packaging material, closure and fitting or valve, which all three combined accounted for 71% of all packaging failures. Plastic/fibre packaging material accounted for 60% of the top 13 package types involved in incidents. Failures to packages are most frequently reported due to mechanical and climate/weather hazards. The top three most frequent classes of dangerous goods involved in transport incidents are Class 3 (flammable liquids), Class 8 (corrosive materials) and Class 6 (toxic substances), which all three combined accounted for 88% of all classes involved in incidents. Hazmat incidents have caused consequences to humans, the environment, property and activities. FN curves of humans (fatalities, injuries, hospitalizations and evacuations) risks and property damage ($) risks in the maritime transport system are found to be well below FN curves of the corresponding aggregated risks of the U.S.’ hazmat supply chain. During the period 1990-2004, the risks of all transport modes combined and maritime transport have generally shown increasing trends in the U.S.

Based on understanding and the results of the risk analysis, recommendations for improving human safety and health, and protection of the marine environment and property are provided in Chapter 7 and Appendix 3, Vol. II. The validating demonstration showed that the constituent components of the risk analysis framework satisfy both validity and reliability conditions. The framework is also applicable to other systems and phenomena (i.e. risks) of interest. The results of the study replicated the framework. Given the representativeness and the large amounts (i.e. the sample size) of diverse datasets used in the study and the universal properties of the systems and risks under the study, many results and recommendations of this study are also valid for other systems and risks in other locations, countries or regions, including the countries of the Baltic Sea Region.

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PART I: STAGE 1 – PREPARATIONS FOR ANALYSIS

1. Stage 1 - Preparations for Analysis

1.1. Introduction

Human safety and health, protection of the environment and property and security concerning the dangerous goods supply chain have become increasingly important issues for many organisations, industries, governmental authorities and the general public (IMO, 1993, 1997, 2004a, 2006; EC, 1997, 2006). Such concerns stem mainly from the production, transport and use of large, and still increasing, amounts of different types of dangerous goods, the severe consequences that could result from unintentional accidents and deliberate acts, and the general belief that risks should be managed in a better way.

As mentioned in Chapter 1, Vol. I, the increasingly large amounts of different types of dangerous goods transported and handled in the BSR (Baltic Sea Region) (estimated over 300 million tons per year) and the consequences of accidents that may results from dangerous goods are also concerning issues for all countries in the region (TSE, 2006). In response to the growing concerns about dangerous good risks, the main objectives of the DaGoB (Safe and Reliable Transport Chains of Dangerous Goods in the Baltic Sea Region) project included: a) to provide up-to-date knowledge of the risks of transport of dangerous goods; and b) to disseminate and transfer the knowledge gained in the project on local, national, regional and international levels.[1]

Many risk studies have mainly been confined to the risks associated with individual systems and activities of the dangerous goods supply chain, and bulk dangerous cargoes carried by water, in particular large oil spills (see Romer et al., 1995; Batten et al., 1998; Gilfillan et al., 1999; Kirchsteiger, 1999; Gade and Redondo, 1999; Goulielmos, 2001; Konstantinos and Ernestini, 2002; Miraglia, 2002). Some of these studies are based on the qualitative analysis of one single or a few accident case histories. Furthermore, many studies have considered only a few variables representing the system and risk elements, in particular human (fatalities and injuries) and environmental consequences, for example in terms of the amounts of the oil spilt at sea.

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[1] The DaGoB project is partly financed by the European Union (European Regional Development Fund) within the BSR INTERREG III B Neighborhood Programme. The project involved numbers of partners from the countries of the Baltic Sea Region (BSR), such as Finland, Sweden, Germany and the Baltic States. For more information see: www.dagob.info

Risk analysis is a rigorous process that is facilitated by specific risk analysis frameworks and techniques. The literature study showed that, in recent years, many risk assessment frameworks and techniques have been developed in many industries and sectors, including the shipping industry (see Chapter 3, Vol. I, and Mullai, 2006b). Thus, as mentioned in Vol. I, the IMO's Formal Safety Assessment (FSA) is a methodology for assessing risks related to ship operations (IMO, 1997, 2002). The FSA is a generic framework that is not intended for application in all circumstances (IMO, 2002). In recent years, efforts have been made to adapt, further develop, or simply test or apply the FSA in several maritime-related systems or issues concerning safety or risks associated with, for example, cruise ships (Lois et al., 2003), bulk carrier (IMO, 2004b) and hatchway watertight integrity of bulk carriers (Lee et al., 2001), oil spills (Ventikos and Psaraftis 2004), fishing vessel (Loughran et al., 2002), offshore industry (Wang, 2002), container ships (Wang and Foinikis, 2001), ports (Trbojevic and Carr, 2000) and ships in general (Wang, 1999), that are not necessarily related to the risks of the maritime transport of packaged dangerous goods.

The FSA is not readily applicable for risk analysis in the maritime transport of packaged dangerous goods. The FSA, as well as many frameworks and techniques studied and presented in Vol. I and Mullai, 2006b, lacks some essential concepts concerning the system and the risks of dangerous goods in general and packaged dangerous goods in particular. The FSA does not contain concepts concerning top events, failures in the packaging system, transport hazards, the list or inventory of dangerous goods and their hazards, release-dispersion-concentration modelling, modes of contacts with dangerous goods, and exposures. Therefore, in order to facilitate the risk analysis process in the field, based on an extensive literature study and analysis of large amounts of diverse empirical datasets collected from various world-wide sources, a risk analysis framework is developed for readily application in the maritime transport system of packaged dangerous goods or hazmat (see Chapter 5, Vol. I).

Given the above context, it is considered very relevant, important and necessary to conduct a comprehensive analysis on the dangerous goods risks. Furthermore, in many domains of science, testing, validating and demonstrating models (including frameworks, techniques, or methods) on the basis of other datasets on the same or other systems, phenomena or settings of interest than those used or considered in the development of models, are common procedures. Therefore, it is equally relevant, important and necessary to validate/demonstrate the risk analysis framework presented in Chapter 5, Vol. I.

The risk analysis framework (see Figures 1.1 and 2.1) is step-by-step demonstrated in the forthcoming chapters (Chapters 1-7, Vol. II). Stage 1 – preparation for risk analysis (Figure 1.1), encompasses many activities, including identifying and formulating the problems, setting the objectives, defining the boundaries, selecting datasets and methods and tools of analysis. Some steps are most relevant to large risk projects. The identification, selection, compilation and preparation of datasets for analysis are some very important activities.

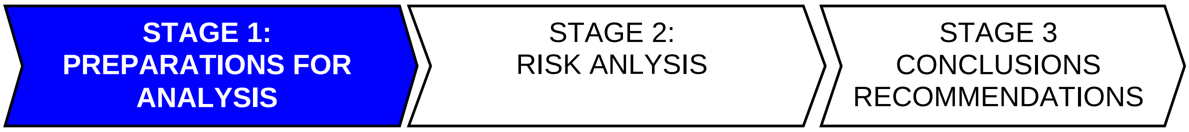

Figure 1.1: Stage 1 – Preparations for risk analysis

1.1.1. Research objectives

Given the above contexts, the twin objectives of this study are: a) *to provide a validating demonstration of the risk analysis framework presented in Chapter 5, Vol. I.*; and thereby b) *to enhance understanding of the risks associated with dangerous goods, and to provide recommendations for improving human safety and health and protecting the marine environment and property*. Understanding risks requires answers to the fundamental questions concerning risks, namely: "What has gone or can go wrong?" "What are the consequences?" "What is the frequency or likelihood? How often, much/many?" – known as "the triplet definition" of risks (Kaplan and Garrick, 1981). The answers to these "simple" questions may often require large amounts of resources and efforts and time of large teams of experts representing a wide range of expertises. These questions lead to other essential questions that require additional answers, and subsequently additional time, resources, efforts and expertise.

Validity and reliability

One purpose of this study is to test validity and reliability and show how the risk analysis framework works in practice. In the following section, the definitions of both "validity" and "reliability" are recapitulated. Some relevant questions that will guide the validating demonstration process are also posed.

Construct validity concerns the degree to which a study accurately reflects or assesses the specific concepts that the researcher is attempting to measure (Yin, 1994). The relevant questions are "Are the constituent concepts of risks in maritime transport of PDG measured correctly and exhaustively? "Can the constituent constructs/variables of the framework reflect the maritime transport system of PDG and the risks associated with it?"

Internal validity is a concern of explanatory or causal studies only, in which an investigator is trying to determine causal relationships, i.e. whether an event, *x*, led to another event, *y* (Yin, 1994; Sue, 1999). The relevant questions are "Are the constituent constructs/variables of the framework related?" "Can the framework enable the investigation of causal relationships among the relevant variables?"

External validity is the extent to which the results of the research can be generalized or transferred to the populations and settings of interest (Sue, 1999). The relevant questions are: "Is the framework applicable to other populations, systems, phenomena or settings of interest, that is, can it be used to analyse risks in other systems, e.g. other modes of transport or other systems and activities of the dangerous goods/hazmat supply chain? Can the results be applied or generalised to other populations, systems, phenomena or settings of interest?”

Reliability is defined as the quality of a measure that possesses reproducibility (Batterham and George, 2003). In connection with the case study approach, Yin (1994: 36) states that the objective reliability test is to be sure that if a later investigator *followed exactly the same procedures* as described by an earlier investigator and conducted the same case study all over again, the later investigator would *arrive at the same results*. By definition, this means that if the results of the validating demonstration replicate the framework, then this is proof of the reliability of the framework. Reliability is a prerequisite for test validity (Sue, 1999).

In sum, if the validating demonstration of the framework and the results of analysis meet the aforementioned requirements, then the framework satisfies both validity and reliability conditions.

1.1.2. Research scope

The risk analysis primarily focuses on the maritime transport system of packaged dangerous goods. However, for the interrelated reasons stated below, the scope of the study is further extended to other systems and activities of the dangerous goods/hazmat supply chain in the United States (U.S.).

- Facilitate data and method triangulations; take advantages offered by the combination of qualitative and quantitative datasets and analysis methods;
- Extend and fill gaps in data;
- Provide a complete validating demonstration of the risk analysis framework, including testing of external validity, which by definition concerns application of the framework to other populations, systems, settings or phenomena of interest;
- Compare and explore relationships among systems and risk elements; put the risks associated with the maritime transport of dangerous goods into perspective;
- Employ a holistic or systems approach, and thereby explore risks and present experiences gained from other systems and activities of the dangerous goods supply chain.

1.2. Data and methods

In order to achieve the objectives and provide answers to the aforementioned questions, and for the interrelated reasons stated above, the validating demonstration of the framework combines qualitative and quantitative datasets and data analysis methods.

1.2.1. Datasets

The framework demonstration is based on *several other datasets* than those used in the model development. Because of quality, quantity and accessibility of the data as well as costs, U.S. data sources were chosen for collecting the relevant data. In terms of the amount, diversity, accuracy, public accessibility and availability of dangerous goods risks-related data, the U.S. may be one of the most advanced countries in the world. The data are *free of charge and available for public use*. The U.S. Freedom of Information Act (1974) requires all federal and national organisations and agencies to make data available in *electronic form* that will serve the public interest. The main datasets used for the purpose of the demonstration include the following:

Qualitative data

- *Marine accident case histories* - the m/v "Santa Clara I" (SCI) accident and several other case histories.

Quantitative/statistical data

- *Hazmat incident data collected from hazmat incident databases*:
  - The U.S. Hazardous Material Information System (HMIS) database (U.S. DOT, 2005a)
  - The U.S. National Response Center (NRC) database (NRC, 2005)
- *Economic censuses: Commodity Flow Survey (CFS) - Hazmat Transportation Reports* (U.S. DOT, 1996, 1999, 2000, 2004a, 2004b). The CFS covers business establishments listed in the North American Industry Classification System (NAICS). The system contains a wide range of establishments, such as manufacturing, mining, wholesale, and retail and service and auxiliaries establishments.
- *Population censuses*: Statistical data on the U.S. population collected from 1990 and 2000 population censuses of the U.S. DOC (Department of Commerce) and U.S. Census Bureau (U.S. DOC, 2000). These censuses contain data on the resident population of all states and territories in the U.S. Employment data are based on various sources, as cited in U.S. DOT, Bureau of Transportation Statistics, and National Transportation Statistics (NTS) 2002.
- *Vessel statistics:* Statistical data on vessel calls and capacity collected from the U.S. Department of Transportation, the Maritime Administration and the Office of Statistical and Economic Analysis (U.S. DOT, 2001-2004; U.S. DOT, 2001a, 2001b). These data cover all types of ocean-going vessels (10,000 dwt and over) calling at U.S. ports during the period 2001-2004.
- *Other databases and data sources:* These include data from the U.S. Department of Transportation (U.S. DOT), the U.S Coast Guard, and the U.S. Bureau of Transportation Statistics.

1.2.1.1. The m/v "Santa Clara I" accident

For the purpose of demonstration, a marine accident case history has been selected. This case, which is representative case of combination of cargo damage and losses overboard, exposure to toxic substances, and the pollution of the marine environment, concerns the m/v "Santa Clara I" (SCI) accident. The accident occurred in U.S. territorial waters. Because of the severity of the consequences and other influencing factors, the accident sparked controversial debates in the U.S., which led to a thorough investigation by the responsible authorities. The case is one of the best known cases in the U.S., and perhaps in the world's maritime community. The review of many other cases also showed that the m/v SCI accident case was one of the most detailed and thoroughly investigated cases. A higher degree of details and a higher quality of data will facilitate framework demonstration in a more efficient way. The following is a brief summary of the m/v SCI accident case.

> **M/v "Santa Clara I" accident**
>
> During the storm on January 4, 1992, the m/v "*Santa Clara I*" (*SCI*) (9,593 grt breakbulk ship, with a Panamanian flag) lost 21 of 25 containers stowed on deck and a heavy piece of machinery in the vicinity of Baltimore Bay (U.S.). The remaining containers were severely damaged. Six of 21 containers lost overboard were loaded with arsenic trioxide drums. The accident posed serious threats to the Mid-Atlantic States' fishing industry. Arsenic trioxide (UN Number 1561) belongs to Class 6.1. The substance is liable either to cause death or serious injuries or to harm human health if swallowed or inhaled, or by skin contact. The search and recovery operation for these arsenic trioxide drums was one of the largest offshore drum removal operations in U.S. history. It involved numerous personnel and sophisticated equipment from different agencies. The operation lasted for five and a half months. It was estimated that over $ 2.2 million were spent to search for, locate and recover the arsenic trioxide drums only.
>
> During the storm, over 363 kg of toxic powder (magnesium phosphide) spilled on the upper deck of the no.1 hold from four damaged drums. The powder had spread and piled several inches high in some areas. Magnesium phosphide (Class 4.3, UN Number 2011) is used as a fumigant. It reacts violently with water, producing phosphine gas, which is highly poisonous and flammable. After the storm, some crewmembers entered the hold to re-secure cargo. Two crewmembers became dizzy and vomited, which is a typical reaction to phosphine gas exposure. In Port Charleston, 37 longshoremen were sent to the hospital for observation after exposure to magnesium phosphide while working inside the hold. The m/v SCI accident remained at the centre of the media and congressional and legal debates for two months.

The m/v SCI case is based on a large amount of various types of data collected from different sources (see references). The main data sources include the accident investigation report prepared by the USCG Board of Inquiry for the U.S. Department of Transportation (U.S. DOT) and the USCG (U.S. DOT 1992) as well as several articles and reports written by experts in the field, including Whipple et al., (1993), McGowan (1993), Merrick (1993) and Crokhill (1992) and (White, 1996). The authors were either experts that participated directly in the search and recovery operations or senior members of a special team of experts (namely the USCG Atlantic Strike Team), which coordinated and executed the operations. Unless otherwise stated, the data in the m/v SCI accident case history are obtained from the aforementioned sources.

1.2.1.2. Hazmat incident databases

The case history does not contain sufficient data for a full demonstration of all the states and steps of the risk analysis. In order to expand and fill gaps in the data and for the reasons mentioned above, every reasonable effort has been made to collect and make use of numerous different sources, including the following hazmat incident databases: the U.S. Hazardous Material Information System (HMIS, 1993-2004) database (U.S. DOT, 2005a) and the U.S. National Response Center (NRC, 1990-2004) database (NRC, 2005)

The scope of databases

The following section describes the scope of both these databases (Table 1.1).

HMIS database (1993-2004): Within the U.S. Department of Transportation (U.S. DOT), the Pipeline and Hazardous Materials Safety Administration (PHMSA) is responsible for the safe movement of hazmat to the industry and consumers by all transportation modes. The Department of Transportation’s Office of Hazardous Materials Safety (OHMS) provides data on Hazardous Materials Incidents. According to U.S. regulations for reporting hazmat incidents (49 CFR 171.15 and 171.16), incidents are reported in two phases on the basis of Incident Report Form 5800.1 and recorded in the Hazardous Materials Information System (HMIS) database.

NRC database (1990-2004): The U.S. National Response Center (NRC) (NRC, 2005) serves as the point of contact for reporting all incidents involving all types of hazmat, including oil, chemical, radiological, biological, and etiological[2] discharges into the environment anywhere in the U.S. and its territories. The data on these incidents are reported by individuals and by a wide range of organisations and agencies, e.g. the U.S. Environment Protection Agency (USEPA); the U.S. Coast Guard (USCG); the Departments of State, Transportation, Homeland Security, the Interior, Defence, Energy, Health and Human Services, and Labor; the Federal Bureau of Investigation (FBI); the National Transportation Safety Board (NTSB); the Nuclear Regulatory Commission (NRC); the National Oceanic and Atmospheric Administration (NOAA); the Chemical Safety Board (CSB) and the *Hazardous Materials Information System (HMIS) (see above).*

From the point of view of water transportation, by definition, types of packaging and cargo transport units included in the HMIS database are packaged dangerous goods (PDG). According to the HMIS database (U.S. DOT, 2005a), vessel incidents involving hazmat in bulk are reported to the USCG (NRC database). The review of incident records indicates that the NRC database (2005a) is not confined to bulk hazmat incidents only. Many different types of ships that carried PDG, e.g. container ships, freight ships, barges, military ships and “other” ships have been involved in incidents.

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[2] That can cause disease (CED, 1992)

Table 1.1: The scope of the HMIS and NRC databases

Nr.	Category	HMIS database	NRC database
1	Modes of transportation/ activities/ aspects	Modes of transportation and related activities: road, rail, air, and water.	All modes, activities and aspects, such as: unknown sheen, vessel, fixed and mobile installations, pipeline, platform, storage tank, railroad, continuous, aircraft, drill/exercise, unknown releases, and terrorist-related incidents.
2	Classes of hazmat	All classes.	All classes.
3	Forms/types of packaging or carriage	Incidents involving hazmat in bulk and non-bulk containers and other cargo transport units (e.g. tank containers) only.	All types.
4	Time	Regular incident records: 1993-2004	Regular incident records: 1982-2004
5	Locations	All states/districts and U.S. territories.	All states/districts and U.S. territories.
6	Types of incident	All hazmat incidents that meet incident reporting requirements for the modes previously mentioned. The OHMS (starting from 2002) has developed a new definition of a hazmat "serious incident."	The NRC receives reports of all types of incidents involving hazmat regulated by the U.S. DOT under the Hazardous Materials Transportation Act and reportable under 49 CFR 171 for the transportation of hazmat, 49 CFR 191 for natural gas and other gases transported by pipeline, and 49 CFR 195 for liquids transported by pipeline.
7	Number and types of variables	The database consists of three main sections that altogether contain some 184 different variables, including: incident identification, modes of transportation, time, location, system and system operators' properties, failures, releases, causes and contributing factors, and consequences (human, environment, and property). The database contains specific variables for incidents involving packaged dangerous goods.	The database consists of 10 main categories of constructs or sets of variables, which altogether contain some 230 different variables. The NRC database contains similar principal categories of variables. However, it has no specific variable for selecting vessel incidents involving PDG.

In sum, these two databases are the primary sources of U.S. national data on safety issues associated with hazmat-related activities. The HMIS database contains data on incidents involving transportation of hazmat bulk and non-bulk containers and other cargo transport units (CTUs). The NRC database has a wider scope. The NRC receives reports of and records all types of incidents, including those reported to the HMIS database, which involve hazmat-related activities regulated and reportable under the U.S. regulations.

1.2.2. Preparing for data analysis

The key procedures for preparing for the data analysis included:

Data compilation**:** Both databases – the HMIS and NRC databases – were downloaded into the computer for preparation for the data analysis.

Reviewing data**:** Initially, the databases were thoroughly reviewed. The review showed that the data could not readily be transferred and used for analysis. The incident data, which were recorded in Excel, consist of many datasets organised by year and variables. Each dataset contained thousands of incident cases, which had to be merged into single datasets. The merging process of datasets could not be performed in the Excel programme because the programme can only handle a limited number of ca. 65,500 cases. Therefore, the datasets had to be merged by means of another programme that could handle the large number of cases.

Selecting variables**:** In both databases, the incident data are compiled and organised according to many different variables that represent different properties of the systems and risk elements and other related factors or aspects. For the purpose of the demonstration, some relevant key variables are selected and used in the risk analysis, including types of incidents, releases, failures, causes and contributing factors, year, location, and consequences. The latter include consequences for humans (fatalities, injuries, hospitalisation and evacuation), for the environment as well as damage. The NRC database contains no specific variable for separating and selecting vessel or marine incidents involving packaged dangerous goods or hazmat. The m/v SCI accident, i.e. a marine accident involving PDG, is recorded in the NRC database.

Selecting datasets**:** The NRC database contains regular incident records for the period 1982-2004. The entire database consists of 230 datasets organised by year and variable set (23 years x 10 variable sets per year). Since 1990, incidents have been compiled in the Excel programme, which is more convenient for transferring the data into a statistical analysis programme, such as the SPSS programme. A total number of 60 datasets (15 years x 4 variable sets per year) were selected from the NRC database for analysis. The HMIS database contained 24 datasets (12 years x 2 variable sets per year) (1993-2004) and all of them were selected.

Transferring data: After the designing of the selected variables and some adjustments, for the purposes of data merging and analysis, the datasets of both databases were transferred from Excel into the SPSS programme's files. The latest version (2005) of the SPSS programme could handle an unlimited number of cases and variables.

Merging datasets**:** In order to make use of all the selected data, all the individual datasets in each respective database were merged together into single datasets. Each merged dataset contained: a) the merged dataset from the HMIS database: 185,612 incident cases (1993-2004)[3]; b) the merged dataset from the NRC database: 453,564 incident cases (1900-1989 and 1990-2004). These two merged datasets from the HMIS and NRC databases could not be merged together further as they come from two separate databases that are not mutually exclusive. According to the source (NRC, 2005), the NRC database includes hazmat incident records from the HMIS database.

Selecting/filtering the cases**:** The review of the merged dataset from the NRC database showed that it contains different incident records. A considerable number of incidents dated back to the period 1900-1989. The incident cases that were regularly recorded during the period 1990-2004[4] were selected by designing and using a filter variable (variable "Year_F"). The rest of the cases, which were irregularly recorded in the NRC database during the 1900-1989, were discarded. The term "incident" is used in the database to denote all categories of undesirable events associated with hazmat-related supply chain systems and activities, including both categories of events – accidents and incidents. The incidents reported to both databases include the categories presented in Table 1.1. In the NRC database, the category of "vessel" incidents (water or marine accidents/incidents) consists of all types of incidents involving ships, including both bulk and non-bulk hazmat shipments. The variable "Vessel_F" was designed and used as a filter variable for selecting and deselecting "vessel" incident cases in both databases. Another variable, "State_F", was designed and used as a filter variable for selecting and de-selecting incident cases in certain relevant states.

1.2.3. Data analysis methods

This demonstration combines several interrelated qualitative and quantitative methods of data analysis, including backward and forward logic analyses, grounded theory, explanation-building, chronological events analysis, categorisation, comparative analysis, content analysis and quantitative data analysis. For more information about these methods, see Chapters 2 and 5, Vol. I. The results of the analysis, which include the severity of consequences and frequency, are evaluated against the risk evaluation criteria available in various sources, including:

- U.S. Department of Transportation (U.S. DOT, 1996)
- U.S. DOT Office of Hazardous Materials Safety (OHMS), within the Pipeline and Hazardous Materials Safety Administration (PHMSA, 2002)
- International Maritime Organisation (IMO, 1996b, 2002)
- Lloyd's Maritime Information Services (LMIS, 1995)
- International Standard Organisation (ISO, 1999)

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[3] Wherever this period is encountered in figures and tables indicates HMIS, 1993-2004.

[4] Wherever this period is encountered in figures and tables it indicates NRC, 1990-2004.

- Department of Environment, UK (DE, 1991)
- Swedish Environment Protection Agency (SEPA, 1998)
- Other sources, including Wright, 1993, and Monnier and Gheorghe, 1996.

The risk analysis is carried out systematically *step-by-step* as shown in the framework (see steps under the **highlighted area** in Figure 1.2). Each main step and sub-step is accordingly **highlighted**.

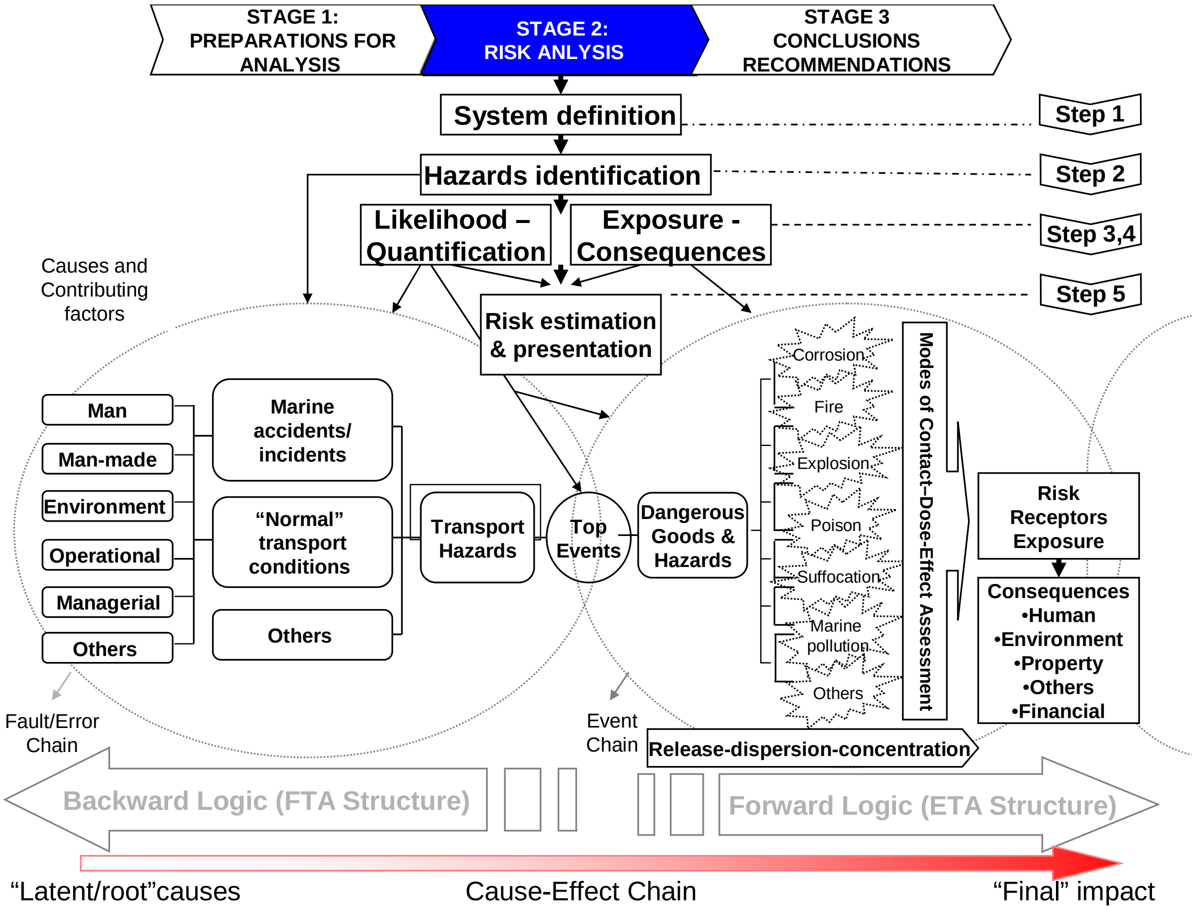

Figure 1.2: Stage 2 – Risk analysis (continued from Figure 1.1)

PART II: STAGE 2 – RISK ANALYSIS

2. Step 1 – System Definition

This step defines and describes the system whose risks are to be analysed, including the following elements: the regulatory systems governing maritime transport of dangerous goods, the ship, the crew, cargo/dangerous goods, types of packaging, the cargo securing system, the marine environment, weather conditions, and the voyage. The m/v SCI accident is described and some key results concerning incidents from the HMIS and NRC databases are presented. Accidents and incidents are the negative outcomes of the systems. Initially, some key abbreviations and measurement units and definitions are provided (see the **highlighted areas** in Figure 2.1).

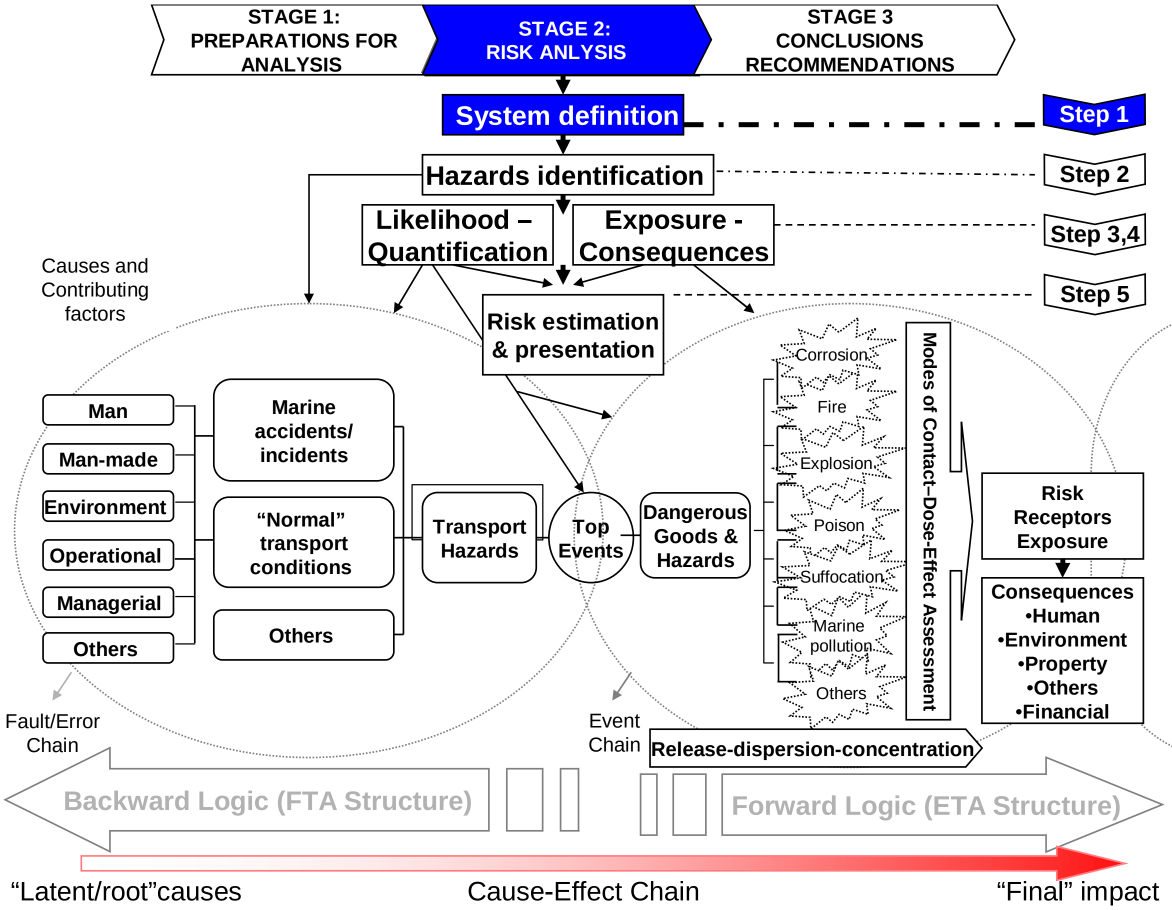

Figure 2.1: Stage 2 – Risk analysis; Step 1 – System definition (continued Figure 1.2)

2.1. Abbreviations and measurements

The following are some abbreviations used in this report:

BLS - Bureau of Labor Statistics, U.S.
CFR - Code of Federal Regulations, U.S.
CSC - International Convention of Safe Containers, 1972
DE - Department of Environment, U.K.
DHHS - Department of Health and Human Services, U.S.
DNREC - Delaware Department of Natural Resources and Environmental Control
DOC - Department of Commerce, U.S.
DOL - Department of Labor, U.S.
DOT - Department of Transportation, U.S.
DRBC - Delaware River Basin Commission
EC - European Commission
FAS - Federation of American Science, U.S.
GM - Ship's meta-centric height
HAZMAT - Hazardous Material
HCB - Hazardous Cargo Bulletin
HMIS - Hazardous Material Information System, U.S.
HSC - Health and Safety Commission/Executive, UK
HSE - Health and Safety Executive, UK
IACS - International Association of Classification Societies
IARC - International Agency for Research on Cancer
IMDG Code - International Maritime Dangerous Goods Code
IMO - International Maritime Organisation
IPCS - International Programme on Chemical Safety
ISO - International Standard Organisation
LC_{50} - Median Lethal Concentration
LD_{50} - Median Lethal Dose
LOEL - Lowest-Observed-Effect Level
MARAD - Maritime Administration (U.S.)
MARS - Marine Accident Reporting Scheme
MARPOL, 1973/1978 - International Convention for the Prevention of Pollution from Ships, 1973/1978
NFWF - National Fish and Wildlife Foundation, U.S.
NIOSH - National Institute for Occupational Safety and Health, U.S.
NJDEP - New Jersey Department of Environment Protection, U.S.

NOAA	- National Oceanic and Atmospheric, U.S.
NOEC	- No-Observed-Effect Concentration
NOEL	- No-Observed-Effect Level
NRC	- National Response Center, U.S.
p.s.i.	- pounds per square inch
PDG	- Packaged Dangerous Goods
pH	- Negative logarithm of the hydrogen ion concentration
PHE	- Physics Encyclopaedia
ppb	- parts per billion
ppm	- parts per million
ROV	- Remote-Operated Vehicle
SCI	- M/v “Santa Clara I”
SEPA	- Swedish Environment Protection Agency
SMA	- Swedish Maritime Administration
SOLAS 1974	- International Convention for the Safety of Life at Sea, 1974
UNEP	- United Nations Environment Protection
UNTAD	- United Nations Conference on Trade and Development
USCG	- United States Coast Guard
HR	- U.S. House of Representatives, U.S.
USEPA	- U.S. Environmental Protection Agency
WHO	- World Health Organization

Measurement units

1 nautical mile = 1,852 meter
1 knot = 1.85 km per hour
1 inch = 2.54 centimetres
1 pound = 0.45 kilograms
1 gallon = 3.79 liters
1 foot = 30.48 centimetres
1 metric ton (MT) = 1,000 kilograms
1 mg – 1 milligram, one thousandth (10^{-3}) of a gram
1 µg – 1 microgram, 10^{-6} of a gram
1 ng – 1 nanogram, 10^{-9} of a gram
$ – U.S. $

Note: Excel and other programmes used in estimating and presenting the results from the datasets described above, are of the Swedish versions. The Swedish system of “comma” (,) and “full stop” (.) in numbers has been converted into the English system. However, because of the technical difficulties, this conversion was not possible in several figures. In figures presenting results and containing numbers with the Swedish system of “comma” (e.g. 1,2) only, the “comma” denotes and should be read “full stop” (e.g. 1.2) in the English system.

2.2. Main components of the systems

In the following sections some key elements of the systems are defined and described.

2.2.1. Supply chain – maritime transport system

The dangerous goods (hazmat or chemical) supply chain encompasses a wide range of systems – including petrochemical extraction, production or manufacturing (e.g. oil and gas inland and offshore industries and chemical production plants), chemical storage, handling and transportation, use (e.g. nuclear power production plants) and wastes disposal. The transport system (chain or network) includes all the main modes of transport, i.e. air, road, rail, water, and pipeline. Intermodal or multimodal transport involves the use of at least two modes in succession between origin and destination (UNTAD, 1995). Maritime transport is vital to the economy of many countries and regions. It is critical for the U.S. economy, as approximately 95 % of the nation's foreign trade by weight consists of waterborne cargo (Wetzel, 2004).

The transport system consists of many elements in very complex, interdependent and dynamic relationships. The system consists of objects of transport (goods and people), means of transport (e.g. ships) and infrastructure and facilities (e.g. ports), which all are related and linked together by the information system and transport-related activities (Sjöstedt, 1993), such as cargo and passenger handling operations, documentation, transport. The human element is a very important one in the system, since it designs, develops, builds, operates, manages, regulates and interacts with other elements of the system. Individuals and groups, their relationships and communication within an organisation form organisational systems.

Maritime transport is vital for the world as well as the U.S. economy. Like many other countries, the U.S. relies very heavily on maritime transport - 95% of cargo tonnage that moves into and out of the country is carried by water (U.S. HR, 2005). About 90 % of U.S.-bound cargo is moved by container (U.S. GPOW, 2003). Each year, more than 7,500 commercial ships make approximately 51,000 port calls (U.S. HR, 2005; Silicon, 2005). Every day, more than 21,000 containers, or over six million containers per year, arrive at U.S. seaports from foreign countries, filled with a wide range of goods (U.S. HR, 2005; Silicon, 2005). This number is expected to reach 30 million over the next 20 years (Silicon, 2005).

2.2.2. Cargo system

Dangerous goods – known in the U.S. as hazardous materials or ***hazmat*** – are substances, articles, and materials classified under regulation 2 of the SOLAS 1974 and MARPOL, 1973/1978 Conventions. Based on the relevant international regulations, the IMDG Code defines and classifies dangerous goods into nine classes according to the hazards they pose, and subsequently some of them are further subdivided into divisions or sub-classes. The main inherent hazardous properties (or hazards) of dangerous goods that can cause harm to risk receptors include fire, explosion, toxics or poison, infection, suffocation, corrosion, radiation, marine pollution, and other hazards (e.g. carcinogens). On the basis of the severity of the pollution, marine pollutants are divided into *marine pollutants* (P) and *severe marine pollutants* (PP) (IMDG Code, 2002). Many dangerous goods pose more than one hazard. Detailed definitions and descriptions of dangerous goods are provided for the respective classes in the IMDG Code. In this report, the terms "dangerous goods" and "hazmat" are often used interchangeably.

Dangerous goods/hazmat movement **and** ***shipment***: For the purpose of a hazmat flow survey, based on and consistent with other sources, the U.S. DOT defines hazmat movement and shipment as follow (U.S. DOT, 1998):

- A hazmat *movement* is transportation by a single means of transportation from a point of origin to a point of either: a) transfer to another mean or mode or b) final delivery of the freight, whichever comes first.
- A hazmat *shipment* or delivery is an individual movement of commodities from the establishment of one company to one customer or to another location of the company, including a warehouse, distribution centre, retail or wholesale outlet. A shipment uses one or more modes of transportation, including road, rail, water, air, pipeline and other modes. A full or partial load can be considered one shipment only if all the commodities are destined for one buyer/receiver at one location. If the means of transportation makes multiple deliveries on a route, each stop is considered (at least) one shipment.

Table 2.1 shows that large numbers and amounts of hazmat are shipped/moved in the U.S. Approximately 0.8 million hazmat shipments and 1.3 million hazmat movements are carried out per day, or approximately 3.2 billion and 3.9 billion tons per year respectively, are shipped and moved in the U.S. (U.S. DOT, 1998). Shipments are defined as the equivalent of deliveries and, in most instances, may be distinguished from the number of movements, trip segments, or other measures (U.S. DOT, 1998). Hazmat consists of three main groups, namely chemicals and allied, oil and oil products and other hazmat. The "other" category includes waste hazardous materials, medical wastes and various other hazmat. A large portion of hazmat tonnage is carried by water transport. In some U.S. sectors, this is the only mode of transportation. Approximately 14.7% (or ca. 1.3 million tons) and 23.7% (or ca. 2.5 million tons) of all hazmat tonnage are respectively shipped and moved by water daily (U.S. DOT, 1998).

Table 2.1: Hazmat shipments and movements (U.S. DOT, 1998)

	Number of Shipments (million)	**Number of Movements (million)**	**Tons Shipped (million)**	**Tons Moved (million)**
Daily Total	0.82	1.26	8.64	10.76
Annual Total	298.64	458.60	3,153.17	3, 927.19

The m/v SCI accident occurred in the vicinity of Delaware Bay. The Delaware River Port Complex (tri-state port complex, in Delaware River and Bay), which includes the ports of the three states, namely Pennsylvania, New Jersey and Delaware, is the fifth largest port complex in the U.S. and one of the largest freshwater ports in the world, in terms of total waterborne traffic (University of Delaware, UD, U.S., 2004; Klein and Nugent, 2004). Every year, over 70 million tons of cargo move through the port (University of Delaware, UD, U.S., 2004). The port is also the second largest oil port in the United States, handling about 85% of the East Coast's oil imports (University of Delaware, UD, U.S., 2004).

Approximately 3,000 ships transit the Delaware Estuary annually (DRBC, 2005) (University of Delaware, UD, U.S., 2004). These ships carry many different types of cargo (Figure 2.3) in large quantities, including dangerous goods. The "others" category of goods includes general cargo, wood, clothes, food, miscellanea, fertilizer and passengers. These ships may range from over 125,000-ton super tankers (VLCC – Very Large Crude Carriers) to reefer ships of 10,000 to 20,000-tons (like those seen in Figure 2.2) (DRBC, 2005; Klein and Nugent, 2004).

Figure 2.2: Ships in Delaware River Port (University of Delaware, UD, U.S., 2004)

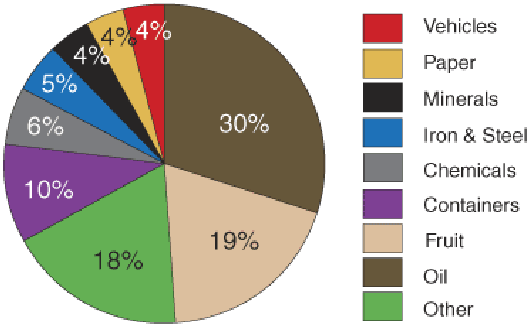

Figure 2.3: Types of cargo (in %) transited Delaware Estuary in 2003 (University of Delaware, UD, U.S., 2004)

Cargo/dangerous goods carried onboard the m/v SCI

Packaged dangerous goods are often carried together with general cargo. The m/v SCI was carrying a large amount of different types of general cargo, such as containers, trucks and breakbulk packages, including lumber, household goods and food staff (cartons of wine). Part of the load included *arsenic trioxide* and *magnesium phosphide* and a large heavy piece of *machinery*, as described below:

Arsenic trioxide (UN Number 1561) is Class 6.1: the substances are liable either to cause death or serious injuries or to harm human health if swallowed or inhaled, or by skin contact (IMDG Code, 2002). Arsenic trioxide was regulated under the U.S. Federal Regulations (49 CFR 171-180) and the IMDG Code for carriage on board the ship. According to the IMDG Code (1990), stowage is permitted "on deck or under deck." Arsenic trioxide was designated a "marine pollutant" in the IMDG Code (1990). For more information about the properties of arsenic trioxide, see Appendixes 1 and 2, Vol. II.

Packing: In accordance with the U.S. Code of Federal Regulations (CRF), arsenic trioxide was packed in 94.7 litre drums with a maximum allowable gross weight of 215.5 kg per drum. Later, the investigation of the cargo manifest indicated that each drum contained 170.1 kg of product. Each container was packed with 108 palletised drums (U.S. DOT, 1992). The drums were packed four to a pallet.

Loading/stowing: 25 arsenic trioxide containers were loaded (in Coquimbo, Chile) onboard the ship. Six containers were stowed on the deck of the no.2 hatch, and the rest (19 containers) were stowed under the deck of the no. 2 hold.

Magnesium phosphide (UN Number 2011) is Class 4.3: substances that, in contact with water, emit flammable gases. The substances in this class are either solids or liquids possessing the common property of evolving flammable gases when in contact with water. These gases may be liable to spontaneous ignition (IMDG Code, 2002). For more information about the properties of magnesium phosphide, see Appendix 1, Vol. II.

Labelling: Although a regulated dangerous cargo, which was clearly and properly labelled, the magnesium phosphide was not identified and listed on the ship's dangerous goods cargo manifest, as required by 49 CFR and the IMDG Code.

Loading/stowing: In Port Valparaiso (Peru), the ship loaded containers and general cargo, including 10 palletised drums of magnesium phosphide. Five pallets, which were banded with two drums each, were stowed on the upper tweendeck of the no.1 hold. Each drum contained about 179.6 kg of product. Magnesium phosphide is also regulated under the U.S. regulations (49 CFR) and the IMDG Code for carriage onboard the ship, with stowage permitted "on deck or under deck." The chemical is required to be labelled as both "toxic" and "dangerous when wet."

The piece of machinery: In Port Elizabeth, the ship loaded an awkwardly–shaped piece of cargo, a calciner weighing 21 tons and 50 feet long. This was a type of machinery used as a drier in the mining industry.

Packing: The machinery was mounted on a heavy steel frame, secured to a wooden skid and wrapped in tarp for shipping. The skid was constructed of 4''x6'' timbers sandwiched between solid hardwood flooring. The overall dimensions of the unit were 15m x 2.1m x 1.6m (LHW), approximately 0.84 m less in width than the container space in which it was stowed.

Stowing and securing: The machinery was stowed on the no.2 hatch cover adjacent to an outboard stack of 20-feet containers on the starboard side (Figure 2.4). The unit rested on eight flat shoe-plates on the hatch cover. It was prevented from transverse movements by friction and lashings around the machinery itself. There were no fittings for the use of cones for twistlocks. As was indicated in the chief mate's drawing (Figure 2.4), the machinery was lashed at three points, with each wire lashing at the ends running diagonally underneath the machinery, up around the top and then back down diagonally across the other side.

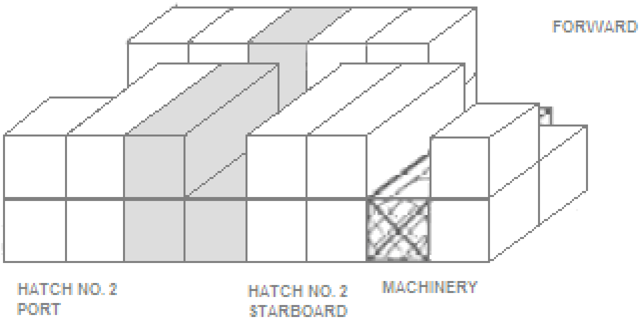

Figure 2.4: Cargo stowage on the no. 2 hatch cover of the m/v SCI (U.S. DOT, 1992)

The IMO provides guidelines (MSC Circular 530) for the stowage, securing and carriage of heavy awkward items. According to the IMO, carrying this type of cargo onboard a ship represents a potential source of danger. Awkwardly-shaped cargoes are often carried on specialised ship types.

2.2.3. Regulatory system

Technical and operational aspects of the dangerous goods supply chain, including the maritime transport system, are highly regulated by a complex and dynamic regulatory system at the international, regional, national and organisational levels. The system encompasses a wide range of instruments or standards of various legal statuses, including conventions, regulations, codes, guidelines, recommendations and many more.

The maritime transport system of PDG is also highly regulated. The most important International Conventions governing the carriage of dangerous goods by sea are: SOLAS 1974 (Part A, Chapter VII) Convention and MARPOL 1973/1978 (Annex III) Convention. These conventions contain mandatory provisions for safety and protecting the marine environment from PDG carried by sea. The principal international regulations for the carriage of PDG by sea are amplified and published in the IMDG Code. The IMDG Code requirements concern various aspects, including technical, operational, human safety and health and the marine environment and property protection. The following are some of the relevant international and federal (U.S.) regulations and recommendations concerning maritime transport of dangerous goods and accidents:

International dangerous goods regulations:
- International Convention for the Safety of Life at Sea, 1974 (SOLAS 1974)

- International Convention for the Prevention of Pollution from Ships, 1973/1978 (MARPOL 1973/78)
- International Maritime Dangerous Goods (IMDG) Code
- International Convention of Safe Containers (CSC) 1972 concerning standards for design, construction testing, inspection, and maintenance of containers
- IMO Resolution A.714 (17) - Cargo Securing Manual
- IMO Guidelines (MSC Circular 530) for lashing and securing heavy items

Federal dangerous goods regulations (U.S.):

- Code of Federal Regulations (29 CFR 1910) concerning planning search and recovery operations of hazardous materials.
- Code of Federal Regulations (29 CFR 1910.1018) concerning appropriate training for people involved in recovery operations of hazardous materials
- Code of Federal Regulations (49 CFR 171 and 176) concerning reporting hazardous incidents and conditions.
- Code of Federal Regulations (49 CFR 450-453) concerning standards for design, construction testing, inspection, and maintenance of containers.
- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

2.2.4. Ship system

Packaged dangerous goods (PDG) are carried onboard many different types of ships of different sizes, including breakbulk or general cargo ships. Because of the number of ports served and the range of goods carried, this type of ship consists of several decks (Brodie, 1994).

Figure 2.5: M/v “Santa Clara I” (U.S. DOT, 1992)

The m/v “Santa Clara I” (SCI)

The m/v SCI was a breakbulk ship (Figure 2.5) with Panamanian registration, 146 m in length, 9,593 grt, built in 1974 (U.S. DOT, 1992). The ship was equipped with four cargo holds, 2-3 levels (tweendecks) each spanning the width of the ship. Unlike containerships (fully cellular ships), this ship type is not specially designed for the carriage of containers. However, the SCI was fitted for carrying containers on the hatch covers (no. 2-4). In 1977, the ship was retrofitted with deck pedestals to increase the capacity from six to eight containers stacked on deck. The ship was equipped with diesel propulsion, 7,385 hp, with a maximum service speed of 16 knots, which was controlled by a variable pitch. The ship operated regularly on routes between ports in South American and the east coast of the U.S. She carried different types of general cargo in different types of packages of different sizes, including freight containers, trucks and other general cargo.

Stability of the ship

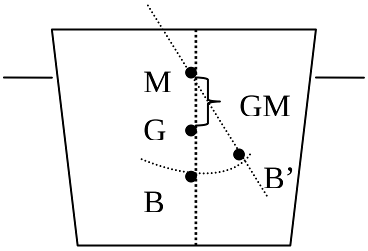

Figure 2.6: Metacentric height (GM)

The principles of the stability and behaviour of ships at sea are discussed in several works on navigation and naval engineering, including these sources (Biran, 2002; Derrett, 1999; Mahfouz, 2004; Jensen et al., 2004. Stability is the tendency of a ship to rotate and get into a position of equilibrium when inclined. Metacentric height (GM), which is a principal measure of the ship's stability, is the height from the centre of gravity (G) to the metacenter (M) (Figure 2.6). The centre of the mass of the ship, “G”, is the point at which all forces of gravity act on the ship (FAS, 2005). The position of "G" and the magnitude of the force, i.e. the GM, depend on the ship's total weight – the amount and distribution of weights. The “M” is an imaginary point, where the lines of buoyant force intersect as the ship is inclined through small angles of heel (FAS, 2005). The ship's centre of buoyancy (B) is the centre of gravity of the volume of water displaced by the ship's hull (PHE, 2005). Depending on various conditions, the GM may take positive, zero or negative values. When the GM is negative, the ship is unstable and will roll until it becomes positive again (or sinks). A ship has two metacentric heights: the transverse metacentric height (GMt) that controls the recovery of a ship from listing, and the longitudinal metacentric height (GMl) that controls the recovery of a ship from pitching. The stability characteristics of a ship fall within a range predetermined by the design of the hull and the centre of gravity of the un-laden ship. Within this range, the stability conditions for any given voyage are determined by different variables, such as cargo loading, fuels and ballast conditions.

Crew

The total number of crew aboard the ship was 28 (U.S. DOT, 1992). The crew was mostly of Peruvian nationality, and the master, who was Spanish, had 25 years’ sea experience, 18 of which years in commanding positions (U.S. DOT, 1992). The master assumed command of the m/v “Santa Clara I” four days before the ship arrived in Port Elizabeth (NJ), U.S. This was his first voyage with the company.

2.2.5. Packaging system

The packaging system is a system in its own right, consisting of many different elements that are necessary for the packaging system to perform as intended. According to the form and state in which they are carried by water, dangerous goods are divided into packaged dangerous goods (PDG) and bulk (liquid and solid) dangerous cargoes. Dangerous goods are carried at various levels of packaging, namely *primary, secondary and tertiary packaging levels* (Paine, 1990). The IMDG Code (2002) categorises packaging into *inner*, *intermediate*, *outer* and *composite* packaging. Packaging varies in size, shape, strength and material. In maritime transport, according to the IMDG Code, the system includes cargo transport units (CTUs) (e.g. freight vehicles, rail freight wagons, freight containers, road and rail tank vehicles/wagons and portable tanks), unit load (e.g. pallets), intermediate bulk containers (IBCs) and small and medium size conventional packaging (e.g. drums, bags, and fibreboard boxes). For packing purposes, dangerous goods, except classes 1, 2, 4.1, 5.2, 6.2 and 7, are assigned to three packing groups in accordance with the degree of danger they pose.

Packaged (hazmat) dangerous goods (PDG)

The IMO (1996a) defines packaged dangerous goods (PDG) as dangerous goods (materials, substances and articles) carried in any form of containment, such as freight containers, cargo tanks, shipborne barges on barge-carrying ships, freight containers, bulk packaging, portable tanks, tank-containers, road tankers, swap-bodies, vehicles, trailers, intermediate bulk containers (IBCs), unit loads and other cargo transport units (CTU). For statistical purposes, U.S. DOT (2005a, 2005b) refers to the carriage of packaged hazmat or dangerous goods as “bulk” and “non-bulk” containers.

Freight containers: Large amounts of different classes of dangerous goods are carried in freight containers. A freight container is an article of transport equipment that is of a permanent character and strong enough for repeated use (IMDG Code, 2002). It has been especially designed to facilitate the transport of goods, by one or more modes of transport, without intermediate reloading. Containers are designed to be secured and/or readily handled, having fittings for these purposes, and are approved in accordance with the International Convention for Safe Containers (CSC, 1972) as amended (IMDG Code, 2002). Various types and sizes of containers are used worldwide, but the most common standard sizes are 20-feet (TEU) and 40-feet ISO containers.

The IMDG Code provides detailed descriptions and general and specific provisions for construction, testing, handling and transport operations of different types of packaging. According to the IMDG Code (2002), packaging should be: a) well made and in good condition; b) capable of withstanding the ordinary risks of handling and transport by sea; and c) adequately constructed, tested, maintained and correctly packed or filled. Standards for design, construction testing, inspection, and maintenance are provided in the International Convention of Safe Containers (CSC, 1972) and the U.S. regulations (49 CFR 450-453).

In the case of the m/v SCI, dangerous goods were packed in primary/inner (drums), secondary/intermediate (pallets) and tertiary/outer (containers) types of packaging. All the containers stowed on the no. 2 hatch were 20- and 40-feet standard freight containers. All the containers except one were made of steel. One container was of a fibreglass-reinforced plastic (FRP) construction sandwiched with plywood panels on the sides, ends and top. FRP has different physical properties from those of steel. FRP has no plastic range. It goes from an elastic range to a break. The containers were tested in accordance with the IMO standards, and were subject to regular inspections under the U.S. regulations (49 CFR 453).

2.2.6. Cargo securing system

Cargo securing consists of the procedures and equipment by which cargo is stowed, lashed, blocked, braced, and tommed aboard ships (GSO, 2005). The terms “packing/ unpacking” and “blocking” and “bracing” are often used to describe the loading (stuffing)/ unloading and securing of cargo inside freight containers. The main components of the system include:

- *Securing/lashing devices, gears or equipment,* including bridges, penguins, wire lashings, turnbuckles, and dunnage.
- *The cargo/packaging system,* including the packaging or container structure itself, corner fittings.
- *The ship system,* including hatch covers, pedestals, flat shoe plates, and D-rings.

The *stowage* is an essential component of the cargo securing system. The aforementioned components acting together serve to hold the cargo in place and transmit the forces on the cargo/packages into the ship’s structure. The effectiveness of the system depends on a variety of factors, including the strength and elasticity of the components, fit tolerance, proper installation and the methods of cargo securing.

The cargo securing system is usually designed and constructed in accordance with the recommendations of classification societies and general industrial design standards. The system should be constructed with sufficient load capacities under tension. IMO resolution A714 (17) recommends providing the cargo-securing manual aboard the ship. The IMO circular on cargo securing describes various aspects in detail, including the securing arrangements and their location, the inventory of gears and their strength, the appropriate methods of application, guidance on stowing and securing non-standard heavy cargo, planning for heavy weather, and an analysis of design forces.

Cargo securing system of the m/v SCI

The m/v SCI was fitted with a basic cargo securing system, dating back to the initial construction of the ship and subsequently extended with the retrofit of deck pedestals. The components of the m/v SCI’s lashing system included (U.S. DOT, 1992) (Figures 2.7~2.10):

- *Flat shoe plates* are devices fitted on the hatch covers and pedestals.
- *Cones* are devices set in place in the recess of the shoe plates.
- *The corner fittings of the container* are fittings that the bottom tier of containers is placed on.
- *Twistlocks* are gears fitted between the bottom and second tiers.
- *Bridges* are gears fitted athwart the ship at the top of adjacent container stacks.
- *Penguins* are gears with hooks that are fitted into the bottom corner fittings of the top containers or the top corner of a single container.

- *Wire lashings* are wire ropes with press-fitted stoppers every few feet and eyes at either end, fitted over the penguin hooks and running diagonally down towards the deck.
- *Turnbuckles* are gears used to tie the lashings to D-rings on deck, hatch covers or pedestals providing tension control for the lashings. The m/v SCI's cargo-securing system contained three types of turnbuckles: claw, unk and hook.

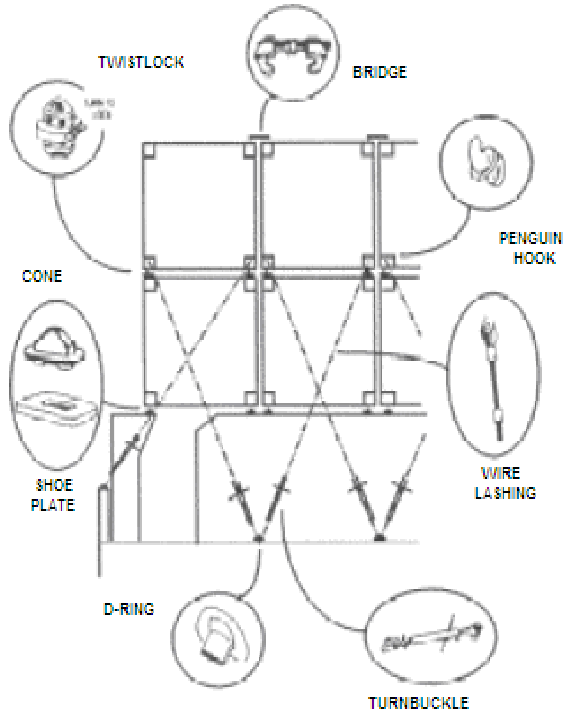

Figure 2.7: Some components of the m/v SCI lashing system (U.S. DOT, 1992)

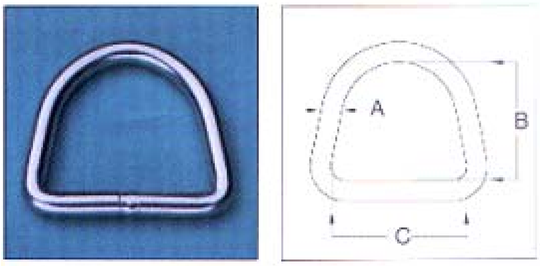

Figure 2.8 D-rings, 316 stainless steel welded (MMM and Accessories, Inch., 2005)

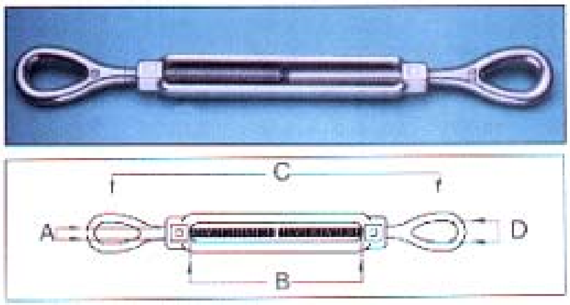

Figure 2.9: Turnbuckle eye & eye, 316 stainless steel (MMM and Accessories, Inch., 2005)

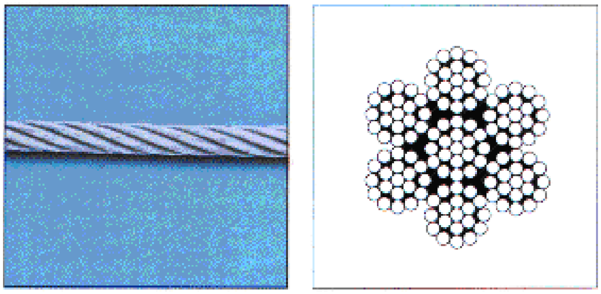

Figure 2.10: Wire rope (7x9), 304 stainless steel polished (MMM and Accessories, Inch., 2005)

2.3. Concept of risks

The dangerous goods supply chain, including the transport system, is a risk source entailing the possibility of undesirable outcomes (Scott, 1996). Numerous sources (HSC, 1991; Ertugrul, 1995; Mullai, 2006a) define, in essence, the concept of "risk" as the likelihood of consequences of undesirable events. Weigkricht and Fedra (1993) define "*dangerous goods risk*" as the *probability* of an *accident* that will cause a release of dangerous goods and the *consequence* of such an *event*. The risk is a function of frequency, exposure and consequences. Risk estimation may combine: a) the likelihood (frequency/probability) (F) and consequences (C), $R=f\ (FC)$; or b) the consequences (C) and exposures (E), $R=f\ (EC)$, which is estimated for one year. The main risk elements include undesirable events (accidents and incidents), hazards, the causes and contributing factors of undesirable events, exposure, the consequences for risk receptors, including human beings, the environment, property, and the likelihood of accidents.

Undesirable events - accidents/incidents*:* Accidents/incidents are the negative or undesirable outcomes of the systems. The term "undesirable events", which is often used as a more neutral and generic term, denotes all types of events, from unsafe situations, near-miss incidents to major or catastrophic accidents involving large numbers of fatalities and injuries and extensive environmental and property damage. The terms "marine accident" and "marine casualty" denote undesirable events in connection with ship operations (IMO, 1996b; LRS, 1996). Marine incidents may involve losses or likely losses overboard of PDG, including those in freight containers, portable tanks, road and rail vehicles and shipborne barges (MARPOL, 1973/1978). There is a distinction between "accident" and "incident" in terms of the severity of the consequences (see Mullai, 2006a). However, for the purpose of simplicity and consistency with the U.S. data sources, the term "hazmat incident" is frequently used in this volume to denote all categories of undesirable events that have or likely to have involved hazmat.

Distribution/transport hazards: Packaging provides the interface and the barrier between goods and the distribution environment (Jönson, 1998), including hazards encountered during transportation. Transport hazards are those physical conditions and agents that directly affect packaging performance and/or dangerous goods. In packaging theory and industry, hazards are generally divided into five main categories (Jönson, 1993; Paine, 1990), namely mechanical, climate or weather-related, chemical, biological and miscellaneous.

Causes and contributing factors: For the purposes of the statistical incident data recording and analysis, many relevant authorities and organisations (e.g. the IMO, the USCG, the U.S. DOT, and the SMA) have establish coding schemes or systems for categorisation of causes and contributing factors of marine accidents and incidents. They are categorised in different ways and from different perspectives. The following are some categorisations: a) primary and underlying causes and contributing factors (IMO, 1994); b) internal, external and unknown causes; (IMO, 1994); c) apparent, propagating and originating causes (U.S. DOT, 1995); human related causes and contributing factors, including personnel, management, decision making, operator, ship, cargo, working environment including sea and weather, individual and social and other related factors or conditions (IMO, 1994; U.S. DOT, 1995).

The concepts of “accident/incident”, “undesirable event”, “hazard”, “cause”, “contributing factor”, “failure”, “deficiency”, “damage”, “error”, “effect”, “impact”, “consequence” and others, which are used in this volume, are the constituent elements of the universal notion of the “*cause-effect”* chain or network. The simplest notion of *cause* is that it may be a person, thing, event, state or action that produces an effect (CED, 1992; Little, 1991). The *effect* is something that is produced by a cause (CED, 1992). The cause(s) always precedes one or more effects. Further, one effect may become the cause for another effect. For example, in response to catastrophic *consequences* of some major marine accidents involving dangerous goods, many significant changes have been made (*i.e. caused*) in the shipping industry and beyond, including changes in the regulatory system governing the maritime transport system of dangerous goods. The latter, in turn, has considerably *affected* parts or the entire maritime transport system as well as its outcomes. It may be often difficult to make a difference between causes and effects. Cause-effect relationships, known as causality or causal mechanisms that link cause and effect, are of simple linear, chain or very complex network or neural forms. For more information about the notion of “cause-effect”, see Mullai, 2006a. However, for the purpose of consistency with relevant terminology used in the field and sources used in this study, specific terms mentioned above are used in specific contexts in this report.

The system and risk elements are defined and classified in a wide range of classification or coding systems. In this volume, the USCG and the U.S. DOT and some other international systems, e.g. the Lloyds Maritime Information Service and the IMO, are mostly employed.

2.4. Marine environment

2.4.1. The m/v SCI accident site - a sensitive ecological zone

The m/v SCI accident occurred 30 miles off the coast of Cape May, New Jersey (U.S.), in 40 m of water, near the entrance to Delaware Bay (Figure 2.15). The marine environment, including the Delaware Bay and the entrance to it and the southern coastline of New Jersey, is a sensitive ecological zone, representing valuable economic and aesthetic resources for the local community. The southern coast of New Jersey is also a constituent part of the zone, which is officially known as the *New York – New Jersey Bight* (NY/NJ Bight) (COA, 2005).

According to the Delaware Department of Natural Resources and Environmental Control (DNREC, 2005), Delaware's beaches are the most heavily utilized outdoor recreation resources in the United States. There are 39.4 km of sandy beaches bordering the Atlantic Ocean from the mouth of the Delaware Bay to the Maryland border. Of this space, 19.3 km are contained within the Delaware State park. Sandy shores are the habitat of a wide variety of life, including horseshoe crabs and plovers (a shore bird). The local fishing industry relies heavily on these marine habitats, in particular on horseshoe crabs and clams (e.g. bivalve molluscs). The Delaware Bay has the largest concentration of horseshoe crabs in the world (U.S. NFWF, 2004). In recognition of its great importance and value, the horseshoe crab was designated as Delaware's official marine animal on June 25, 2002 (DNREC, 2005). Biomedical researchers utilize horseshoe crabs to test the purity of drugs. In addition, each year over 6 million visitors to the coastal area contribute a significant amount of money to the Delaware State's travel industry net income of over $ 850 million a year (DNREC, 2005).

The NY/NJ Bight is an ecologically rich region inhabited by more than 300 species of fish, nearly 350 species of birds, seven species of sea turtles, and many marine mammals, such as 10 species of whales and several species of seals and porpoises (COA, 2005). The region is also economically important for the local communities, since the fishing industry here supports millions of people.

2.4.2. Arsenic-contaminated ecosystem – the context

The marine environment is a constituent element of the ecosystem. Many different players with different converging and often-conflicting interests are linked with the marine environment and its valuable resources.

The data available for the coastal zone of the state of *New Jersey* have shown that coastal sediments are polluted with toxic substances (COA, 2005; USEPA, 2001a). For many years, the NY/NJ Bight has served as an ocean dumpsite for large amounts of many different wastes, including dredged material, cellar dirt, sewage sludge, acid wastes, wood incineration, and industrial wastes (COA, 2005). These wastes may have contained toxic substances.

The third largest U.S. petrochemical port and five of the largest U.S. East Coast refineries (DRBC, 2005) are located in the Delaware River and Bay. Approximately 159 million liters of crude oil are moved on the Delaware River on a daily basis (COA, 2005). Arsenic levels are higher than recommended limits in some parts of the region because of water discharge associated with petroleum hydrocarbon recovery operations (NJDEP, 2000).

The Delaware River is the longest un-dammed river east of the Mississippi, extending 330 miles. The river is fed by 216 tributaries (DRBC, 2005). The river and its tributaries collect and discharge land-based arsenic into the Delaware River Basin and beyond. The Basin contains 13,539 square miles, draining parts of Pennsylvania (50.3%), New Jersey (23.3%), New York (18.5%), and Delaware (7.9%), including also the 782-square-mile Delaware Bay, which lies between the states of New Jersey and Delaware (DRBC, 2005). Approximately 15 million people (or approximately 5% of the U.S. population) live and rely on vast resources of the Delaware River Basin (DRBC, 2005).

Figures 2.11~2.14 show estimated arsenic in use during the period 1900-1980 and distributions of arsenic in the environment (streams, soil and stream sediments, and ground water) in the state of *New Jersey* (Vowinkel et al. 2001). Because arsenic is naturally occurring and widely used in New Jersey, almost all ecosystems have been exposed to arsenic, with many plants, animals and people at risk. Figure 2.12 shows that many sites in New Jersey have arsenic concentrations exceeding levels of 20 mg/kg, which are higher than the recommended criteria, for example soil clean-up level of 20 mg/kg (Vowinkel et al. 2001) (NJDEP, 2000). Arsenic concentrations are elevated because of a wide use of arsenic, particularly as herbicide and pesticide, and waste disposal from industrial sites. For example, inorganic arsenics have been used as cotton desiccants and organic arsenics as herbicides in rice-producing areas. During the period 1900-1980, approximately a total of 30,391 tons (67 million pounds) of arsenic was applied directly to soils (Vowinkel et al. 2001, from Murphy and Aucott, 1998).

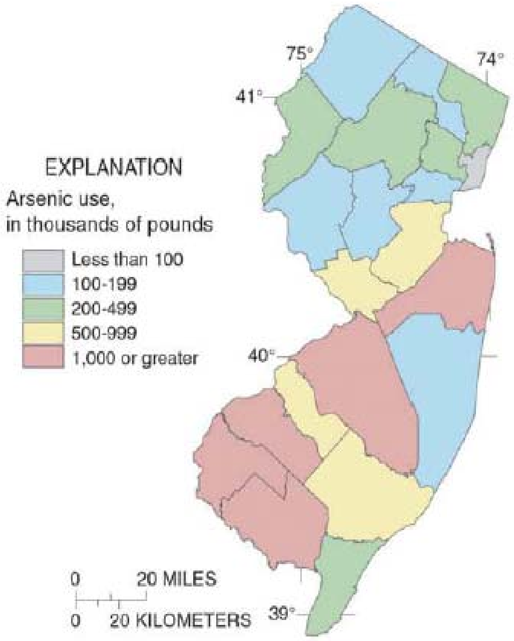

Figure 2.11: Estimated arsenic in use in New Jersey 1900-1980 (Vowinkel et al. 2001, from Murphy and Aucott, 1998)

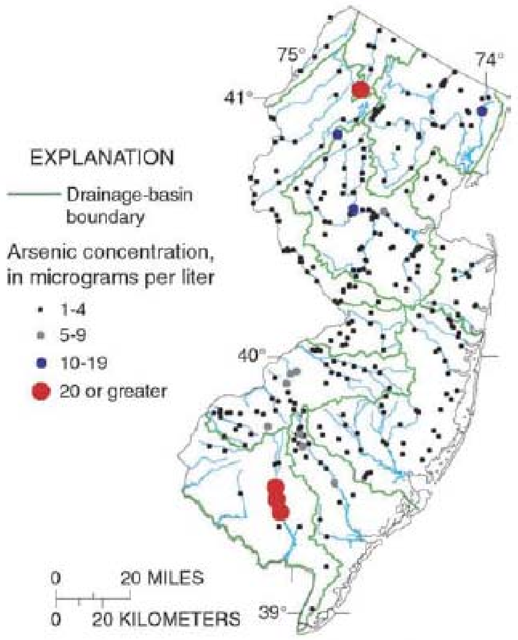

Figure 2.12: Distribution of concentration of total arsenic in streams in New Jersey, by major drainage basin (Vowinkel et al. 2001, from U.S. Geological Survey National Water Information System database)

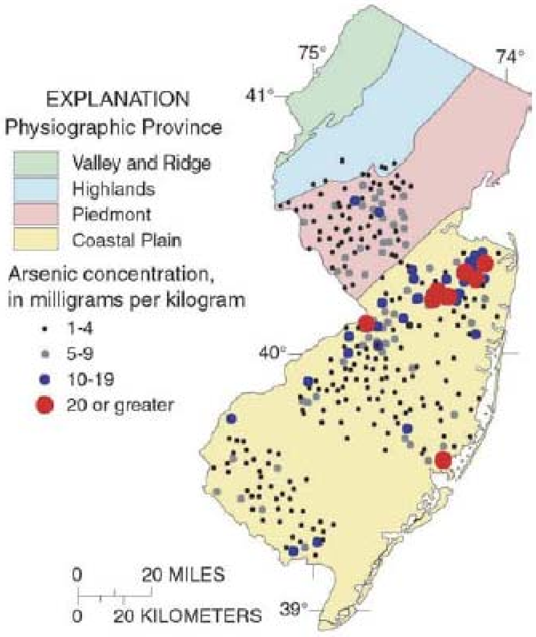

Figure 2.13: Distribution (mg/kg) of arsenic in soil and streambed sediments in New Jersey, by physiographic provinces (Vowinkel et al. 2001, from National Uranium Resource Evaluation Program database in Grosz et al., 2000)

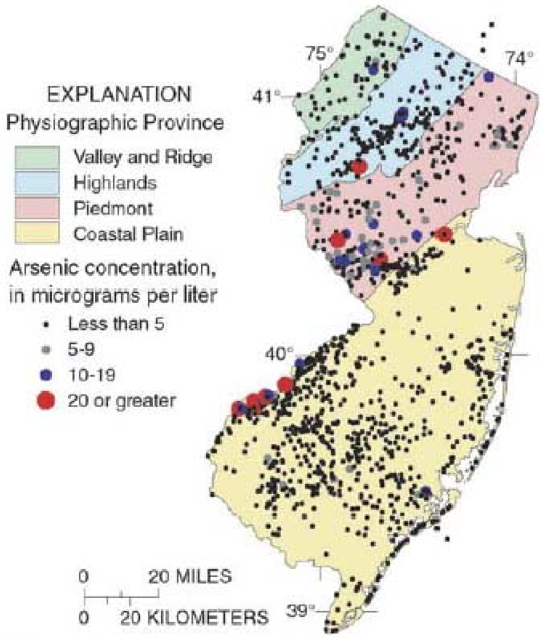

Figure 2.14: Distribution (mg/l) of arsenic in soil and streambed sediments in New Jersey, by physiographic provinces (Vowinkel et al. 2001, from National Uranium Resource Evaluation Program database in Grosz et al., 2000)

A large portion of New Jersey's population is already exposed to arsenic from various sources. Approximately 5 million residents of New Jersey are potentially exposed to arsenic in ground water sources of drinking water (NJDEP, 2001). There have been 4 cases of cancer related to drinking water only (NJDEP, 2001). Arsenic from land-based sources enters into the marine environment of the state, particularly in estuaries and coastlines, affecting background concentrations of the seawater, sediments and marine biota. For more information about the properties and effects of arsenic compounds, see Appendixes 1 and 2, Vol. II.

2.4.3. Stockholm Convention on Persistent Organic Pollutants (POPs)

The Stockholm Convention (2001) (UNEP, 2004) on Persistent Organic Pollutants (POPs) is a global treaty whose main objective is to protect human health and the environment from persistent organic pollutants. The Convention became legally binding on May 2004, after being ratified by all 50 states. In implementing the Convention, the parties to the Convention are required to take measures to reduce or eliminate releases from intentional production and use, unintentional production and stockpiles and wastes of these persistent organic pollutants: *Aldrin, Chlordane, Dieldrin*, *Endrin*, *Heptachlor, Hexachlorobenzene* (HCB), *Mirex, Toxaphene, Polychlorinated Biphenyls* (PCB), *DDT* (1,1,1-trichloro-2,2-bis (4-chlorophenyl) ethane) *Polychlorinated dibenzo-p-dioxins* and *dibenzofurans* (PCDD/PCDF) (Stockholm Convention, 2001) (UNEP, 2004). The first nine chemicals are required to be eliminated or banned for the production and use.

Many chemicals are used as pesticides (e.g. DDT). Since 1998, around 100 different types of pesticide residues have been found in the various fruit and vegetables tested (FOE, 2002). In 2001, 1.5% of fruit and vegetables tested had pesticide residues that exceeded the Maximum Residue Level (MRL), which is the legal level of pesticide residue that can be present in food (FOE, 2002). According to the UNEP (2004), POPs are among the most dangerous pollutants released into the environment by human activities. They possess toxic properties, resist degradation and persist in the environment, bioaccumulate in the tissue of living organisms, and they are transported, through air, water and migratory species, across international boundaries (Stockholm Convention, 2001). These highly toxic chemicals have caused deaths, injuries or diseases to the people and wildlife. They have induced cancer and damage to the nervous, reproductive and immune systems (UNEP, 2004). POPs have also caused uncounted birth defects (UNEP, 2004).

However, none of the inorganic and organic arsenic compounds, which share similar, if not worse, properties and effects for humans and other living organisms with the aforementioned POPs, have been included in the list. Arsenic trioxide was one of the chemicals involved in the m/v SCI accident. For more information about the properties and effects of arsenic compounds, see Appendixes 1 and 2, Vol. II.

2.5. Weather conditions

The coast of Virginia, south of the m/v SCI accident site, is the most favourable region on the U.S. Atlantic coast for the development of low pressure or cyclonic storms, which are often called “Hatteras storms” (U.S. DOT, 1992). They are frequently very intense. On the voyage to Port Baltimore, the m/v SCI encountered this type of storm. Cyclonic storms tend to move NE along the Gulf Stream. Although often unpredicted and variable, storms move with an average speed of about 30 knots during winter months. Sometimes, storms accelerate at a speed of up to 70 knots.

Prior to the departure from Port Elizabeth, weather forecasts issued by various weather forecast services were relevant and available onboard the m/v SCI. The offshore water and high seas forecasts issued warnings for a storm moving through Cape Hatteras (approx. 170 km south of Delaware Bay), with the most severe weather – winds 40-60 knots and seas 6.7-10.7m (U.S. DOT, 1992). Throughout January 3rd, weather forecasts continuously updated the position of the storm centre. The anticipated ship’s trackline was within the range of the most dangerous quadrant of the storm.

The master’s weather forecast assessment focused on a low pressure area, which, according to his recollection, was south of Cape Hatteras, moving north at a speed of 10 knots, with forecast winds of maximum 20 knots and seas 3.1-3.7 m. According to the investigation report (U.S. DOT, 1992), the master believed the ship was caught between the low-pressure area from the south and the high-pressure area from the north, the New York area.

2.6. The m/v SCI’s voyage

The m/v SCI was on a regular voyage between South America and U.S. ports. The ship had started her voyage to Port Valparaiso (Peru) on December 2, 1991, planning port calls in Chile and the U.S. After loading containers and general cargo, including 10 drums of magnesium phosphide, in the no.1 upper tweendeck, the ship left Port Valparaiso (Peru) and bound for Port Coquimbo (Chile), where she loaded 25 containers of arsenic trioxide – 19 and 6 containers respectively under and on the deck of the no.2 hatch. After Port Coquimbo (Chile), the ship continued her voyage to U.S. ports.

On Thursday, January 2nd, 1992, the ship arrived in Port Elizabeth, New Jersey (U.S.). Stevedores discharged containers from the no.2 and no.3 hatches, re-stowed several containers onto the no. 2 hatch, and loaded containers and general cargo in the no.3 hold and on no.1, 2, and 3 hatches. Cargo stowage on the no.2 hatch included 15 fully loaded containers, 10 empty containers, and a 50-feet machine.

For more information about definitions and concepts concerning system and risk elements provided in this section, see Chapter 3, Vol. I, and Mullai 2006a, 2006b.

2.7. The m/v SCI accident

Accidents and incidents are the negative outcomes of the system. The following section provides a summary of chronological events of the m/v SCI accident.

On January 3rd, 1992, after discharging and loading of containers and other general cargo, the m/v "Santa Clara I" (SCI) departed from Port Elizabeth (New Jersey, U.S.) and headed for Port Baltimore (Maryland, U.S.), with a forecast including dangerous storm warnings in the area. The ship was loaded with, among other things, 25 containers of arsenic trioxide and a piece of machinery. Six containers were stowed on the deck of no. 2 hatch. The master declined to use a shore-based lashing gang in Port Elizabeth, opting for cargo lashings by the ship's crew after leaving the dock. The master misinterpreted and underestimated weather hazards. Despite weather forecast service warnings of a dangerous cyclonic storm, the master decided to get the ship underway.

The ship left Port Elizabeth with fuel and ballast tanks fully loaded and a draft, as recorded in the deck log, of 17'06'' forward and 24'00'' aft (U.S. DOT, 1992). Upon departure, based on the stability condition book and actual loading data, the master calculated the ship's metacentric height (GM) value at 1.86 m (6.1 feet), which was later proved by the USCG's experts to be accurate (U.S. DOT, 1992). The GM was not consistent with the requirements for smaller container-carrying ships like m/v SCI. According to U.S. regulations, in order to reduce or avoid heavy synchronized rollings, the ship should have had a GM of approximately 0.444 m. The master of the m/v SCI described the ship's GM (1.86 m) as "very good" (U.S. DOT, 1992).

At 1517 hrs, on January 3rd, the ship left her berth with docking and Sandy Hook pilots aboard. Under the supervision of the bosun, the crew began lashing/securing cargo and containers on deck at the no.1, 2 and 3 hatches and inside the no.3 hold. At 1740 hrs, the Sand Hook pilot disembarked. By this time, it was dark. The crew reported that they had completed cargo securing. However, according to the pilot's memory, he never saw any on-deck cargo lashing activity while he was aboard (U.S. DOT, 1992). The ship headed towards the port of destination (Port Baltimore), setting a course of about 180° with a speed of 12-14 knots. Figure 2.15 shows the m/v SCI trackline – the times and respective positions on January 3rd and 4th.

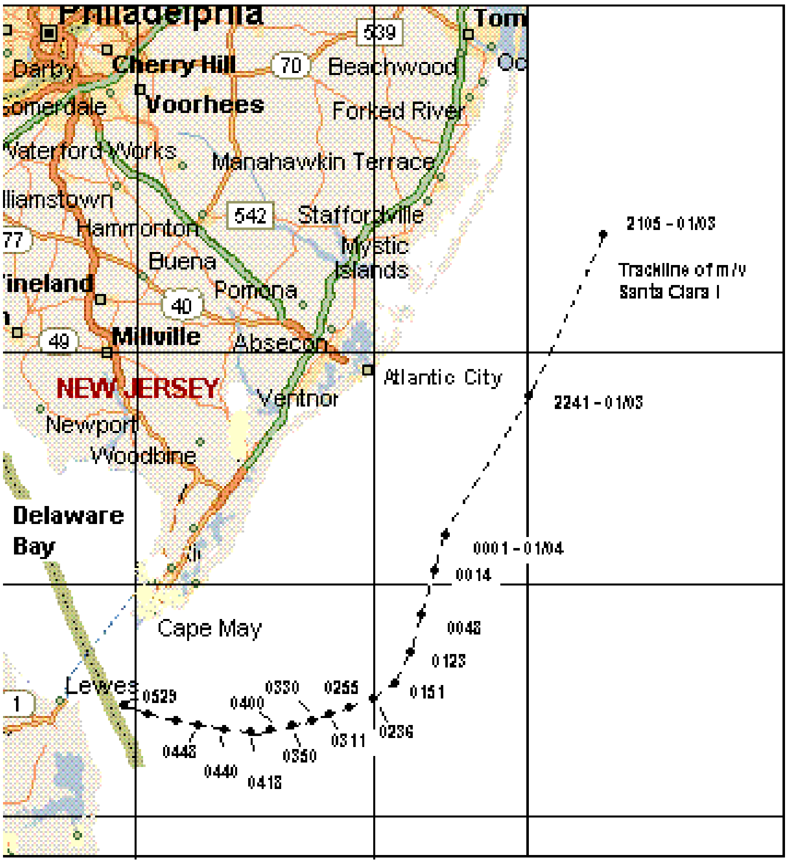

Figure 2.15: The trackline of the m/v "Santa Clara I" (map from Microsoft Corporation, 2005 and U.S. DOT, 1992)

During the night, on January 3rd, as the ship headed south off the New Jersey coastline, the weather conditions (NE winds) deteriorated very rapidly. In heavy seas, the ship began rolling and pounding heavily, surfing and taking green water on deck. Despite the severe weather ahead, the master continued heading the ship southward towards Port Baltimore. He expressed concern that, due to shallower waters, he could not steer the ship further to starboard. Due to the risks of losing the entire deck cargo or even the ship, the master could not turn the ship to port and return to the port of departure (Port Elizabeth). The ship proceeded at full speed. According to the master, he considered several times to reduce the speed by adjusting propeller pitch. However, as the master claimed, the ship lost steering control under 11 knots (18 pitches). In fact, the investigation showed that the master did not attempt any of the options to avoid or minimise the effects of the severe weather conditions.

On January 4th, 0130-0230 hrs, with heavy weather conditions – wind speed 34 knots (gusting 41 knots) and wave height 4.3 m – the ship experienced the most severe motions. Containers, drums and the machinery locations on the ocean floor confirmed that cargo loss occurred during this period. The chief engineer reported that one heavy roll (35°) was registered on the bridge's inclinometer. At some point during this period, the cargo securing systems of on-deck and hold-stowed cargo failed. Subsequently, the ship lost overboard 21 containers and one piece of machinery from the stowage on the no. 2 hatch. On-deck-stowed containers with arsenic trioxide drums broke loose and were damaged. Four of these containers were lost overboard in 38 m of water, some 30 nautical miles off the coast of Cape May, near Delaware Bay. Many arsenic trioxide drums broke loose on the deck. Nine drums were lost overboard (Whipple et al., 1993). Other containers that remained on board were also damaged.

The master stated that heavy rains and poor visibility prevented any observations on the ship's deck. Therefore, he did not report container loss and damage to the relevant authorities in due time.

Two other ships and a barge reported container losses in the same severe weather conditions (McGowan, 1993). The storm was very intense, causing heavy damage along the Maryland and New Jersey shorelines. According to another source (U.S. DOT, 1992), three hours later in about the same location of the SCI accident, another ship lost two on-deck-stowed containers.

At 0603 hrs, on January 4th, the ship arrived at Delaware Bay and took the pilot onboard. The pilot reported that a container was hanging over the portside bulwark at the no.2 hatch (Figure 2.16). The chief mate and crewmembers inspected the cargo on deck, and found only four containers remaining aboard on the no.2 hatch, two of which with arsenic trioxide drums; all had shifted from their stowed positions and been damaged. All six on-deck-stowed arsenic trioxide containers broke loose and opened up during the storm. Four of these containers were lost overboard entirely. Several blue drums were scattered, damaged and spilled their white powder contents on the deck and hatch cover. By looking at drums (which were labelled) and with reference to the IMDG Code, the master confirmed that they contained arsenic trioxide. Arsenic trioxide is a poisonous substance presenting hazards by inhalation and ingestion. It was also designated a "marine pollutant" in the IMDG Code (1990). The master ordered all personnel off the deck until the ship arrived at Port Baltimore.

Figure 2.16: Damaged container on the no. 2 hatch cover of the m/v SCI on arrival in Port Baltimore (U.S. DOT, 1992)

At 1355 hrs, on January 4th, approximately 8 hrs after the first observations, the master informed the ship's agent in Port Baltimore of cargo losses and damage. He requested arrangements for cleanup operations prior to discharging.

At 1525 hrs, on January 4th, the ship arrived at berth in Port Baltimore. On arrival, the port authority, police, fire department, the USCG, and shipping company representatives boarded the ship. A specialised cleanup contractor was hired.

At 0200 hrs, on January 5th, the cleanup operations began in the no. 2 hatch. Later that morning, after removal of damaged containers and drums and cleaning up, cargo discharging began. According the investigation report (U.S. DOT, 1992) and the report prepared by the USCG Atlantic Strike Team (Whipple et al., 1993), which participated in cargo search and recovery operations, of the total number of 648 drums in deck-stowed containers, 234 drums were recovered inside the two remaining containers or on deck in Baltimore (U.S. DOT, 1992). Approximately 13 drums were reported damaged or breached (Merrick, 1993). An estimated amount of two tons of arsenic trioxide powder had spilt onto the deck (Merrick, 1993).

Prior to or during discharging, crewmembers inspected all holds. The cargo inspection on under-deck-stowed arsenic trioxide containers showed that many pallets had tipped over, but with drums still intact. Several containers, trucks and breakbulk packages below deck were found broken and damaged. Four magnesium phosphide drums also broke loose, turned over, were damaged and spilled their contents onto the deck inside the hold. The chemical was mixed with other cargo including lumber and damaged cartons of wine. Magnesium phosphide drums were clearly labelled, but they were not listed on the ship's dangerous goods cargo manifest as required by 49 CFR and the IMDG Code (U.S. DOT, 1992). Magnesium phosphide is used as a fumigant. It reacts violently with water, producing phosphine gas, which is a highly poisonous and flammable gas. The crew and stevedores who worked in the hold did not identify the spilled chemical until the ship arrived in Port Charleston (South Carolina, U.S.). At least two other dangerous cargoes were set adrift and damaged in other holds.

In Port Baltimore, stevedores discharged the magnesium phosphide drums, including six drums still intact on pallets and four loose and broken drums. Over 393 kg of spilt magnesium phosphide remained on the upper tweendeck of the no.1 hold (U.S. DOT, 1992; Merrick, 1993). After discharging the drums, one stevedore working a forklift inside the hold noticed sparks as the forklift's rubber tires spun on the grey, granulated product on the deck. He promptly left the hold. One supervisor reported the situation to the port captain, indicating he had a problem, but nothing more.

In Port Baltimore, several crewmembers entered the enclosed space in the upper tweendeck of the no.1 hold to check and re-secure the cargo. Two crewmembers became dizzy and one of them vomited – this is a typical reaction to phosphine gas exposure. However, the incident was reported neither to the ship's medical officer nor to the master. At least four crewmembers including the chief mate observed the drum spilled in the no.1 hold, but none of them recalled any hazardous label. Two crewmembers stated that they knew nothing about dangerous cargo labels. The bosun stated that he was familiar with dangerous goods cargo labelling, but his ability to interpret them was limited. Neither the crew nor the shore personnel took seriously the hazardous situation inside the no.1 hold or reported to the Coast Guard as requested by 49 CFR Parts 171 and 176.

At 0645 hrs, on January 6th, the ship left Port Baltimore and headed for Port Charleston. The ship arrived in port at 2220 hrs, on January 7th. The next day, on January 8th, the work began on board the ship. Being unaware of the danger, and after exposure to magnesium phosphide in the no.1 hold, 37 stevedores were sent to the hospital for observation, and were later released (U.S. DOT, 1992). On the same day, prompted by the seriousness of the situation, the USCG in Port Charleston ordered evacuation of the ship. With a few essential crewmembers on board, the ship left the dock and anchored in Port Charleston harbour for recovery and cleanup operations. A specialized cleanup team spent several weeks in very delicate, specialised, time and resource intensive operations. Operations were completed on February 8th – approximately after one month. A total amount of 393 kg of magnesium phosphide was recovered and deactivated.

2.8. Search and recovery operations

The following section describes the search and recovery operations in connection with arsenic trioxide containers and drums lost at sea.

Because of the danger of the arsenic trioxide drums washing ashore or getting caught up in fishing nets, and because the public demanded action, a massive research and recovery operation was launched. A fisherman recovered an arsenic drum in a net (Whipple et al., 1993). According to the National Oceanic and Atmospheric (NOAA, 1992a, 1992b) environmental assessment, the arsenic trioxide drums lost at sea pose high risks to the marine environment and people.

The search and recovery operation concerning the arsenic trioxide drums lost from the m/v SCI was considered one of the largest operations of its kind in U.S. history. The operation involved many different specialised agencies and organisations, sophisticated and specialised equipment and large amounts of resources. The On Scene Coordinator (OSC) team employing the HAZMAT response strategy of Recognition, Evaluation and Control coordinated the operation. A team of experts (Atlantic Strike Team), which consisted of representatives (20 members) of every agency involved, executed the entire search and recovery operation. The operation lasted 5 and half months, costing over $ 2.2 million (Whipple et al., 1993).

The helicopter searches covered 305 nautical miles of the ship’s trackline and 98.5 square miles of ocean (Whipple et al., 1993). Salvage crews spent approximately two months searching a large ocean area (60 km x 1 km) before all the arsenic trioxide containers and drums were found. Another month was spent in recovering the arsenic trioxide drums from the ocean floor. The search and rescue operations were hampered by bad weather conditions.

Immediately after the accident was reported, several USCG aircrafts were sent to the scene. The initial search, which continued for three days, found no containers, drums or debris. At the same time, an investigation began to determine the type and amount of cargo lost overboard. Due to errors in the ship's cargo manifest, the information was initially inconclusive. On the third day, a floating container was observed off the Chincoteague coast (VA), south of Delaware Bay. Based on examination of the container description, it was identified as one of those lost from the m/v SCI. According to the ship's cargo manifest, the container was loaded with lumber.

The USCG initiated an underwater search for the lost containers. It was difficult to find out where all the arsenic trioxide containers and drums had landed. Due to their weight, the drums might have broken through the sides and ends of the container at various points of the ship trackline. By using information on the ship's positions coinciding with the heaviest rolls, and applying estimated drift of the cargo lost overboard, the search area was focused to the west of the ship's trackline between 0151-0226 hrs, January 04th. The field of containers and drums was located with Remotely Operated Vehicles (ROVs). On January 12th, a large debris field was discovered south of the 0151 hrs position. Initially, by means of ROV, three of four arsenic trioxide containers were located. The information of each container matched that listed in the cargo manifest of m/v SCI. Containers were broken open and many drums had spread to a large area on the ocean floor. One container was severely damaged and apparently contained no drums. On January 27th, a fourth container was located and identified as one listed on the m/v SCI's cargo manifest. The container was badly damaged, with one side entirely missing. The container contained only two drums marked as arsenic trioxide (Whipple et al., 1993). A large pile of drums was located close to the fourth container. The missing side was found under the pile. The side of the container was identified as one listed on the cargo manifest of the m/v SCI. The drums appeared impacted or crushed.

On April 8th, 1992, the P&I Club representing the shipowner took action and initiated salvage operations. Specialised salvage and diving companies carried out the operations. Recovery was performed by means of ROVs with mechanical arms. Drums were brought on deck and stored in containers, and offloaded onto another ship. Then, they were taken to the port, loaded onto a trailer and sent to a disposal facility. According to the report prepared by the USCG Atlantic Strike Team (Whipple et al., 1993), only 320 drums were retrieved from the sea floor. Some of the drums were breached and an estimated amount of 200 kg of arsenic trioxide was lost at sea (Whipple et al., 1993). Initially, the USCG and the USEPA considered the arsenic trioxide as a hazardous material and attempted to send the product back to the manufacturer. Because it was contaminated with water, the arsenic trioxide was considered as a hazardous waste instead of a hazardous material.

On May 7th, the Atlantic Strike Team (AST) personnel were demobilized. On May 19th, another extensive sonar and ROV search was conducted on the areas determined as environmentally critical, but no more drums were found. The m/v SCI case was formally closed on October 5th, 1992. Many drums remained unrecovered. Responsible authorities issued instructions to the maritime community about what to do in case drums were located or caught by nets.

2.9. NRC database – m/v SCI accident details

In order to *extend, fill gaps and triangulate data*, the records of two of the largest U.S. hazmat incidents databases have been reviewed. Table 2.2 provides, with some modifications in the structure, exact details of the m/v SCI accident as reported. The details are extracted from the 1992 records of the U.S. National Response Center database (2005). The search of the entire 1992 records, which contain information for 27,662 incidents, of which 2708 involve ships, showed that the m/v SCI accident was recorded three times under three separate incident numbers or codes[5] (nr. 102015, 102097, and 102213 – see Table 2.2). The fourth number (nr. 114837) is also the incident number for the m/v SCI, but involved in another incident (oil spill) under another name (i.e. the m/v Santa Mercedes) and probably owned by another shipowner. Although the latter incident is not related to the case being studied, the information of this case will provide support for the analysis. The reviews of records and comparison with other sources of information show that some categories of information are incompatible, missing or inaccurate. For example, the "natural phenomenon" and "other" category of causes were recorded as the sole two causes of the m/v SCI accident. Further, the consequences to people, the marine environment and properties have been recorded as either "unknown" or "none" (see Table 2.2).

Table 2.2: The m/v SCI accident details according to 1992 records (NRC, 2005)

Details of the m/v SCI accident					
Calls					
Nr. incident	*Date/time received*	*Responsible Company*	*Responsible organisation type*		
102015	1992-01-08 11:32	ENF Lines	Private enterprise		
102097	1992-01-08 17:39	M/V Santa Clara I	Private enterprise		
102213	1992-01-09 13:29	Kyriakopouls Int.	Private enterprise		

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[5] NRC Report Number: this is a unique identifier assigned to each report (known as SEQNOS) (NRC, 2005)

114837	1992-04-20 12:12		Unknown		
Incident commons					
Nr. incident	*Description of incident*	*Type of incident*	*Incident cause*	*Incident data/time*	*Incident detected*
102015	M/V Santa Clara I hold area; drums overturned releasing material during heavy seas	Vessel	Natural phenomenon	1992-01-03 23:00	Occurred
102097	M/V Santa Clara I; vessel hit by rough seas and drums within a hold broke loose and opened up; caller was buying material which broke loose	Vessel	Other	1992-01-08 15:30	Discovered
102213	M/V Santa Clara I lost 4 containers off the ship during heavy weather	Vessel	Unknown	1992-01-04 07:00	Discovered
114837	Unknown sheen sighted; sheen size: unknown: possible release from M/V Santa Mercedes (Santa Clara I)	Unknown sheen	Unknown	1992-04-20 11:50	Discovered
Incident commons					
Nr. incident	*Location: incident*	*Location: city/port*	*Location: state*	*Location: county*	
102015	Port of Charleston	Charleston	South Carolina (SC)	Charleston	
102097	Port of Charleston; pier: unknown	Charleston	South Carolina (SC)	Charleston	
102213	Off the coast of New Jersey; near	Cape May	New Jersey (NJ)	Unknown	
114837	Dunalk marine terminal; berth 7	Baltimore	Maryland (MD)	Baltimore	
Incident details					
Nr. incident	*Evacuations*	*Injuries/ hospitalized*	*Fatalities*	*Damage*	
102015	N[6]	U[7]	U	N	
102097	N	U	U	N	
102213	N	U	U	N	
114837	N	U	U	N	
Incident details					
Nr. incident	*Waterway closed*	*Road closed*	*Major artery*	*Track closed*	*Medium description*
102015					Unknown

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[6] Assumed ”None”
[7] Assumed ”Unknown”

102097	N	N	N	N	Unknown
102213					Water
114837					Water
Incident details					
Nr. incident	*Additional medium information*	*Release secured*			
102015	Hold on M/V Santa Clara I				
102097	Within the hold of the ship	U			
102213	Atlantic Ocean				
114837	Patapsco river				
Incident details					
Nr. incident	*Description of remedial action*	*Community impact*	*Additional information*		
102015	Hazmat team on scene to remove chemical				
102097	Three environmental response team is cleaning contaminated hold; caller has 3 company personnel en route	N	Will notify department of health; caller discovered incident on 8 Jan 92; due to his not knowing shipment was on vessel		
102213	None				
114837	None				
Material involved					
Nr. incident	*CHRIS Code*	*Amount of material*	*Unit of measure*	*Name of material*	*If reached water*
102015	NCC	0	Unknown amount	Unknown: possibly toxic material	YES
102097	NCC	600	Pounds	Magnesium phosphide	YES
102213	ATO	441	Barrels	Arsenic trioxide	YES
114837	OUN	0	Unknown amount	Unknown oil	YES
Material involved					
Nr. incident	Unit of measure reached water				
102015	None				
102097	None				
102213	Barrels				
114837	Unknown amount				

2.10. Hazmat incidents – statistical data

The m/v SCI accident is one among thousands of hazmat incidents occurring each year in U.S. waters. In order to *further explore and quantify hazmat incidents* (e.g. incidents by year, location, ship or system), the demonstration of the framework is extended to analysis of statistical data from the HMIS and NRC databases. Further, in order to enhance *external validity* of the framework, the demonstration is extended to other systems of the dangerous goods supply chain, including other transport modes.

Terminology: For the purpose of consistency with the terminology used in both U.S. databases, in this and other parts of the volume providing the results from both databases, terms similar with the databases are used. The following terms share similar meanings:

- Maritime transport – vessel or water transport/transportation
- Marine accidents/incidents – vessel or water transport/transportation incidents
- Dangerous goods – hazardous materials (hazmat)

For more information about the key definitions, terms and concepts, including the above terms and concepts, see Chapter 3, Vol. I, and Mullai 2006a, 2006b.

As mentioned in Chapter 1, Vol. II, hazmat incidents in the U.S. are, among other things, reported and recorded in two main federal and industry-based databases, the National Response Center database (NRC, 1990-2004) and the Hazardous Material Information System database (HMIS, 1993-2004). The following presents and discusses some key results from both databases (see Figures 2.17~2.39).

NRC database (1990-2004): The U.S. National Response Center (NRC) records all types of incidents anywhere in the U.S. and its territories. The incident data are reported by individuals and many organisations and agencies, including the U.S. Department of Transportation's Office of Hazardous Materials Safety (OHMS), which maintains the *Hazardous Material Information System (HMIS)* database. The following presents and discusses some key results from the NRC database (1990-2004).

Supply chain incidents: The total number of all types of incidents reported to the NRC database during the period 1990-2004 (15 years, excluding incidents irregularly recorded during the period 1900-1989) is 453,129 incidents. On average, 30,209 incidents are reported each year (Figure 2.19). These incidents span a wide range of systems and activities of the hazmat supply chain. Based on the systems, activities or sources of hazmat releases or involvement, incidents reported to the NRC, which are ranked according to the number of occurrences (as % of the total), are categorised into[8]: *fixed, unknown sheen, vessel, mobile, pipeline, platform, railroad, storage tank, railroad non-release (NR), continuous, aircraft* and *unknown* (Figure 2.18). The category of *plant* incidents, which comprises categories of *fixed* and *continuous* incidents combined, is the largest (48% of all incidents, excluding unknown sheens) category of incidents (Figure 2.20). The category of “fixed” and “continuous” incidents consists of incidents reported at various shore-based systems, activities or processes such as chemical plants, power plants, manufacturing facilities, waste treatment facilities and a wide range of other facilities/systems. The sources of a large number of incidents, approximately 14% of the total number of incidents, were unknown, including both categories of “*unknown*” and “*unknown sheen*” (Figure 2.18). The category of “mobile” incidents consists of incidents reported in road transport. For the category “mobile” incidents as well as other categories of transport incidents, the NRC database contains variables for measuring the properties of means of transport such as trucks, trailers, railcars or wagons, vessels, and aircrafts. Prior to 2000, the category of “storage tank” (or storage) incidents are reported as fixed incidents. According to the USCG (NRC, 2005), since 1998 the NRC collects and records incidents caused by deliberate acts such as terrorist and suicide acts. The database contains no variable for showing and subsequently selecting this category of incidents. The entire population of incidents reported to the NRC (U.S. 1990-2004) largely constitutes the *supply chain incidents*. The number of incidents reported to the NRC (U.S. 1990-2004) has shown increasing trends (Figures 2.17, 2.19 and 2.21).

Transport incidents: Figure 2.20 shows the share of contribution of each main system in the supply chain incidents, excluding “unknown” categories. Transport incidents, including *vessel, mobile or road, railroad, and aircraft* incidents, constitute the second largest (41.7%) category of all incidents (including railroad NR incidents, but excluding unknown incidents) (Figure 2.20). The number of transport incidents reported each year to the NRC (U.S. 1990-2004) has also shown increasing trends (Figure 2.21). The category of railroad incidents includes both categories of *railroad* and *railroad non-release* (or railroad NR) incidents. The label “non-release” suggests that this category is intended to record railroad incidents that have not been directly associated with hazmat releases or involvement. However, a thorough review of the entire NRC database records show that, in many cases, hazmat releases or involvement might have occurred or remained potential (Table 2.3). In addition, many of these incidents have caused suspensions or disruptions of the system and activities. Approximately 35% of all railroad incidents (or 7.2% of all transport incidents) are railroad NR incidents (Figure 2.23). The following (Table 2.3) is a summary description of some typical incidents reported to the NRC database under the category of “railroad NR” incidents.

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[8] As recorded in the NRC database (1990-2004)

Table 2.3: Description of railroad incidents as reported under the category of "railroad non-release" (NR) incidents to the NRC (2005)

Nr.	Category	Description
1	*Type of incidents*	• *Collisions*: Collisions with freight and passenger trains, trucks, trailers, buses, personal vehicles, and other objectives. • *Derailments*: Trains/railcars have derailed underway on tracks and at yards. • *Others types*: This category includes a large number of fatal and injury incidents due to accidental failures, deliberately, negligent or reckless behaviour and actions. Such incidents have, in many cases, caused disruptions or suspension in the system and activities. In some cases, containers and other packages are reported to have been blown by strong winds or fallen off railcars.
2	*Causes*	• The main categories of causes include: human, technical, operational and other causes. In many cases, causes of incidents are unknown or not reported.
3	*Means of railroad transport and packages*	• *Types*: freight railcars or wagons, tank containers or cars, freight containers, trucks and trailers. • *Number*: The number of railcars involved in the incidents ranged from one to as many as 36. In many cases, the number of railcars or packages is unknown or not reported at the time of incident reporting.
4	*Commodities/ hazmat*	• *Types*: a) hazmat such as residues (e.g. Hexamethylenediamine solution), caustic soda, explosives, flammable liquids and other unspecified hazmat; b) unspecified goods. In many cases, types of hazmat are unknown or not reported at the time of incident reporting. • *Amounts*: The amounts of cargo and hazmat involved in the incidents are generally unknown or not reported at the time of incident reporting. As mentioned above, the number of railcars involved in the incidents varied from one to as many as 36.
5	*Hazmat release*	• No release of hazmat or other materials reported. • No release of hazmat or other materials reported at the time of incident reporting. • No release hazmat or other materials, but reported that a potential release existed. • The release of hazmat or other materials is unknown or not reported.

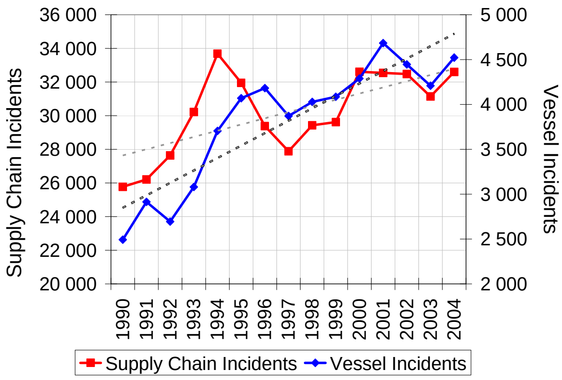


Figure 2.17: Supply chain and vessel incidents (U.S. 1990-2004)

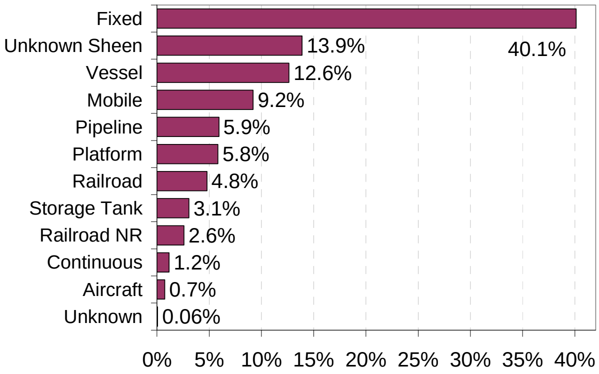


Figure 2.18: Ranking of supply chain incidents (U.S. 1990-2004)

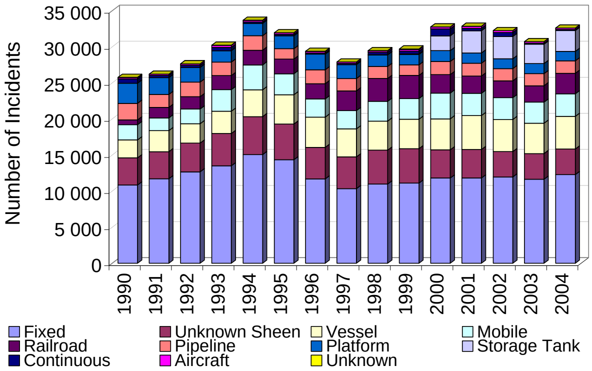


Figure 2.19: Supply chain incidents by year and system (U.S. 1990-2004)

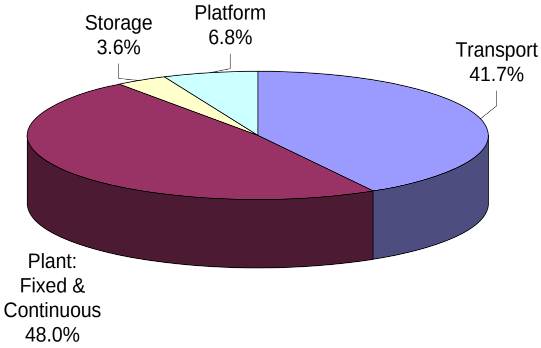


Figure 2.20: Supply chain incidents by system, excluding unknown incidents (U.S.1990-2004)

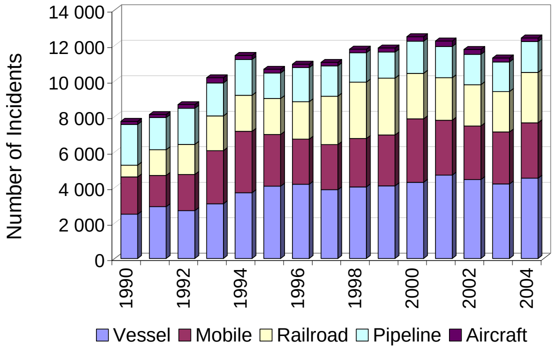


Figure 2.21: Transport incidents by year and transport mode, including railroad NR incidents (U.S. 1990-2003)

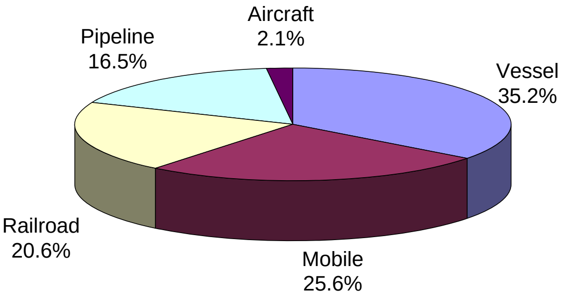
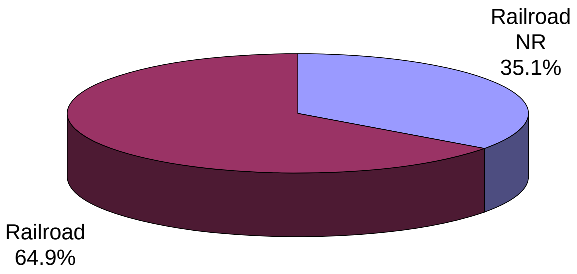


Figure 2.22: Transport incidents by transport mode, including railroad NR incidents (U.S. 1990-2004)



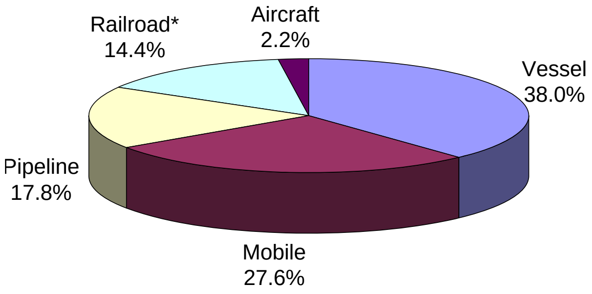


Figure 2.23: Railroad transport incidents (U.S. 1990-2004)

Figure 2.24: Transport incidents by transport mode, excluding railroad NR incidents (U.S. 1990-2004)

Vessel incidents: The total number of vessel incidents reported to the NRC during the period 1990-2004 is 57,274. On average, 3818 vessel incidents (or 12.6% of all types of incidents) have been reported each year. The vessel incidents are a large contributor to the supply chain and transport incidents. This category is ranked (%) third or second if the "unknown sheen" and "unknown" categories are excluded, in the list of incidents reported to the NRC (Figure 2.18). Vessel incidents constitute 35.2% of the total number of transport incidents, including railroad NR incidents (Figure 2.22). During the period 1990-2004, all types of incidents combined, and vessel incidents, have shown increasing trends, which have respectively increased by 26.5% and 81.3% (Figure 2.17). During this period, the number of vessel incidents per year has steadily increased – from approximately 2500 (in 1990) to 4500 incidents in 2004. Compared to 1990, the number of vessel incidents reported per year to the NRC database will double in the near future, if it continues at the same rate of increase.

Vessel incidents by location: Approximately 8.7% (or 332 of 3818 incidents) of the total number of vessel incidents reported each year to the NRC (1990-2004) have been reported in the five states shown in Figure 2.25, of which 38.5% (or 128 of 332) in the state of New Jersey (Figure 2.25). The m/v SCI accident, which in various ways involved the mentioned states, was one of many vessel incidents occurring each year in the territorial waters of these states. As described in Step 1 "System definition", Chapter 2, Vol. II, this geographical area is characterised by a high level of industrial and commercial activities, including water transport of hazmat.

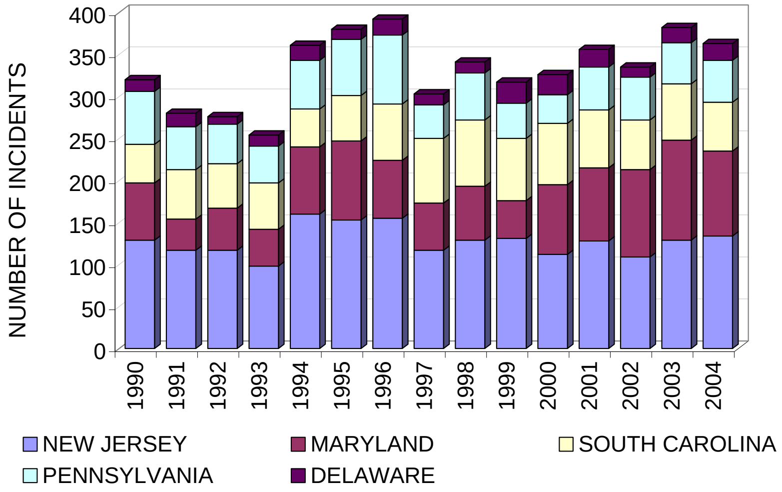


Figure 2.25: Vessel incidents reported in the states of New Jersey, Maryland, South Carolina, Pennsylvania and Delaware (U.S. 1990-2003)

Ships carrying PDG: Many different types of PDG are carried at various quantities in different types of ships. For more information about types of ships and PDG carried onboard these ships, see Chapter 3, Vol. I, and Mullai, 2006a. The NRC database contains no variable(s) for separating PDG from bulk hazmat and other types of vessel incidents. The results show that approximately 38% of all types of ships/facilities involved in vessel incidents (1990-2004) were cargo/military ships (Figure 2.26), including ships carrying PDG, such as dry cargo ships (6.9%), container ships (6.5%), military ships (20.5%) and barges (46.5%) (Figure 2.27). The m/v SCI was a dry cargo (breakbulk) ship type. Passenger ships (e.g. cruise ships), pleasure boats and passenger/cargo ships (e.g. ferry ships) and other types of ships may also carry PDG. PDG in the form passengers' luggage or belongings are carried onboard passenger ships (18.7%). In many cases, ships carrying PDG have been involved in incidents such as foundering, grounding and fire/explosion. The data suggest that a large portion of ships/objects involved in vessel incidents, such as military ships, barges, fishing boats, service ships and offshore facilities may be owned by shipowners of the U.S. nationality and/or flying the U.S. flag.

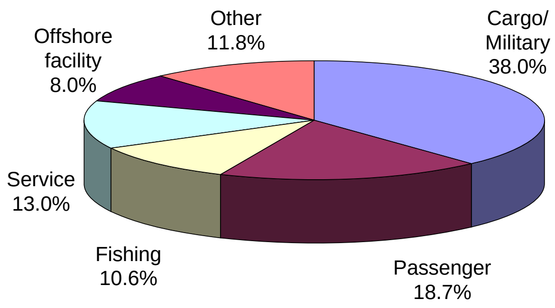


Figure 2.26: Types of ships/facilities involved in incidents (U.S. 1990-2004)

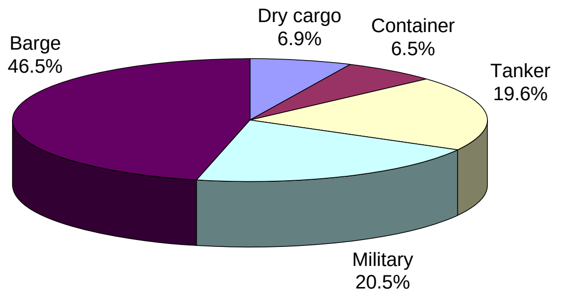


Figure 2.27: Types of cargo/military ships involved in incidents (U.S. 1990-2004)

HMIS database (1993-2004): This is a very specialised database that records incidents in transport modes (air, road, rail and water – excluding pipeline) involving packaged dangerous goods (PDG)/hazmat, including bulk (e.g. road and rail tank containers and bulk freight containers) and non-bulk (e.g. ISO freight containers and other cargo transport units). From the water transport system point of view, by definition, types of packages and cargo transport units involved in incidents reported to the HMIS database are PDG. The database contains many specific variables for PDG transport and incidents that may not be found elsewhere, including the NRC databases and many other databases reviewed. According to the HMIS database (U.S. DOT, 2005a), vessel incidents involving bulk hazmat are reported to the NRC database. The above results and the review of many incident records show that the scope of the NRC database is wider than HMIS database. The NRC database is not confined to bulk hazmat incidents. The *m/v SCI accident*, i.e. a vessel accident involving PDG, was reported to the NRC. The results also show that many different types of ships carrying PDG, such as container ships, freight ships, barges, military ships and "other" type of ships have been involved in incidents including foundering, explosion and fire. The following presents and discusses some key results from the HMIS database.

Transport incidents – vessel/water transport incidents: During the period 1993-2004, a total number of 185,612 incidents have been reported in all transport modes, excluding pipeline. The numbers of air and road transport incidents reported to the HMIS database are larger than those reported to the NRC database. However, both databases show quite similar trends of increase in the number of incidents (compare Figures 1.17 and 1.28). According to the HMIS database records, the number of incidents increased by 14.8% during the period 1993-2004. The combined records of the HMIS database and earlier U.S. DOT (2005a) records (from 1983) show that since 1983 the number of transport incidents has increased significantly (ca. 2.5 fold), in particular after 1992 (Figure 2.32). Since 2001, however, excluding water and pipeline transport incidents, the number of transport incidents reported per year has declined from 17,979 to 14,742 (Figure 2.28). Road transport is the largest contributor by far (approx. 87% of all incidents) to transport incidents. Rail and air transport account respectively for 6.5% and 6.6% of the total number of incidents (Figure 2.30). The majority of transport incidents (76%) have been reported during cargo handling operations, during unloading (59.2%) and loading (16.8%) respectively (Figure 2.31). For the reasons mentioned earlier, the number of vessel/water transport incidents reported to the HMIS database is significantly smaller – approximately 10 incidents per year or 0.1% of all transport incidents (Figure 2.29) – compared to other modes (13,580 incidents per year) and vessel incidents (3818 incidents per year) reported to the NRC database (Figure 2.22). The means of transport and cargo transport units (CTU) that have been involved in water transport incidents reported to the HMIS database include freight ships, barges, trailers, trucks, vans, freight containers, tank and portable tank containers and other unspecified vehicle and CTU types.

Figures 2.34 and 2.35 show the patterns of transport incidents, excluding pipeline incidents, by one and four-hour intervals respectively. The number of incidents has increased during the early hours (early in the morning) of the day, reached the peak (the maximum value of ca. 13,600 incidents, which is ca. three fold higher than the minimum value of ca. 4,200 incidents reported at the interval between 22.00-23.00 hrs) at around 08.00-09.00 hrs, than declined afterwards. Two possible explanations could be: a) from my own 12 years seagoing experience, it is difficult to stay focused and alerted and to perform properly the duty during the early hours (between ca. 02.00-06.00 hrs), in particular when one is very tired after a long and hard working day and without a good sleep; b) the early hours (around 08.00 hrs) are rush-hours characterised by higher levels of movements, traffic or activities than other intervals of the day. Other traffic or movements may interfere and influence freight traffic. The U.S. response teams should plan and allocate the right amounts of resources for the right time, i.e. according to the intensity of incidents.

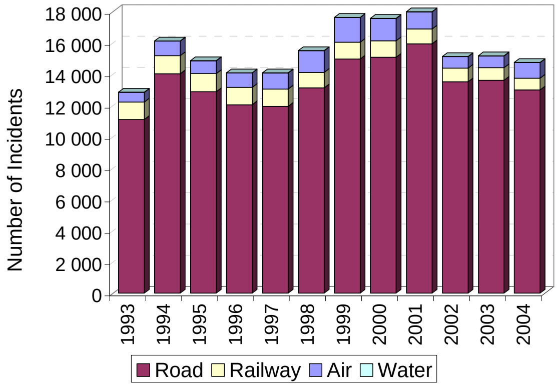


Figure 2.28: Transport incidents by mode and year, excluding pipeline (U.S. 1993-2004)

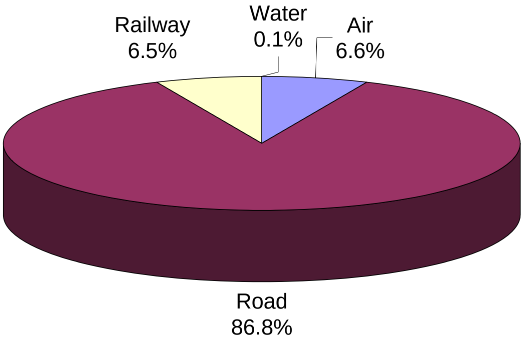


Figure 2.29: Transport incidents by mode (U.S. 1993-2004)

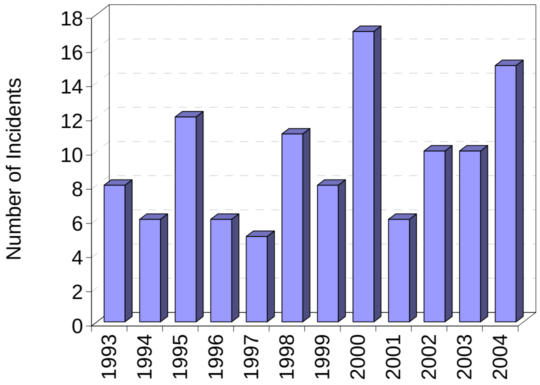


Figure 2.30: Vessel/water transport incidents (1993-2004)

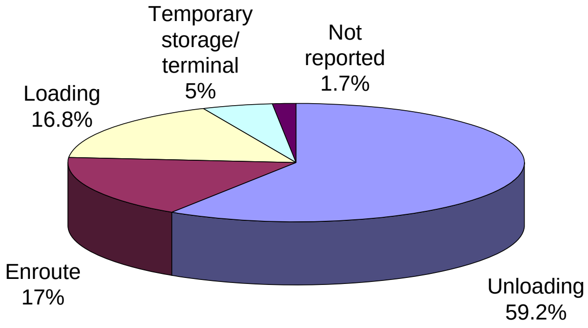


Figure 2.31: Transport incidents by phase (U.S. 1993-2004)

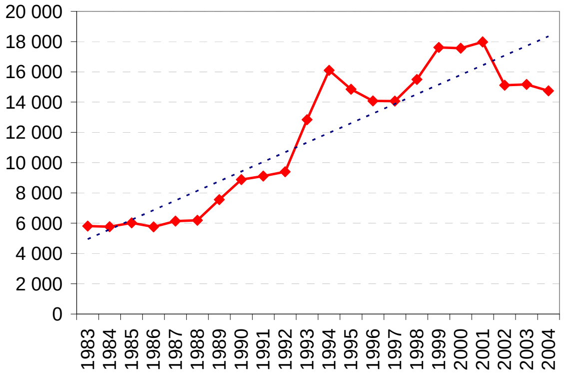


Figure 2.32: Transport incidents by year, excluding pipeline (U.S. 1983-2004)

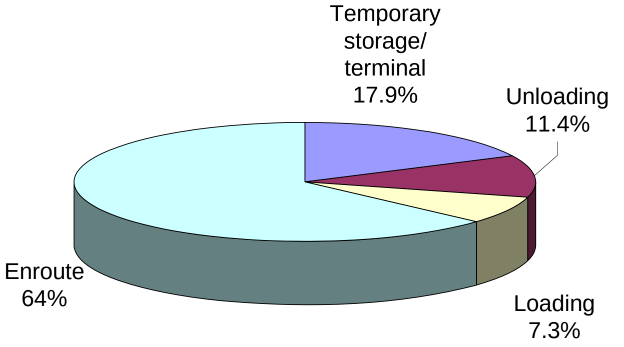


Figure 2.33: Vessel/ water transport incidents by phase (U.S. 1993-2004)

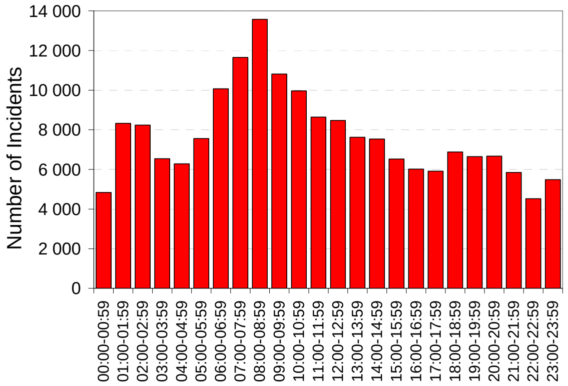


Figure 2.34: Transport incidents by 1-hour interval, excluding pipeline (U.S. 1993-2004)

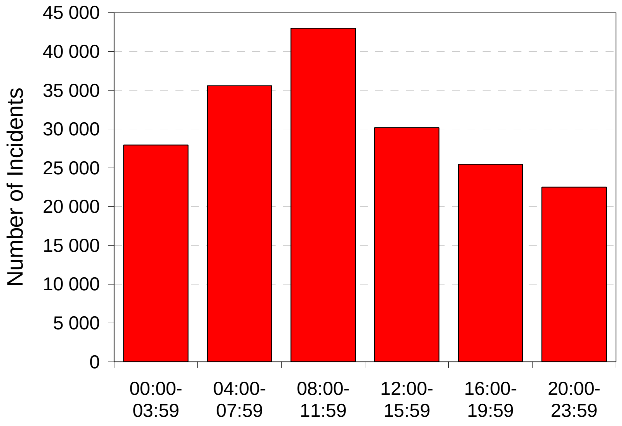


Figure 2.35: Transport incidents by 4-hour interval, excluding pipeline (U.S. 1993-2004)

NRC (1990-2004) and HMIS (1993-2004) databases records combined: As shown above, the databases are diverse, but at the same time they share overlapping areas. After some adjustments and estimations, the results of incident data records from both databases are integrated. Only the largest number of incidents (i.e. the worst-case scenarios) from one database is taken into consideration for respective activities or systems. For example, the number of vessel incidents recorded in the NRC database is taken into consideration because the number of vessel incidents reported to the NRC is larger than vessel incidents reported to the HMIS database. In order to avoid any overlapping and overestimation, vessel incidents reported to the HMIS database are not counted in this case. The following presents and discusses some key results from both databases combined. Given the diversity of databases, these results differ, to some extent, from the results of individual databases.

Supply chain and transport incidents: The total number of supply chain incidents reported in the U.S. (i.e. recorded in both databases) during the period 1990-2004 is 607,071. On the average, 40,471 incidents are reported per year, which is approximately one incident per 6500-7000 inhabitants per year. During this period, the number of incidents per year has steadily increased from 31,795 (1990) to 43,254

(2004), which is an increase of approximately 36% (Figure 2.33). Compared to incidents in other systems of the supply chain, transport incidents have increased the most – approximately 68% (Figure 2.35). Since 2001, however, there has been a slight decline in the total number of incidents. Combined results of two databases show that the transport system is the largest contributor (52.1%) to supply chain incidents (Figure 2.34). After road transport (58.4%), the water transport mode is the second largest contributor (18%) to the total number of transport incidents (Figure 2.36). Vessel incidents have shown the highest increase (approx. 81%) in transport incidents (U.S. 1990-2004).

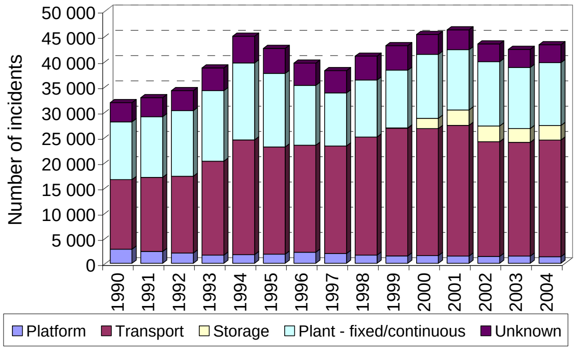


Figure 2.36: Supply chain incidents by year and system (U.S. 1990-2004)

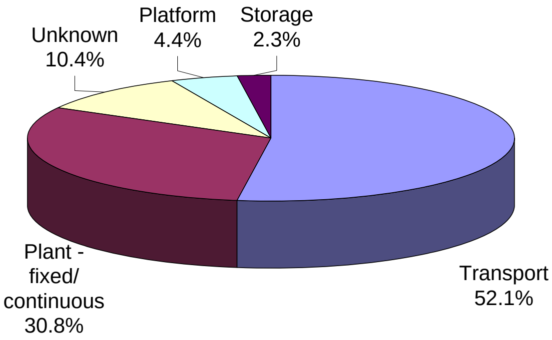


Figure 2.37: Supply chain incidents by system (U.S. 1990-2004)

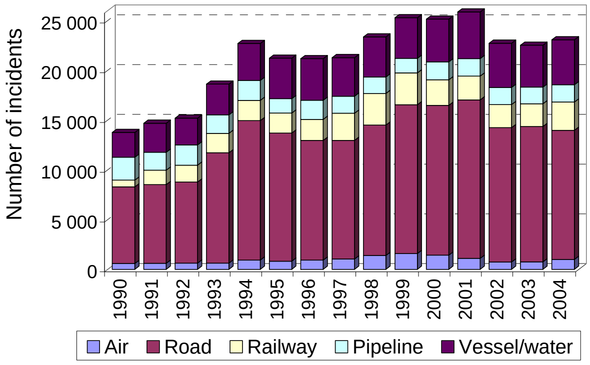


Figure 2.38: Transport incidents by year and mode (U.S. 1990-2004)

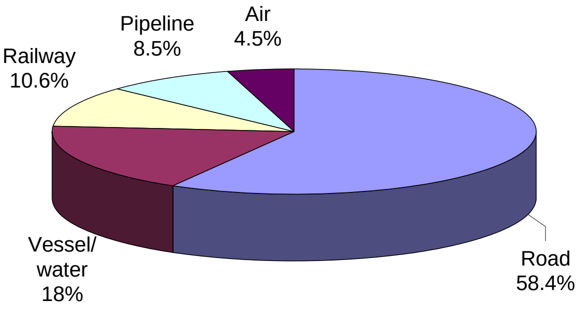


Figure 2.39: Transport incidents by mode (U.S. 1990-2004)

Some plausible explanations for the large numbers of transport and vessel incidents include:

- The transport system is characterised by many elements in interdependent, complex and dynamic relationships. Large amounts of many different types of hazmat are transported in the U.S. and other parts of the world.
- Because of the mobility factor, the transport system becomes vulnerable to many hazards. It is exposed to a wider range of hazards than many other systems. Certain transport hazards, such as transport incidents (e.g. collision), static and dynamic forces (e.g. acceleration/ deceleration), and weather or environmental hazards (e.g. sea hazards), are very specific for the transport system.

- The transport system elements, including hazmat, packages and means of transport, are exposed to excessive distribution or transport hazards for a long duration. In addition, the maritime transport system is exposed to higher values of dynamic and static forces for a longer duration than any other mode of transport. These values may often exceed the system design and construction conditions. It is no surprise that 64% of vessel incidents were reported during the voyage or en route phase of the transport-related activities (see Figure 2.33).
- Failures or deficiencies are generated and propagated across transport systems and activities. Many deficiencies may go “undetected” or unreported and subsequently they are not eliminated or mitigated. As the transport systems are linked, deficiencies may be inherited or accumulated from one system, subsystem or phase to another. Figure 2.31 surprisingly shows that the majority (59.2%) of transport incidents are reported during the unloading phase, which is overrepresented compared to the loading (16.8%) and enroute (17%) phases.
- The quality of safety systems in place and application and enforcement of the regulatory system governing hazmat-related activities, including the incident reporting systems and procedures, may vary among systems.

3. Step 2 – Hazard Identification

Questions: "What has gone or can go wrong?" and “How often, many/much?”

Tasks: Define, explore and quantify top events. Explore and quantify transport hazards, cause and contributing factors, and the sequence of events that have led or can lead to packages’ failures and subsequently to loss of containment and/or involvement of dangerous goods (see the **highlighted areas** in Figure 3.1).

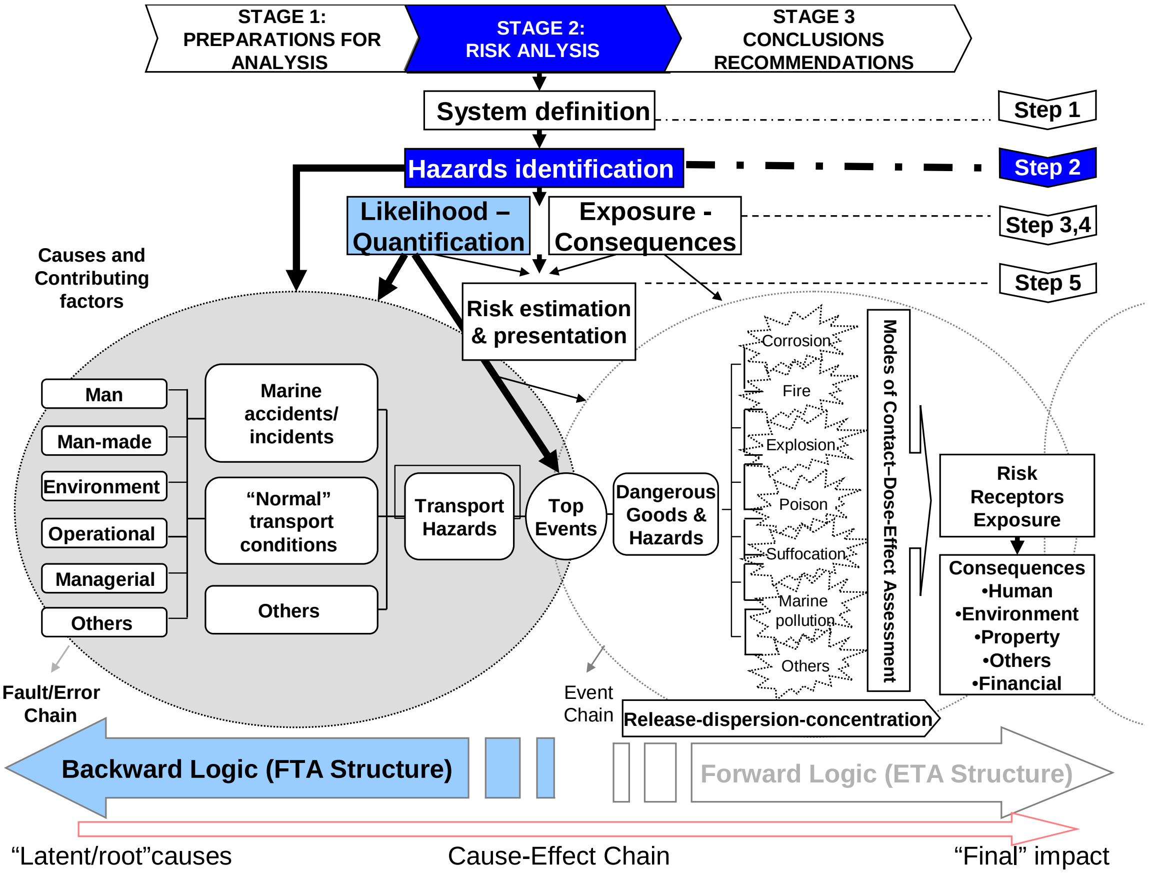


Figure 3.1: Stage 2 - Risk analysis; Step 2 – Hazard identification (continued from Figure 1.2)

The analysis process begins with hazards identification, which involves identification or exploration of transport hazards, causes and contributing factors of the m/v SCI accident. The hazard identification process is accomplished by employing the "*backward logic*" analysis asking: “*Why and how did this accident happen*?” or “*What were the causes and contributing factors of the m/v SCI accident*?” The purpose of this line of procedures is to identify and model those events and conditions that solely or in combinations led to the m/v SCI accident, together with their logical relationships. Because of the large number of complex events, prior to the analysis it is important to identify a set of events (i.e. the top events) from which the analysis process begins.

The review and analysis of many accident case histories (e.g. HCB, 1986-2003; U.S. DOT, 2005a; NRC, 2005) have shown that each marine incident is, to a certain extent, unique. The m/v SCI accident case is no exception. The analysis is based on the available data describing the course of events of this particular accident. The accident investigation and the search and recovery operations were primarily focused on the packages containing dangerous goods and the piece of machinery.

3.1. Define top events

Tasks: Define, explore and quantify top events (see the **highlighted areas** in Figure 3.2).

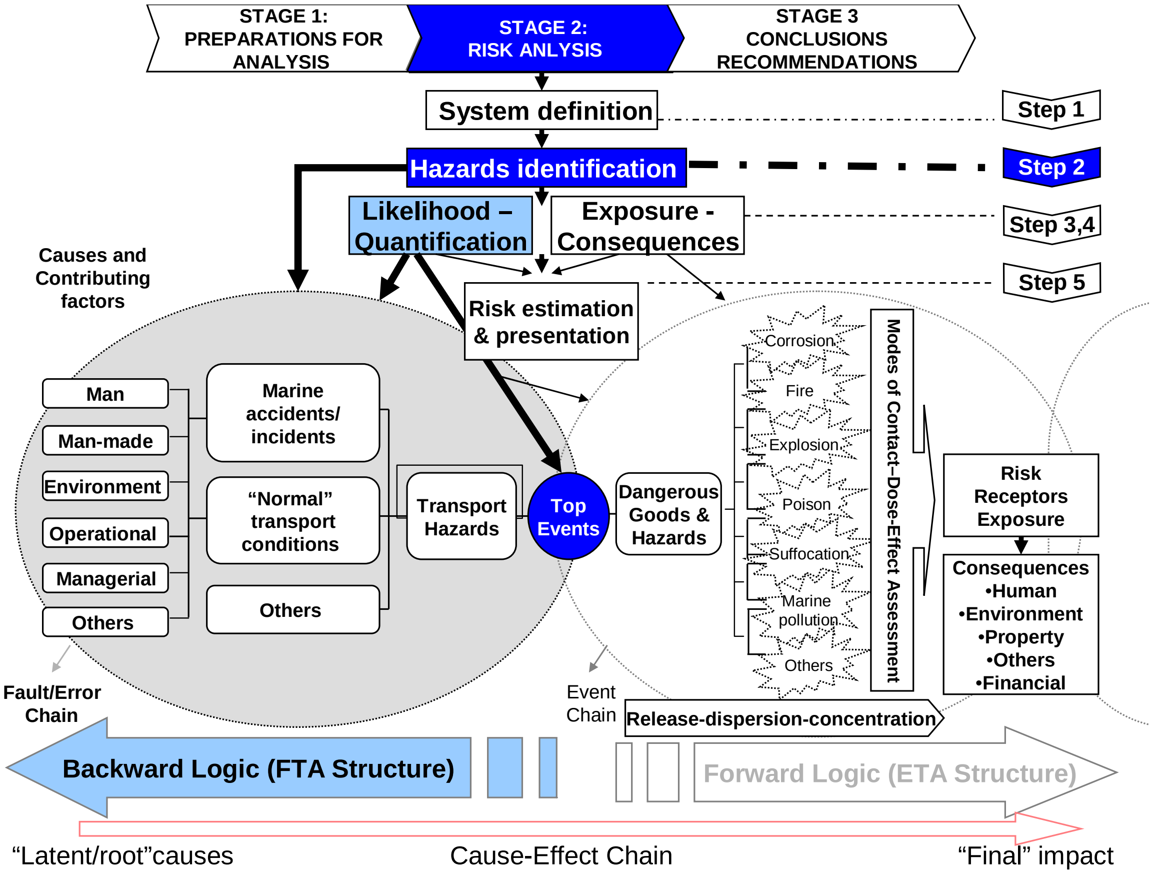


Figure 3.2: Stage 2 – Risk Analysis; Step 2 – Hazard identification, top events (continued from Figure 1.2)

For the purpose of the risk analysis of the m/v SCI accident case history, the breaches of packages leading to the release of dangerous goods are identified as the top events (Figure 3.3). This includes ruptures, punctures, pierces and other forms of failures experienced by packages. The release and involvement of dangerous goods led to the exposure of the risk receptors, including the crew of the m/v SCI, the port and local community and other people, the marine environment and properties.

Figure 3.3: Top events: breach-release events

The hazard identification focuses on the *backward logic analysis of the left side of the top events* (see the **highlighted area** in Figure 3.3), which is the analysis of causes and contributing factors of the breach of packages. Based on the data available, the failure modes of packages in respective locations aboard the m/v SCI will be explored in some detail. The following section explores the course of "breach" events.

On-deck-stowed cargo - no.2 hatch

Arsenic trioxide containers lost overboard: During the storm, due to heavy rolling and green waters and subsequently the failure of the cargo securing system, the ship lost overboard 21 of 25 containers and a piece of machinery stowed on deck. Four of six on-deck-stowed arsenic trioxide containers were lost overboard. By means of Remotely Operated Vehicles (ROVs) all four arsenic trioxide containers were located. All four containers were found broken open, and many drums were scattered on the sea floor. Due to damage sustained prior to the loss overboard and the great weight of the drums, they could have broken through the sides and ends of the container at various points of the ship trackline. Container damage prior to the loss is supported by the fact that of a total number of 648 drums in on-deck-stowed containers, 234 drums were recovered inside the two remaining containers and on deck. One of the arsenic trioxide containers found on the sea floor was badly mangled (disfigured, destroyed, crushed, torn), with one side entirely missing. The missing side was found under a large pile of drums. The container contained only two drums marked as arsenic trioxide. Both drums appeared crushed.

Figure 3.4: An impacted drum found on the sea floor by ROV (IMO, 1992)

According to the initial search reports, drums that landed on the sea floor appeared impacted, but still with their integrity intact (probably like the drum seen in Figure 3.4). After the recovery of drums, both the USCG and USEPA agreed to consider the arsenic trioxide as a hazardous product as opposed to hazardous waste. Attempts were made to ship the chemical back to the manufacturer. But this was unsuccessful as the arsenic trioxide was contaminated with water and, therefore, was considered as hazardous waste. Water contamination indicates that the integrity of the drum had failed. During the recovery, drums were placed into overpack drums by using the RVO with mechanical arms. Then, the overpack drums were filled with grout (sand) material. The exact number of damaged drums and the amount of arsenic trioxide spilt at sea were not specified. The estimation indicated that a total amount of 200 kg of arsenic trioxide was lost at sea. Contrary to the initial reports and hydraulic pressure tests, the above facts suggest that many drums lost overboard were breached.

Arsenic trioxide containers damaged: The fact that the main ship's deck and several hatches were covered with arsenic trioxide indicates that many drums (of 234 drums recovered on deck) broke through their containers, were damaged and spilt their contents. One damaged container was hanging over the side when the ship arrived at Baltimore Bay.

Under-deck-stowed cargo - no. 1 and 2 holds

Palletised magnesium phosphide drums: In the upper tweendeck of the no.1 hold, two of five pallets banded with two magnesium phosphide drums each (each containing 179.6 kg) had shifted, turned over and broken loose. All four drums had broken open, spilling their contents on the ship's deck.

Arsenic trioxide containers: In Port Charleston, the cargo inspection on some of 19 under-deck-stowed arsenic trioxide containers (no. 2 hold) showed that pallets had tipped over. Blocking and bracing were broken, pallets had shifted, but no breach of drums or spill of arsenic trioxide contents was reported. Given the situation of under-deck-stowed containers and the greater forces acting on deck-stowed cargo, arsenic drums in containers stowed on deck could have been upset in a similar way.

Other packages in other holds: Many packages including those with dangerous goods were also broken loose and damaged in other holds. Types and numbers of packages and the nature of cargo/dangerous goods involved were not reported.

Summary

The accounts of events showed that the breach occurred at different levels of packaging (drums-pallets-containers) in different cargo spaces (on deck and under deck). The breach of drums, i.e. the first level of packaging, was the necessary and sufficient condition for arsenic trioxide, magnesium phosphide, as well as other unreported dangerous goods, to have been released. Subsequently, the breach of drums was the direct cause of the dangerous goods release. For every breached drum, the "breach" events preceded the "release" events. However, accident case histories (HCB, 1986-2003) have shown that many dangerous goods accidents are not necessarily associated with the breach of package and/or the release of dangerous goods. The latter category falls in the "other" category of top events.

3.1.1. Top events - statistical data

Only one category of top events (i.e. *breach/damage* of packages) has been explored based on the analysis of the m/v SCI accident case history. The quantification of top events by means of the analysis of a single case was not possible. Therefore, in order to *explore and quantify other categories of top events*, the demonstration of the framework is extended to the analysis of statistical data from the HMIS database (U.S. 1993-2004). The statistical data analysis also explores and quantifies other related elements, such as package types and materials involved in incidents and packaging components and areas failed or damaged. The following section presents and discusses results from the HMIS database (U.S. 1993-2004).

3.1.1.1. Package types and materials

HMIS database (1993-2004): Hazmat/dangerous goods are carried in a wide range of different package types and sizes. For more information about definitions and concepts concerning packaging systems, see Chapter 3, Vol. I, and Mullai 2006a. The top 13 package types shown in Figure 3.5 constituted approximately 75% of all package types reported involved in transport incidents (U.S. 1993-2004). On top of the list (as % of all types of packages involved in transport incidents) are *fibre box* (22.0%), *metal drum* (12.1%), *plastic bottles* (8.0%)/*jugs* (6.5%), and *plastic containers* (4.2%). Container types and materials are not reported in 3.1% of all incidents. Approximately 77% of the top 13 package types involved were box, drum, and bottle/jug (Figure 3.6). Plastic/fibre package material comprised 60% of the top 13 package types involved in incidents (Figure 3.7). Package types and materials involved in the m/v SCI accident included metal and fibreglass-reinforced plastic (FRP) containers and metal drums. In the U.S. as well as many other countries, large quantities and shipments of hazmat are carried in these package types/materials. However, the large number of incidents involving these package types and materials may be attributed to other factors, including design and construction properties. *In the case of m/v SCI accident*[9], the analysis showed that the FRP container inherited design and construction weakness and inadequate in-service structural strength with diminished performance. The FRP container failed disastrously.

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[9] Qualitative (i.e. m/v SCI accident case history and other cases) and quantitative (i.e. statistical data from the NRC and HMIS databases) data analyses support each other.

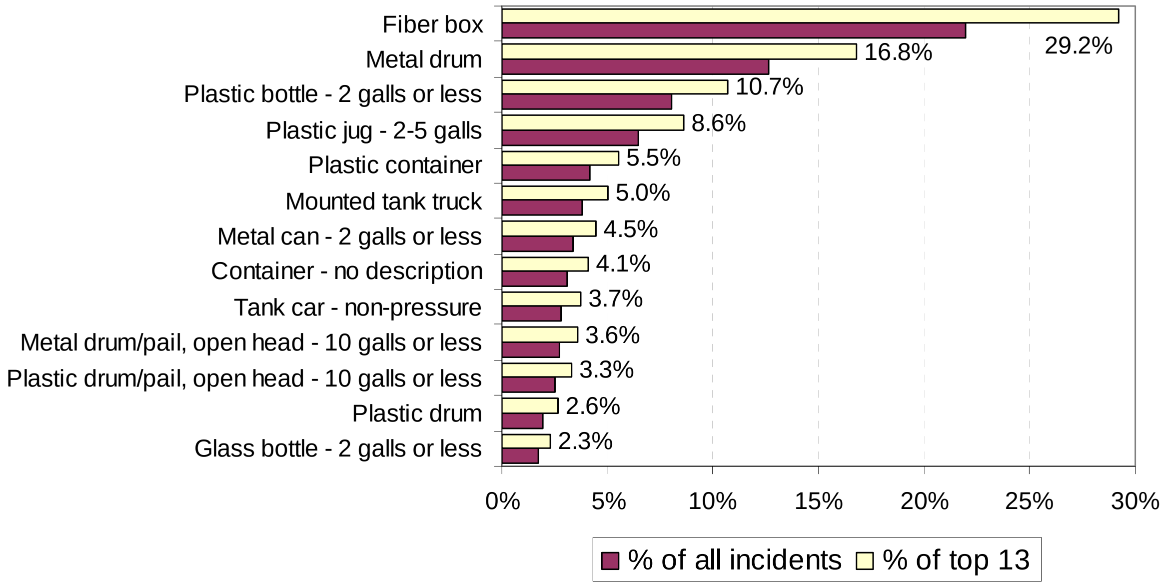
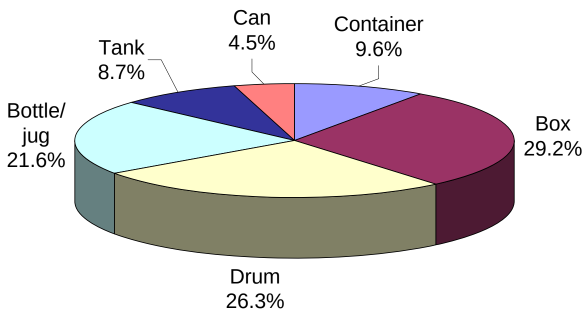


Figure 3.5: Top 13 package types involved in transport incidents (U.S. 1993-2004)



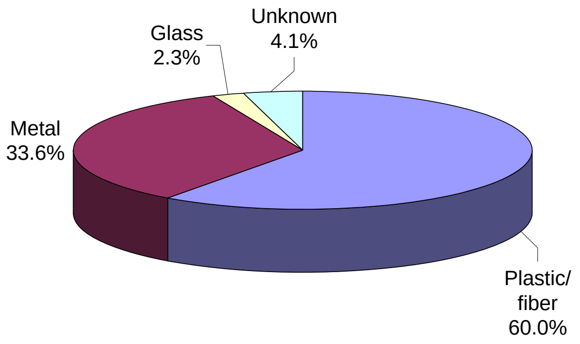


Figure 3.6: Package types of the top 13 package types involved in transport incidents (U.S. 1993-2004)

Figure 3.7: Package materials of the top 13 package types involved in transport incidents (U.S. 1993-2004)

3.1.1.2. Categories of top events

HMIS database (U.S. 1993-2004): The following categories of damage/failures and deviations from the intended functions of packaging system or hazmat transport have been identified as the top events of hazmat releases/involvements in transport (U.S. 1993-2004):

- Breach (damage/failures) of one or combinations of package elements, such as bursting, breaking, smashing, cracking, splitting, collapsing, fracturing, puncturing, rupturing, depressing, denting, cutting, tearing, holes etc. (see Figure 3.8).
- Failures other than the breach of package, such as those due to improper/wrong operation, defects and weaknesses in the package system design and construction, for example:
  - Overflowed, overfilled, overloaded
  - Package not properly secured

  - Devices/equipment (cap/valve) left loose, not tight
  - Devices/equipment (cap/valve) left open, not capped
  - Missing devices/equipment
  - Defective devices/equipment
- Other – other than the above:
  - Contamination - odour
  - Frozen hazmat
  - Wet: in contact with water, other liquids, moisture
  - Fire/explosion – not as the result of the above
  - Radiation
  - Moulding
- Deliberate or intentional releases


Figure 3.8: Drum ruptured by forklift (IMO, 1992)

Some of the above events such as contaminations and contacts with water and other liquids have not necessarily involved any hazmat release. The data indicates that the majority of hazmat releases are attributed to the first two categories, i.e. breach (damage/failures) and other failures. In the m/v SCI accident case, the releases of dangerous goods were as the result of the first category of top events.

3.1.1.3. Damage/failures of packaging components

HMIS database (U.S. 1993-2004): Packaging consists of receptacles and other components or materials for the receptacle to perform its containment functions (IMDG, 2002). Receptacles are containment vessels for receiving and holding substances or articles, including any means of closing (IMDG, 2002). For more information about definitions and concepts concerning packaging systems, see Chapter 3, Vol. I, and Mullai, 2006.

The top 3 weakest and/or the most vulnerable packaging components have been reported: *packaging material* (41.3%), *closure* (22.3%) and *fitting or valve* (7.9%) (Figure 3.9), which combined accounted for approximately 71% of all reported damage/failures (286,661). The packaging materials (0.423) and closure devices (0.229) have shown the highest probability of failures. The “other” category includes failures in a wide range of other packaging components, such as caps, vents, manifolds, nozzles, gaskets, gauges, connections and seals. On average, every transport incident sequence (in total 279,922) has been associated with 1.024 failures in packaging components. This means that in many incident sequences, two or more packaging components have simultaneously failed. The packaging material constitutes the largest part of packaging and, subsequently, the most vulnerable part of packaging. Some explanations for the large number of failures in packaging components, such as package material, fittings, valves and closures, include: a) inherent weaknesses in packaging material, design and construction (e.g. inherent properties of plastic/fibre materials); b) inherent properties and large amounts of hazmat transported (e.g. gases, liquefied gases, liquids, corrosive and oxidizing substances); c) exposure to transport hazards (e.g. mechanical forces); d) operational or handling errors (e.g. overflow during loading and unloading); and e) defective devices or equipment (e.g. valve and closure).

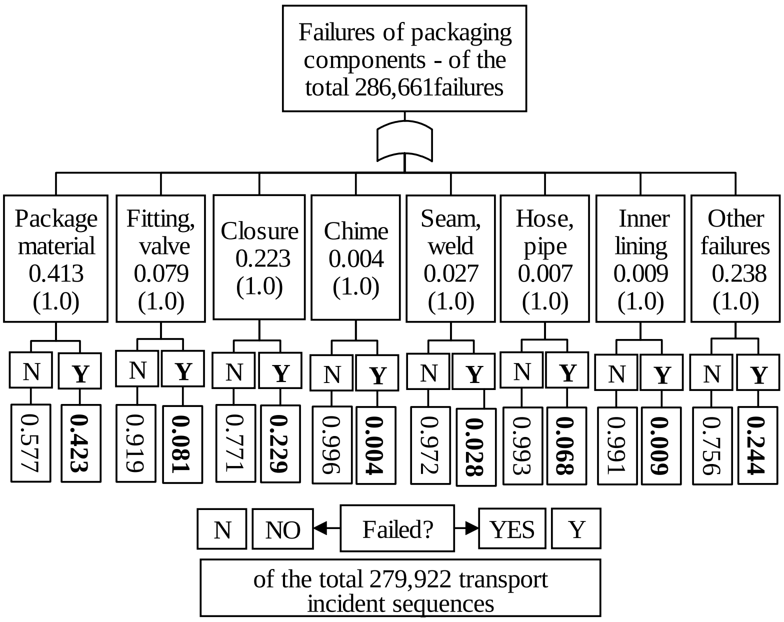


Figure 3.9: Fault tree of packaging components damage/failures (U.S. 1993-2004)

3.1.1.4. Damage/failure areas

HMIS database (U.S. 1993-2004): A package consists of a number of areas (Figure 3.10). The weakest and/or the most vulnerable areas (e.g. containers and other CTUs) to transport hazards have been reported: *top* (36.5%), *bottom* (24.4%) and *sides* (left and right) (10.5%) (Figure 3.10). The combined damage/failures in top and bottom areas constituted approx. 60% of all reported damage/failures (296,863). Both these two areas have shown higher probabilities of being damaged or failing than other areas. In many cases (24%), packages have been damaged or failed in between the areas shown in Figure 3.10 and other areas. Packages have often been completely destroyed. They have experienced damage/failures in one or combinations of the areas shown in Figure 3.10. On the average, every sequence of transport incidents (in total 279,922) has been associated with 1.061 damage/failures in the areas mentioned. The end-forward and rear areas are not relevant for many types of packages. The most frequent pairs of package areas that have simultaneously been damaged or failed are *top-bottom, top-side left, top-side right, bottom-side left and bottom-side right*. Some explanations for the large number of damage/failures, in particular in top and bottom areas, include a) exposure to transport hazards such as compression, racking and other mechanical forces, b) operational/handling errors (e.g. stacking, loading and unloading), c) contact with water, moisture and other liquids, and d) inherent weaknesses in packaging design and construction in these areas.

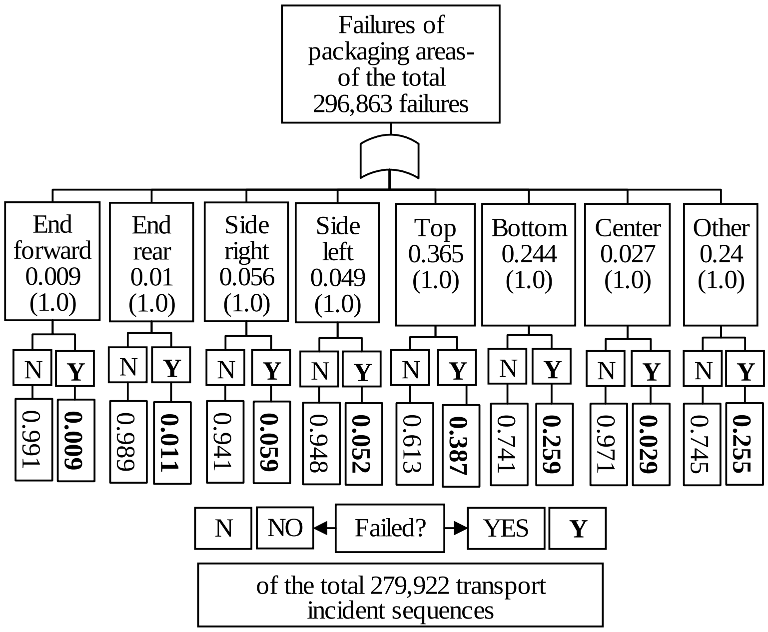


Figure 3.10: Fault tree of packaging damage/failure areas (U.S. 1993-2004)

3.2. Maritime transport hazards

Task: Explore and quantify transport hazards (see the **highlighted areas** in Figure 3.11).

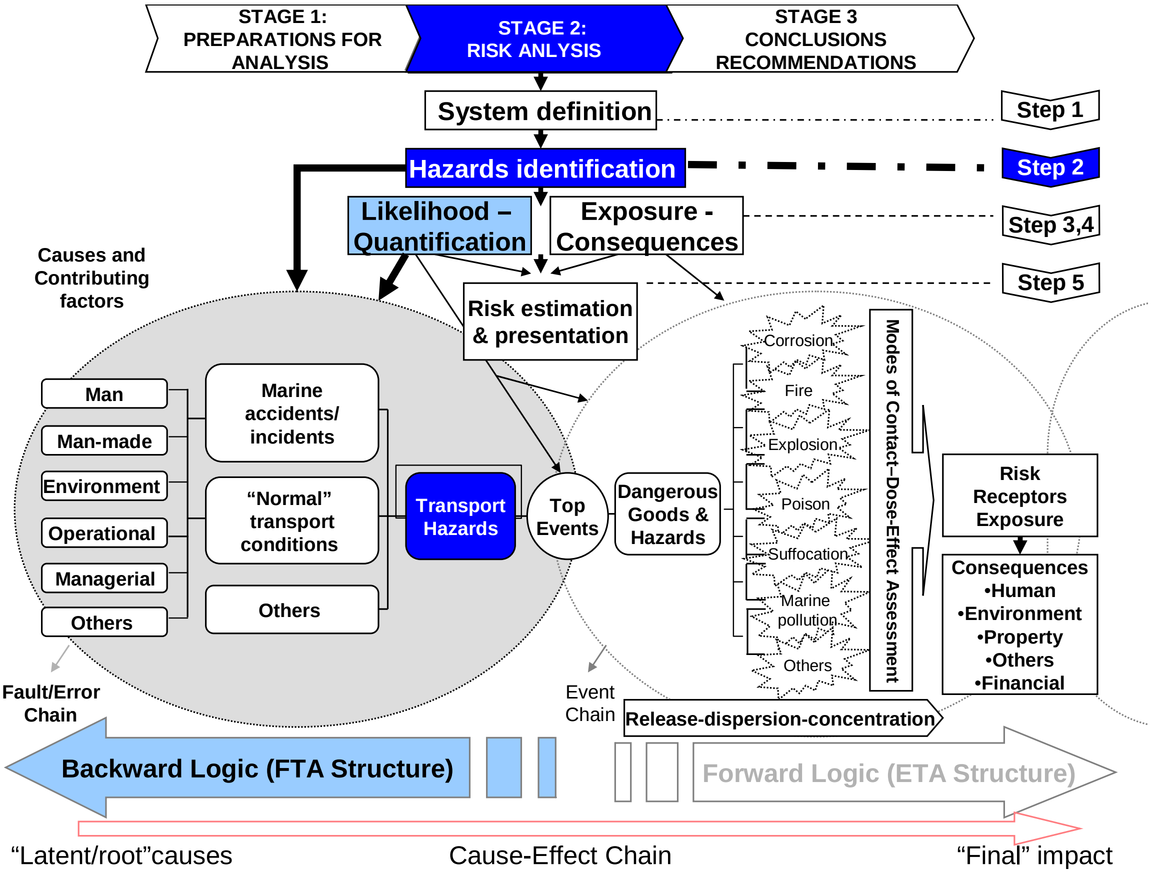


Figure 3.11: Stage 2 – Risk Analysis; Step 2 – Hazard identification, distribution/ transport hazards (continued from Figure 1.2)

According to the accident investigation report (U.S. DOT, 1992), many drums lost at sea and spread on the ship’s deck were breached. The following are two relevant questions:

How did the breach of drums happen? What were the direct causes of the breach?

The m/v SCI accident investigation and search and recovery operation data showed that the direct causes of the breach of drums was the exposure to maritime transport hazards (Figure 3.12). This step explores the effects of these hazards (Figure 3.13).

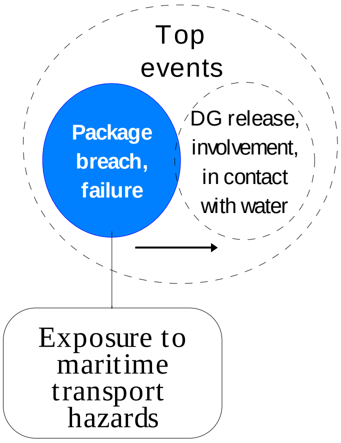


Figure 3.12: Exposure to transport hazards led to top events – breach of drums

In heavy weather conditions, the entire system including the ship itself, the cargo/packagings system and the cargo securing system was exposed to hazards. Although the precise timing, the place, the degree and sequences of damage were unclear, packages were exposed to a combination of the following hazards:

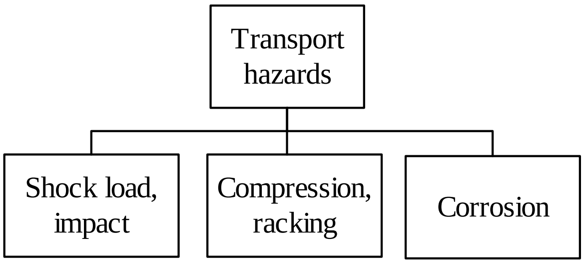


Figure 3.13: Transport hazards

The specific hazards explored in the m/v SCI accident case can be raised to a higher level of abstraction as shown in Figure 3.14. Two categories of transport hazards shown Figure 3.14 (i.e. *mechanical and electro-chemical*) are consistent with those shown in Figure 5.7 in Chapter 5, Vol. I. In addition, this is an example demonstrating how the constructs of the framework and their values are explored through empirical data.

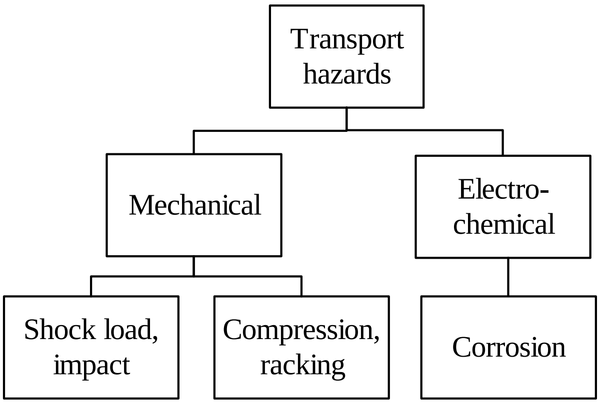


Figure 3.14: Specific transport hazards raised to a higher level of abstraction

Table 3.1 explores in detail the effects of maritime transport hazards.

Table 3.1: Transport hazards

Location of drums	**Categories of hazards**	**Description of probable scenarios**
Under deck	• *Shock load, impact on*: - Other drums, containers and other packages - Ship structure • *Compression, racking*: - Other drums and container sides	Due to forces exerted in ship's heavy motions and failure of the cargo securing system: *No.1 hold - pallets* with magnesium phosphide drums experienced: • Pallets shifted - Drums impacted and compressed against each other, other packages/cargo and ship's structure • Two pallets with two drums each turned over - Four drums impacted on the steel floor and broke loose - Loose drums rolled over the deck impacting other packages/ cargo and ship structure • Other packages/cargo probably broke free impacting magnesium phosphide drums *Results*: four drums did not withstand impacts and subsequently breached. *No. 2 hold - containers* (inspected) with pallets of arsenic trioxide drums experienced: • Pallets shifted and tipped over - Drums compressed and impacted against each other and container sides *Results*: no drum was reported breached in the inspected containers; they were probably deformed, but still intact.
On deck	• *Shock load, impact on*: - Other drums, containers and other packages - Ship structure - Green water • *Compression, racking*: - Other drums and container sides	*No.2 hatch cover/deck – containers* with pallets of arsenic trioxide drums experienced: • Containers stowed on deck were exposed to heavy ship's motions and weather hazards; all six arsenic trioxide containers were broken open; one container was hanging over the ship's side - Drums inside containers compressed and impacted against each other and

Location of drums	**Categories of hazards**	**Description of probable scenarios**
		container sides - Many drums broke through container sides - Drums broke loose from damaged containers, rolled over the hatch cover/deck - Loose drums were probably lost overboard impacting on the sea surface and floor and undergoing hydrostatic pressure - Drums impacted each other, containers, the machinery and ship structure - Drums exposed and impacted by green waters Results: 13 drums reportedly breached spilling an estimated amount of two tons of arsenic trioxide onto the deck.
On deck: lost at sea – while falling, sinking and on the sea floor	• *Shock loads, impact on*: - Other drums and container sides - Sea surface - Sea floor • *Compression, racking*: - Other drums and container sides - Hydrostatic sea water pressure • *Corrosion*	A total of 21 containers including one piece of machinery were lost overboard; of these four were containers with arsenic trioxide (324) drums: • While falling overboard and sinking, drums were compressed and impacted each other and container sides; many drums broke through containers • Drums impacted on the sea surface and floor, and other debris • Drums underwent hydrostatic pressure • Many drums, which were never found, were also exposed to the corrosion hazard and other conditions for a much longer time *Results*: water contamination indicates that a number of arsenic trioxide drums lost overboard were breached.

3.2.1. Hydrostatic pressure and impact on the sea floor

The following describes in some detail the exposure of the drums to hydrostatic pressure and impact on the sea floor. In order to determine the state of arsenic trioxide drums on the sea floor, hydrostatic pressure and impact tests were conducted on two drums from the m/v SCI (Whipple et al., 1993). Drums were filled with cement simulating the arsenic trioxide and placed inside a tank. Both drums underwent the mentioned tests. For 30 minutes, drums underwent two pressure tests – 30 p.s.i. (pounds per square inch) or the equivalent of 18.3 meters and 60 p.s.i. or equivalent of 36.6 meters. Then, one drum was released to fall 2 feet (61 cm) onto the cushion simulating the impact force when the drum hits the sea floor. The tests were also to simulate recovery operations. The tests showed that the drums under pressure (in 18.3 and 36.6 m water depths) and impacts had sustained crumpling (collapsing, crushing, and wrinkling) with a slight leakage of water, but no release of contents was observed. The test results concluded that the drums maintained their overall integrity. However, the tests were considered not completely conclusive. Many different factors affect drums' design performance under hydrostatic pressure on the sea floor, including the duration under the given conditions, corrosion, and impact due to rolling caused by underwater currents. For approximately two months, 320 drums were exposed to hydrostatic pressure and other mentioned conditions.

3.2.2. Comparing packaging design and hazards conditions

The performance of packaging, i.e. the drums, pallets and containers, depends greatly on the design conditions. In the case of the m/v SCI accident, in order to explore the causes and contributing factors to the failure of drums, answers to some important questions are needed, namely: What were the drums' design and construction properties? Were they adequately designed, constructed and tested? Were they well maintained and in good condition? Were they correctly filled? Did the hazards exceed design conditions? Were they capable of withstanding ordinary transport hazards? The case history provides very little information concerning the above questions. The only reference to regulations indicates that the arsenic trioxide was packed in accordance with the U.S. Code of Federal Regulations (CRF) in 94.7 liters drums with a maximum allowable gross weight of 215.5 kg per drum. The investigation of the cargo manifest indicated that each drum instead contained 170.1 kg of product. This deviation did not play any significant role in the failure of packages. However, case histories (HCB, 1986-2003) have shown that the amount and the way in which packages are packed or filled, in particular large packages, such as tank or freight containers, can significantly affect packaging performance.

According to the IMDG Code (2002), because of their hazardous properties, arsenic trioxide and magnesium phosphide are assigned respectively to packing groups II and I. Both substances were packed in steel drums, which provided substantial protection, in particular for drums lost at sea. However, the fact is that many drums did not withstand the hazards to which they were exposed. Subsequently, largely due to impact and compression, many drums were breached. This suggests that, at some points, for many drums, these hazards probably exceeded design conditions. The hydrostatic pressure tests (in simulated conditions of 18.3/36.6 meter water depths) of two drums from the m/v SCI showed that both drums sustained crumpling with a slight leakage of water. The leakage is an indication of water ingress and, therefore, of the failure of the drums' integrity.

Summary

Many packages (drums/containers) were (and expected to be) damaged and breached due to the exposure to one or combination of hazards, such as shock loads, impacts, compression, racking and corrosion. The analysis showed that not all of the exposed drums were breached. The probability and the extent of damage were a function of the type, the extent/intensity and the duration of hazards acting on packages. The failure of packages is also a function of packaging design and construction conditions. Some of the hazards probably exceeded these conditions.

3.2.3. Transport hazards – statistical data

Based on the analysis of the m/v SCI accident case history, only two categories of transport hazards are explored, namely: *a) mechanical hazards* – shock load, impact, compression, racking; and *b) electro-chemical hazards* – corrosion. The quantification of transport hazards by means of a single case was not possible. In order to further explore and quantify the wide range of transport hazards involved in hazmat releases, as well as to test and enhance the external validity, the demonstration of the framework is extended to the analysis of statistical data from the HMIS database (U.S. 1993-2004).

HMIS database (U.S. 1993-2004): Figures 3.15 and 3.16 show transport hazards, causes and contributing factors of hazmat release incidents, which are presented as they are recorded in separate variables in the HMIS database (U.S. 1993-2004). In accordance with the relevant classification systems of causes (see Chapter 3, Vol. I, and Mullai, 2006a) and the data available at hand, some arrangements and adjustments have been made in the categorisation and labelling, in particular in the upper levels of resolutions. Transport incidents have often been followed by more than one sequence of events. Further, in many cases, transport incidents have involved more than one means of transport, commodity/hazmat or package. Top events are attributed to combination of a wide range of transport hazards, causes and contributing factors. As mentioned earlier, the latter (i.e. transport hazards, causes and contributing factors) and other (e.g. failures, damage, deficiencies etc.) notions, which are mentioned in this and other sections of this volume, are constituent elements of the universal notion of "cause-effect" chain or network.

The total number of incidences of transport hazards, causes and contributing factors reported in all transport incidents is 840,259. The category of transport hazards accounts for approximately 24.6% of the total number (Figure 3.15). The data show that, in many cases, transport hazards have preceded failures of packages. The most frequent failures reported are those due to these transport hazards: a) *mechanical hazards* such as puncturing, crushing, cracking, rupturing and pressure; and b) *climate/weather hazards* such as contact with water, ground and floor (Figure 3.16). The incidences of failures due to transport hazards may be even higher than those recorded in the HMIS database because causes and contributing factors of failures

(Figure 3.15) are largely associated with combinations of transport hazards, including those shown in Figure 3.16. For example, packages have been damaged due to mechanical forces (e.g. impact and crushing) and other hazards exerted in transport accidents and cargo handling operations. The data indicate that failures and hazmat releases are not always necessarily due to transport hazards. The wide ranges of causes and contributing factors of failures in the systems, hazmat releases and exposures are explored in detail Sections 3.4, 3.7 and 4.1.

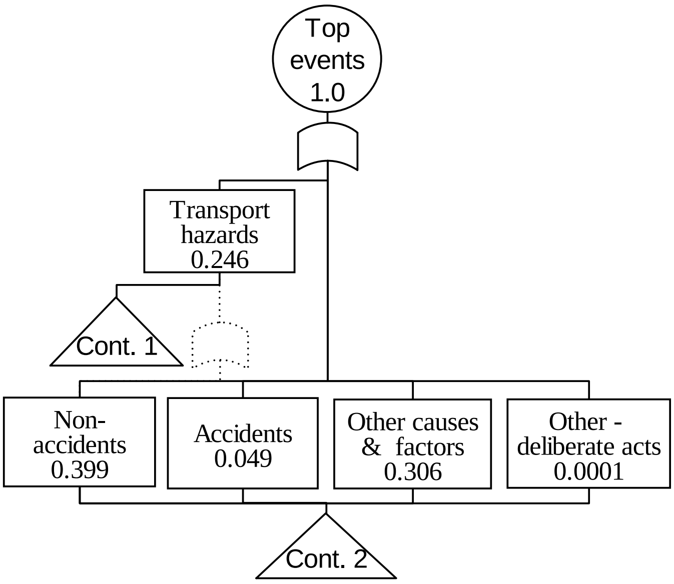


Figure 3.15: Fault tree of transport hazards and causes and contributing factors of incidents (U.S. 1993-2004)

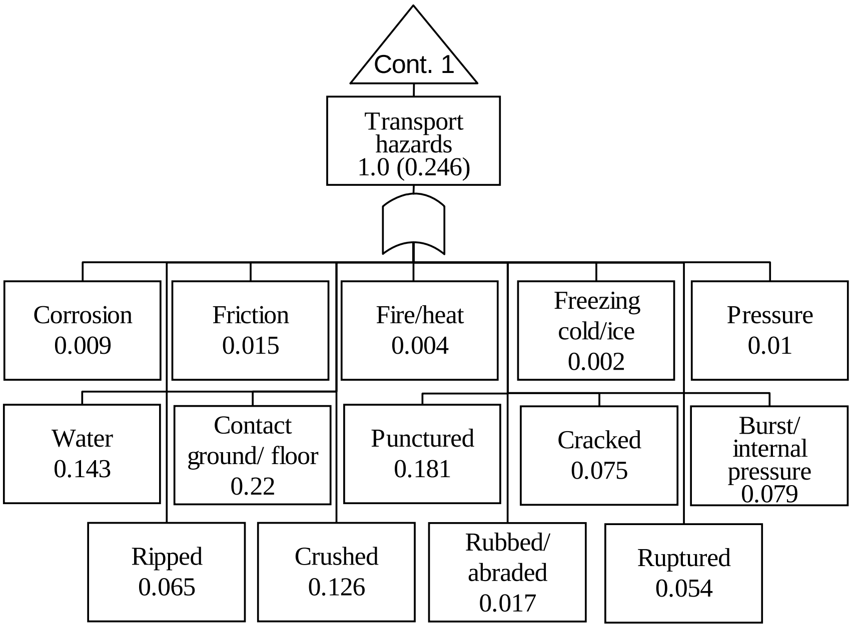


Figure 3.16: Fault tree of categories of transport hazards (continued from Figure 3.15) (U.S. 1993-2004)

3.3. “Normal” transport conditions – cargo losses and damage

By definition, the m/v SCI accident – cargo losses and damage – falls in the “other” category of the marine accidents and incidents as defined by the maritime organisations and authorities, such as the International Maritime Administration (IMO), Lloyd’s Register of Shipping (LRS), the U.S. Coast Guard (USCG) and the Swedish Maritime Administration (SMA). For the purpose of the risk analysis of maritime transport of PDG, this category of marine events is defined as *“normal” transport conditions* (see the **highlighted area** in Figure 3.17). For more information about definitions and concepts concerning marine accidents/incidents, see Chapter 3, Vol. I, and Mullai 2006a.

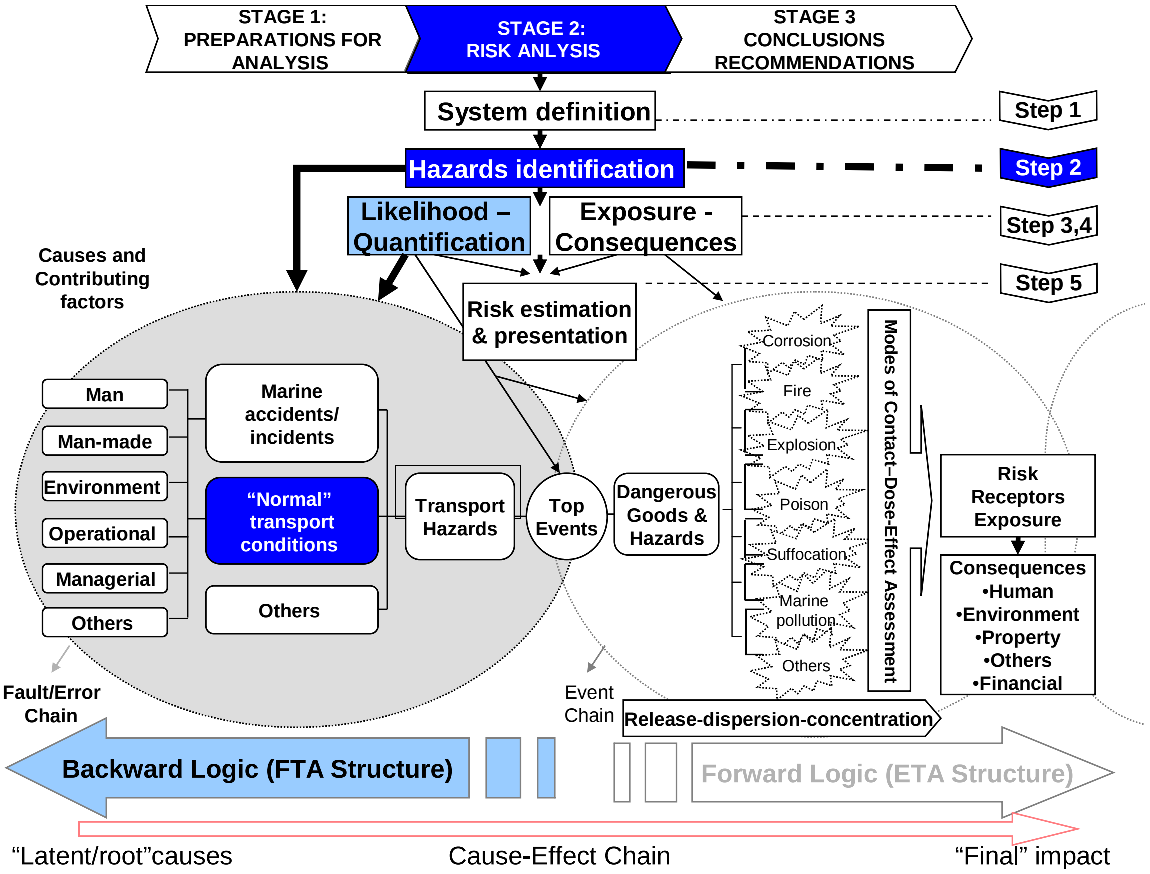


Figure 3.17: Stage 2 – Risk Analysis; Step 2 – Hazard identification, causes and contributing factors (continued from Figure 1.2)

In the case of the m/v SCI accident, the “normal” transport conditions – cargo losses and damage – preceded the exposure of containers and drums to the aforementioned transport hazards, explored in Section 3.2. This is one of three categories of marine accidents/incidents presented in the framework (Figure 3.17). The quantification by means of a single case was not possible. In Section 3.7, based on the analysis of the statistical data from the HMIS and NRC databases, two other categories of incidents as well as their causes and contributing factors are explored and quantified.

3.4. Causes and contributing factors

Based on the combination of the m/v SCI accident case history, other data sources, personal education and formal training, seafarer and research work experiences, the following section explores causes and contributing factors of the m/v SCI accident (cargo losses and damage). As Tables 3.4 and 4.5 show, causes and contributing factors of the m/v SCI accident, which are explored in the following sections, fall into these main categories: *man/human, man-made, environmental, operational, and managerial and others* (see the **highlighted areas** in Figure 3.18).

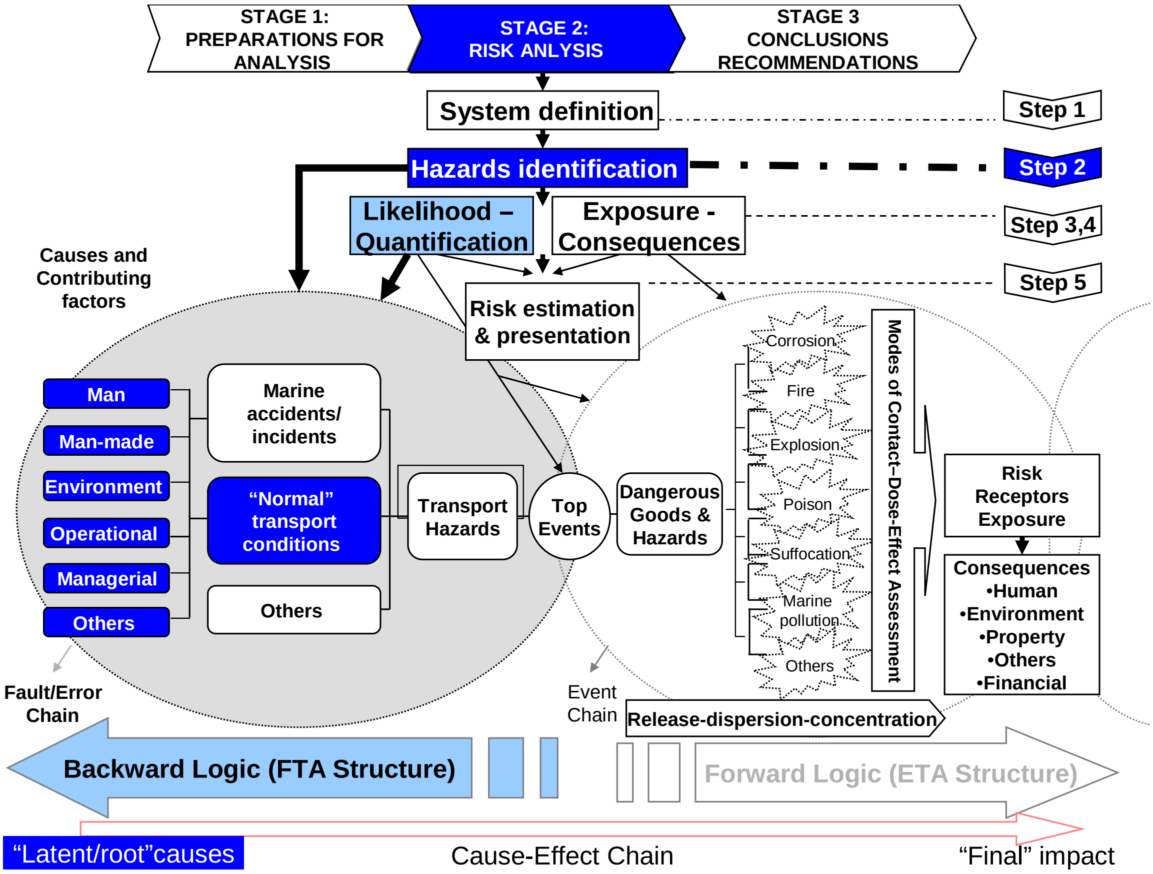


Figure 3.18: Stage 2 – Risk Analysis; Step 2 – Hazard identification, causes and contributing factors, the next level of resolution (continued from Figure 1.2)

The sequences of specific causes and contributing factors are explored by employing the *backward logic analysis* for specific system elements in time and space – as they actually happened.

3.4.1. Failure of the cargo securing system

The course of events showed that cargo losses and damage onboard the m/v SCI were directly attributed to the failure of the cargo securing systems. The cargo securing system consists of numerous interrelated components, whose principal purpose is to secure the cargo from moving. In the case of the m/v SCI accident, the cargo securing system failed, particularly for the cargo stowed in the no.2 hatch and hold and the no.1 hold. The relevant question is:

What and how did it happen?

The entire system, including the ship, the cargo/packaging and the cargo securing systems, was subjected to static and dynamic forces exerted during the navigation in heavy weather conditions. The following section explores the probable scenario of the system failures aboard the m/v SCI on January 4, 1992.

- ***Hold no.1***: Although under the same conditions of exposure (i.e. heavy ship motions, in particular heavy rolling) as the containers of arsenic trioxide drums in hold no.2, all pallets with magnesium phosphide drums in no.1 hold shifted, two of them turned over, and four drums broke loose. All four drums were exposed to impacts and subsequently breached.

- ***Hold no.2***: No shifting or damage was reported in the arsenic trioxide container stowed in no.2 hold. However, the internal cargo securing system failed to some extent. Many pallets shifted and turned over, but no breach or spill of arsenic trioxide was reported. All under-stowed containers were intact, providing a good deal of cargo protection. Cargo movements inside containers were very much confined. Subsequently, forces exerted in the impact and compression probably did not exceed the packaging/cargo securing system design and operational performance limits.

- ***Hatch no.2***: Due to weather conditions, heavy ship motions, and faults in the cargo securing system, the following sequence of events might have happened on no.2 hatch cover and deck:
    - Due to “small” gaps between pallets/drums and compression, the cargo inside containers began to shift and move;
    - Slight movements of containers/machinery began to work the lashings and other gear, which progressively loosened;
    - As the weather conditions deteriorated further, the ship’s motions began became more sluggish and green waters began washing over the deck, impacting containers and lashing gear; the securing system developed increasing slack;
    - Due to adverse weather conditions the crew was unable to re-tighten initial small slacks;
    - Small lateral movements of the hatch covers and slack in the lashings began introducing shock loads;
    - Synchronized heavy rollings further increased the transverse forces acting on the cargo/cargo securing system;
    - As the lashings loosened in the wire clips and gave away, the machinery began sliding on the hatch cover; at some point, the machinery began to impact adjacent containers;
    - Due to continued racking of containers the lashings and bridges were alternatively strained and slackened; some of the lashings jumped out of the turnbuckle hooks and/or slipped off penguin hooks; some others parted;
    - Failures in one part of the cargo securing system caused increasing loads/stresses on the other parts, leading to collapse of the system; the containers shifted on the deck;

- The machine swept the deck in an arc; as the machine slid overboard, it wiped out containers and the two middle pedestals on the starboard side;
- Seven separately secured blocks of containers all failed. Some containers broke open. At approximately 0150 hrs, containers on the starboard side went overboard first and containers on the port side began to go overboard very shortly after. At about 0210 hrs, most of the containers (21 of 25), including four arsenic trioxide containers, and the machine were lost overboard. One container was hanging overboard when the ship entered Delaware Bay. Only four damaged containers (4 of 25), including two arsenic trioxide containers, remained onboard at the no.2 hatch. The no.2 hatch cover and deck were littered with drums and white powder (arsenic trioxide).

Given the number and features of the cargo securing system's components and exposure conditions, the failure modes in various parts of the stowage shared similarities and differences. In this case, the exposure of cargo to loss and damage were directly attributed to *the failures of the cargo securing system*, which subsequently led to the collapse of the stowage. Had the cargo securing system maintained its integrity, the collapse of the stowage would not have occurred. Consequently, the drums would not have been exposed to impacts, shock loads, hydrostatic pressure or compressions. Accident case histories (HCB, 1986-2003 and U.S. DOT, 2005a) have shown that many dangerous goods damage and spill incidents are not necessarily attributed to failures of the cargo securing system, or secondary or tertiary (e.g. containers) packaging. However, in this specific case, as the course of events showed, the integrity of the cargo securing system played a determining role in the m/v SCI accident. The failure of the cargo securing system, which led to the exposure of maritime transport hazards, preceded the breach of drums (Figure 3.19).

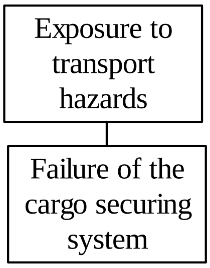


Figure 3.19: The failure of the cargo securing system led to exposure to transport hazards

The next step explores in detail the failure modes of the cargo securing system. The questions are:

How and why did the m/v SCI's cargo securing system fail? What were the causes and contributing factors?

Given the massive failures in the cargo securing system and the degree of detail provided in the investigation and recovery operations reports, the next step of the analysis primarily focuses on the containers and the piece of machinery stowed on the no.2 hatch cover and deck. As the container (elements of the container structure) and the stowage/packing are constituent components of the cargo securing system, the causes and contributing factors to failures of containers and pallets (i.e. packaging levels III and II) are analysed in the context of the failures of the cargo securing system.

The cargo losses and damage were due to the failure of the cargo securing system. As mentioned earlier, the failure of the system led to exposure of drums to maritime transport hazards. The failure of the system was the result of a large menu of technical, operational and managerial deficiencies in combination with the effects of weather conditions. Based on the available data and by employing backward logic, attempts have been made to explore causes and contributing factors, at various levels of resolution, and their logical sequences. The first level consists of two categories of events (i.e. the immediate causes and contributing factors) that led directly to the failure of the cargo securing system: *exposure to forces acting on the system* and *inherent faults in the cargo securing system* itself (Figure 3.20). Each category is further explored in detail at the next levels of resolution.

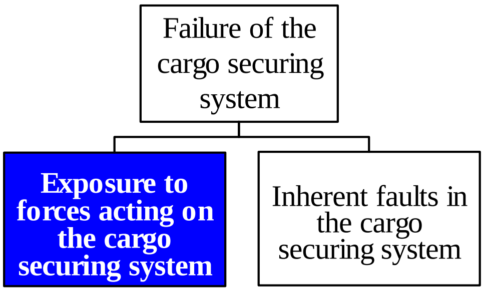


Figure 3.20: Immediate causes and contributing factors to the failure of the cargo securing system

The next step explores the exposure to forces acting on the cargo securing system of the m/v SCI (see the **highlighted area** in Figure 3.20).

3.4.1.1. Exposure to forces acting on the cargo securing system

The m/v SCI accident case showed that the entire cargo securing system was directly exposed to and affected by combined static and dynamic forces associated with the ship's motions (Figure 3.23), heavy weather and operational conditions, including: gravity, acceleration, forces of winds and green waters, vibrations and other additional forces (Figure 3.21, continued from Figure 3.20). Some of these forces and their effects, which fall under the category of transport hazards acting on the primary packaging (i.e. arsenic trioxide and magnesium phosphide drums), are explored in detail in Section 3.2.

The following section explores (*from left to right*) types and effects of forces acting on the m/v SCI's cargo securing system (Figure 3.21, continued from Figure 3.20), including the ship, containers, the piece of machinery and cargo securing equipment and gear.

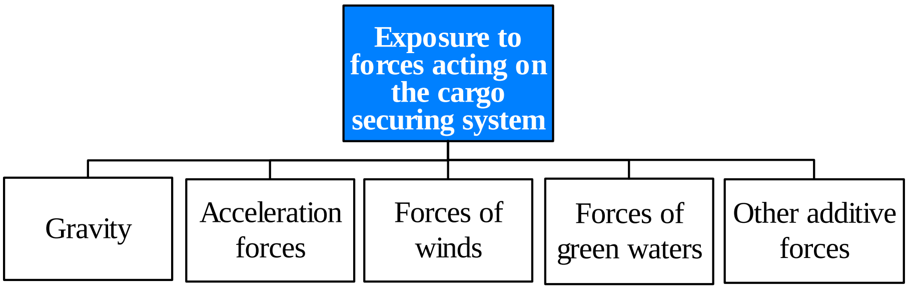


Figure 3.21: Types of forces acted on the m/v SCI's cargo securing system (continued from Figure 3.20)

Gravity: The gravity component acts both normal (perpendicular) to and across the deck as the ship inclined in any direction. Gravity added to other forces acting on the system (Figure 3.22).

Acceleration forces: Inertial acceleration/deceleration forces exerted due to the ship's motions affected the system. Figure 3.22 shows that forces acting on the system at any given moment may equal the vector sum of static and dynamic forces.

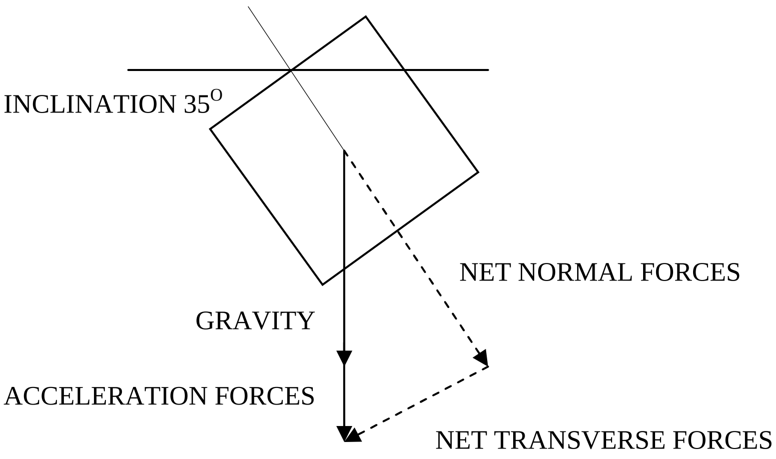


Figure 3.22: Gravity and traverse acceleration forces acting on the systems

Acceleration forces are principle mechanical factors acting on the system. Accelerations are vertical (e.g. forces exerted in pitching and heaving), longitudinal (e.g. forces exerted in surging and pitching) and traverse (e.g. forces exerted in rolling) (Figure 3.23). Given the ship/sea interactions, the order of magnitude of maximum vertical accelerations may not last very long, perhaps only for several hours. Inadequate cargo securing and a low friction factor might have added to effects of longitudinal acceleration. The ship may experience rollings as much as 30^{o}. In freak weather conditions, a ship's rollings may exceed 30^{o}.

According to the British Standard Institute (BSI) (Knott, 1994 from BSI, 1982), the orders of magnitude of peak (maximum) acceleration forces that may be encountered at sea under severe weather conditions are *vertical acceleration* (2g), *longitudinal acceleration* (2g) and *traverse acceleration* (0,8g). The m/v SCI accident case history provides no information on whether the magnitude of accelerations reached or came close to their maximum values. On the morning of January 4th, between 0130-0230 hrs, which coincides with the time of cargo loss, the m/v SCI experienced the most severe motions. In particular, the ship experienced synchronous heavy rollings, as the conditions for synchronizing were present during the voyage. The ship's natural rolling period (12 seconds) synchronized with the dominant wave period (11-12 seconds). The ship's rollings were so heavy that the chief engineer reported one heavy roll (35^o) registered on the bridge's inclinometer. The heavy rollings are supported by the following facts. The second mate was knocked over and slid some 12 metres (40 feet) across the bridge deck. Several crewmembers reported being thrown out of their bunks (beds). A 680.4 kg spare piston broke loose from the bulkhead in the engine room. The autopilot alarm began sounding frequently, indicating the ship was getting more than 10^o off the set course. The effects of static and dynamic forces might have been added together at the point of maximum rollings as well as pitchings. At the point of the maximum rolling (35^o), the traverse acceleration might have reached or even exceeded its maximum value.

Due to the approximation in the ship length (149 m) and wavelength (156-192 m), the m/v SCI encountered severe rotational and pounding forces.

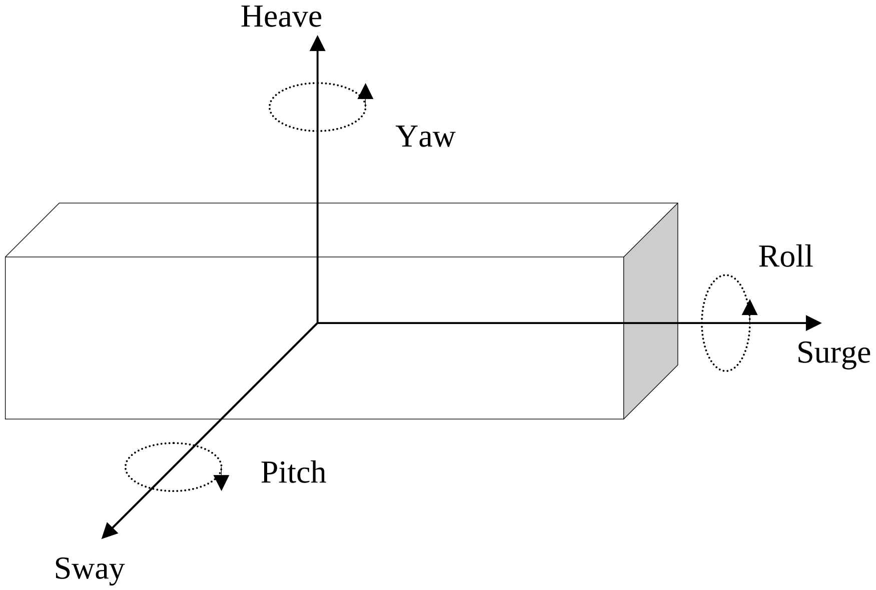


Figure 3.23: Six directions of ship's motions (Knott, 1994 from BSI, 1982)

Forces of winds: The forces of winds added to other mentioned forces and vibrations acting on the system. The effects of winds might have also contributed to the difficulty in ship handling at sea, particularly affecting the speed and course, establishing the conditions for heavy motions of the ship. The crew reported the worst weather conditions, with winds up to 50 knots, between 0130-0230 hrs, January 4th. The effect of winds is a function of the following factors: a) the speed/direction of winds; b) speed/direction of winds relative to the speed/course of the ship; and c) the size, shape and strength of the object (ship structure and cargo/packages on deck) exposed to winds.

Figure 3.24: Weather hazards – green waters (from Knott, 1994)

Forces of green waters: The forces exerted by green waters (boarding seas) on ship's deck are powerful (as seen Figure 3.24). Case histories (HCB, 1986-2003) have shown that green water in combination with excessive acceleration forces and deficiencies in the cargo securing system are some of the main contributor factors of cargo damage and losses (see Figure 3.25). Provided the departure drafts and trim of the m/v SCI, the top edge of the no.2 hatch would have been submerged in calm waters at an inclining angle of about 40^{o}. In seas, the degree of submergence depends on different factors, including the rolling angle, the wave profile and the side (the height of freeboard + bulwark) of the ship. Given the high seas, the low side of the ship, and the extensive rolling angles experienced (35^{o}), green waters might have considerably contributed to dislodging of cargo, the failure of the cargo securing system, collapse of the stowage, and the loss of the on-deck–stowed cargo. Several windows in the wheelhouse of the m/v SCI were broken (Klein and Nugent, 2004) due to green waters. The green waters in combination with heavy rains might have also contributed to lowering the friction between the cargo (containers and machinery) and the ship's deck. Although exposed to similar static and dynamic forces, but not to green waters and winds, the under-deck-stowed containers did not have the same fate as the on-deck-stowed containers and machinery. None of the under-deck-stowed containers was reported damaged. Case histories (e.g. HCB, 1986-2003) have shown that even large specialised containerships (with higher sides than breakbulk cargo ships) have often reported container damage and losses due to the destructive effects of green waters.

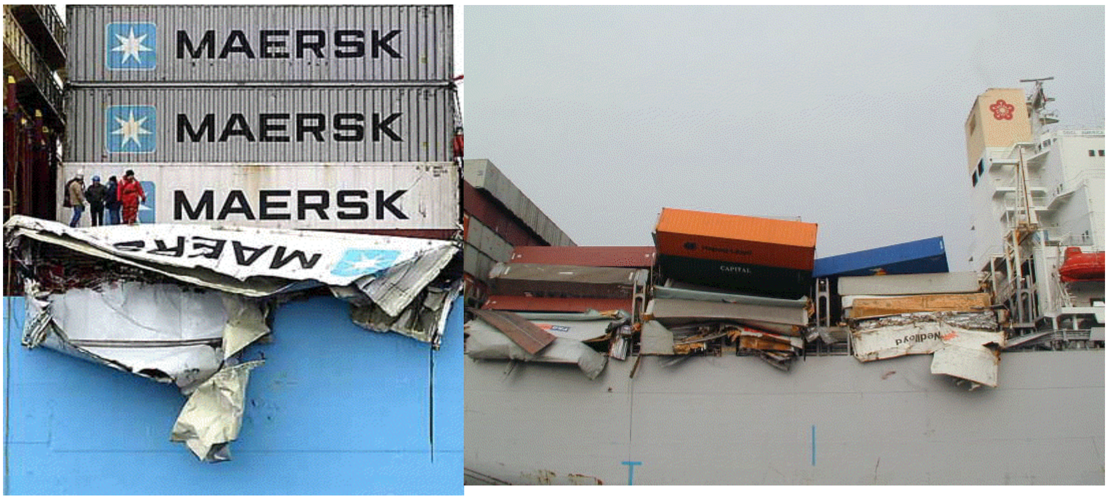


Figure 3.25: Container damage onboard large container ships (P&I Club, 1999)

Ships are designed and built to withstand extreme weather conditions estimated on the basis of the linear equations. The linear theory of waves maintains that shapes and heights or amplitudes of waves are stable (UCB, 2006). The ship structure is assumed to travel in regular sinusoidal shape waves (Bishop et al., 1986). The water actions on the structure are determined by means of established theories, models or techniques of naval hydrodynamics, which study the behaviour of a flexible body through a liquid (Bishop et al., 1986). The hydro-elasticity theory, which is based on a linear analysis of the responses of the ship hull travelling in seas, has been developed and further extended by Bishop, Price and others from 1979 to 1986 (Bishop et al., 1986). The design and construction of a ship have been based on consideration of static or quasi-static analyses, whereas in fact the ship operates in conditions determined by winds and seas (Bishop et al., 1986).

These theories have dominated naval engineering and hydrodynamics for many years. Ships have been designed and built to withstand forces of 15 tons/m^2, and a maximum of double these forces. Packaging and cargo securing systems are designed and constructed to withstand less than these forces. The data from satellite images, has shown that sea waves, including “freak or monster” waves that have reached up to 30 m in height, are non-linear or instable. Large waves are observed more frequently than previously predicted by linear theory. Forces exerted from impacts of very large waves may exceed ship design conditions. Case histories have shown that, in some cases, the ship hull and superstructure have been ripped apart by the enormous impact of “freak” waves. Furthermore, in many cases, ships have disappeared without a trace (HCB, 1986-2003). They have disappeared so fast that they have not even been able to send a single distress signal.

Vibrations: The m/v SCI experienced considerable vibrations due to combinations of heavy motions (in particular due to poundings in surging and heaving), weather conditions (impact of waves, green waters and winds), and the main and auxiliary engines. Vibrations are transmitted from the ship’s structure to packaging, goods, and cargo securing gear. Vibration is a function of frequency and amplitude. Means of transport (ships), packagings and goods have their own natural frequency (Jönson, 1993). When the natural frequency enters into resonance with the frequency of the ship while in motion, vibration becomes critical and can cause large displacements and deflections (Jönson, 1993). According to Paine (1990), damage is most likely to occur in vibrations with a frequency band of 1-15 Hz, because, for many packages, the resonant frequency falls within this range. In combination with different factors and conditions, vibrations may lead to a wide range of effects. In the case of the m/v SCI, vibrations might have primarily contributed to: a) shifting of packages, pallets, containers and the machinery, and even the collapse of the stowage including pallets inside containers; and b) loosening or slacking in the cargo securing system including bracing and blocking, lashing wires, turnbuckles, penguins and bridges. There was no indication that vibrations might have directly contributed to the failure of the primary packaging (drums).

Other additive forces: The system was exposed to various variables, which imposed additional forces, including: forces exerted due to loose cargo inside the containers; additive forces from adjacent containers and the machine inadequately lashed and broken loose; pre-tensioning in the lashings; and shock loads from slacks in lashings.

In summary, the system was exposed to a combination of static and dynamic forces, some of which were excessive. Excessive forces exerted during heavy synchronous rollings, in combination with green waters on deck, were key contributing factors to damage and losses of containers and the piece of machinery.

What were the factors that caused, amplified or contributed to exposure to forces acting on the system?

The above-mentioned forces were the result of a combination of the ship's motions, weather and operational (e.g. pre-tensioning in the lashings) conditions. The magnitudes and effects of forces acting on the system depend on the combination of different factors, including ship's properties, weather conditions (winds and waves), and ship's course/speed relative to wind and wave's direction/speed. Course adjustments and/or speed reduction are some of the measures for reducing the effects of these forces. The next step explores (*from left through to right*) each contributing factors (Figure 3.26, continued from Figure 3.20).

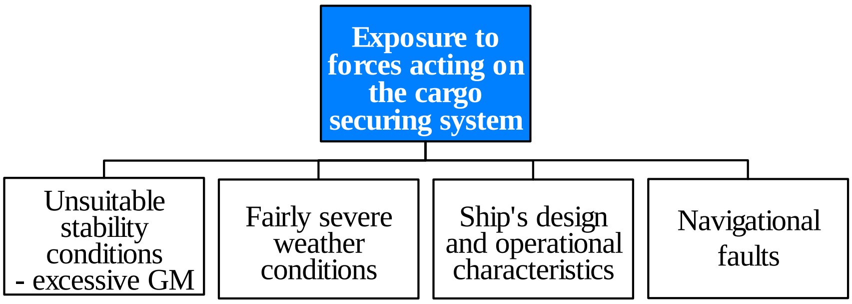
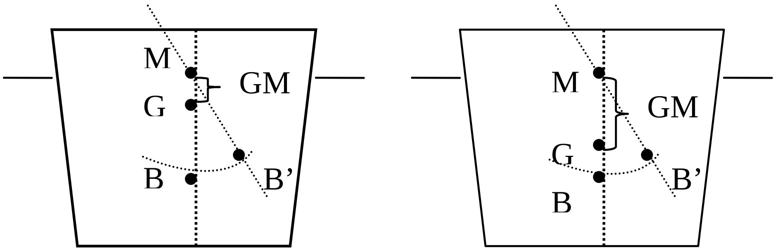


Figure 3.26: The main categories of contributing factors to the exposure to forces acting on the m/v SCI's cargo securing system (continued from Figure 3.20)

3.4.1.2. Unsuitable stability conditions – excessive GM

The stability of the m/v SCI was mismanaged. The ship left Port Elizabeth with an unsuitable stability, in particular for the carriage of containers/cargo on deck, setting the conditions for greater forces exerted in severe motions and wave actions in rough weather conditions.

Metacentric height (GM) is the most significant element that determines the ability of the ship to right herself, the ship's natural roll period, and the overall "tenderness/stiffness" of the ship. The relationship between GM and stability is that due to a large righting arm, a larger (longer) GM means greater stability, and vice versa. Figure 3.27 shows two situations. A less stable ship, as shown on the left, has a shorter GM and a longer ("softer" or "more tender") roll period. The ship is more vulnerable to capsizing. A ship with very a long GM, which was the case of the m/v SCI, is "snappy" and “stiff.” The ship has greater stability, tending to be very resistant to rolling over or capsizing, but it is very uncomfortable because it tends to snap upright very quickly. In that event, the acceleration forces exerted are greater. Although theoretically a longer GM means greater stability, due to heavy rollings/pitching and excessive acceleration forces exerted, ships with a long GM are also vulnerable to listing/ capsizing. Accident case histories (HCB, 1986-2003) have shown that certain types of ships, such as general cargo ships, ro-ro ferries and dry bulk carriers, have been more exposed to listing/capsizing events than other types of ships such as oil and chemical tankers. Many listing/capsizing events have been attributed to cargo shifting in adverse weather conditions. Given the ship and weather conditions, due to heavy rollings and excessive acceleration forces the m/v SCI probably experienced massive cargo shifting, which would have caused listing, capsizing or even sinking of the ship.



Short GM - “tender” rollings *Long GM - “stiff” rollings*

Figure 3.27: The relation between GM and rollings – the m/v SCI had a long GM and “stiff” rollings

Prior to departure from Port Elizabeth, by referring to the ship’s stability condition book and actual loading data, the master of the m/v SCI calculated the GM at 1.86 m. The USCG Marine Center estimations confirmed quite a similar value (1.87m). The m/v SCI’s GM prior to departure was an extensive GM. The GM was several times larger than the value associated with sample loading conditions for on-deck-stowed cargo as given in the stability book for the m/v SCI. The large GM reduced the rolling period, resulting in “snappier” and heavy rollings. Severe motions of the ship increased the forces acting on the cargo and the cargo securing system. The principal contributor to high forces was the large GM – acting both directly (increasing acceleration forces) and indirectly (increasing roll angle in resonance with the seas). According to the accident investigation report, the excess GM might have accounted for up to 23% of the forces acting on the system (U.S. DOT, 1992). The IMO and other relevant organisations have cautioned against the undue GM in order to avoid the hazards of excessive accelerations. Many experienced and trained masters and deck officers are well aware of the effects of the excessive GM.

Figure 3.28 (continued from Figure 3.26) shows the fault tree of the unsuitable stability of the m/v SCI. The following explores (*from left to right*) each contributing factor (Figure 3.28).

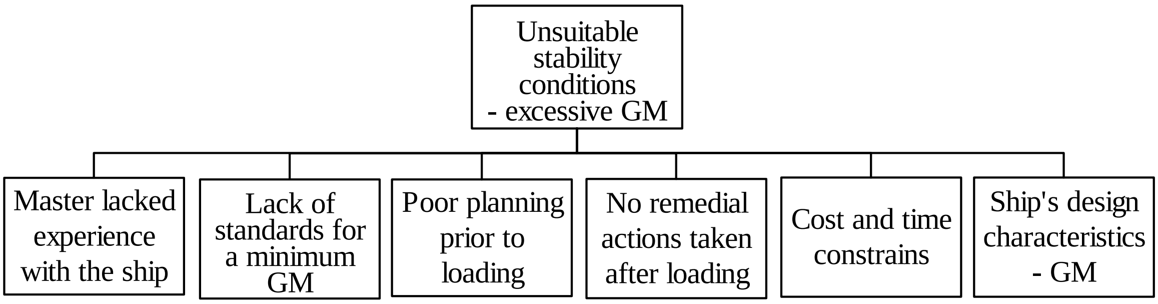


Figure 3.28: Contributing factors of the unsuitable stability of the m/v SCI (continued from Figure 3.26)

Master lacked experience with the ship: The master characterised the GM of 1.86 m as “a very good GM.” According to the Board of Inquiry (U.S. DOT, 1992), the departure of the ship from Port Elizabeth with a long GM was consistent with the master’s experience in large tanker ships, but inconsistent with the requirements for smaller container-carrying ships such as the m/v SCI.

Lack of standards – a minimum GM: A minimum safe GM (determined from the GM curve for various loading and operating conditions) is, for example, established in the U.S. regulations (46 CFR 170.170) for U.S. flagged ships. In the case of the m/v SCI, such a value was not available. The master and the chief officer were not aware of the minimum value. By applying the formula from U.S. regulations to the m/v SCI, which was based on the given departure conditions of the ship, a rough benchmark of 0.444 m GM was estimated. Probably the ship would have sustained lesser damage and fewer losses if the GM had been shorter than 1.86 m. However, a very short GM would have reduced the ship’s stability, subsequently increased her vulnerability to listing/ capsizing and foundering.

Poor planning prior to loading: The GM predetermines how the ship will react at sea. Prior estimation and control of the GM are key responsibilities of the master as well as the chief officer. As mentioned above, the GM is, among other things, a function of cargo loading, fuel and ballast. There was no indication that the master or the chief officer made any estimation of the GM prior to loading. They failed to control the GM with good cargo planning. In addition, six arsenic trioxide containers were stowed on deck. On-deck-stowed cargoes, especially the furthest outboard and nearest the ends of the ship, were most vulnerable to severe motions and weather hazards, in particular to heavy rollings and green waters.

No remedial measures taken after loading: After loading, the master and the chief officer failed to take appropriate measures to raise the centre of gravity and thereby reduce the GM by combining, for example, re-stowing of cargo, deballasting, or manoeuvring with fuels and other ship’s reserves. In Port Elizabeth, the ship carried out some cargo re-stowing – several containers were re-stowed onto the no. 2 hatch, but with no intention of reducing the GM. Unnecessarily, the ship left Port Elizabeth with fully laden ballasts.

Costs and time constraints: Due to costs and time constraints as well as voyage specifications, it may often be impossible to take any remedial measures, in particular in re-stowing cargo or making any change in the amount and/or location of fuels onboard the ship. The m/v SCI was on a regular round-trip voyage between South America and U.S. ports. Major cargo re-stowing may be a time consuming and cost inefficient operation, in particular for short voyages. The voyage between Port Elizabeth and Port Baltimore was a voyage of less than 24 hours.

Ship's design characteristics - GM: The GM is a design characteristic of a ship. A large number of design as well as operational factors determine the value of the GM, including the ship's length-beam ratio, underwater cross-sectional profile, water-plane coefficient, bilge and keel shape, the amount and placement of weights, and the height of freeboard. Unlike fully cellular ships, although with a retrofitted cargo securing system, the m/v SCI was not specially designed for the carriage of containers on deck.

3.4.1.3. Fairly severe weather conditions

Weather conditions in combination with other factors significantly contributed to severe motions of the m/v SCI, in particular to heavy synchronous rollings. High forces, such as acceleration/ deceleration, impact, shock loads, and compression, which are associated with ship's motions, winds and green waters directly contributed to the failure of the cargo securing system and subsequently to the cargo damage and losses.

Fairly severe weather conditions: The crew reported the worst weather conditions between 0130-0230, with NE winds up to 50 knots and seas up to 6.1-7.6 m (20-25 feet) (over 40 feet according to the second mate). The crew described the seas as strong waves with short periods, sometimes "confused." The Sandy Hook pilot (at Port Elizabeth) reported easterly winds of 10-20 knots and seas of 0.91-1.22 m as he piloted the m/v SCI out of the harbour. The Delaware Bay pilot reported winds up to 80 knots when the ship reached Cape Henlop. There were disparities between crew observations and instrument measurements from various sources. Measurements from the weather buoy and light station showed values that were more conservative. Instrument measurements from weather buoys have a higher degree of reliability. According to measurements, weather conditions were fairly severe. The most severe weather conditions in the area were recorded several hours later, when the actual weather conditions equalled the forecasts.

The intense storm caused heavy damage along Maryland and New Jersey shorelines. During the same storm, approximately 3 hrs later and in the same location where the m/v SCI lost her cargo, another ship lost two deck-stowed containers.

Figure 3.29 (continued from Figure 3.26) shows weather conditions that, in combination with other factors, contributed to the m/v SCI accident. Most of their effects are described in detail earlier in Section 3.4.1.1. The following section explores (*from left top-down to right top-down*) each element (Figure 3.29).

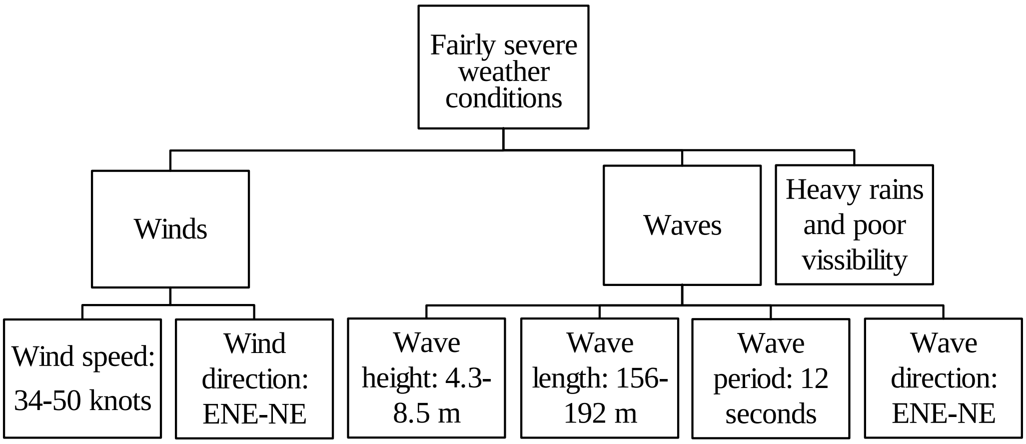


Figure 3.29: The m/v SCI encountered fairly severe weather conditions (continued from Figure 3.26)

Winds: The effects of winds are described in Section 3.4.1.1. The waves generated by winds are a function of the speed, direction and duration of the winds and the area over which the winds blow. There is a correlation between the size of the waves and the factors mentioned. The faster the wind, the longer the wind blows, and the bigger the area over which the wind blows, the bigger the waves. As strong winds blew steadily during January 3-4th over a large area of the North Atlantic, the waves came into equilibrium with the winds, turning into a fully developed heavy sea.

Wind speed: On January 4th, at 0200 hrs, approximately at the time of cargo loss, measured winds along the ship trackline increased from 20 to 34 knots (gusting at 41 knots). Between 0400-0600 hrs, measured wind gusts exceeded 50 knots.

Wind direction: The winds steadily shifted direction from 076 ° to 055° true, which is approximately NE.

Strong winds made navigation very difficult. The Delaware Bay pilot recalled:

> "*That was the most difficult and toughest night I ever spent on the water. The biggest danger we faced was the 'rock pile' at the Henlopen breakwater. We were blowing toward it, and the wind was coming so hard out of the northeast that I could not get the ship to turn. And I knew that if I did not turn it, we were going to head on into the rock pile*" (Klein and Nugent, 2004).

Waves: The waves (Figure 3.30), in combination with the m/v SCI's stability and properties and shiphandling factors, resulted in very heavy seas. In seas, the angle of inclination and effects of green waters vary with the wave profile and ship design characteristics. The properties of waves reported and estimated in the case of the m/v SCI accident are described below. Principles are provided in a number of sources including (University of Winnipeg, UW, Canada, 2005; Texas A&M University, U.S., 2005).

Wave height: The wave height is the vertical distance between a crest and the preceding trough. Wave crest is the portion that is displaced above the still water line, often referring to the highest point of the wave. Wave trough is the part of the wave that is displaced below the still water line. On January 4th, at 0200 hrs, measured seas increased from 2.1 to 4.3 m. Due to very high winds, measured seas reached up to 8.5 m at around 0800-0900 hrs.

Wavelength: The wavelength (λ) is the distance between neighbouring crests or troughs. The wavelength was estimated between 156-192 m.

Wave period: The wave period (T) is the time that elapses between the passage of two successive wave crests (or troughs) past a fixed point. The period can be expressed in terms of speed and wavelength: $T=\lambda/v$. The dominant wave period lengthened from about 6 seconds at the outset of the voyage to 10-11 seconds at around 2000 hrs, on January 3rd, approximately six hours prior to cargo loss. Later, the wave period became 11-12 seconds. In combination with stability and shiphandling factors, the wave period presented very heavy seas.

Wave direction: The direction of wave propagation (i.e. waves induced by winds) follows the wind direction. According to weather records in the m/v SCI's deck log, the wave direction was NE. The crew described the seas as sometimes "confusing." This was consistent with changes in wind directions (ENE-NE directions) as well as deviations in the ship course.

Wave speed: The wave speed (v) is the rate at which the crests (or troughs) move forward. The speed can be expressed in terms of the length and period: $v=\lambda/T$. The wave speed is estimated: $v= 156\text{-}192\text{m}/12\text{s} = 13\text{-}16$ m/s. The m/v SCI had a maximum service speed of 16 knots (or 29.6 km/h = 8.23 m/s), which was less than the wave speed.

Wave frequency: The wave frequency (f) is the number of crests (or troughs) that pass by per unit of time. It is equal to the inverse of the period: $f=1/T$. The wave frequency is estimated: $f=1/12$ s = 0.083 hertz.

Heavy rains and poor visibility: The storm was associated with heavy rains and poor visibility. Heavy rains in combination with green waters contributed in lowering the friction between the cargo (containers and machinery) and the ship's deck. In addition, heavy rains and poor visibility in combination with darkness might have prevented the master and deck officers to observe various things (e.g. wave directions, green waters, slacking in lashings, damage and losses of containers) and subsequently to take possible measures to avoid or minimise their effects.

3.4.1.4. Ship's design and operational characteristics

Due to design and operational characteristics, each ship type behaves differently at seas. The m/v SCI's natural rolling/pitching frequency and length were two important properties that affected the ship’s behaviour in heavy seas (Figure 3.30 continued from Figure 3.26).

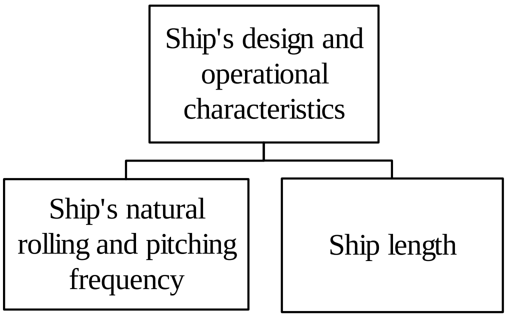


Figure 3.30: Ship’s design and operations characteristics (continued from Figure 3.26)

Ship’s natural rolling and pitching frequency: Because of mass distribution and righting characteristics, each ship has her natural rolling/pitching frequency. Given her design characteristics as well as loading conditions, the m/v SCI had a natural rolling/pitching frequency of 12 seconds. The ship tended to roll at her natural frequency under the conditions of wave motions. During the voyage, the wave period (11-12 seconds) approximated the natural period of the ship (12 seconds) setting up conditions for synchronized heavy rollings.

Ship length: Due to large ship length, the effects of seas were exacerbated. During the voyage, the wavelength (156-192 m) might have approximated the m/v SCI’s length (149 m). The ship encountered heavy rotational and pounding forces. According to crew accounts, the ship experienced surfing and difficulties in holding course, which is consistent with the mentioned conditions.

Summary

Both the ship’s natural rolling and pitching frequency and length amplified the effects of heavy seas. The master failed to understand and respond appropriately to offset these effects.

3.4.1.5. Navigational faults

Navigation is a very important activity of the ship, which includes: a) planning and preparation of the ship as a whole for navigation, including pre-estimation and controlling of ship stability and navigational equipment and devices; collection and assessment of the relevant weather forecast data; planning the voyage; and b) navigation at sea. In the case of the m/v SCI accident, several navigational faults were identified in preparing the ship for sea and navigation in heavy weather conditions. Cargo damage and losses were partly attributed to heavy motions of the ship and shiphandling in severe weather conditions. The ship encountered a cyclonic storm. A cyclonic storm consists of two semicircles (Figures 3.31 and 3.32): a) the most dangerous semicircle, which is the side to the right of the storm centre and direction of the path; b) the least dangerous (navigable) semicircle, which is the side to the left of the storm centre and direction of the path.

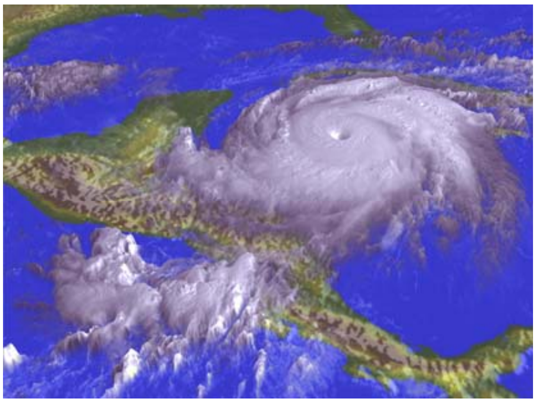


Figure 3.31: A cyclonic storm – a satellite image (University of Kansas, U.S., 2005)

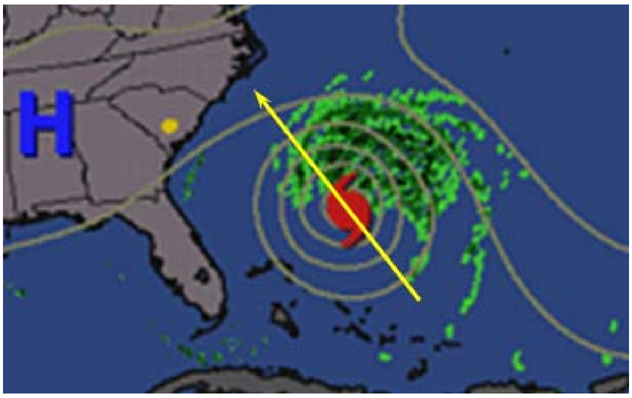


Figure 3.32: The path, centre and semicircles of a cyclonic storm – a radar image of Hurricane Bonnie (University of Kansas, U.S., 2005)

Navigational, naval engineering and other relevant texts provide detailed ship navigation guidelines and information on ship/sea interactions. When navigating in a cyclonic storm, two interrelated objectives are crucially important in manoeuvring the ship safely: a) avoiding the centre or the most dangerous semicircle of the storm, and possibly manoeuvring out of the storm; and b) minimising the severe motions of the ship induced by waves and winds. The most severe weather conditions are encountered near the centre (eye) and the most dangerous semicircle of the storm (Figures 1-61 and 1-62). While within the storm, the master should combine navigational tactics for avoiding and minimising the effects of the storm. The master of the m/v SCI failed in achieving both objectives *(a)* and *(b)*.

Based on the backward logic, the analysis follows the reverse sequence of events. It begins with the failure modes in navigation at sea, when the ship sustained cargo loss and damage, back through to failure modes (i.e. the failures to avoid the storm) prior to departure from Port Elizabeth. The following explores factors contributing to inadequate navigation in the storm (see the **highlighted area** in Figure 3.33 continued from Figure 3.26).

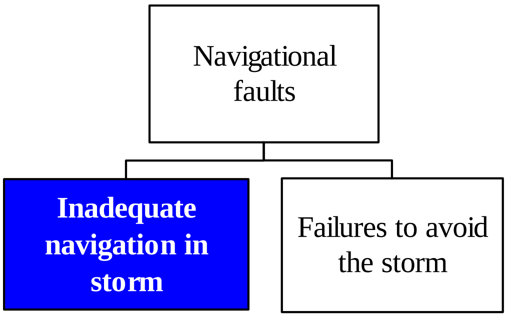


Figure 3.33: Navigational faults (continued from Figure 3.26)

Inadequate navigation in storm

Both prior to departure and in the early stages of the voyage, the master missed several key options to avoid the cyclonic storm altogether. Despite heavy weather and ship loading conditions, the master headed southwards (190-195^{o}). Subsequently, the m/v SCI ran into the most dangerous semicircle of the cyclonic storm. However, although being caught in a cyclonic storm, the ship still had options available to avoid and minimise severe effects of the storm. Figure 3.34 (continued from Figure 3.33) shows the fault tree of inadequate navigation in the storm. The following explores (*from left top-down to right top-down*) each contributing factor (Figure 3.34).

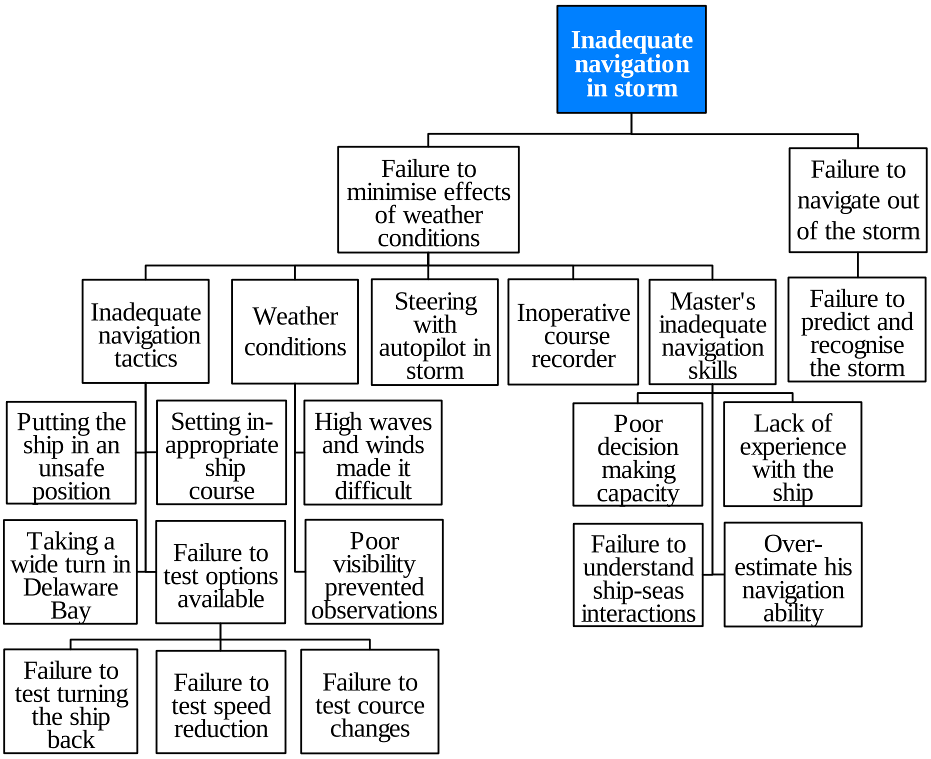


Figure 3.34: Fault tree of inadequate navigation in storm (continued from Figure 3.33)

Failure to minimise the effects of weather conditions: The m/v SCI was caught in the most dangerous semicircle of the storm, and subsequently exposed to its severe effects. Navigation tactics in heavy weather conditions are varied. Depending on the weather conditions, ship's properties and behaviour at sea and other situational factors, adjustments in ship course and/or speed are generally made for an easy riding. But the master failed to minimise or offset the effects of heavy weather conditions.

The effects of weather conditions depend, among other things, on the ship heading and speed relative to the wave direction of propagation and speed. Figure 3.35 illustrates some elements of the wave and the ship course relative to wave direction. Ship rollings increases as the ship runs diagonally across the sea. They reach their largest angles when the sea is on the beam or the ship is in the trough of the waves. The most threatening roll conditions exist when the wave period approximates the natural period of the ship, setting up the conditions of synchronization. The ship will continue to roll to the maximum limit until something is done to interrupt the synchronization.

Synchronous rollings can be interrupted by changing course and/or speed. Ship rollings tend to minimise when the ship runs with the sea or directly into it (at angles equal or close to 90^o). However, heading into the sea usually produces violent poundings due to heavy pitching and surging. A principal navigational rule when a ship is running into the sea is: the lower the speed at which the ship is running, the easier the ship will ride and the less pounding it will take. However, a substantial speed reduction may cause the ship to loss her steering capacity, setting the ship adrift and probably aground. Pitching and surging are considerably decreased when the ship runs with the sea. However, the ship still will pitch and surge when her speed is slower than the wave speed. Pitching and surging are considerably reduced when the ship runs with the sea with an equal or faster speed than the waves. Provided that the ship course does not run into shallow waters or other navigational hazards and the ship speed is equal or faster than the wave speed, one of the best alternatives for minimising the effects of ship's motions (pitching, surging and rolling) is to run with the sea at full speed. In other situations – for example, when the ship position relative to navigational hazards is unsafe, the ship speed is slower than the wave speed, and other conditions permitting – in order to minimise simultaneously synchronous pitching/surging and rolling, the ship should steer (with/into the seas) at an angle of approx. 45^o relative to the waves.

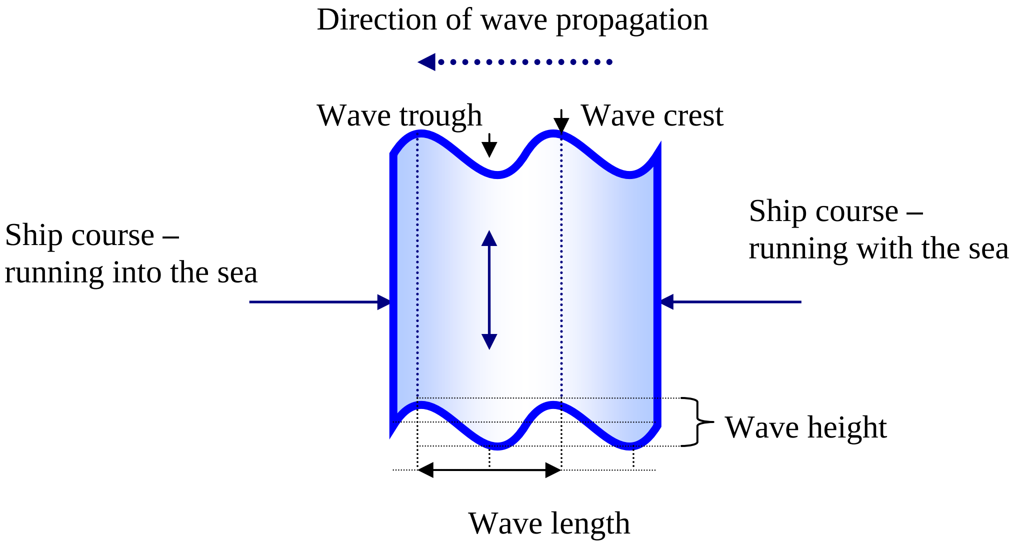


Figure 3.35: The ship course relative to the wave – the ship running with/into sea and in the trough of the wave

As mentioned above, the master of the m/v SCI took no actions to offset the effects of heavy weather. Despite heavy rolling, pounding, surfing and green waters on deck, the master proceeded on the planned course. The question is: *Why did the master fail to minimise the effects of heavy weather conditions?*

The following are identified as contributing factors:

Inadequate navigation tactics: Inadequate earlier actions left the ship with limited options. Even after the accident, the master believed that the ship was caught in the middle of a low and high-pressure centre. However, while in the open sea, the master had the task to closely follow the weather conditions, regardless of the type of the storm, and take sufficient earlier actions. The following were identified as factors of inadequate navigation tactics:

Placing the ship into an unsafe position relative to navigational hazards (shallow waters): The position of the ship in relation to shallow waters was an important factor. One important navigation tactic was to position the ship where she could have freely manoeuvred with the course and/or speed once she encountered heavy weather. By the time heavy weather conditions were upon the ship, the position of the m/v SCI was as such that it left her with very limited options available. Prior to and during the voyage, the master had various options to put the ship into a safe position. However, he failed to consider any of these options. Despite changes in the situation, the master proceeded on the planned course, placing the ship in an unfavourable position. Before departure from Port Elizabeth, the master revised the planned trackline along the New Jersey coast, previously prepared by the second mate, to take the ship off shallow waters along the coast. After leaving the traffic separated area outside New York harbour, the initially planned course of 210^o was modified to 207^o. Given the weather forecast warnings and the ship course relative to the wind/wave direction (NE winds/waves), this modification (only 003^o) was insufficient.

***Setting and keeping an inappropriate ship course relative to the wind/wave direction*:** The m/v SCI course relative to the wind/wave direction (Figure 3.36) played an important role in cargo damage and losses. This set the conditions for heavy motions, particular heavy synchronized rollings. By following the planned course, the master unnecessarily exposed the ship to the mentioned conditions for a considerably long period – between 1741 hrs, January 3rd, and 0226 hrs, January 4th. The effects of running at a narrow angle to the waves were: a) the ship tended to align itself parallel to the wave troughs causing heavy rollings; b) the ship surfed as she was hanging on the crest of the waves; and c) the ship yawed as unequal water pressure affected her bow and rudder significantly. In order to keep the ship further away from the coastline than planned and exposing the ship less to the mentioned conditions, the master should have made significant changes in the course.

At 1740 hrs, on January 3rd, after the pilot disembarked, the ship set out on her planned course of 180^o. Initially, this put the winds approx. 45^o abaft (aft of) the beam (off the port quarter). Later, despite of increasing deterioration of weather conditions, the ship still proceeded on her planned course until 2105 hrs. Then, the ship set on a course of about 195^o. From the outset and during the voyage, instead of following the planned course, the master should have adjusted the ship's navigation to the situation. In order to keep the ship at a safe distance from the shallow waters and place her later in a better position, he should have proceeded further to the east.

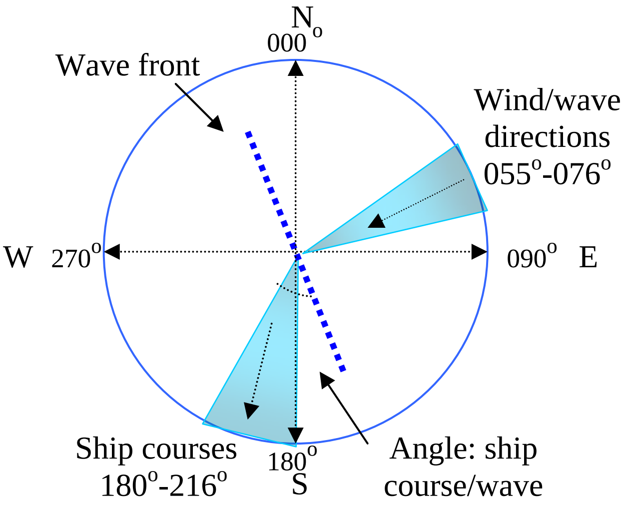


Figure 3.36: The m/v SCI's courses relative to wind/wave

Failure to test options available - several options remained untested: Given the heavy weather conditions and violent behaviour of the ship at sea, when asked by the Board of Inquiry (U.S. DOT, 1992) if he had considered any options to avoid or minimise the effects, the master responded as follow:

> ***Failure to test turning back and take shelter***: Due to shallow waters, synchronous rollings and the risk of losing the entire ship, the master could not turn back to the nearest port because it was too dangerous.
>
> ***Failure to test speed reduction***: When running into the seas, in order to minimise heavy pitching and surging, and particularly avoid synchronization, a speed reduction is generally recommended. The master claimed that due to weather conditions the ship could lose steering control under a speed of 11 knots (18 pitches). Therefore, he could not reduce the speed below this limit. Given heavy weather conditions and the distance from shore, a substantial speed reduction would have set the m/v SCI adrift into shallow waters within a few miles to starboard.
>
> ***Failure to test course changes***: A course change in combination with speed reduction (when running into the seas) would have minimised the effects of heavy weather. The master expressed his concerns that, due to shallow waters, the ship could not head further to starboard. Nor could the ship turn to port for fear of losing the entire cargo or being caught in wave troughs (trenches). As the ship was heading on the planned course, the master kept her inside the most dangerous semicircle or towards the centre of the storm.
>
> The master probably would have interrupted synchronous motions and improved the overall shiphandling at sea by manoeuvring skilfully with the course and speed. However, he made no attempt to test any of the options available. The fact that several options remained untested suggests weaknesses in shiphandling at sea and poor decision-making ability.

***Unnecessarily taking a wider turn into Delaware Bay*:** Shortly after 0151 hrs, as winds and seas battered the ship off the port side, the m/v SCI made a wide turn into the entrance of Delaware Bay (Figure 2.15). The ship set a course of 216^o and held to this course over the next 35 minutes. According to crew accounts, the cargo losses occurred between 0130-0230 hrs, which includes the time in which the ship was sailing on the course of 216^o. In order to minimise the effects of weather, the master should have set, as early as 1051 hrs, a direct course (approximately 240^o) to Delaware Bay and run with the maximum service speed of 16 knots. The ship was sailing at a distance of 30 nautical miles off the coast of Cape May in 38 metres (125 feet) water depth with a maximum draft of 7.32 m (5.33 and 7.32 m – forward and aft respectively). She had sufficient under water clearance (approx. 30 metres) to manoeuvre safely. Given the ship course and speed (8.23 m/s) relative to the wave direction and speed (13-16 m/s), the ship's motions would have been reduced considerably on this course. In fact, at 0226 hrs, the ship behaviour at seas improved significantly when the master ordered a change of course to 240^o towards the entrance of Delaware Bay. The wind/wave was observed off the port beam. As the ship turned, although the weather conditions became even severer, the master and 2nd mate noted the ship began to ride more easily in the seas. But this change was made too late.

Weather conditions affected navigation: Heavy seas, winds and limited visibility made navigation difficult:

> ***Heavy weather conditions (waves and winds) made navigation difficult***: As seas and winds battered the ship, the m/v SCI had trouble holding her heading. The autopilot alarm began sounding frequently, indicating that the ship was getting more than 10^o off the set course. This was an indication that the ship was rotating, surfing and pounding heavily. On the other hand, difficult shiphandling set the conditions for heavy motions (rolling and pitching) and exposure to green waters on deck. The crew described the seas as "confusing," which was probably in part attributable to the deviations in the ship's course.
>
> ***Heavy rains and poor visibility prevented any observations and measurements***: According to the crew accounts, the heavy rains and poor visibility prevented observation of the situation, such as the wave direction and green waters on deck. Subsequently, this might have prevented the master from taking any measure to avoid or minimise their effects. Losses and damage were first noticed after the accident, on the morning of January 4th, when the Delaware Bay pilot boarded the ship.

Steering with autopilot in severe weather conditions: Due to heavy ship motions (rolling, pitching and yawing), the autopilot alarm began to sound frequently indicating that the ship was getting more than 10^o off the set course. In order to "steer easy", the master decided to switch steering from autopilot to helmsman. Considering the ship's course relative to the wave/wind direction, ship motions were probably exacerbated by steering with autopilot that allowed the ship to get more than 10^o off course. Heavy rollings suggest that the ship might have been caught in the wave troughs (trenches). The master should have made the switch earlier.

Inoperative course recorder: The course recorder was inoperative and turned off. The description of the ship courses was based on plotted positions (Figure 2.15) and recollections of the master and deck officers. An operative course recorder would have shown course oscillations. This, in turn, would have provided a better picture of the ship's behaviour (e.g. surfing) in heavy seas. Probably the master would have taken earlier remedial measures, for example, switching ship steering from autopilot to helmsman.

Master showed inadequate navigational skills: In many ways, throughout the navigation process, from preparations at Port Elizabeth through the navigation to the entrance of Delaware Bay, the master demonstrated that his navigational skills were inadequate.

Poor decision-making ability: The master did not recognise the point at which he needed to take decisive actions to avoid the storm and minimise the effects. Despite the changing situations, the master proceeded according to the plan. Once the ship began reacting violently in the weather, his shiphandling at sea was inadequate. For example, the decision to change course was taken too late.

Master inexperienced with breakbulk cargo ship: The master had no previous experience with this particular ship (m/v SCI), i.e. the breakbulk cargo ship. He assumed command of the ship four days prior to arrival in Port Elizabeth. The inexperience of the master played an important role in improper navigation. The master showed that he was unfamiliar with the ship's properties, particularly with ship behaviour in heavy weather. Each ship type reacts differently to the seas. Due to mass distribution and righting characteristics, each ship has her natural frequency. A ship tends to roll at this frequency under all conditions of wave motions. Prior to departure from Port Elizabeth, given the ship's design properties and loading conditions, the m/v SCI had a natural frequency of about 12 seconds. The data available suggest that the master was neither aware of nor made any attempt to estimate the natural frequency of the ship or the wave period. The master was not aware of the conditions for synchronous rollings, which were present throughout the voyage. The ship's natural rolling period and the dominant wave period were 12 and 11-12 seconds respectively.

Master failed to understand ship-sea interactions: On the morning of January 4th, between 0130-0230 hrs, which coincides with the time of cargo losses, the m/v SCI experienced the most severe synchronized rollings (35°). The data available suggest that this was expected. The conditions for the synchronized motions were present from the outset of the voyage. As early as 2400 hrs, weather conditions deteriorated considerable and the ship was rolling and pounding heavily. However, the master failed to understand the interaction between the ship and waves, which, at some point, would have led to synchronized rollings. The master did not attempt to minimise heavy motions, particularly to interrupt synchronous rollings. Approximately after the severe rollings, the master probably realised the severity of the situation and reacted by changing course. As mentioned earlier, at 0226 hrs, the master ordered a course to 240° towards the entrance of Delaware Bay. The wind/wave was observed off the port beam and the ship began to ride more easily in the seas.

Master overestimated his navigational ability: The master overestimated his navigational ability to react in the increasingly heavy weather conditions and ship motions. During the early stage of the voyage, despite substantial deterioration of the weather conditions and heavy motions and with options to avoid the storm still open, the master proceeded on the planned course towards the storm. Having 25 years sea experience, of which 18 years in command positions, the master probably thought he could get the m/v SCI through the storm safely. The ship and her crew arrived safely at port, but part of her cargo was severely damaged or lost overboard. The master underestimated the effects of heavy weather conditions, particularly on the deck-stowed cargo.

Failure to avoid (navigate out) the most dangerous semicircle of the storm: For the reasons mentioned in this section, the m/v SCI was caught up in the most dangerous semicircle of the cyclonic storm. The time when the ship was caught within the range of the dangerous semicircle of the storm was unclear. This probably coincided with substantial deterioration of weather conditions, heavy motions and subsequent cargo damage and losses. The available data do not indicate whether the ship was near the centre (eye) of the storm. However, according to the Delaware pilot and available weather data, the most severe weather conditions, which are consistent with conditions near the centre, were recorded when the ship had arrived at Delaware Bay – between 0400-0900 hrs, on January 4th. The master made no attempt to avoid the most dangerous semicircle of the storm or even to avoid the storm altogether. In addition, in any heavy weather conditions, regardless of the type of storm, the master has quite similar tasks – avoid the storm/heavy weather conditions and minimise their effects. The master took no action to avoid heavy weather conditions. He did not return to the nearest port for shelter as a measure of avoidance.

Failure to recognise and track the cyclonic storm while within it: As the ship was caught in the most dangerous semicircle, the master still had the task to keep track of the storm and take appropriate actions to manoeuvre out of the semicircle. However, just as prior to departure and during the early stage of the voyage, the master failed to recognise and subsequently track the storm while within it. Without knowledge of the situation in which the ship had found herself, the master could not manoeuvre out of the most dangerous semicircle.

Failure to avoid the storm

In the following section, failures to avoid the storm (see the **highlighted area** in Figure 3.37 continued from Figure 3.33) are explored.

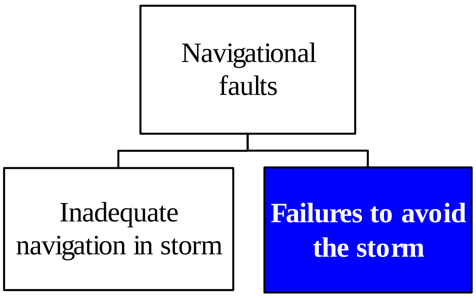


Figure 3.37: Navigational faults (continued from Figure 3.33)

In the event a ship is expected to encounter a cyclonic storm, all navigation and other relevant literature, as well sound judgment, strongly advise that the safest measure is to avoid the cyclonic storm altogether. Both at sea, particularly during the early stage of the voyage, and prior to departure from Port Elizabeth, the master failed to take early measures to avoid the storm; he put the ship in a dangerous situation with limited safe alternatives remaining.

Why did the master fail to avoid the storm?

The fault tree (Figure 3.38 continued from Figure 3.37) shows failure modes to avoid the storm. The following section explores (*from left top-down to right top-down*) each contributing factor (Figure 3.38). The analysis follows the *backward logic* of sequences of events, which begins with failures at sea back through to failures prior to departure from Port Elizabeth – from the left top-down through to the right top-down.

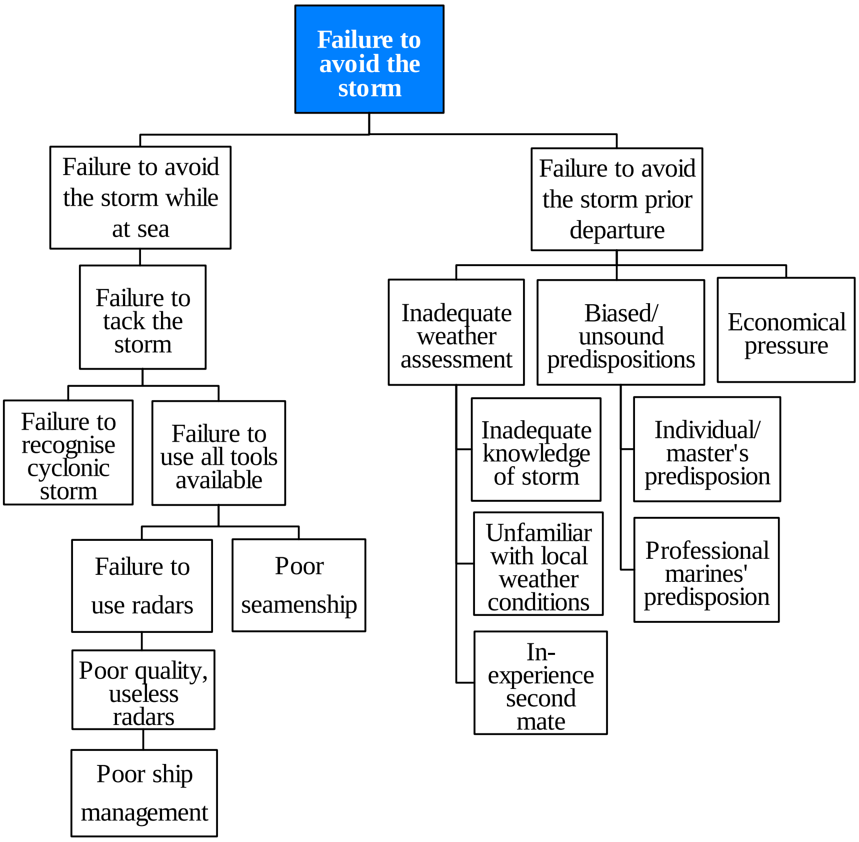


Figure 3.38: The fault tree of failures to avoid the storm while at sea and prior to departure (continued from Figure 3.37)

Failures to avoid the storm at sea

Inappropriate navigational decision - failure to avoid the storm while at sea: Despite weather conditions and ship behaviour at sea, particularly heavy rolling and pitching, the master failed to avoid the storm while at sea, i.e. before the ship ran into the most dangerous semicircle of the storm. Given the ship's position and course relative to the centre and path of the storm, in order to avoid the storm the master should have determined and set a course that would have provided the greatest distance between the ship and the storm centre in the least amount of time. Maximum speed on such a course was the most appropriate avoidance action. At the early stage of the voyage (sometime between 2000-2200 hrs or even earlier), one available course for avoiding the storm was to turn the ship northwards and take shelter in the nearest port, such as Port of New York. Instead, the ship proceeded on her planned course southwards towards her destination, running into the most dangerous semicircle of the storm.

Why did the master fail to avoid the storm while at sea, i.e. before running into the most dangerous semicircle of the storm?

In addition to some other factors mentioned in this part, the following are identified as the contributing factors.

Failure to track the storm while at sea: The master failed to track the storm appropriately while at sea. In order to avoid the cyclonic storm in the ship's path or manoeuvre out of the storm when caught by it, the key elements to be determined and plotted include a) the position of the ship relative to the storm centre/eye and axis and b) the direction/path and velocity of the storm. Ships are required to take regular (every 3-6 hrs) weather observations. The master of the m/v SCI was forewarned of the approach of the cyclonic storm, but he did not properly determine the location, the proximity of the ship in the most dangerous semicircle. He provided little information regarding the mentioned parameters. The relative wind (speed and direction) was never plotted. Observations took no account of significant changes in the ship's course and speed.

An appropriate tracking of the storm would have provided the master with a clearer picture of the situation and options available to him in avoiding the storm. It would have clarified the ship's position relative to the centre of the storm. It would also have shown whether the ship was in the most or least dangerous (navigable) semicircle of the storm. An early decision would have allowed the master to use all necessary speed to gain the safest possible geographic position before the storm was upon the ship.

Failure to recognise the cyclonic storm while at sea: The master as well as deck officers failed to recognise the cyclonic storm while the ship was at sea. As the ship was heading southwards and the storm was moving in NE direction, the range between the storm and the ship position was closing faster. The signs of the cyclonic storm became even clearer. The master's weather forecasts assessment was proving to be incorrect. At Port Elizabeth, the master hoped he could reach Delaware Bay before the storm came through. But, in fact, the storm was upon the ship before she arrived at the bay.

All observations aboard the m/v SCI suggested that the ship encountered a cyclonic storm. As the ship headed to destination, unaware of the cyclonic storm, she ran into the most dangerous semicircle of the storm. On January 3rd, at 1740 hrs, when the pilot disembarked and the ship set a course of about 180° and increased speed to 12-14 knots, winds were about 20 knots from E-NE. By 2000, the weather as recorded in the deck log indicated 1018 millibars (mb), strong NE winds of 22-27 knots and NE seas 12-18 feet. This was associated with heavy rain and poor visibility. The ship continued on its course of 180° until 2105 hrs, and then set a course of about 195°. By 2200 hrs, the weather conditions had deteriorated substantially. The master noted a drop in the barometer. The third mate also noted the start of very bad weather by an entry in the deck log. Over the next two hours, the master made several trips between his cabin and the bridge. The ship continued on the planned course of about 195°, with a speed between 11-13 knots. By 2400 hrs, the master noted a "big drop" in barometer pressure (from 1018 to 1010 mb) and further increasing winds. He assumed command of the ship with the assistance of the second mate and helmsman. The radio operator was obtaining and delivering to the master frequent weather reports. The weather conditions deteriorated even further. On January 4th, by 0200 hrs, approximately at the point of cargo loss, winds became stronger and waves higher. The measured winds along the ship trackline increased from 20 to 34 knots (gusting 41 knots), which later exceeded 50 knots, and seas increased from 2.1 to 4.3 m. At 0400 hrs, the weather was again recorded in the deck log, noting estimated winds of 48-55 knots and seas over 13.7 m, both from the east; the barometer indicated 1001 mb pressure.

All the aforementioned weather conditions, namely steady fall of atmospheric pressure (from 1018 to 1010 mb and later to 1001 mb), increasing strong winds (from 20 knots to gusting 41 knots, and then later to over 50 knots), heavy rain and poor visibility, were clear indications of a storm. Based on wind speed, cyclonic storms are categorised as shown in Table 3.2. Given wind speed over 50 knots, the m/v SCI encountered a tropical storm (i.e. category TS, see Table 3.2). As mentioned earlier, even after the accident, the master was still convinced that the ship got caught between the low pressure from the south and a high-pressure centre in the New York area.

Table 3.2: Categories of cyclonic storms (University College London, UCL, 2005)

Tropical Cyclone Wind Speed Scale				
Strength	**Category**	**1 Minute Maximum Sustained Winds**		
		knots	mph	km/hr
Tropical Depression	TD	<34	<39	<63
Tropical Storm	TS	34-63	39-73	63-118
Severe Cyclonic Storm	Cat 1	64-82	74-95	119-153
Severe Cyclonic Storm	Cat 2	83-95	96-110	154-177
Severe Cyclonic Storm	Cat 3	96-113	111-130	178-210
Severe Cyclonic Storm	Cat 4	114-135	131-155	211-250
Severe Cyclonic Storm	Cat 5	>135	>155	>250

Inadequate knowledge of cyclonic storm characteristics: Failure to recognise the cyclonic storm indicates that master as well as deck officers had inadequate navigational knowledge including cyclonic storm characteristics.

Failure to use all tools available for tracking the storm: The master had the task to track the storm by all means available. Yet he failed to use these means, such as radars, for tracking the storm.

> ***Failure to use radars***: Radars are very useful tools for tracking a storm. By means of the radar experienced navigators (masters and deck officers) can observe, for example, water clutters due to strong winds and heavy rains, and track the movements of the storm (Figures 3.32 and 3.39). Even when the eye of the storm is out of radar range, spiral bands may indicate storm direction from the ship. There was no indication that the m/v SCI used any radar to track the storm.
>
> > ***Poor quality/useless radar***: The Delaware Bay pilot found the quality of the radar image poor and even useless.
> >
> > > ***Poor ship management***: Useless radars onboard the m/v SCI indicate poor management on both shore and shipside. Radars are essential navigational tools. The ship should always be fitted with operative radars in good condition.
> > >
> > > ***Poor seamanship***: Failure to use all means available, including radars, demonstrates poor seamanship on the part of the master as well as deck officers.

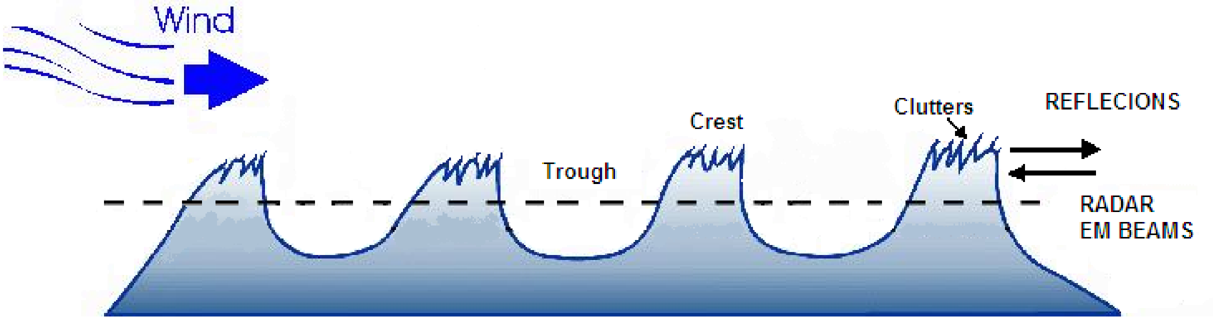


Figure 3.39: Observation of wave clutters by means of radar

Failures to avoid the storm while at port - prior to departure

Inappropriate navigational decision – failure to avoid the storm prior to departure: The master failed to take early measures to avoid the storm prior to departure from Port Elizabeth. The master's concerns about the weather at Port Elizabeth suggest that he was aware of adverse weather forecasts. He anticipated, to some extent, weather conditions near the actual order of magnitude. His decision to take the ship into heavy weather conditions was an inappropriate navigational decision. Should the master have decided to wait in Port Elizabeth until the dangerous storm had moved out of the area of the ship's trackline, the ship would not have been exposed to weather hazards and, subsequently, sustained cargo damage and losses.

Why did the master fail to avoid the storm prior to departure? Why did he decide to leave the port despite weather forecast warnings?

The following are identified as contributing factors:

Inadequate assessment of weather forecasts prior to departure: Prior to departure, weather forecasts issued by the national weather forecast services were relevant and available onboard the m/v SCI. Storm warnings were issued for the area as early as the evening of January 2nd. Over the 24-36 hour period preceding the casualty, the Offshore Water Forecast and High Seas Forecast services warned of a dangerous storm moving through Cape Hatteras (105 miles south of the entrance to Delaware Bay) with the most severe weather – winds between 40-60 knots and seas between 6.7-10.7 m. Weather forecast services issued warnings to all marine interests. Throughout January 3rd, forecasts updated the position of the storm centre. The storm was expected to move north-northeast through the area, with the NE quadrant most dangerous. Forecasts consistently put the ship (i.e. the anticipated ship's trackline) within range or near the most dangerous quadrant of the storm. The master's reconstruction of the weather forecasts revealed misinterpretations that subsequently led to an inadequate assessment of weather forecasts. Instead of focusing on the dangerous storm, the master focused on a low-pressure area, which, as he recalled, was to the south of Cape Hatteras. According to the master, it was moving north at a speed of 10 knots, with forecast winds of about 20 knots and seas between 10-12 feet. The master believed that the low-pressure centre never went north of Cape Hatteras. He speculated that the ship got caught between the low pressure from the south and a high-pressure centre in the New York area. As the ship left the harbour, the master and the Sand Hook pilot discussed the low-pressure system coming up the coast. The master stated that he hoped he could reach Cape Henlopen (Delaware Bay) before the storm came through. Unfortunately, the storm moved faster than the speed anticipated (10 knots) by the master. Subsequently, the ship was caught in the most dangerous semicircle of the storm before arriving in Delaware Bay.

Inadequate knowledge of cyclonic storm characteristics: Tracking a storm requires careful assessment of weather forecasts, including key weather readings and a good knowledge of storm behaviour. This is an important subject of the formal training. The master failed to recognise the cyclonic storm characteristics as provided by the relevant weather forecast services. Failure to recognise the signs of the cyclonic storm suggests that the master and deck officer lacked adequate knowledge of cyclonic storms. Prior to departure, although the weather forecasts were relevant, timely, and clear, providing an accurate picture of the weather conditions in the area, storm tracking was simply qualitative, inaccurate and inadequate for making good navigational decisions. Besides, throughout January 3rd, the forecast services clearly and implicitly warned all mariners of a dangerous cyclonic storm moving through the Cape Hatteras.

Master and deck officers' unfamiliarity with local weather conditions: Navigation directives and other relevant navigational literature provide detailed weather information for all parts of the world. Failure to recognise the signs of the cyclonic storm and understand its behaviour suggests that the master as well other deck officers were unfamiliar with the prevailing local weather conditions. On the U.S. Atlantic Coast, the most favourable region for low pressure or cyclonic storm development is the coast of Virginia (U.S. DOT, 1992). The cyclonic storms generated in this area, often called "Hatteras storms", are frequently very intense. They tend to move NE along the Gulf Stream, with an average speed of about 30 knots during winter months. North of 30^{o}N latitude, the speed of the storm may become unpredictably variable. On occasion, unexpected accelerations up to 70 knots have been reported. The master/deck officers were not aware of these local weather characteristics.

Inexperienced second mate: The data available does not indicate which deck officer was directly in charge of navigation matters onboard the m/v SCI. Preparations of the ship's trackline by the second mate suggest that he was in charge. The second mate had only one month of onboard experience. A well trained and experienced second mate (and other deck officers and the radio officer), employing adequate interpretations and assessment of weather forecasts readings and understanding of cyclonic storm behaviour, would have provided the master with the relevant information and good advice. The Board of Inquiry tendency was primarily to put entire blame on the master. Although the master was in command of the ship given their formal training/education, responsibilities and tasks, deck officers and other ship personnel share responsibility for the accident. Good ship management relies on teamwork.

Biased unsound predispositions: A general prevailing expectation is that a commercial ship will get underway.

Individual/master's predisposition: The master was aware of ship conditions and adverse weather forecasts. But he was anxious to get the ship loaded and underway. When the Board of Inquiry asked him if he had considered staying in Port Elizabeth until weather conditions were improved, he responded: "We are sailors – we go to the sea."

Industry/professional mariners' predisposition: According to the Board of Inquiry (U.S. DOT, 1992), the master's predisposition ("We are sailors – we go to the sea") was shared by other respected professional mariners.

The above predisposition is unsound. Certainly, the perils of the sea are part of maritime transport. However, this does not justify exposing a ship deliberately and, by all means, to those perils. Seasoned mariners, who are well aware of and anticipate the limitations and abilities of a ship and her cargo to withstand adverse weather conditions, would have taken appropriate decisions based on sound judgments. Given the combination of the following factors, a reasonable delay, perhaps for one or two days, in Port Elizabeth would have been a better decision in the interest of safety of the crew, the ship and her cargo, and the marine environment:

- Ship stability (large GM 1.86m);
- Ship design and operational properties;
- The environmental sensitivity (arsenic trioxide) and the position (on-deck-stowed) of cargo;
- Fairly severe weather conditions, particularly the winds/waves direction relative to the ship's course.

In addition, the ship would have avoided considerable costs, delays, negative publicity and legal litigations. However, other factors described elsewhere in this section hampered the master's ability to take an appropriate navigational decision.

Economic pressure: The pressure to meet the schedule in Port Baltimore might have led the master to take biased navigational decisions, particularly prior to departure and during the early stages of the voyage. As mentioned above, the master was anxious to get the ship loaded and underway. Despite substantial deterioration of the weather conditions, the master took no measure to avoid the storm, but went ahead with the schedule.

Summary

Due to the combination of the aforementioned factors, the master in association with other ship personnel failed to avoid the storm while at sea and prior to departure from Port Elizabeth. Not only did the master fail to offset the effects of heavy weather conditions, but, on the contrary, his poor shiphandling at sea considerably amplified these effects.

3.4.1.6. Inherent faults in the cargo securing system

In Section 3.4.1.1, *the exposure to forces acting on the system* (see the box on the left of Figure 3.40 continued from Figure 3.20) has been explored. The following section explores *inherent faults or deficiencies in the m/v SCI's cargo securing system* itself (see the **highlighted box** in Figure 3.40).

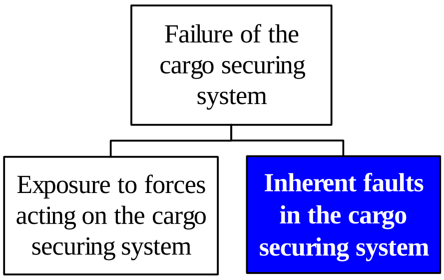


Figure 3.40: Immediate causes and contributing factors to the failure of the m/v SCI's cargo securing system (continued from Figure 3.20).

The m/v SCI case presented a large menu of faults/ deficiencies in the cargo securing system. Based on the data available, these faults are explored in conjunction with the failure modes of individual components of the system as shown in the fault tree (Figure 3.41).

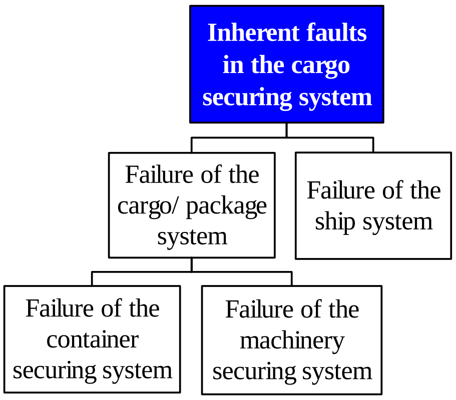


Figure 3.41: Fault tree of failures of components of the m/v SCI's cargo securing system (continued from Figure 3.40)

Because of massive failures and concerns about the losses overboard of arsenic trioxide containers, the investigation report and other relevant sources provided, to some degree, detailed data about the failures and deficiencies in the stowage and securing of on-deck and below-deck-stowed containers and the piece of machinery. However, very little information is provided for magnesium phosphide pallets stowed in the upper tweendeck of the no.1 hold and cargoes in other holds. Therefore, the analysis primarily focuses on containers and the piece of machinery stowed on deck.

As mentioned earlier, the main components of the m/v SCI's cargo securing system included: a) securing/lashing devices, gear or equipment; b) the cargo/packaging system; and c) the ship system, each of which consists of a number of components. Packing of cargo inside containers and stowage of cargo/containers onboard the ship are also important components of the cargo securing system. Given the data available and sequences of events, the top levels of the fault tree (see fault tree in Figure 3.42) explore failures in the cargo/packaging system (i.e. container and machinery securing systems) and the ship system (hatch covers and pedestals). Failures/deficiencies in securing devices, gear or equipment and packing and stowage are explored in conjunction with each component depicted in the fault tree. The analysis begins with failures or deficiencies in the container securing system, through the machinery and ship system.

3.4.1.7. Failure of container securing system

The m/v SCI case history showed that sequences of failures in the cargo securing system were unclear. All containers stowed aboard the m/v SCI were 20 and 40-foot standard containers. Except one, all containers were of steel construction. One container was fibreglass-reinforced plastic (FRP) sandwiched with plywood core panels on the sides, ends and top. The failure of the container securing system onboard the m/v SCI was attributed to: a) failure of container structure; b) failure of cargo securing inside containers; and c) failure of container securing on board the ship (see fault tree in Figure 3.42 continued from Figure 3.41).

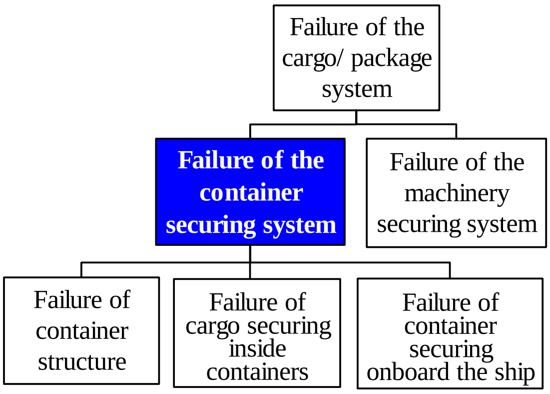


Figure 3.42: Fault tree of failures of the container securing system (continued from Figure 3.41)

The following section explores (*from left to right*) each factor **under the highlighted box** in Figure 3.42.

3.4.1.8. Failure of container structure

The container structure itself is an important element of the cargo securing system. Some important concerns for shipboard container stowage are racking, with the tendency to get out-of-square, corner post collapse, and local structural failures of the containers. Standards for container dimensions, design, construction, testing, inspection, and maintenance have been established under the International Convention of Safe Containers (CSC) and the U.S. regulations (49 CFR 450-453). Dimensional specifications for containers have been highly standardised by commercial necessity. There was no evidence of any deviations from these specifications with any of containers aboard the m/v SCI.

Standards for container construction are performance-oriented. According to standards (U.S. DOT, 1992), the containers must be able to withstand applied test loads of:

- 15 tons (transversely) on the structure for racking;
- 0.6 times the container's maximum payload (0.6 x 27 tons = 16.2 tons) on the sidewalls; and
- 1.8 times the maximum stacking weight (based on 6-high container stacks) spread across the four corner posts.

The Board of Inquiry (U.S. DOT, 1992) estimated transverse forces in casualty conditions over 21 tons. Stacking weight was probably not an issue in the case of the m/v SCI as the containers on the hatch were stacked two-high. There was no evidence that any of the container corner posts failed in compression.

The performance properties of a container change over the time. In compliance with the relevant requirements, containers should be inspected and maintained regularly. In-service inspection and maintenance are the responsibilities of the container owner. Detailed repair standards have been published in the industry. In accordance with U.S. regulations, maintenance records must be available to the USCG for examination.

Failure of container structure: Several containers sustained damage during the storm. In particular, the FRP container, which was one of the four containers remaining aboard on the no.2 hatch cover (Figure 2.16), broke apart, splitting at the top, sides and end walls. Whether the failure of the FRP container preceded the collapse of the stowage and the securing system was uncertain. However, it was certain that the failure of the FRP container preceded the release of cargo.

Why did container structure fail?

In combination with other factors and conditions, the following contributing factors to the failure of the container structure are explored (see fault tree in Figure 3.43 continued from Figure 3.42).

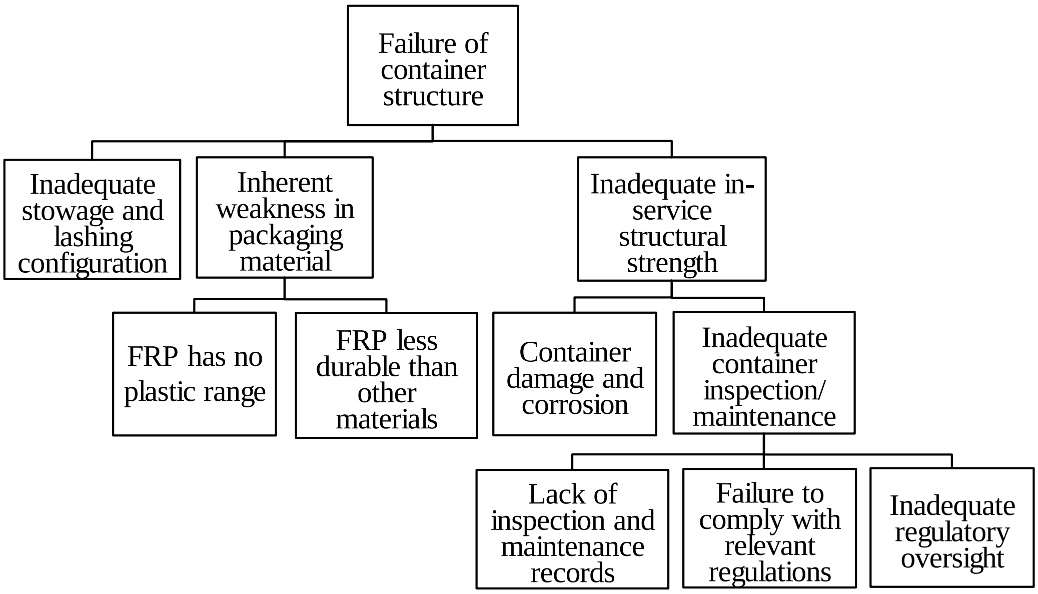


Figure 3.43: Fault tree of failure of the container structure (continued from Figure 3.42)

The following section explores (*from left top-down to right top-down*) each factor (Figure 3.43).

Inadequate stowage and lashing configuration: Although it was not an especially high stacking weight by itself, one steel container loaded to a gross weight of 20 tons of cotton was stowed on top of the FRP container. In addition, six containers were bridged in a block with the FRP container, subjecting it to cumulative racking forces combined with crushing forces. A lashing system can enhance stacking resistance of the containers when properly installed. On the contrary, when securing equipment and gear are improperly used, the entire cargo securing is likely to fail regardless of how well designed and strong the system is. Without lashing support throughout the stowage, combined transverse forces across bridged stacks are only absorbed by the container structure itself. Given high transverse forces exerted in heavy motions (estimated over 21 tons), the cumulative racking forces for the entire stowage in the casualty condition might have exceeded the racking resistance (15 tons) of containers. Several containers had sustained racking at the door ends.

Inherent weakness in packaging material: The physical properties of FRP are different from steel in two key interrelated respects: the elastic/plastic range and durability:

FRP has no plastic range: Steel under load goes through, first, an elastic range (where it will spring back to its original shape), and then a plastic range (where it will show some permanent deformation, but still be intact) to its breakpoint. FRP has no plastic range. It goes from an elastic range to its breakpoint. In the case of the m/v SCI, while many of the steel containers left on deck and observed underwater showed substantial distortion and deformation, the FRP container did not. The FRP container had just broken apart.

FRP less durable than other materials: Although it was not confirmed independently during the inquiry, the Board of Inquiry noted a number of general concerns in the industry regarding FRP containers. It particular, FRP is less durable than other materials, showing problems that are more frequent at fastenings to the side rails. The FRP containers suffer damage from dunnaging more easily than steel construction containers.

Inadequate in-service structural strength – degraded performance of FRP container: According to the investigation report, all containers loaded on board the m/v SCI were tested in compliance with IMO standards. They were also subject to regular inspection programmes according to U.S. regulations (49 CFR 453). However, for at least one container (i.e. FRP container) on the no.2 hatch, there were signs that the in-service strength was inadequate. The structure of the FRP container appeared to provide degraded in-service performance, raising doubts about its suitability for the unrestricted carriage of dangerous goods aboard the ship. In addition, the fact that several containers sustained damage and racking at the door ends suggests that they might have had inherent structural weaknesses. These weaknesses might have contributed to the failure of the container itself and subsequently to the failure of the container stowage and securing system. In principle, the cargo stowage and securing act like “a pack of cards” – if one element fails, the entire system may collapse.

Container damage and corrosion: Container structural weakness might have been exacerbated by any possible earlier damage and corrosion.

Mismanagement – inadequate container inspection and maintenance: Inadequate in-service strength, for whatever reason including possible damage and corrosion, indicates that containers might have not been adequately inspected and maintained. The responsibility lies with the owner of the container and responsible authorities.

Lack of inspection and maintenance records: During the course of the investigation, the USCG received little feedback on maintenance histories of containers. In particular, the attempt to examine the maintenance history of the FRP container produced negative results. The container owner said that the lessee had records, but the lessee pointed to the owner. Although the investigation report stated that all containers were tested in conformance with IMO standards and they were also subject to regular inspection programs according to U.S. regulations (49 CFR 453), neither party produced any in-service inspection records. The absence of records suggests that containers might not have been adequately inspected and maintained.

Failure of the container owner to comply with relevant regulations: To comply with relevant regulations, the container owner was responsible for container inspection and maintenance. In addition, U.S. regulations stipulated that maintenance records must be available to the USCG for examination. The negative results to produce inspection and maintenance records indicate that the container owner might have failed to comply with relevant regulations.

Inadequate regulation compliance and enforcement oversight: The absence of inspection and maintenance records showed, in this case, that the responsible authorities did not adequately oversee compliance and enforcement of relevant regulations. It also showed negligence on their part. The relevant authorities and agencies are, among other things, responsible for the oversight of regulation compliance and enforcement. They have all the required power and means to obtain inspection and maintenance records. Despite the facts that container inspection and maintenance are the responsibilities of container owners and that U.S. regulations stipulate that maintenance records must be available to the USCG for examination, the USCG, as an enforcement agency, has the responsibility and means to keep records of the violators and take appropriate enforcement measures, if necessary. The USCG should not have waited to receive maintenance histories of containers after the accident. Therefore, it was partly responsible for the lack of inspection and maintenance records, and consequently for any possible inadequate container inspection and maintenance.

3.4.1.9. Failure of cargo securing inside containers

Container performance, such as the resistance of container ends, sidewalls and floors, is significantly affected by inadequate cargo packing, blocking and bracing. Container packing certificates recommended by the IMDG Code, as prerequisite for accepting containers for shipment, were available aboard the m/v SCI.

Failure of cargo securing inside containers: In Port Charleston, the interior inspection of a sample of below-deck-stowed arsenic trioxide containers showed that the stowage had collapsed. Blocking and bracing had broken and many pallets had shifted or turned over. Given the greater forces affecting on-deck-stowed containers, it is reasonable to suggest that arsenic trioxide drums in other containers stowed on the hatch covers were similarly upset. Once broken loose inside the container, shifting cargo can exert impact loads that can be much greater than the forces associated with ship’s motions. The latter forces compound the impact. In the case of m/v SCI, according to estimations of the Board of Inquiry (U.S. DOT, 1992), the maximum force (16 tons) acting against sidewalls of containers was within the range of test loads. However, impact loads due to cargo shifting inside containers might have caused slight deformations and shifting of containers themselves.

Why did cargo securing inside containers fail?

The following contributing factors to the failure of cargo securing inside containers are explored (see fault tree in Figure 3.44 continued from Figure 3.42).

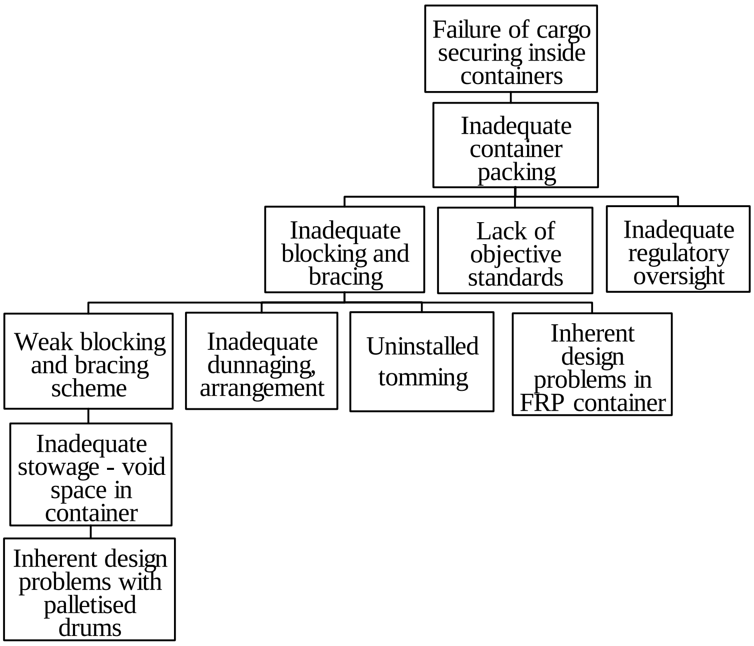


Figure 3.44: Fault tree: failure of cargo securing inside the container (continued from Figure 3.42)

The following section explores (*from left top-down to right top-down*) each factor (Figure 3.44).

Inadequate container packing: Despite attempts to follow the required packing procedures, packing of arsenic trioxide drums inside containers carried aboard the m/v SCI was inadequate (compare container packing in Figures 3.45 and 3.46).

Figure 3.45: Palletised arsenic trioxide drums packed inside a container aboard the m/v SCI (U.S. DOT, 1992)

Figure 3.46: Un-palletised drums packed inside a container in accordance with regulations and good practices (Gefährliche Ladung, 1998)

Inadequate blocking and bracing: Stowage inside containers was undermined by inadequacies in cargo securing inside containers. Because of inadequate blocking and bracing, arsenic trioxide drums shifted and turned over inside containers, inducing shock loads on the containers and the cargo securing system.

Weak blocking and bracing scheme: Appropriate blocking and bracing can transmit some forces to a container's floor and side rail. In the case of m/v SCI, the overall blocking and bracing scheme employed revealed weaknesses, including:

Inadequate stowage - too much empty space inside containers: Tight stowage is a prerequisite for effective cargo securing. Palletized arsenic trioxide drums packed inside containers resulted in too much empty space across the container floor, making a tight stow difficult (Figure 3.45).

Inherent design shortcomings with palletized drums: Palletisation enhances cargo handling, but undermines proper cargo stowage and securing. The empty space created across the container floor was the result of the pallet configuration. Un-palletised drums are more easily stowed in a tight and balanced arrangement (Figure 3.46).

Inadequate dunnaging materials and arrangement: Due to the configuration of palletized cargo and cargo securing procedures, dunnaging materials and arrangements appeared inadequate. In particular, the triangular brace provided an inadequate angle and tie-in to the container side rails for resisting heavy transverse loads (Figure 3.45).

Uninstalled tomming: Tomming is the securing of cargo to prevent upward movement (Figure 3.46). No tomming equipment was installed between the tops of the drums and the ceiling of the container for tightening the stowage (Figure 3.45).

Inherent design shortcomings in FRP container: In the case of the FRP container, its sides had no corrugations to permit effective wedging of dunnaging materials.

Lack of objective standards for blocking and bracing arrangements: U.S. regulations (49 CFR 176.76) provide basic performance standards for container packing. The IMO, U.S. National Cargo Bureau (NCB), and the U.S. Maritime Administration offered additional guidance. But, according to the Board of Inquiry, objective standards for blocking and bracing arrangements were nonexistent (U.S. DOT, 1992). The packing of intermodal containers was described as more art than science.

Inadequate regulatory oversight - container packing: Regulatory oversight and enforcement concerning container packing was limited and lagging behind.

3.4.1.10. Failure of container securing onboard

Components of the cargo securing system, which act together, work to transmit forces on cargo into the ship’s structure. Achieving that aim depends on a variety of factors, including the strength and elasticity of the components of the cargo securing system, fit tolerance and proper installation.

Lacking shipboard documentation and detailed analysis, the Board of Inquiry evaluated the cargo securing system of the m/v SCI based on Lloyd’s recommendations and general industry design standards. Overall, most of the components appeared to represent standard and strong construction, with sufficient load capacities under tension. The m/v SCI was fitted with a basic stack–lash system which, dating from the initial construction of the ship and extended with the retrofit of deck pedestals, was considered as a well-designed system.

Container losses and damage were attributed to the failure of the cargo securing onboard the ship. The system is used for securing containers and other CTU and cargoes.

Why did the cargo/container securing onboard the ship fail?

The fault tree in Figure 3.47 (continued from Figure 3.42) shows factors contributing to the failure of the container securing system onboard of the m/v SCI.

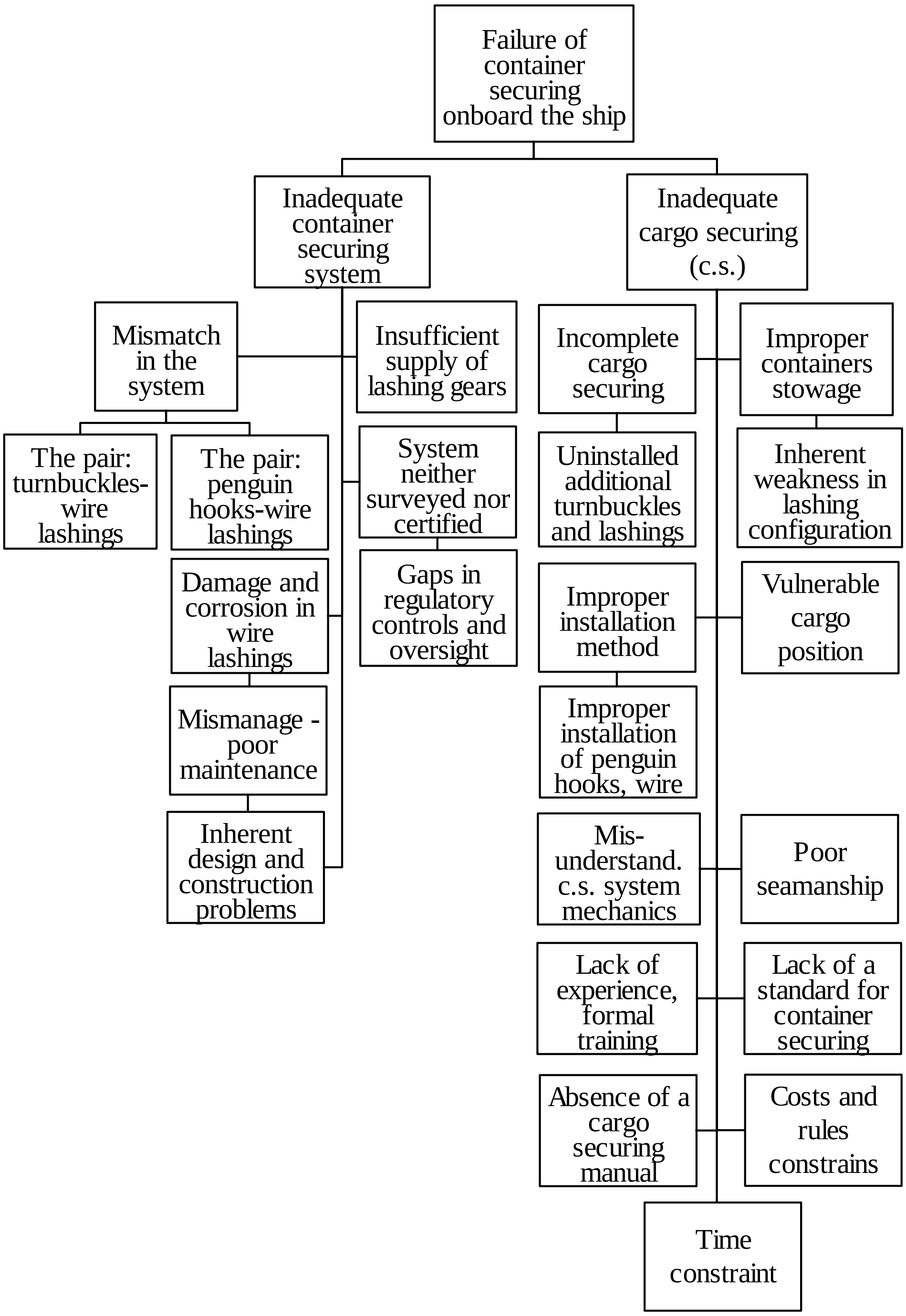


Figure 3.47: Fault tree of failure of the cargo/container securing onboard the m/v SCI (continuous from Figure 3.42)

The following section explores (*from left top-down to right top-down*) each factor (Figure 3.47).

Inadequate cargo/container securing system: Although most of its components appeared to be of a standard construction, the cargo/container securing system proved inadequate to withstand static and dynamic loads imposed upon it. The following are deficiencies in the m/v SCI's cargo securing system and contributing factors:

Mismatches in the cargo securing system: Despite a well-designed system – this dated from the initial construction of the m/v SCI in 1973, the cargo securing system installed in 1992 reflected mismatches in improvised installation. The most evident mismatches in the actual installation aboard the m/v SCI were: a) the pair of rigid hook-type turnbuckles with wire lashings; and b) the pair of penguin hooks with wire lashings

The pair of rigid hook-type turnbuckles with wire lashings: The most noticeable irregularity was a mismatch between rigid hook-type turnbuckles and wire lashings. The m/v SCI was equipped with wire-lashings with press-fitted stoppers every few feet and eyes at either end. The press-fitted lashings are designed for use with turnbuckles with cylindrical claw fittings. Approximately half the turnbuckles aboard the m/v SCI had cylindrical claw fittings. An equal number of turnbuckles were fitted with rigid hooks. Both types of turnbuckles were used on hatches no. 3 and 4. The investigation found some of the rigid hooks had sustained a severe bend of about 75^o, which apparently created unbalanced strains on wire lashings. Due to bending, the bearing surface was also significantly reduced, presenting conditions for slackened wires to jump out of the hooks.

The pair of penguin hooks with wire lashings: A potential failure point of the cargo securing system was the mismatch in the pair of penguin hooks with wire lashings. The penguin hooks are most commonly used with rod-type lashings. The pair of penguin hooks with wire lashings was a standard lashing configuration aboard the m/v SCI.

Insufficient supply of lashing equipment and gear – long bridges unavailable onboard: The investigation found no evidence that longer-than-usual bridges were available aboard the m/v SCI. These bridges were needed to tie 20-feet container stacks together longitudinally.

Damage and corrosion in wire lashings: The strength reduction resulting from the mismatch was compounded by earlier damage and corrosion in the wire lashings. The investigation found several wire lashings with earlier permanent deformation and broken strands on the un-reinforced eye (Figure 3.48). The wire lashings in inventory and use were also found corroded, with broken strands on the outside of the bend. The wire lashings were probably the weakest link (lowest breaking strength) in the cargo securing system of the m/v SCI.

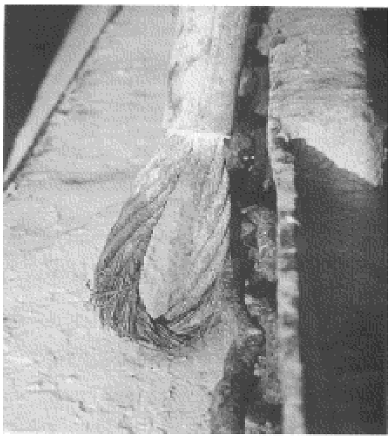


Figure 3.48: A damaged un-reinforced eye aboard the m/v SCI (U.S. DOT, 1992)

Mismanagement - poor maintenance: Lack, mismatch, earlier damage and corrosion in the lashing equipment and gear suggest that the m/v SCI's cargo securing system was mismanaged and poorly maintained. Some indicators of poor management of the cargo securing system include:

- Rogue securing equipment in use/inventory
- Improper maintenance of securing equipment in use/inventory
- Insufficient supply of correct securing equipment.

The m/v SCI's container securing system was neither surveyed nor certified: Classification societies, particularly the Germanischer Lloyd and Lloyd's Register, began publishing relevant rules as early as 1973. The m/v SCI, which was built in 1974 and classed by the Lloyd's Register, was neither surveyed nor certified for its container securing system. The certification was optional.

Gaps in regulatory controls and oversight programs: According to the Board of Inquiry (U.S. DOT, 1992), regulatory controls and oversight programmes showed significant gaps in safety for the carriage of containerised dangerous cargo in U.S. waters. The IMO and classification society rules and guidelines systematically outline the development of good securing systems. The classification society certification for the cargo securing system was optional. No government had issued regulations for cargo securing (U.S. DOT, 1992). Neither the U.S. nor the Panamanian government had implemented (1992) the IMO guidelines concerning the cargo securing system (U.S. DOT, 1992).

Inherent design and construction shortcomings: The ship design and construction, including cargo-securing systems, are complex processes that require a large number of assumptions and approximations for each individual ship and component. They require a coherent picture of the forces acting on the systems. Over the years, a variety of methods have been developed. This development has been an iterative process, in which assumptions and approximations for calculating forces and design criteria have been refined. In order to prevent damage and losses to deck-stowed cargo, the classification societies began developing rules for securing of containers onboard a ship since the early 70's. All major class societies have published their rules. In 1981, the IMO published relevant guidelines for cargo stowage and securing onboard non-cellular ships.

In a 1983 study for the U.S. Maritime Administration, C.R. Crushing (U.S. DOT, 1992) identified and compared six different analytical methods used by the classification societies and the IMO. The study found that methods varied. They have produced a wide range of different results for any given ship. Variations in ship characteristics, loading conditions, weather conditions, and shiphandling at sea make difficult any exact estimation of maximum forces for design purposes. The variety of calculation methods used by different classification societies reflects this to some extent. For example, calculations generally assume loading conditions that would produce the largest forces, and targeted those cargoes or containers that would be subject to the most severe conditions of these forces. Methods assume a maximum rolling angle of 30^o. The casualty conditions for the m/v SCI span the range in some of these factors. GM and max roll angle might have exceeded the values for the design condition.

In the design of ships, the consideration of ship's motions and acceleration is also important, among other things for assessing the cargo securing system. Generally, the classification society rules contain explicit formulas for calculation of design values. These formulas take into account only the main dimensions of the ship, such as length, breadth, block coefficient and forward speed. The operational profile of the ship is not explicitly included in these formulas (Jensen et al., 2004). They largely rely on engineering judgment of the relevant parameters. Without an operational profile, the naval architect cannot properly assess the factors influencing the ship's motions and acceleration. In recent years, however, attempts have been made to develop more efficient methods, which would enable naval architects to predict with sufficient accuracy the motions and acceleration in the conceptual design phase (Jensen et al., 2004).

In summary, the variability of results generated by different methods leads to variations in the design and construction of ships, containers and other cargo transport units and cargo securing system components. The design and construction of the systems are, to various extents, based on numerous estimations, approximations and guesswork.

Inadequate cargo securing: During the investigation, the Sandy Hook pilot (Port Elizabeth) stated that he never saw any on-deck lashing activity while he was aboard the m/v SCI. At 1740 hrs, on January 3rd, as the pilot disembarked, the crew reported completing cargo lashing. By this time, it was dark. The ship was one mile west of the Ambrose Light, sailing in open seas on a course of 180^o and increasing speed to 12-14 knots, with E-NE winds of about 20 knots. The m/v SCI left Port Elizabeth with cargo inadequately secured. The following are the deficiencies in cargo securing and contributing factors:

Incomplete cargo securing: The investigation found strong evidence showing that the crew most likely did not complete cargo lashing. Container lashing at the no.3 hatch was the most revealing evidence. In Port Charleston, containers stowed in the no.3 hatch were found fully bridged, but only partly lashed. In Port Baltimore, a similar pattern of incomplete cargo lashing configuration was found. Interior container stacks were left unlashed.

Uninstalled additional turnbuckles and lashings: In order to enhance cargo securing, the crew claimed that additional turnbuckles and lashings were installed. But the type of turnbuckles described by the crew was missing. The Board of Inquiry considered several possibilities for explaining the "missing" turnbuckles. The suggestion that they had fallen overboard did not match with the fact that the predominant mix of turnbuckles fitted with bolted clevis jaws or pelican hooks with keepers at the bottom found aboard were not the specified type of additional turnbuckles. According to the Board of Inquiry, the only really credible explanation was that the additional turnbuckles and lashings were not installed in the first place (U.S. DOT, 1992).

Improper container stowage - inherent weakness in lashing configuration: An inherent weakness in the lashing configuration, in particular in the no. 2 hatch, was stowage of 20-foot containers in 40-foot spaces on both outboard sides. Stowage left no room for lashing of the adjacent ends of containers, which were separated by only 7.62 cm. At the base, containers rested on cones only. These containers were secured at one side only, leaving the other side of each container stack completely unsecured. The longitudinal bridge as drawn between these 20-feet stacks, if they existed, would have been practicably ineffective in tying them together. The investigation found no evidence of the existence of "longer-than-usual" bridges onboard the m/v SCI.

Improper application of installation methods: Indiscriminate and poor methods were observed in the installation of wire lashings. About half the wire lashings were found improperly installed. While wire lashings were fitted with eyes at both ends, only one end incorporated a rope thimble, which is a standard practice to maintain rope strength and reduce wearing. The "soft eyes" (i.e. those without thimbles – see Figure 3.48) were installed over the penguin hooks. The wire was pulled to a tight radius, which would have probably reduced the connection efficiency (according to the Board of Inquiry, by as much as 10%) as the wire was flatted and strained under load.

Improper installation of penguin hooks/wire lashings: The degree of turn of penguin hooks and the flexibility of lashings were parts of the problem. By design, penguin hooks are fitted into the container corner casting by turning them into place. The way in which they were installed aboard the m/v SCI, some penguin hooks were turned at a substantial angle to the axis of the lashing. In at least one case, the lashing was partially twisted, riding up on the projected hook and taking a bight above the elbow of the hook. With alternative tensioning and slackening, the lashing might have either incrementally turned the penguin hook or fallen off the hook. After the accident, the investigation found several turnbuckles and lashings remaining attached to the ship. Four wire lashings were still threaded through turnbuckles, all of them showing intact eyes. In this case, the connection at the penguin hooks was the most likely failure point.

Misunderstanding of cargo securing system mechanics: In the course of the investigation, several crewmembers were asked to sketch from memory the lashing arrangements on the no.2 hatch. The sketches were consistent, showing a standard "inside-diagonal" lashing configuration, with four extra long lashings. The crew described long lashings on top of the upper containers as “extra” lashings for heavy weather conditions. However, the cargo lashing was incomplete in the first place. Without systematic lashings on each container, these extra long lashings, if actually installed, would have provided no support half of the time as the ship rolled from side to side. If installed, extra long lashings would have tended to build up unbalanced racking tensions in the containers themselves.

Vulnerable cargo position: Deck-stowed cargo, especially the furthest outboard and nearest the end of the ship, is most vulnerable to weather hazards. As mentioned earlier, arsenic trioxide was regulated under the U.S. Federal Regulations (49 CFR 171-180) and the IMDG Code for carriage onboard a ship. According to the IMDG Code, stowage is permitted “*on deck or under deck*.” Arsenic trioxide was designated a “marine pollutant” in the IMDG Code (1990). Under the MARPOL 1973/78 Convention (Annex III, Regulation 5), harmful substances shall be “*properly stowed and secured so as to minimise the hazards to marine environment without impairing the safety of the ship and persons on board*.” Annex III was optional for MARPOL parties. In 1992, the U.S. Research and Special Programs Administration (RSPA) made proposals to adopt these guidelines into the U.S. regulations and modify the stowage requirements for arsenic trioxide by adding: “*Where stowage is permitted ‘on the deck or under deck’ under deck stowage is preferred except when a weather deck provides equivalent protection”* (U.S. DOT, 1992). A similar requirement is provided in the IMDG Code. In the case of the m/v SCI, in compliance with the existing rules, six arsenic trioxide containers were stowed on the weather deck over the no.2 hatch cover, which apparently did not provide sufficient protection. Four of these six arsenic containers, together with other 17 containers and the piece of machinery, were lost overboard.

Poor seamanship: Stevedores stated that the practice of leaving interior container stacks unlashed was not uncommon. Even when shoreside-lashing gangs did the work, the cargo lashing was generally determined and directed by the chief mate. An inadequate system and improper and incomplete cargo securing demonstrated poor seamanship.

Lack of experience and specific formal training: Without a cargo securing manual and other relevant instructions, cargo stowage and securing aboard the m/v SCI were planned and performed on the basis of ship personnel experience. The deficiencies in the cargo securing demonstrated that the ship personnel, including the master, deck officers, bosun and AB seamen, lacked adequate experience in cargo securing. The master had no previous experience with the carriage of containerised or unitized cargo. None of the crew had ever had any specific formal training in cargo securing.

Lack of a standard approach for container securing: According to the Board of Inquiry (U.S. DOT, 1992), the shipping industry lacked a standard approach to container securing onboard ships. Each set of rules has generated different results. Non-standard containers, special equipment and awkward (odd-shape) cargo are often stowed together with standard intermodal containers and other cargo transport units. In these cases, cargo securing has often been improvised.

Absence of a cargo-securing manual: The absence of a cargo-securing manual aboard the m/v SCI was a key deficiency. IMO resolution A714 (17) recommends provision of this manual aboard the ship. The IMO document provides details on securing arrangements and their location, inventory of securing gear and their strengths, correct methods of application, guidance on stowage and securing non-standard cargoes, plans for heavy weather and other relevant operational factors, and an analysis of design forces. The information contained in the manual would have helped the master and crew to avoid those conditions for which the cargo securing system had not been designed. In addition, Lloyd's Register and cargo securing system suppliers routinely provide relevant instructions as part of the setup or review package. However, the master of the m/v SCI was unable to produce any specific cargo-securing manual for the ship. He provided only two general reference books. In the absence of the cargo-securing manual and other relevant instructions, the ship personnel, whose experience and training proved inadequate, improvised cargo stowage and securing onboard the m/v SCI.

Costs and rules constraints: Probably for cost, company policy or rules reasons, the master declined the usage of the shoreside lashing gang in Port Elizabeth, opting for securing the cargo with the ship's crew after leaving the dock. This was a common practice in U.S. ports for foreign ships. Furthermore, perhaps for financial reasons, labour union rules in Port Elizabeth prohibited cargo securing alongside the pier when the shoreside lashing gang was not used. Economic considerations, policies or rules on whatever side (ship or shore side) jeopardized the safety of the crew and ship and the marine environment. The fact is that the ship left the port with cargo inadequately secured.

Time constraint: The pressure to meet the schedule in Port Baltimore might have biased the master's decision. Despite heavy weather conditions, he decided to leave the dock at Port Elizabeth hastily, with cargo still unsecured. As mentioned earlier, on 3rd January, at 1517 hrs, as the ship left the dock with the undocking and Sandy Hook pilots aboard, the crew supervised by the bosun began cargo securing. Darkness was falling and the ship was preparing to get into open seas. At 1740 hrs, the crew reported completion of cargo lashing. Given the scope of the task and significant time constraints, it was unlikely for the crew to have adequately completed cargo securing. It supposedly took less than 2 ½ hrs (exactly 2 hrs 23 min) for the crew to complete the entire cargo securing (including bridging, locking and lashing) on the deck of no. 1, 2 and 3 hatches and inside the no. 3 hold. The cargo was not secured adequately because the crew was also under time pressure while leaving the port in bad weather conditions. The Sandy Hook pilot reported that he saw no one on deck securing containers during his piloting. The investigation found that, in some areas, cargo securing was incomplete.

3.4.1.11. Failure of machinery securing

The following section explores failure of the machinery securing (see the **highlighted box** in Figure 3.49 continued from Figure 3.41).

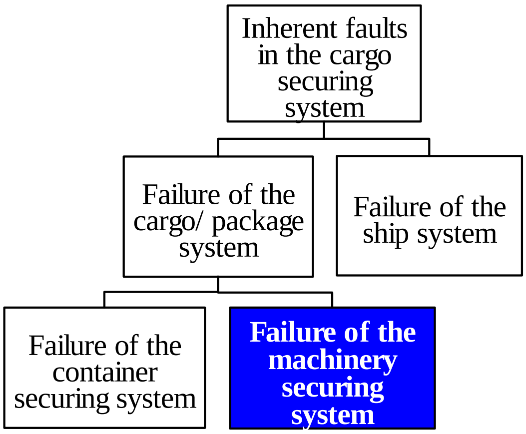


Figure 3.49: Fault tree of faults in cargo securing (continued from Figure 3.41)

The carriage of the piece of machinery onboard the m/v SCI was proven to be a source of danger. The failure of the machinery securing led to the loss of the machinery itself, and damage and loss of adjacent container. Some evidence was found onboard the ship and on the sea floor. An inspection on the ship's deck in Port Charleston found a wide arc scraped across the starboard side of the no. 2 hatch cover, which was the stowage location of the machinery. Of the 21 containers and the machinery lost overboard, by means of ROV, 15 containers and the machinery were located in an extended debris field approximately along the trackline of the m/v SCI between 0150-0210 hrs. The cargo was roughly clustered by stowage location from the no.2 hatch cover. The machinery was found near three other containers from the starboard side. The most likely scenario is that, at some point, machinery securing failed and the machinery broke free. It began sliding on the hatch cover, impacting adjacent containers. As it swept the deck in an arc and slid overboard, the machinery wiped out containers and two middle pedestals on the starboard side. The relevant question is:

Why did the securing of the machinery fail?

The fault tree in Figure 3.50 (continued from Figure 3.49) shows factors contributing to the failure of machinery securing.

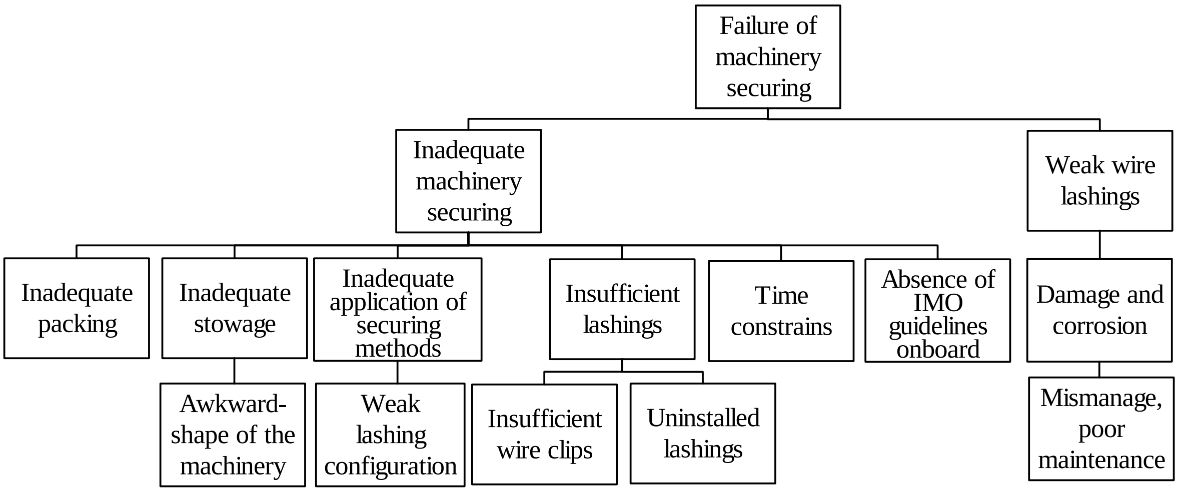


Figure 3.50: Fault tree of failure of machinery securing (continued from Figure 3.49)

The following section explores (*from left top-down to right top-down*) each factor (Figure 3.50).

Inadequate machinery securing: In combination with other factors mentioned elsewhere, including forces exerted in heavy motions of the ship and green waters, the failure of machinery securing was largely attributed to extensive irregularities and deficiencies in the securing of the machinery. The machinery was prevented from moving by insufficient friction and lashings around the machinery itself.

Inadequate packing of the machinery: The machinery was improperly packed for carriage by sea. It was packed in a way that made cargo securing difficult. The machinery was mounted on a heavy steel frame and secured to a wooden skid. The overall dimensions of the unit (machinery + steel frame) (15m x 2.1m x 1.6m) were incompatible with container spaces on deck. The packer had not installed on the machinery itself and/or the steel frame any securing point or special fitting to facilitate securing the machinery onboard the ship. There were, for example, no fittings for the use of cones for twistlocks. The machinery could have been mounted on a standard cargo transport unit such as flat rack or platform. The standard unit could have been better fitted into the standard container space on deck.

Inadequate stowage of the machinery: Despite the incompatibility between dimensions of the unit and container spaces on deck, the machinery was stowed on the no.2 hatch cover adjacent to outboard 20-foot containers stacked on the starboard side. The unit rested on at least 8 flat shoe-plates on the hatch cover, which reduced the point of contact with the surface of the hatch cover. The small frictional surface area provided by the flat shoe-plates reduced resistance. In addition, given the unit (1.6 m) and container (2.44 m) widths, the unit was approximately 0.84 m narrower than the container space in which it was stowed. The space (approximately 0.42 m) between the unit and containers in each side was, at the same time, too narrow for the crew to make a proper lashing and too wide for the adjacent containers to provide support and prevent sliding. The machinery could have been stowed in another, more spacious location aboard the ship.

Awkward shape of the machinery: The very awkward shape of the machinery made it difficult for packing, stowage and securing. The IMO and other relevant organisations have highlighted the potential dangers associated with the carriage of this type of cargo.

Inadequate application of cargo securing methods: The IMO and other relevant industry guidelines provide information concerning cargo securing of heavy items without securing points. However, the crew followed neither these guidelines nor good practices in the industry.

Weak lashing configuration: The lashing configuration showed weakness. In order to prevent transverse movements, the IMO guidelines for lashing of heavy items (MSC Circular 530) specify that effective lashings are to be brought around the unit and both ends secured at the same side (Figure 3.52). The lashings of the machinery, as depicted by the chief mate in his drawing, were improperly installed, permitting the machinery to shift easily. The machine was lashed at three points, with each wire lashing at the ends running diagonally underneath the machine, up around the top, and back down diagonally across the other side (Figure 3.51). The lashing configuration as well as the relative width of the unit in an 8-foot wide space left too much room for the machine to slide.

Insufficient machinery lashing: Machinery lashing contained an insufficient number of wire clips and uninstalled lashings.

Insufficient number of wire clips installed: The number of wire clips used to secure the lashings was insufficient, presenting a weak link in the system. According to the Board of Inquiry, standard marine practices require a minimum of two clips for wires of 1/2-inch diameter, and three clips for wires of 5/8-inch diameter or greater. The investigation found the broken wire lashings remaining on the deck in Port Baltimore were at least 1/2-inch. According to the chief mate’s account and drawing, there were two clips per wire, but the investigation found only one clip remaining on the wire. Other supporting evidence was found in the no. 3 hatch. The investigation found that the crew had used only a single clip per wire in lashing the buses stowed on the no.3 hatch. Probably some wire lashings parted at wire clips.

Uninstalled lashings: The investigation found that the middle wire rope lashing in the machinery, as drawn by the chief officer (Figure 3.51), was missing when the ship arrived at Port Baltimore. According to the Board of Inquiry, this lashing was more likely not to have been installed in the first place. If it was not installed, the actual lashing was insufficient to have provided proper securing of the machinery in heavy motions.

Time constraints: The crew lashed the machinery as well as containers under time constraints while departing from Port Elizabeth.

Absence of IMO guidelines for heavy items: In the absence of IMO guidelines for heavy items onboard the m/v SCI as well as special fittings, securing of the machinery, which was proven to encompass numerous deficiencies, was improvised by the crew.

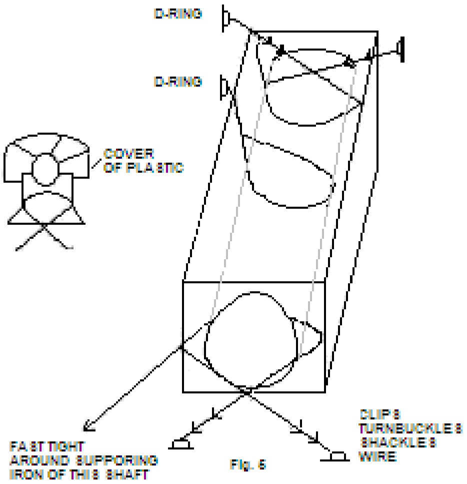


Figure 3.51: Securing of the machinery aboard the m/v SCI as drawn by the chief mate (U.S. DOT, 1992)

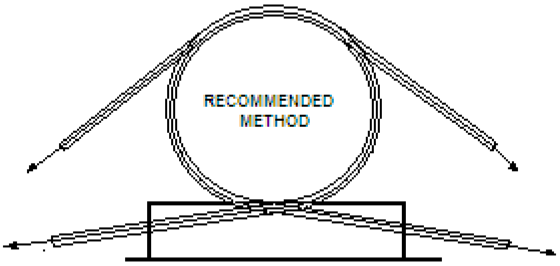


Figure 3.52: Securing of heavy items as recommended by the IMO guidelines (from U.S. DOT, 1992)

Weak wire lashings – one wire lashing broke: The investigation showed that one of the lashings of the machinery, that is the one at the forward end, failed before the clip did, indicating that the strength of the wire rope was weaker than the clip holding it.

Damage and corrosion in wire ropes: The weakness in the wire ropes can be explained by damage and corrosion (Figure 3.48).

Mismanagement – poor maintenance: Damage and corrosion in wire ropes and insufficient supply of wire clips and wire lashings suggest that the cargo securing system onboard the m/v SCI was poor maintained and mismanaged.

In summary, compared to the extensive irregularities in securing containers, particularly on the no.2 hatch cover, securing of the machinery presented even greater deficiencies. Impacts due to free movement and sliding of the machinery on deck might have significantly contributed to the failure of the container securing system, and subsequent damage and loss overboard of containers.

3.4.1.12. Failure of the ship system

The following section explores failure of the ship system (see the **highlighted box** in Figure 3.53 continued from Figure 3.41).

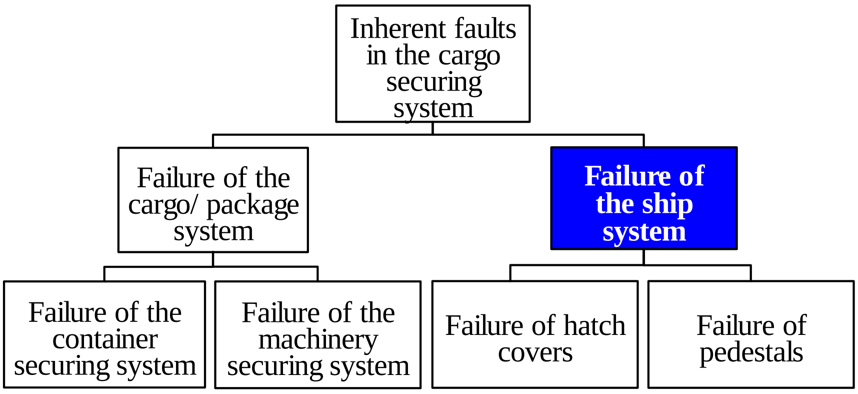


Figure 3.53: Fault tree of failures of the ship system (continued from Figure 3.41)

Many marine accidents/incidents, including damage and losses overboard of PDG, are attributed to weather hazards. Specially designed ships, such as containerships, have often reported cargo damage and losses. However, the carriage of packaged goods onboard non-specialised ship types is particularly sensitive to heavy weather conditions. Marine accident case histories (HCB, 1986-2003) have shown that cargo losses and damage are frequently reported on breakbulk ships carrying containers on deck and on hatch covers. Heavy motions of the ship in combination with green water on deck are common causes of cargo losses and damage. In the North Atlantic and North Sea, the greatest container losses and damage are experienced during the stormy winter months.

Failure of hatch covers

The hatch covers on the m/v SCI were constructed of eight panels each, folding open/closed by a chain-drive mechanism. They were secured (dogged down) by means of bolts. The hatch covers provided most of the structural support for the containers. They provided an immediate structure for transmitting forces from the containers and lashings to the ship’s hull via D-rings and shoe-plates. Loading capacities for the hatch covers were unavailable aboard the m/v SCI. The port captain (Port Elizabeth) pointed out that he used a rule-of-thumb in planning the stowage (U.S. DOT, 1992). The ship design had foreseen container stacks up to three-high. The m/v SCI had not been carrying deck containers higher than two-high for some time. There was no indication the static load capacities of hatch covers was an issue.

Failure of hatch covers – shifting and moving: The inspection showed that during the storm bent rollers on the outboard side of the port hatch cover had sustained damage, preventing the hatch cover from opening. This suggests that hatch covers might have shifted and moved at some point during the voyage. The shifting and movements probably preceded the breakdown of the stowage.

Why did hatch covers fail/move?

The fault tree in Figure 3.54 (continued from Figure 3.53) shows factors contributing to the failure of hatch covers.

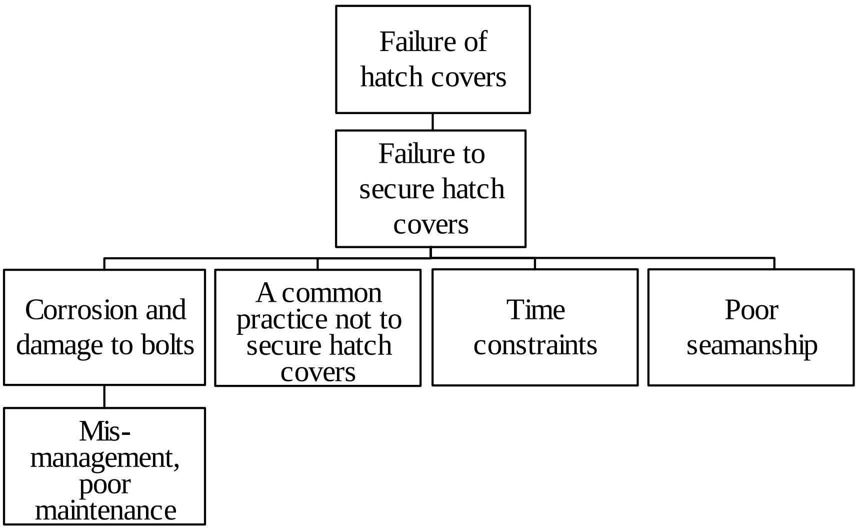


Figure 3.54: Fault tree of failure of hatch covers (continued from Figure 3.53)

The following section explores (*from left to right*) each contributing factor (see Figure 3.54).

Failure to secure hatch covers: Examination of hatch covers after the accident showed that none of them were dogged down at the time of the accident. Bolt threads in all bolts were badly rusted and damaged, making them useless. Probably none of hatch covers had been dogged down for some time – at least for several months, if not for years. While most of the cargo rested on the hatch cover, at least 2/3 of the lashings were secured to stationary D-rings on the deck. None of the D-rings were broken. The failure to dog down the hatch covers weakened the stowage and increased the likelihood of lateral movements. Forces exerted in the heavy motions, particularly at the top of rollings, could have reduced the cargo weight enough to substantially reduce, in turn, the friction between the gasket and the edge of the hatch covers and lift the hatch covers off, allowing them to move. As the hatch covers moved, most of the lashings would have been affected, resulting in greater tension for some and in increased slack for others. Subjected to loads, small movements might have begun to work the lashings, which gradually loosened, contributing to the collapse of the stowage.

Why did the crew fail to secure hatch covers?

Corrosion and damage: Bolt threads in all bolts were badly caked with rust. In addition, several bolts were either bent or damaged, preventing their use.

Mismanagement - poor maintenance: Rust, bends and damage in bolts indicate mismanagement and poor maintenance, if there was any maintenance at all.

A common practice not to secure hatch covers in coastal voyages: The Board of Inquiry (U.S. DOT, 1992) noted that it was a common practice to leave hatch covers unsecured during coastal voyages. Classification societies did not require hatch covers to be dogged in coastal voyages.

Time constraint: Under the time pressure while leaving the port at night and heading into the storm, the crew, probably tired after a long day at work, may have decided not to secure hatch covers.

Poor seamanship: Regardless of the type of voyage, leaving the port in heavy weather conditions with hatch covers unsecured, and poor maintenance of lashing equipment, demonstrate bad practices and poor seamanship.

Failure of pedestals

Containers stowed aboard the m/v SCI were supported on hatch covers and outboard on the elevated deck pedestals. Each hatch cover was arranged to accommodate eight stacks of 40-foot containers and another eight stacks of 20-foot containers, all stowed longitudinally. Extra deck fittings were provided to stow two 20-feet containers in the absence of any 40-foot container. Although designed for container stacks up to three-high, the m/v SCI never carried more than two-high.

Failure of pedestals: Two deck pedestals near the no.2 hatch failed disastrously. Both pedestals were bent completely over the bulwark, by 100-120^{o} from their original upright position (see Figure 3.55). These pedestals were strong double-width pedestals with double web frames. Several other pedestals near the no.2 hatch showed some signs of compression damage at the base, but were still intact (see Figure 3.56). The weakest pedestal, with only a single web frame, which supported a two-high stack and about twice the weight, did not fail.

Figure 3.55: Failed deck pedestals-starboard (U.S. DOT, 1992)

Figure 3.56: Compression damage at the bottom of pedestal (U.S. DOT, 1992)

Did the failure of pedestals play any role in the accident?

Provided the forces exerted in heavy weather conditions, the course of events, the location and structure of damaged pedestals and the degree of damage, the failure of two pedestals on the starboard side (Figure 3.55) was unlikely to have been an initial casual element in cargo loss and damage. The failure of these pedestals may not have preceded the collapse of the stowage and securing system. The most plausible explanation for the disastrous failure of two starboard pedestals was the impact from the piece of machinery. Given the heavy weight (21 tonnes) and the length (15.2 m) of the machinery, and the heavy steel frame in which it was mounted, the machinery removed two starboard pedestals on its way as it slid and rolled over the side. The location of the machinery on the ocean floor indicated that it went over the starboard side. The other pedestals near the no.2 hatch (Figure 3.56) bent under excessive compression forces. Such bending may have affected the cargo securing system.

3.5. Comparing system design and casualty conditions

Given the response of the ship in heavy weather conditions, an important question arises: Did the casualty conditions exceed system design conditions? The variations in weather conditions, loading conditions, ship characteristics, and shiphandling make it difficult to estimate exact maximum forces for design purposes. Classification societies have employed a wide variety of methods for estimation of these forces. The methods reflect, to some degree, the variations in the mentioned conditions. For calculation purposes, some common approaches and assumptions are used. Based on the data available, the following compares design and casualty conditions for some elements.

Wind speed and wave height: Design conditions commonly consider, as the worst weather conditions, winds up to 80 knots and wave heights of 10-12 m or above with an encounter probability of once every 20 years of continuous ship operation in the North Atlantic. In the case of the m/v SCI, given the measured weather conditions, the design conditions (wind speed and wave height) were not reached.

Metacentric height GM: Based on the departure conditions and the formula from U.S. regulations, the Board of Inquiry estimated a GM of 0.444 m, which would have been an appropriate GM for the m/v SCI to avoid or minimise cargo damage and losses. The actual GM (1.86 m), at which the m/v SCI left Port Elizabeth, by far (several times) exceeded this value (0.444 m).

Rolling angle: Most methods for calculation of forces assume a maximum rolling angle of 30^o. The casualty conditions for the m/v SCI case suggested that during the voyage the rolling angle (35^o) might have exceeded the maximum value (30^o) for the design conditions.

Transversal and perpendicular forces: For design purposes, calculations of forces generally assume the loading conditions in which the largest forces would be exerted.

The containers/cargoes that would be subject to the most severe effects of these forces are selected for calculations. In order to determine whether the forces exerted in casualty conditions exceeded those of design conditions, based on Lloyd's Register rules and the investigation data, the Board of Inquiry estimated and compared the design and casualty conditions for the m/v SCI (Table 3.3). Both conditions targeted the containers on the no.2 hatch, i.e. containers exposed to damage and losses.

Table 3.3: Forces of design and casualty conditions for the m/v SCI (U.S. DOT, 1992)

Forces	Design conditions (Tons)	Casualty conditions (Tons)
Transverse forces	25.1	21.1
Normal/ perpendicular forces – top of roll	12.1	9.6
Normal/ perpendicular forces – bottom of roll	48.7	38.5

The comparison (Table 3.3) showed that most force values in the casualty conditions were within the boundaries of design conditions. Employing several other methods from other classification societies, the Board of Inquiry performed similar estimations and comparisons. The investigation report, however, did not provide any result, but only stated that the results varied in magnitude (U.S. DOT, 1992).

Given the estimated transverse force of over 21 tons for the container analysed on the m/v SCI, the cumulative racking forces for the entire stowage in the casualty condition could have exceeded the net racking resistance of the containers (15 tons). There were signs of racking at the door ends of several containers.

Forces of green waters: Green water is a very significant and highly variable factor. As mentioned in Section 3.4.1.1, case histories (HCB, 1986-2003) have shown that green waters have often caused cargo damage and losses. In design conditions, a higher level of uncertainty is introduced with forces of green waters on deck. To some degree, Lloyd's Register rules take into account the effects of green waters. The rules apply a 20% multiplier for the forces on the deck-stowed cargo in the forward 1/4-length. In the case of the m/v SCI, given the casualty conditions, including the excessive synchronized rollings (up to 35^o), wave and wind factors, and the facts of cargo damage and losses, the forces exerted by green waters on deck of the m/v SCI might have exceeded the design conditions.

Other additive forces: As mentioned in Section 3.4.1.1, the system was exposed to various additive forces, such as: impact/compression from loose cargo inside the containers, forces from adjacent cargo inadequately lashed, pre-tensioning in the lashings, and shock loads from slacks in the lashings. These forces have not been addressed significantly in any of the calculation methods. However, all methods have applied a design safety factor to account for unanticipated forces as well as for possible weaknesses in the system. For example, Lloyd's Register has employed a safety factor of 3 for wire lashings. In the case of the m/v SCI, given the heavy weight (21 tonnes) of the piece of (steel) machinery (50 feet long) and sequences of events, the additive forces exerted by impacts of the loose machinery might have exceeded design conditions for containers and the cargo securing system. As it slid overboard, the machinery wiped out several containers. The system had not been designed and constructed to withstand such shock loads.

Summary

Some casualty conditions might have exceeded design conditions, but some others did not. The casualty conditions such as rolling angle (35^o) and GM (1,86m) might have exceeded design conditions, whereas other factors, such as container weight (some containers were empty) and wind speed had substantially lower values. Cargo stowage on the no.2 hatch consisted of 25 containers, of which 15 were loaded and 10 were empty. The forces that acted on the deck-stowed cargo were probably very high, perhaps near the extreme values of the design conditions. The main factor contributing to these high forces was the excessive GM. It contributed to the casualty both directly (by increasing acceleration forces) and indirectly (by increasing rolling angle in resonance with the seas). According to the Board of Inquiry (U.S. DOT, 1992), the excessive GM might have accounted for up to 23% of the forces acting on the cargo.

3.6. Summary – causes and contributing factors

Table 3.4 summarises the main and sub-categories of causes and contributing factors of the m/v SCI accident, i.e. cargo loss and damage – the category of “normal” transport conditions. According to the 1992 accident records (see Table 2.2 – NRC, 2005), the m/v SCI accident was attributed to two categories of causes only, i.e. “natural phenomena” and “other”. The analysis also confirmed that the most apparent and direct cause of cargo loss and damage was severe weather conditions. The m/v SCI would have arrived safely at her port of destination despite all the deficiencies had the weather conditions been good. However, hazard identification showed that the environment was not the only category of causes. The m/v SCI accident was attributed to combinations of a wide range of items of causes and contributing factors. The main categories were: *human/man, man-made, environmental, operational, and managerial and other factors* (Figure 3.1). The number in each main and sub-category indicates the number of incidences reported (Table 3.4). The largest number of incidences of deficiencies was related to the cargo securing system and procedures and navigation. The analysis showed that some of the repeated root causes included: a) unsound individual and industry predispositions; b) business constraints – cost and time constraints; c) poor seamanship; and d) poor handling or mismanagement of the systems. The master was largely responsible for the accident, but he was not the only culpable party. Other individuals and authorities were also responsible for the accident, including: a) the shipowner and other ship personnel; b) shore personnel, including shippers and stevedores, who packed and stowed containers and the piece of machinery; and c) relevant authorities or organisations that are responsible for designing, setting, enforcing and overseeing the compliance with rules, standards or programmes concerning the design, construction, operation, and management of the systems.

Table 3.4: Causes and contributing factors of the m/v SCI accident

The accident: the main and sub category of causes and contributing factors				
Human/Man (23)	**Man-made (28)**	**Environment (15)**	**Operational (42)**	**Managerial (17)**
1. Ship personnel (21) ***1.1 Master (10)*** • Lack of experience with breakbulk cargo ship (2) • Biased unsound predisposition: “We are sailors – we go to the sea” (1) • Poor decision-making capacity (1) • Inappropriate navigational decision (2) • Inadequate navigational skills (1) • Inadequate assessment of weather forecasts (1) • Failure to understand ship-sea interactions (1) • Overestimation of navigational ability (1) ***1.2 Master/deck officers (7)*** • Unfamiliar with local weather conditions (1) • Inadequate knowledge of cyclonic storm characteristics (2) • Failure to recognise the cyclonic storm (2)	**1. Hardware/technical (23)** ***1.1 Ship (5)*** • Navigational equipment (2): - Poor quality/useless radar (1) - Inoperative course recorder (1) • Ship’s design and operational characteristics (3): - Ship’s GM design characteristics – excessive GM (1) - Ship’s length relative to wave length (1) - Ship’s natural rolling and pitching frequency relative to wave period (1) ***1.2 Cargo securing systems (18)*** • Inherent faults in the cargo securing system: ship, packaging and lashings ***1.2.1 Ship system (5)*** • Inherent design and construction shortcomings (1) • Unspecialized ship type (1) • Failure of hatch covers (1): - Corrosion and damage (1) • Failure of pedestals (1) ***1.2.2 Packaging system –***	**1. Weather conditions (9)** • Fairly severe weather conditions contributed to losses and damage: - Wind properties: speed, direction (2) - Waves’ properties: height, length, period, direction, speed, frequency (5) • Heavy weather conditions made navigation difficult (1) • Heavy rains and poor visibility prevented any observation and measures (1) **2. Forces (6)** • Exposure to forces acting on the system: - Gravity (1) - Acceleration forces (1) - Forces of winds (1) - Forces of green waters (1) - Vibrations (1) - Other additive forces (1)	**1. Cargo loading/discharging (3)** • Unsuitable stability conditions – excessive GM (1) • Poor planning prior to loading (1) • No remedial measures taken after loading (1) **2. Cargo stowage, packing, securing (24)** ***2.1 Cargo stowage on deck (3)*** • Inadequate stowage of containers (1) • Inadequate stowage of the machinery (1): - Inherent weakness in stowage configuration (1) ***2.2 Container packing (5)*** • Inadequate container packing (5): - Inadequate blocking and bracing (1) - Weak blocking and bracing scheme (1) - Inadequate stowage - too much void space inside containers (1) - Inadequate dunnaging materials and arrangement (1) - Uninstalled tomming (1) ***2.3. Container securing (8)***	**1. Regulatory system management: inadequate compliance and enforcement (8)** • Inadequate container inspection and maintenance (1) • Lack of inspection and maintenance records (1) • Failure of the container owner to comply with relevant regulations (1) • Inadequate regulation compliance and enforcement oversight (1) • Inadequate regulatory oversight for container packing (1) • Absence of a cargo securing manual (1) • SCI’s container securing system neither surveyed nor certified (1) • Absence of IMO guidelines for heavy items (1) **2. Mismanagement: poor maintenance and insufficient supply (9)** **2.1.** ***Cargo securing systems (7)*** • Mismanagement – poor maintenance (3)
		Other (9)		

The accident: the main and sub category of causes and contributing factors				
• Inexperienced second mate (1) • Misunderstanding of securing system mechanics (1) ***1.3 Crew: master, officers, bosun, AB seamen (4)*** • Poor seamanship (3) • Lack of experience and specific formal training for cargo securing (1) **2. Industry/professional mariners (2)** • Industry/professional mariners' biased unsound predisposition (1) • The common practice not to secure hatch covers in coastal voyages (1)	***containers and machinery (9)*** • Failure of container securing system – inside and outside (1) • Failure of container structure (2): - Inadequate in-service structural strength (1) - Container damage and corrosion (1) • Inherent design shortcomings in FRP container (3): - Inherent weakness in packaging material (1) - FRP has no plastic range (1) - FRP less durable than other materials (1) • Inherent design shortcomings with palletized drums (1) • Failure of machinery securing system (1): - Awkward shape of the machinery (1) ***1.2.3 Lashing equipment system (4)*** • Wire lashings broke (1): - Damage and corrosion in wire lashings (2) - Weak wire lashings (1) **2. Regulations/standards (5)** • Lack of standards – a minimum GM (1) • Regulatory faults – vulnerable cargo position (1) • Gaps in regulatory controls and oversight programs (1) • Lack of objective standards for blocking and bracing arrangements (1)	**Business constrains (9)** • Costs (3) • Time (5) • Rules (1)	• Failure of container securing on deck (8): - Inadequate cargo securing (1) - Mismatches in the cargo securing system (1) - The pair of rigid hook-type turnbuckles with wire lashings (1) - The pair of penguin hooks with wire lashings (1) - Improper application of installation methods (1) - Improper installation of penguin hooks/wire lashings (1) - Incomplete cargo securing (1) - Uninstalled additional turnbuckles and lashings (1) ***2.4 Awkward cargo (machinery) packing and securing (7)*** • Failure of machinery securing (7): - Inadequate securing of the machinery (1) - Inadequate packing of the machinery (1) - Inadequate application of cargo securing methods (1) - Weak lashing configuration (1) - Insufficient machinery lashing (1) - Insufficient number of wire clips installed (1) - Uninstalled lashings (1) ***2.5 Hatch cover securing (1)*** • Failure of hatch cover: - Failure to secure hatch covers (1) **3. Navigational faults (15)** • Failure to avoid the storm prior to	- Rogue securing equipment in use/inventory (1) - Improper/ poor maintenance of securing equipment in use/inventory (1) - Insufficient supply of correct securing equipment (1) - Insufficient supply of lashing equipment and gears – long bridges unavailable onboard (1) 2.2. Navigational system: inadequate supply and maintenance (2) • Useless radars (1) • Inoperative course recorder (1)

The accident: the main and sub category of causes and contributing factors				
	• Lack of a standard approach for container securing (1)		departure and while at sea (2) • Failure to track the storm while at sea (1) • Failure to use all tools available for tracking the storm: - Failure to use radars (1) • Failure to avoid (navigate out) the most dangerous semicircle of the storm (1) • Inadequate navigation in the storm (1) • Steering with autopilot in severe weather conditions (1) • Inadequate navigation tactics (2): - Placing the ship into an unsafe position relative to navigational hazards (1) - Setting and keeping an inappropriate ship course relative to the wind/wave direction (1) • Failure to minimise the effects of weather conditions (1) • Failure to test options available (4): - Several options remained untested (1) - Failure to test turning back and take shelter (1) - Failure to test speed reduction (1) - Failure to test course changes (1) • Unnecessarily taking a wider turn into Delaware Bay (1)	

3.7. Causes and contributing factors - statistical data

The analysis of the m/v SCI accident case explored *only category of marine accidents/ incidents*. Causes and contributing factors of the m/v SCI accident are, to some extent, explored and quantified. In order to *fully explore and quantify other categories of incidents*, including their causes and contributing factors (see the **highlighted areas** in Figure 3.57), the demonstration of the framework is extended to the analysis of statistical data from the HMIS and NRC databases. In addition, in order to enhance *external validity*, the demonstration is extended to other transport modes.

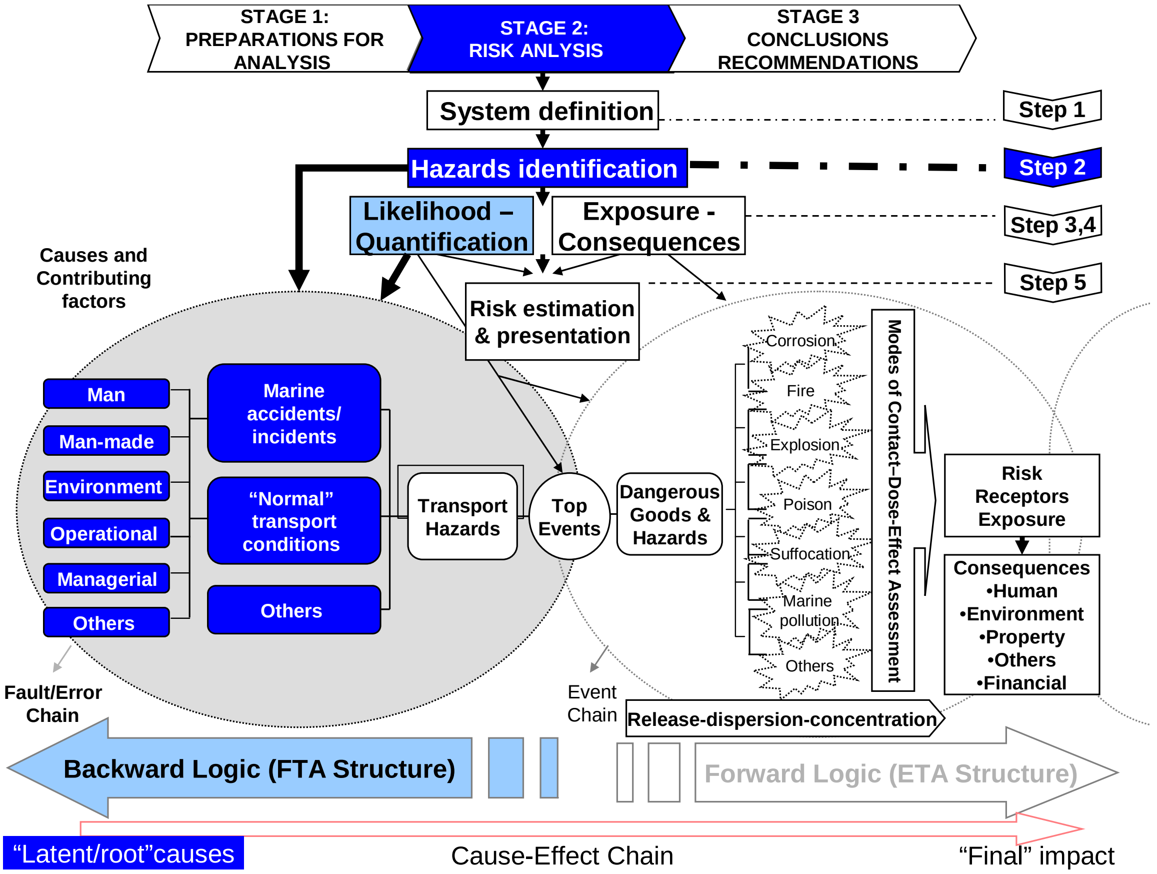


Figure 3.57: Stage 2 – Risk Analysis; Step 2 – Hazard identification, causes and contributing factors (continued from Figure 1.2)

The following presents and discusses some key results from the NRC and HMIS databases concerning hazmat releases due to vessel/water transport and other transport modes, and their causes and contributing factors, including their respective frequencies.

3.7.1. Causes and contributing factors of vessel incidents

NRC database (1990-2004): Figure 3.58 shows the fault tree of the main and sub-categories, including their frequencies (total incidences 39,279), of causes and contributing factors of vessel incidents reported to the NRC (U.S. 1990-2004). Vessel incidents have a high (0.943) probability of being caused by the "non-vessel incident" (or "normal" transport conditions) category, including combinations of these sub-categories: human, man-made, environment and other factors with respective frequencies as shown in the fault tree (Figure 3.58). The "*vessel incident*" category, such as sinking or foundering, explosion, and other types of incidents, shares similar principal categories of causes and contributing factors with "*non-vessel incident*" category. According to 1992 records of the NRC database (1990-2004), *which is also conformed by the analysis of the case histo*ry, the main direct cause of the m/v SCI accident was reported to be "natural phenomenon" (environmental hazards - heavy weather conditions), which falls under the category of "non-vessel incidents". Given the specifications of the system, the maritime transport system is exposed to environmental hazards to a larger extent than other modes of transportation – compare fault trees in Figures 3.58, 3.59 and 3.60.

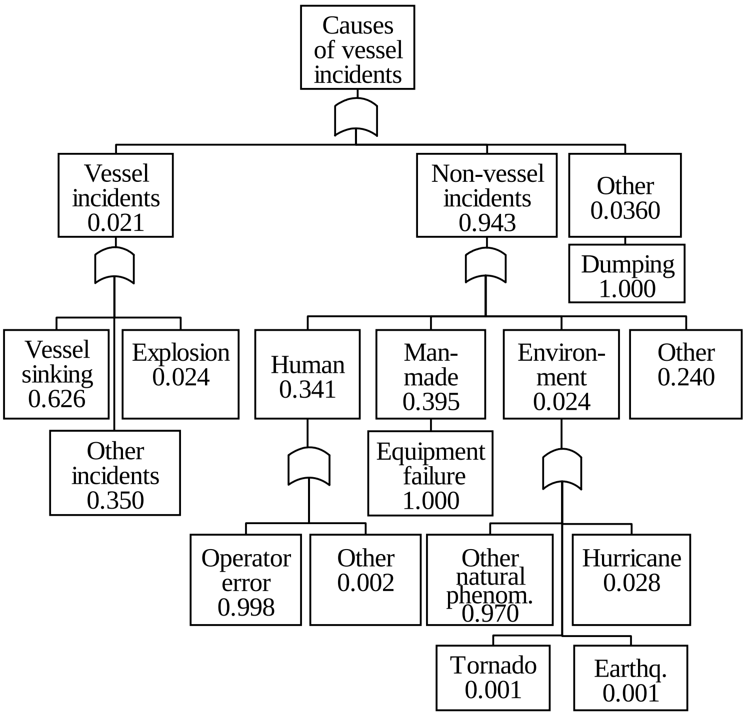


Figure 3.58: Fault tree of causes and contributing factors of vessel incidents (U.S. 1990-2004)

3.7.2. Causes and contributing factors of transport incidents

HMIS database (1993-2004): Figures 3.59 and 3.60 respectively show fault trees of the *general* and *specific* causes and contributing factors of transport (excluding pipeline) incidents as they are reported to the HMIS database (U.S. 1993-2004). They largely represent transport modes other than water transport because the number of water transport incidents reported to the HMIS is insignificant (0.1%) compared to other modes. Figure 3.59 shows that the majority of hazmat releases are attributed to the non-accidental category of causes (ca. 97% of all reported general causes), including human errors and failures to packages. In some cases, the cause of the hazmat release is unknown. The upper levels of the fault trees of causes and contributing factors of vessel/water transport and other modes of transport incidents share similarities in the principal categories – compare fault trees in Figures 3.59 and 3.60. Given its specialisations and the high degree of details and precision, the HMIS database contains a wide range of variables for describing and measuring specific categories (the total incidences 840,259, including incidences of transport hazards, see Section 3.2.3) (at the lower levels of resolution of the fault tree) of causes and contributing factors – as shown in the fault tree in Figure 3.60. The review of many other databases shows that many of these variables are not found elsewhere. These and other variables contained in the HMIS database as well as the NRC database are very important for learning lessons, facilitating informed decision makings, and taking appropriate measures for reducing risks in hazmat transport. The fault tree in Figure 3.60, which is a continuation of the fault tree shown in Figure 3.15, Section 3.2.3, shows the following results:

- *Man-made errors* (28.2% of the non-accidents or "normal" transport condition category) including defective fittings, packaging overused or of defective manufacture, nails or protrusions and incompatible materials;
- *Operational errors* (59.2%) including container overfilling, fitting or closures left loose, cargo handling such as dropping and striking packages, improper loading and forklift operation errors, and improper blocking of cargo inside containers and other CTUs; and
- *Managerial errors* (12.6%): the management at different levels in an organisation is largely responsible for failures to list hazmat in the shipping document and meet relevant hazmat requirements.

The discrepancy between the number of transport incidents and the incidences of causes and contributing factors indicates that, in many cases, incidents are attributed to combinations of two or more categories of causes and contributing factors. The results of the m/v SCI accident case analysis, which are largely consistent with some results of the statistical data analysis, provides detailed explanations concerning numerous categories of causes and contributing factors as well as transport hazards shown in the fault trees presented in Figures 3.15, 3.59 and 3.60.

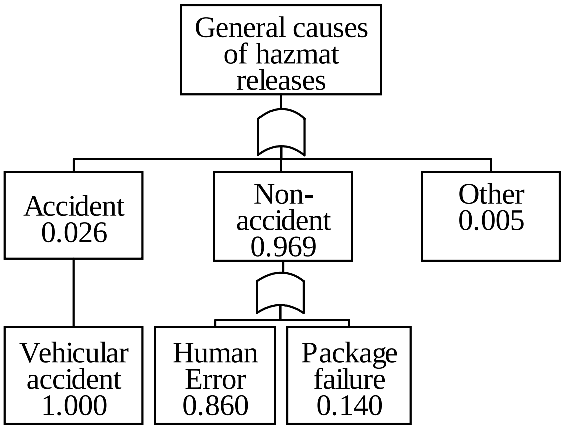


Figure 3.59: Fault tree of general causes and contributing factors of transport incidents (U.S. 1993-2004)

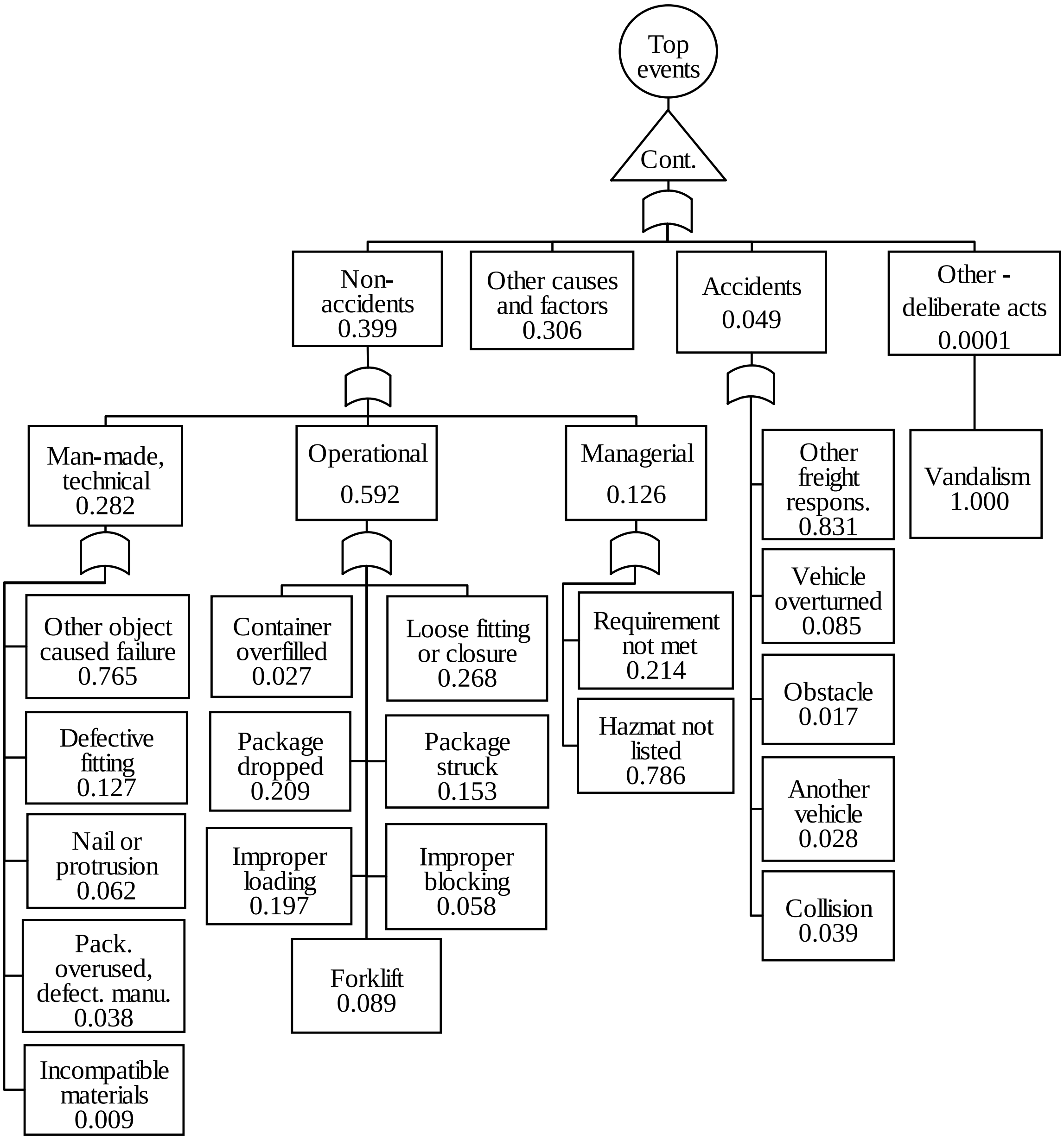


Figure 3.60: Fault tree of specific causes and contributing factors of transport incidents (U.S. 1993-2004) (continued 2, Figure 3.15)

4. Step 3 – Exposure and Consequences Analysis

Questions: What has happened or could happen after dangerous goods are released? Who is exposed to dangerous goods hazards? How are they exposed? What are the actual consequences? How often, many/much?

Tasks: Explore and quantify risks receptor exposure and actual consequences to risk receptors (see the **highlighted areas** in Figure 4.1).

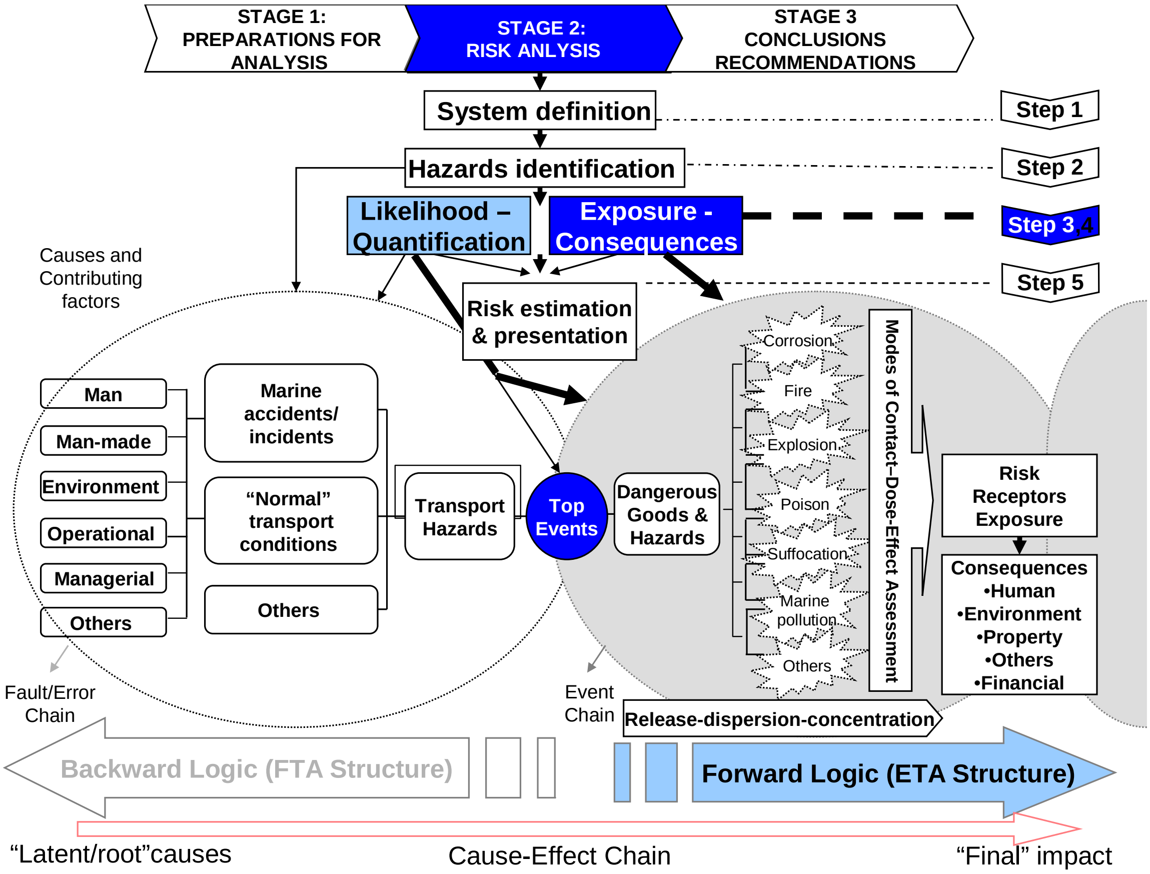


Figure 4.1: Stage 2 – Risk analysis; Step 3 - Exposure and consequences analysis (continued from Figure 1.2)

For the purpose of the risk analysis of the m/v SCI accident, the top events have been defined in Section 3.1. The hazards identification focuses on the *backward logic analysis of the left side of the top events* (Figure 4.2), whereas the exposure and consequence analyses focus on the *forward logic analysis* (see the **highlighted area** in Figure 4.1) of the *right side of the top events* (see the **highlighted area** in Figure 4.2).

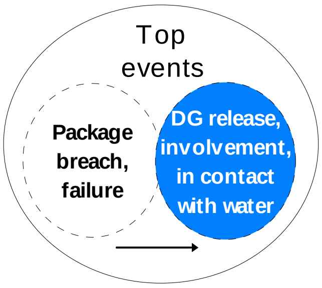


Figure 4.2: Top events: breach-release events

The "gap" between the initial hazmat release events and the actual and "final" consequences is often characterised by a very complex chain of events. On the basis of forward logic analysis, attempts have been made in the following section to explore some important events in the chain: "What are the consequences?" "How many?" or "How likely is it?" Prior to answering these questions, it is important to provide answers to questions concerning the types and amounts of hazmat, release, dispersion, concentration, routes of exposure, dose-effect relationship and exposure to dangerous goods (arsenic trioxide and magnesium phosphide). In the following analysis, attempts have been made to provide answers to a series of questions, including "What was the fate of dangerous goods after being released?" "What risk receptors were exposed?" and "How were they exposed?"

The following example demonstrates an exploration and quantification of the correlation between the variables "number of packages releasing hazmat" and "number of packages transported".

Example: Correlation between the variables: "number of packages releasing hazmat"- "number of packages transported"

HMSI database (1993-2004): The correlation analysis shows that the "number of packages releasing hazmat" variable is positively correlated with the "number of packages transported" variable by a correlation coefficient of 0.192. This means that any reduction in the number of packages in a shipment, for example in a container, trailer and or CTU or aboard the ship may lead to a reduction in the probability of hazmat releases. However, unless there is a reduction in the hazmat flow, reduction the number of packages in a shipment may lead to an increase in the frequency of shipments, which, in turn, may offset the reduction of hazmat releases. However, a limitation of the number of packages in a shipment may be needed for certain sensitive transport modes, means of transport (e.g. air transport and ferry ships), routes and locations (e.g. environmentally and economically sensitive and densely populated areas), and classes of hazmat.

4.1. Exposure to dangerous goods

4.1.1. Dangerous goods and their hazards

Questions: What types or classes of dangerous goods have been involved in incidents? How many?

Tasks: Explore and quantify the list of dangerous goods/hazmat involved and their hazards (see the **highlighted areas** in Figure 4.3).

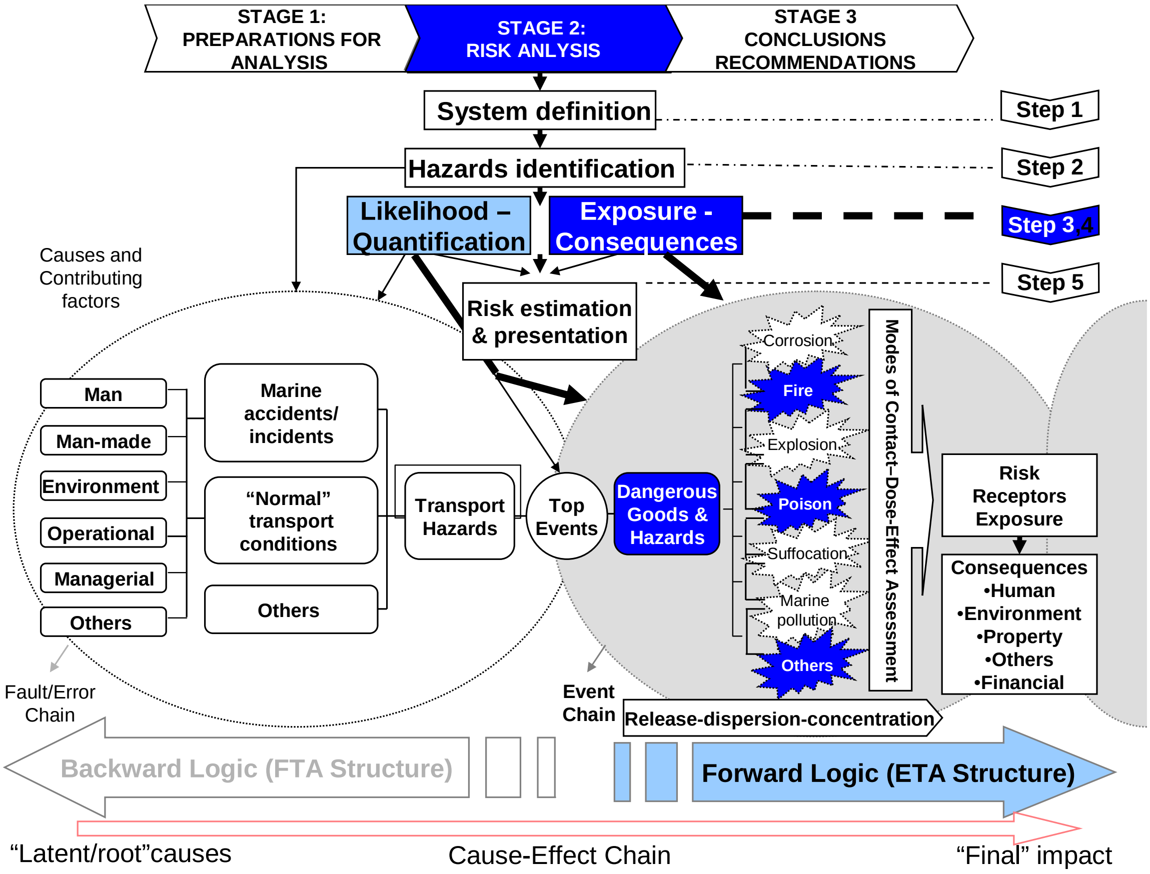


Figure 4.3: Stage 2 – Risk Analysis; Step 3 – Exposure and consequences analysis, dangerous goods list and hazards (continued from Figure 1.2)

Dangerous goods/hazmat hazards have played an essential role in the course of events, including the release, dispersion and concentration of dangerous substances, modes of contact, the exposure and consequences to risk receptors, and search and recovery operations. For example, by knowing about the most frequent classes of dangerous goods involved in incidents, the relevant authorities can design and construct appropriate search and recovery equipment and devices, and plan and execute response operations effectively and efficiently. The following section presents the list of dangerous goods carried onboard the m/v SCI and describes their hazardous properties.

4.1.1.1. The list of dangerous goods

The m/v SCI was carrying arsenic trioxide, magnesium phosphide and other unknown dangerous goods. Table 4.1 shows the locations and amounts of dangerous goods loaded onboard the m/v SCI. A total number of 25 arsenic trioxide containers (40'x8'x8') were loaded (in Coquimbo, Chile) on board the ship. Six containers were stowed on the no.2 hatch, and the rest (19 containers) were stowed under deck of the no. 2 hold. In accordance with the U.S. Code of Federal Regulations (CFR), the arsenic trioxide was packed in 94.7-liter (25-gallon) drums with a maximum allowable gross weight of 215.5 kg (475 pounds) per drum. The cargo manifest indicated that each drum contained 170.1 kg (375 pounds) of product. Each container was packed with 108 drums (a total number of 6x108=648 drums) palletised four to a pallet. A total amount of approximately 459.3 tons of arsenic trioxide was loaded onboard the m/v SCI, i.e. 110.2 and 349 tons on deck and under deck respectively. The m/v SCI's dangerous goods list included 10 palletised drums (or ca. 1,796 kg) of magnesium phosphide. Five pallets banded with 2 drums (179.6 kg per drum) each were stowed on the upper tweendeck of the no.1 hold. Unspecified amounts and types of dangerous goods that were also carried onboard the ship are added to the total amount of dangerous goods.

Table 4.1: Locations and amounts of arsenic trioxide carried on board the m/v SCI"

Dangerous goods	Location		Container / pallet	Drums per container / pallet	Total no. of drums	Amount (kg)
Arsenic trioxide	On deck	No.2 hatch	6	108	648	110,225
	Under deck	No.2 hold	19	108	2,052	349,045
	Total		25	108	2,700	459,270
Magnesium phosphide	Under deck	No.1 hold	5	2	10	1,796
Unknown	N/A*		N/A	N/A	N/A	N/A
	Total		25/5+		5,400+	461,066+

* N/A – Not Available

In sum, large amounts of dangerous goods were carried aboard the m/v SCI, including arsenic trioxide (459.3 tons) and magnesium phosphide (1.8 tons).

4.1.1.2. Dangerous goods hazards

The following section describes the dangerous goods hazards involved in the m/v SCI accident: *arsenic trioxide* and *magnesium phosphide*.

Arsenic trioxide: Class 6.1 (UN Number 1561) is an extremely *poisonous* metal oxide used as an insecticide, herbicide and wood preservative. It is a dense, white amorphous powder, slightly soluble in water and corrosive to metal in the presence of moisture. Arsenic trioxide is an arsenic compound. Arsenic gives no warning, as it is tasteless and odourless. The lack of warning signs makes it a very deadly substance (Kamrin, 2005). Arsenic is both toxic and carcinogenic. The solution in water is a weak acid, which may react with reducing substances producing very toxic gas (IPCS and EC, 2001). The substance presents hazards by inhalation, ingestion and contact. It is also a suspected human carcinogen. The U.S. Occupational Safety and Health Administration (OSHA) have established a maximum permissible exposure limit for workplace airborne inorganic arsenic of 10 micrograms per cubic meter averaged over an eight-hour day (Kamrin, 2005). The IMDG Code regulates carriage of the substance by sea. Stowage is permitted "on deck or under deck."

Magnesium phosphide: Class 4.3 (UN Number 2011) is used as fumigant. The substance is shipped as a grey granulated powder. It reacts violently with water, producing phosphine gas, which is a highly *poisonous* and *flammable* gas. In the concentration 1.8% (18,000 ppm) by volume, it can lead to spontaneous combustion or explosion. The IMDG Code regulates carriage of the substance by sea, with stowage permitted "on deck or under deck." The Code requires the substance to be labelled both as "toxic" and "dangerous when wet." Although classified as a dangerous cargo and clearly labelled, magnesium phosphide was not listed on the ship's Dangerous Goods Manifest and other shipping documents, as required by the IMDG Code.

Other unspecified dangerous goods: According to the investigation report, other packages with dangerous goods had also broken loose and been damaged in other holds (U.S. DOT, 1992). However, for reasons unknown, the report contains no information about the nature and amount of these dangerous goods.

For more information about the properties of arsenic trioxide and magnesium phosphide, see Appendixes 1 and 2, Vol. II.

4.1.2. The list of hazmat and their hazards – statistical data

The analysis of the m/v SCI accident case explored only a very limited list of dangerous goods (i.e. *arsenic trioxide and magnesium phosphide*) and their hazardous properties (such as *poison/toxic, flammable, carcinogenic, i.e. the "others" category*) (see **highlighted areas** in Figure 4.3). In order to explore and quantify the long list of dangerous goods/hazmat and their hazardous properties involved in incidents (see the **highlighted areas** in Figure 4.4), the demonstration of the framework is extended to the analysis of statistical data from the HMIS and NRC databases. Furthermore, in order to enhance the *external validity*, the demonstration is extended to other modes of transport of dangerous goods.

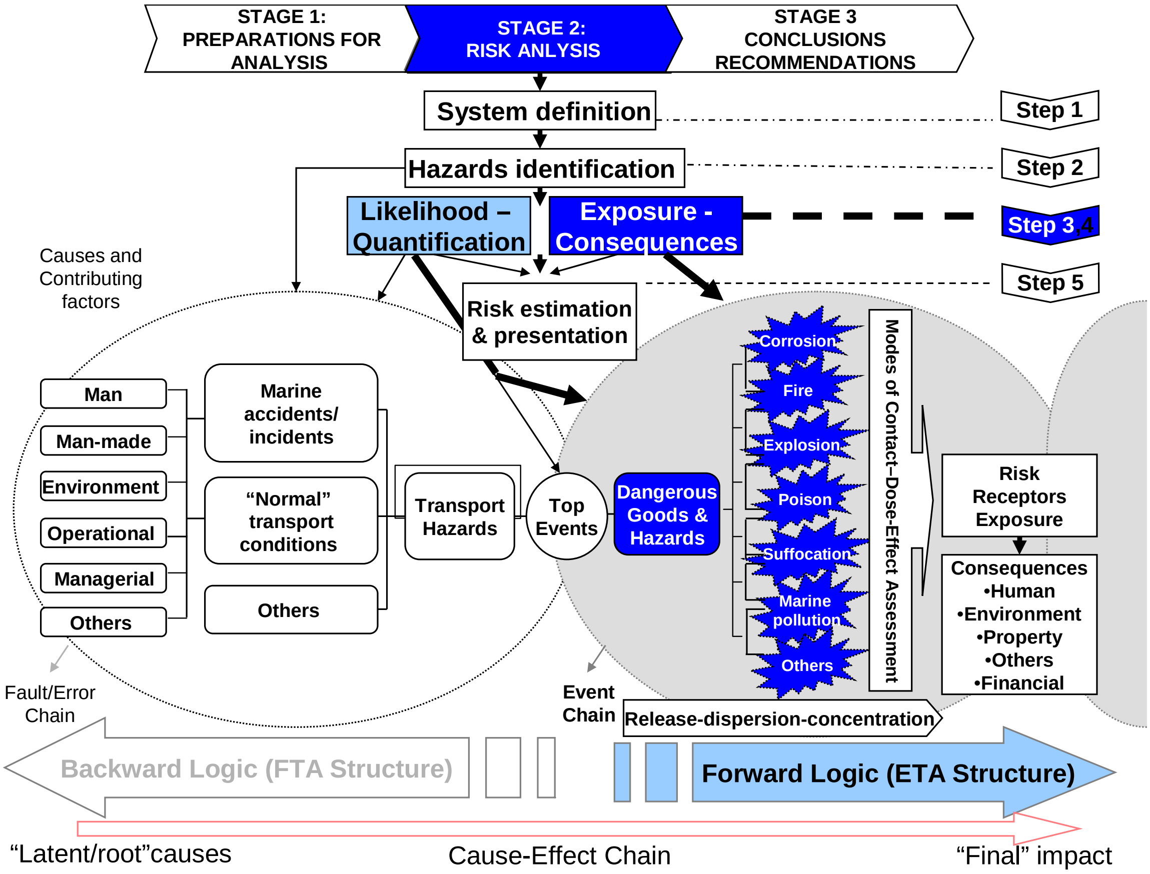


Figure 4.4: Stage 2 – Risk Analysis; Step 3 – Exposure and consequences analysis, list of dangerous goods and hazards (continued from Figure 1.2)

4.1.2.1. Classes of hazmat

The U.S. DOT (2005a) classifies hazmat in the main classes 1-9, including constituent classes (or sub-classes) and divisions of the respective main classes, as shown in the list below. A similar classification system is provided in the IMDG Code (2002). According to the IMDG Code (2002), materials, substances (including mixtures and solutions) and articles subject to the provisions of the Code are assigned to one of the classes 1-9 according to the hazards or the most prominent of the hazards they present. For more information about definitions and concepts concerning dangerous goods or hazmat, see Chapter 3, Vol. I, and Mullai 2006a.

HMIS database (U.S. 1993-2004): Here follows a presentation and discussion of some key results from the HMIS database records concerning the classes of hazmat involved in packaged hazmat transport incidents, excluding pipeline (U.S. 1993-2004).

Class 1: Explosives

- Division 1.1: Explosive mass explosion hazard
- Division 1.2: Explosive projection hazard
- Division 1.3: Explosive fire hazard
- Division 1.4: Explosive no blast hazard
- Division 1.5: Very insensitive explosive

Class 2: Gases

- Class 2.1: Flammable compressed gases
- Class 2.2: Non-flammable compressed gases
- Class 2.3: Toxic gases

Class 3: Flammable liquids

Class 4: Flammable solids

- Class 4.1: Flammable solids
- Class 4.2: Spontaneously combustible
- Class 4.3: Dangerous in contact with wet materials

Class 5: Oxidizers and organic peroxides

- Class 5.1: Oxidizing substances
- Class 5.2: Organic peroxides

Class 6: Toxic materials and infectious substances

- Class 6.1: Toxic materials
- Class 6.2: Infectious substances

Class 7: Radioactive materials

Class 8: Corrosive materials

Class 9: Miscellaneous hazardous materials

Classes of hazmat – transport incidents by class: The top three most frequent classes of hazmat reported to be involved in transport incidents are Class 3 (42.8%), Class 8 (37.8%) and Class 6 (7%), which combined accounted for approximately 88% of all the classes involved in transport incidents (Figure 4.5). The most frequent classes/divisions within the respective main classes are: divisions 1.4 and 1.5 (75% of all explosives), Class 2.2 (59.3%), Class 4.1 (71.4%), Class 5.1 (74.9%) and Class 6.1 (93.2%) (see Figures 4.6~4.10). The top 20 hazmat shipping names, which account for approximately 51% of all the hazmat involved in transport incidents, are shown in Table 4.2. Corrosive and flammable liquids are the most frequent types of hazmat reported to be involved in transport incidents in the U.S. (1993-2004). This can mainly be attributed to the large amounts transported and/or the properties of substances (gas, liquid and corrosive).

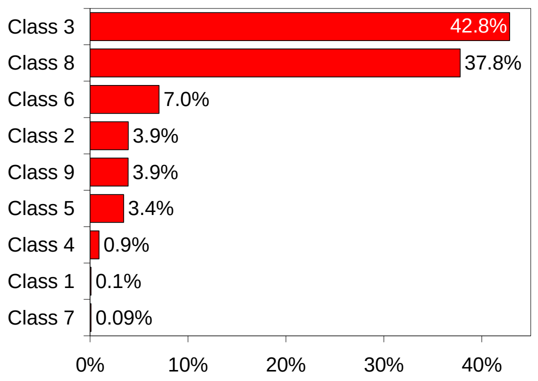


Figure 4.5: Ranking of hazmat classes reported in transport incidents (U.S. 1993-2004)

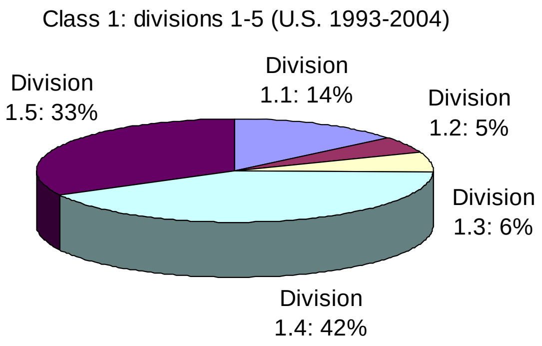


Figure 4.6: Divisions 1-5 within class 1 (U.S. 1993-2004)

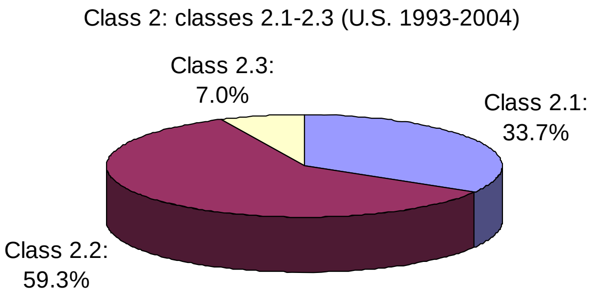


Figure 4.7: Classes 2.1-2.3 within class 2 (U.S. 1993-2004)

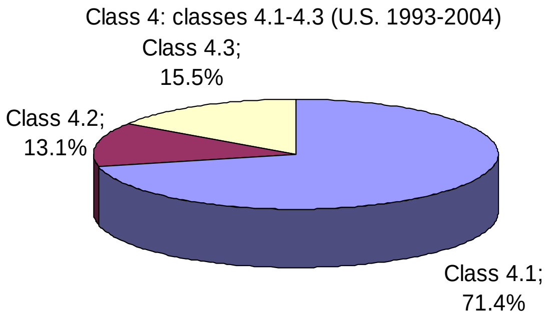


Figure 4.8: Classes 4.1-4.3 within class 4 (U.S. 1993-2004)

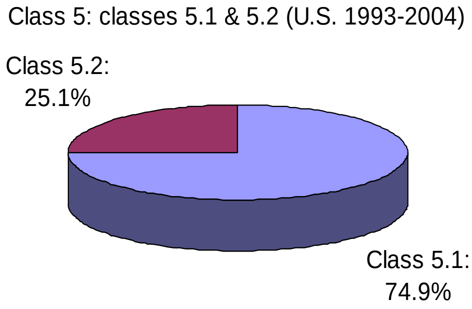


Figure 4.9: Classes 5.1 and 5.2 within class 5 (U.S. 1993-2004)

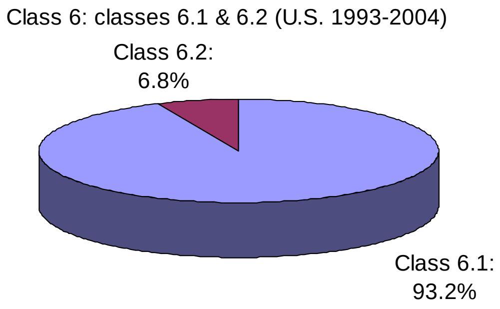


Figure 4.10: Classes 6.1 and 6.2 within class 6 (U.S. 1993-2004)

Table 4.2: Top 20 hazmat shipping names (U.S. 1993-2004)

Rank	Shipping name of hazmat	Number of incidents	% of the total of top 20	% of the total
1	Corrosive liquids N.O.S.	14 028	14.6%	7.4%
2	Flammable liquids N.O.S.	13 827	14.4%	7.3%
3	Resin solution	7 384	7.7%	3.9%
4	Sodium hydroxide solution	5 990	6.2%	3.2%
5	Adhesives	4 500	4.7%	2.4%
6	Hydrochloric acid solution	4 472	4.6%	2.4%
7	Gasoline	4 248	4.4%	2.3%
8	Isopropanol	4 102	4.3%	2.2%
9	Paint or paint-related	3 876	4.0%	2.1%
10	Phosphoric acid	3 815	4.0%	2.0%
11	Corrosive liquid basic inorganic	3 814	4.0%	2.0%
12	Sulphuric acid	3 655	3.8%	1.9%
13	Potassium hydroxide solution	3 196	3.3%	1.7%
14	Corrosive liquid acidic inorganic	3 103	3.2%	1.6%
15	Caustic alkali liquid N.O.S.	3 092	3.2%	1.6%
16	Corrosive liquid acidic organic	2 971	3.1%	1.6%
17	Compound cleaning liquid	2 764	2.9%	1.5%
18	Fuel oil (NO. 1,2,4,5,6)	2 541	2.6%	1.3%
19	Ethanol	2 476	2.6%	1.3%
20	Printing ink flammable	2 404	2.5%	1.3%
	Total of top 20	96 258	100.0%	51.1%
	Total	188 325		

Classes of hazmat – vessel incidents: Figure 4.11 shows a ranking (in %) of the classes of packaged hazmat involved in vessel incidents. The five most frequent classes reported to be involved in vessel incidents are: Classes 8, 3, 6, 9 and 2. Classes 8 and 3 combined account for over 60% of all the classes. Within the main classes (Classes 2 and 6), Class 2.2 (non-flammable compressed gas) and Class 6.1 (toxic materials) were most frequently involved. The top 16 shipping names of hazmat accounted for approximately 50% all the hazmat involved in vessel incidents (Table 4.3). None of the hazmat involved in the *m/v SCI accident*, i.e. arsenic trioxide and magnesium phosphide, was found in the lists of hazmat involved in vessel incidents reported to the HMIS database.

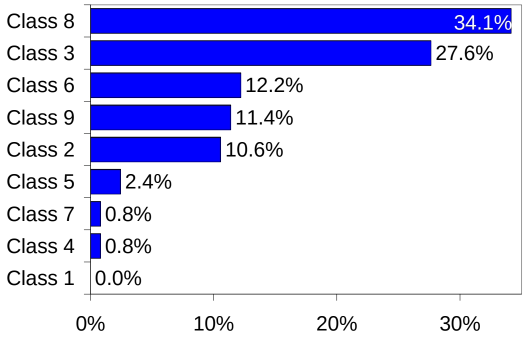


Figure 4.11: Ranking of hazmat classes involved in vessel incidents (U.S. 1993-2004)

Table 4.3: Top 16 hazmat shipping names involved in vessel incidents (U.S. 1993-2004)

Ranking	Hazmat shipping name	Nr. of incidents
1	Phosphoric acid	12
2	Ammonia anhydrous	8
3	Environmentally hazardous liquid	7
4	Flammable liquids N.O.S.	5
5	Resin solution	4
6	Hydrochloric acid solution	4
7	Extracts flavouring liquids	4
8	Combustible liquids N.O.S.	3
9	Aluminium chlorine solution	3
10	Vehicle self-propelled	2
11	Toluene diisocyanate	2
12	Sulphuric acid	2
13	Sulphuric molten	2
14	Sodium hydroxide solid	2
15	Phenetidines	2
16	Hydrobromic acid solution	2
	Total	64

NRC database (U.S. 1990-2004): The review of the NRC database records showed the following results concerning arsenic incidents in the U.S (1990-2004).

Arsenic incidents: Arsenic has been released into the environment from different sources. During the period 1990-2004, a total number of 353 arsenic incidents were reported to the NRC. The number of incidents per year varied from 12 to 33, on average, 24 arsenic incidents alone per year (Figure 4.12). The types of arsenic involved in incidents included: a) arsenic contaminated soil, liquids/waters and objects; b) arsenic compounds and mixtures and c) arsenic liquid and solid wastes (see the list below). Approximately 5.6%, or 20 incident cases, involved arsenic trioxide (see the list below), which is an arsenic compound similar to the one involved in the m/v SCI accident.

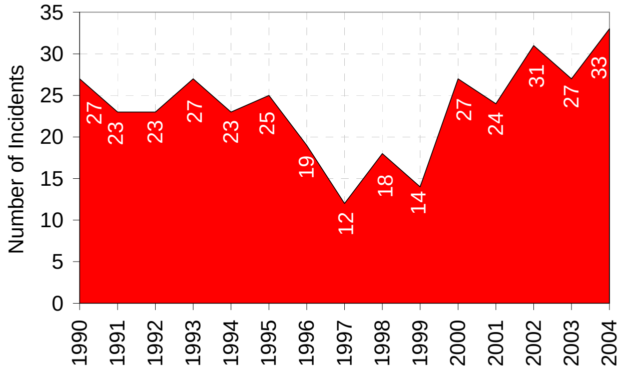


Figure 4.12: Arsenic incidents reported in the U.S. (1990-2004)

Type of arsenic involved in incidents

- *Arsenic contaminated (34 incidents)*
  - Soil, liquids/waters, objects
- *Arsenic compounds and mixtures*
  - Arsenic acid
  - Arsenic pentoxide
  - Arsenic sulphide
  - Arsenic trioxide (5.6% or 20 incidents)
  - Arsenic trisulfide
  - Arsenic trisodium
  - Copper-chromium-arsenic compound
  - Copper-chromic-arsenic acid
  - Dimethyl arsenic acid
- *Arsenic liquid and solid wastes*

4.1.2.2. Hazmat hazards

Hazards are the inherent hazardous properties of dangerous goods or hazmat, e.g. chemical, biological, and radioactive and a wide range of other hazards. Many types of hazmat present more than one, or multiple, hazards. The danger may come from combinations of different hazards. For example, toxic gases can be flammable and corrosive. These substances, however, are assigned to the respective classes according to the most prominent hazard (primary hazard) they present. Other hazards (secondary hazards) are indicated in, for example, the IMDG Code List. In the IMDG Code (see IMDG Code, Chapter 2.10, 2002), in accordance with the criteria of MARPOL (1973/1978), many of the substances assigned to Classes 1-9 are identified as substances harmful to the marine environment and, therefore, deemed as being marine pollutants. Certain marine pollutants have an extreme pollution potential and are identified as severe marine pollutants in the IMDG Code (see the IMDG Code List and Chapter 2.10, 2002). For more information about the hazardous properties of dangerous goods/hazmat, see Chapter 3, Vol. I, and Mullai 2006a. The following section presents and discusses some key results from the HMIS database (1993-2004) concerning the hazards of hazmat involved in transport and vessel incidents.

HMIS database (1993-2004): Figures 4.13 and 4.14 show the hazmat hazards (primary hazards) involved in all modes of transport combined (excluding pipeline) and water transport incidents. A wide range of hazmat hazards has been involved in transport incidents. Case histories, including the m/v SCI accident, have shown that, in many cases, mixtures of hazmat presenting more than one hazard have been involved. However, in both categories of incidents, the vast majority (approximately 75-85%) of incidents have involved hazmat presenting fire/explosion and corrosion hazards (Figures 4.13 and 4.14). Large amounts of flammable/explosive and corrosive materials and substances are transported and involved in incidents. Materials and substances in numerous classes and sub-classes (e.g. Classes 1 to 5) present fire/explosion hazards. Class 5, for example, consists of oxidizing substances and organic peroxides. Oxidizing substances in themselves are not necessarily combustible, but by yielding oxygen, they can cause or contribute to the combustion of other materials. Organic peroxides are liable to exothermic decomposition at normal or elevated temperatures. The decomposition can be ignited by heat, impurities (e.g. acids and heavy metal compounds), friction or impact. Class 2.2 non-flammable, non-toxic gases, present asphyxiate hazards, as they may dilute or replace oxygen. This class also includes oxidizing gases, which cause or contribute to the combustion of other materials by providing oxygen. Class 9 (miscellaneous hazmat) comprises materials and substances, including marine pollutants, that are not covered by other classes and are not subject to SOLAS (Part A, Chapter VII, 1974), but that are subject to MARPOL (Annex III, 1973/1978). The data indicate that, in case of a transport incident in the U.S., there is a high probability that response teams will be called out to deal with hazmat releases presenting fire/explosion and corrosion hazards. The high frequency of involvement of the classes and shipping names mentioned above is mainly attributed to the inherent properties of hazmat and large numbers of shipments.

The dominant bulk cargoes carried by water are oil and oil products, LNG and LPG, which pose hazards of fire, explosion, and toxic and environmental pollution. Some of the world’s worst hazmat disasters, e.g. Halifax, Canada (1917), Texas City, USA (1947), Seveso, Italy (1976), Bhopal, India (1984), Exxon Valdez, Alaska, USA (1989), and Chernobyl, USSR/Ukraine (1986), have involved dangerous substances posing hazards of fire, explosion and toxic, radiation and environmental pollution. Response teams should be well equipped and prepared to deal with all possible scenarios, in particular for the aforementioned hazards.

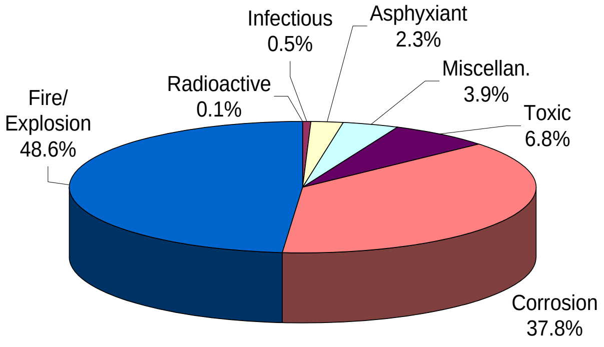


Figure 4.13: Hazmat hazards involved in transport incidents (U.S. 1993-2004)

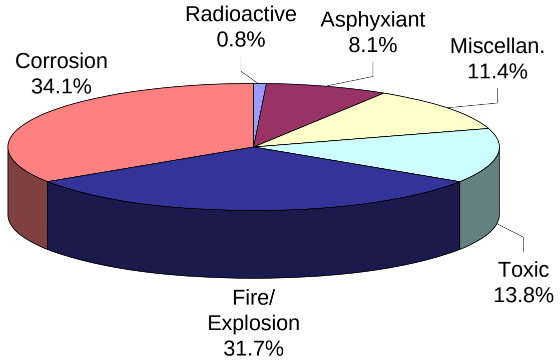


Figure 4.14: Hazmat hazards involved in water transport incidents (U.S. 1993-2004)

4.1.3. Release-dispersion-concentration of dangerous goods

Question: What is the fate of dangerous goods once released/involved?

Tasks: Explore the sequences of events following the release, dispersion and concentration of dangerous goods that can lead to exposure and consequences for risk receptors (see the **highlighted areas** in Figure 4.15).

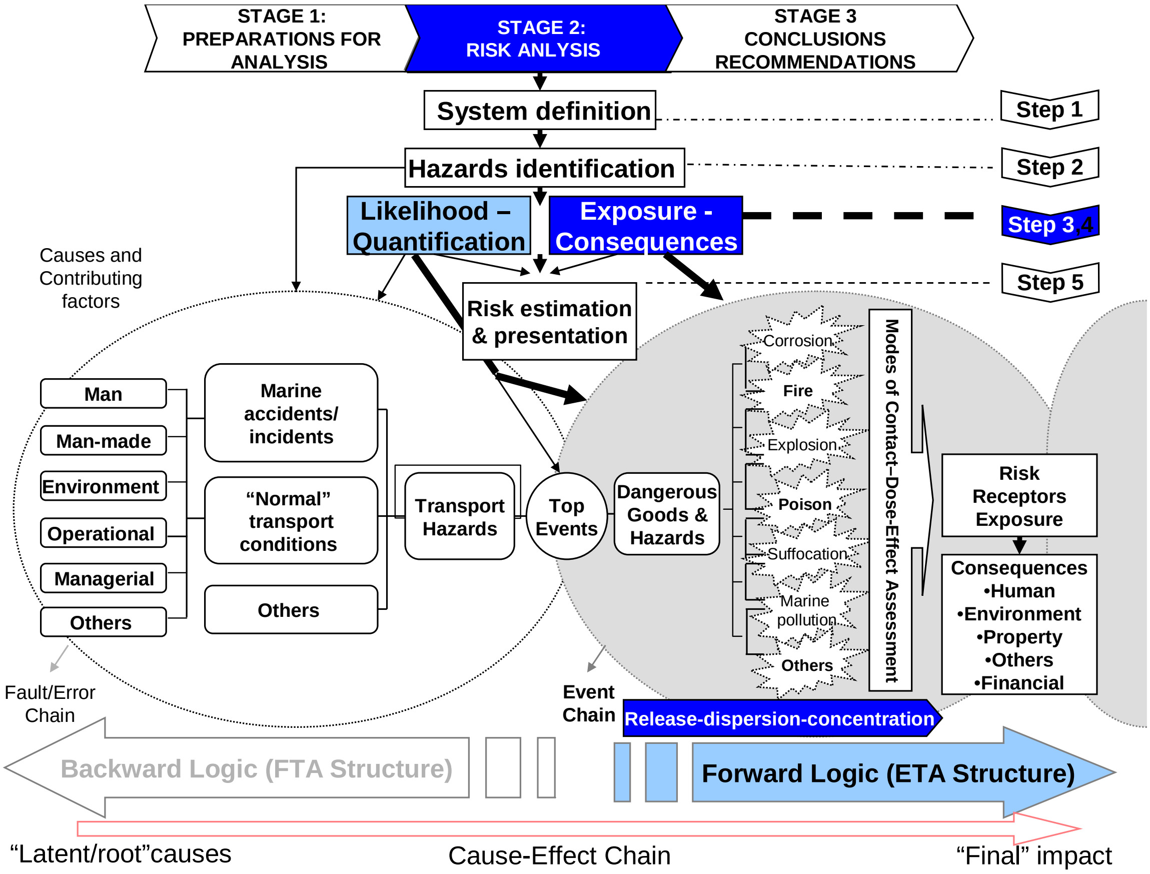


Figure 4.15: Stage 2 – Risk analysis; Step 3 – Exposure and consequences analysis, dangerous substances release, dispersion and concentration (continued from Figure 1.2)

Neither the HMIS nor NRC databases, nor many other incident databases, provide any data on some essential events. In order to fill gaps and extend the data, the events are explored on the basis of the m/v SCI incident case history and other data sources, which are neither exhaustive nor cover the wide range of possible scenarios. However, they provide some valuable insights into understanding, preventing and mitigating the consequences of hazmat incidents.

In the case of the m/v SCI accident, the release of dangerous substances was a necessary condition for dangerous substances to get in contact with risk receptors and cause harm. The “breach” of drums preceded the “release” of dangerous substances. Many drums breached and released dangerous substances several times to various degrees and at different times and locations. The fate of dangerous substances lost at sea and spilt onboard the ship is explored by means of *forward logic* analysis. The following are the main sequences of events:

- At sea: loss, sinking and spreading of arsenic trioxide containers and drums.
- At sea: release, dispersion and concentration of arsenic trioxide.
- Aboard the ship: release, dispersion and concentration of arsenic trioxide and magnesium phosphine.

4.1.3.1. At sea: loss, sinking and spreading of containers and drums

The release, dispersion and concentration of PDG into the marine environment and their consequences depend very much on the fate of the packages themselves. Given the chemical properties of arsenic trioxide, the entire investigation as well as the search and rescue operations, i.e. the data available, focused primarily on the loss and damage of arsenic trioxide containers. As mentioned earlier, all six arsenic trioxide containers that were stowed on deck were damaged or broke loose during the storm. Four of these containers as well as another 17 containers stowed on deck and the machinery were lost overboard. On arrival at Delaware Bay, one container with general cargo was hanging over the portside bulwark at the no.2 hatch. Containers stowed on deck had been broken open while onboard or fallen overboard. As the containers were falling into the sea, some drums, due to their heavy weight, probably broke through the sides and ends of the containers at various points on the ship's trackline. Many arsenic drums broke loose on deck, some of which were lost overboard.

What was the fate of the containers/drums after they were lost? How and where did they land?

Some pieces of evidence were found on the sea floor. Initially, the USCG treated the case of the m/v SCI accident as a Search and Rescue (SAR) mission. Several USCG aircraft were sent to the scene. The initial search flights found no signs of containers, drums or debris, suggesting that they had sunk shortly after falling overboard. However, the initial search began several hours (ca. 12 hrs) after the accident, because the ship failed to report it in due time in accordance with the relevant regulations. According to the master's accounts, which were questionable, cargo loss and damage were not noticed because of the severe weather conditions and, therefore, not reported. Some 10 containers lost overboard were empty (i.e. with initial positive buoyancy) and their fate was unclear. Probably those empty containers were so severely damaged that they were filled with water and sank immediately.

The search operations continued for three days. By that time, efforts were made to determine the nature and amount of the cargo lost. Initially, due to errors in the ship's cargo manifest, the information was inconclusive. On the third day (January 7, at 12.00 hrs), approximately 82 hours after the cargo loss, a floating container was observed off Chincoteague (VA), south of Delaware Bay. The container was identified as one lost from the m/v SCI. According to the cargo manifest, that container was loaded with lumber, which is why it was still afloat. Due to the compounded effects of strong winds, waves and currents, the container had drifted southwards (south-south-west) some 97 km from the accident scene. The container, which presented danger to navigation, was drifting at an estimated speed of about 1.2 km/hour.

On January 19, after failing to detect lost containers/drums from the air, the USCG initiated an underwater search. Initially, it was difficult to discover the location of containers and drums. Salvage crews spent approximately two months searching a vast area of the ocean (60 km x 1 km) before the entire debris was located. By using the master's information about the ship's positions associated with the heaviest rollings and by applying the estimated drift, the search was focused to the area on the west side of the ship's trackline between 01.51–02.26 hrs, on January 4. With ROV provided by USEPA and the Navy's supervisor of salvage, a field of containers/drums was located in the targeted search area. Fifteen of 21 containers lost overboard and the machinery were located in an extended debris field approximately following the ship's trackline from about 01.50-02.10 hrs (Figure 4.16). The cargo was largely clustered by the stowage location of cargo from the no.2 hatch. The machinery was found near three other containers from the starboard side. Initially, three of four arsenic trioxide containers were positively identified. All three were broken open, and many drums were scattered on the sea floor. On January 27, a fourth container was located and positively identified as one listed in the cargo manifest of the m/v SCI. This container was badly crushed, with one side entirely missing, and contained only two crushed drums marked as arsenic trioxide. That same day, a large pile of drums was located close to the fourth container. The missing side was observed under the pile. The container was identified as one from the m/v SCI. The drums appeared impacted and crushed.

It was difficult to conclude that this site was the location where all the drums had landed. Only 320 arsenic trioxide drums were found and recovered. Many drums were never found and remained on the sea floor. These drums had fallen outside the debris field, which was approximately on the ship's projected trackline between 01.50-02.10 hrs. Due to heavy rollings, drums may also have broken through containers at various points of the ship's trackline prior to 01.50 hrs.

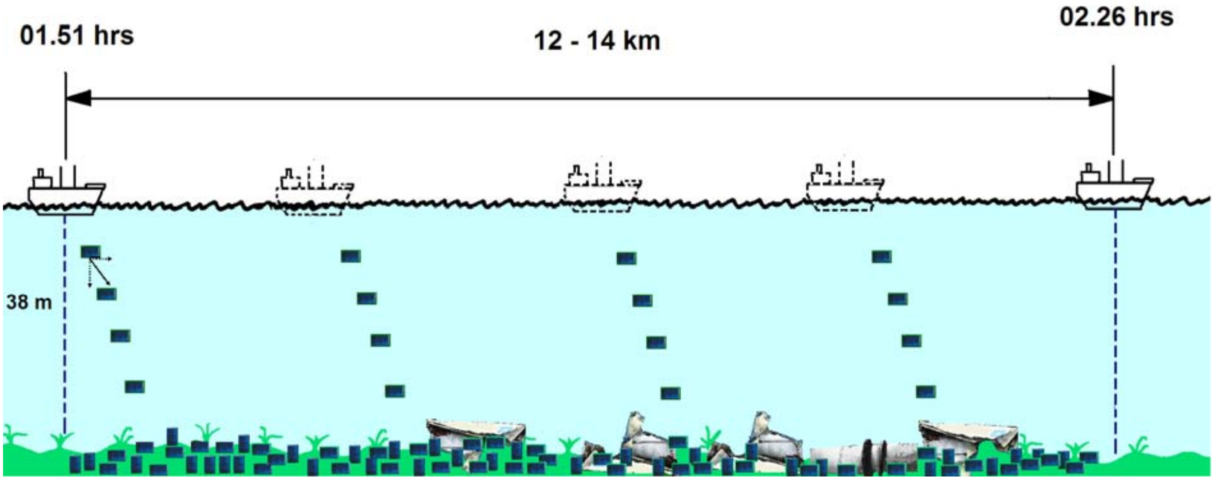


Figure 4.16: Spreading of cargo on the sea floor

In sum, due to heavy weight, damage and negative buoyancy, arsenic trioxide containers and drums sank immediately after falling overboard. Strong winds, waves and sea currents might have had some effect on the drifting and spreading of containers/drums. As they were falling overboard, containers and many drums landed on an extended area along the ship's projected trackline (between 01.51-02.26 hrs) on the sea floor. Based on the distance covered by the ship between 01.51-02.26 hrs, the area in which foundered containers/drums were scattered on the sea floor is estimated to be about 12-14 km long. Many drums were never found. They may have landed outside the debris field, probably on the projection of the ship's trackline prior to the ship's position at 01.51 hrs.

4.1.3.2. At sea: release, dispersion and concentration

The fact that the arsenic trioxide was contaminated by seawater suggests that the seawater penetrated the drums and came into contact with the arsenic trioxide. This chemical is slightly soluble in water (1.82g/100g) (IMDG Code, 2002). Due to a combination of differences in pressure and temperature, water currents and other environmental conditions, diluted arsenic trioxide was released from the broken drums and dispersed into the sea. An amount of approximately 200 kg of arsenic trioxide was released from 320 drums recovered from the sea floor. Given its chemical properties and the extent of damage to the drums, the arsenic trioxide at sea may have been in dissolved and solid forms. Numerous samples were taken in and around the debris, but the case history contains no figures on the levels of arsenic trioxide concentration in the seawater column, sediments and marine organisms. For more information about arsenic properties and concentrations, see Appendixes 1 and 2, Vol. II.

4.1.3.3. Aboard the ship: release, dispersion and concentration

Both arsenic trioxide and magnesium phosphide are solid substances. As the drums rolled across the deck, and due to the combined effects of gravity, impact, vibration, rain, wind and green waters (for the drums stowed on deck), the substances poured out of broken drums and spread on deck. The amount of substances released was dependent on the extent of the breach and exposure to the conditions mentioned. The following section describes the course of events for each substance, i.e. arsenic trioxide and magnesium phosphide.

Arsenic trioxide – no.2 hatch: On deck in the no.2 hatch, many drums broke loose. In Port Baltimore, 234 drums were recovered inside two remaining containers or on deck (Whipple et al., 1993). Some 13 drums broke open, spilling their contents. An estimated amount of two tons of loose arsenic trioxide spread on deck (Merrick, 1993). The spreading was not confined to the no. 2 hatch cover only. When the ship arrived at the pier in Port Baltimore, the inspection revealed that the main deck and several other hatches were completely covered with arsenic trioxide (see Figure 2.16). Blown by strong winds and diluted by rain and green waters, an unknown amount of spilled arsenic trioxide ended up in the sea. The Delaware Bay pilot recalled that, while he was boarding the m/v SCI, he saw the debris of splintered wreckage sliding back and forth along the deck with every wave (Klein and Nugent, 2004). He also noticed several puddles of "a white, milky liquid" that had leaked from a group of smashed drums near the damaged wheelhouse (Klein and Nugent, 2004). The ship was leaking arsenic trioxide all the way to Port Baltimore. Evaporation of arsenic trioxide at 20°C is negligible (IPCS and EC, 2001). In the area (i.e. the New Jersey coast), the ambient temperature in January may have been below 20°C. However, a harmful concentration of airborne particles can be reached quickly (IPCS and EC, 2001).

Magnesium phosphide – no.1 hold: On the upper tweendeck of the no.1 hold, four of 10 palletised magnesium phosphide drums broke open. As drums rolled across the deck, an amount of over 393 kg of toxic powder was spilt, dispersed and piled several inches high in some areas of the hold. Magnesium phosphide is Class 4.3, i.e. "toxic" and "dangerous when wet." The fact that numerous people who entered into the hold showed symptoms of exposure to poisonous gas (dizziness and vomiting) indicates that the magnesium phosphide had reacted in contact with moisture or water inside the hold, giving off toxic and flammable phosphine gas. The probable sources of moisture/water were: a) the moisturised air (humidity) entrapped inside the hold during loading/discharging in ports (Port Elizabeth and Port Baltimore); b) moisture or water contained in the hold, cargo, packaging, and dunnage materials. The water may have come from the chemical itself, as oxidation of phosphine yields phosphorus oxides or oxyacids and water (IPCS, 1989). In the heavy weather conditions during the voyage, seawater and rain might have penetrated through the unsecured hatch covers into the hold.

The phosphine gas concentrated in the no.1 hold atmosphere. The gas might have escaped from the no.1 hold and penetrated into other holds and locations. The concentration varied during the time that the spilt chemical was aboard the ship. The data available do not indicate the level of gas concentration. However, medical analyses of stevedores in Port Charleston, who were sent to hospital after being exposed to the chemical, showed that the phosphide concentration in their bodies was 400 ppm. The level of gas concentration inside the hold, particularly before it was opened in Port Charleston, might have been very high. As the hold was closed, the concentration increased during the voyage, particularly during the voyage between Port Baltimore and Port Charleston, where it probably reached its highest level. The level of concentration was a function of different factors, including the rate of gas emission, the enclosed space and the air tightness of the hold. The amount of gas emitted was very much dependent on the amount of moisture or water inside the hold and the amount of spilled magnesium phosphide that came in contact with moisture or water.

Example: Chemical release, dispersion and concentration modelling

The m/v SCI case history provided no data on the release, dispersion and concentration of dangerous substances into the marine environment. For the purpose of illustration, another marine incident case is presented. The case consists of the data collected from the accident investigation report prepared by the Swedish Nature Protection Agency (SNV, 1974) and Looström (1979, 1991b). The case concerns a German flagged general cargo ship (the m/v "Viggo Hinrichsen"), which sank on 28th September 1973 within the Swedish territorial waters (east coast in the Baltic Sea). The ship was carrying chromium compounds (400 tons in 1,800 steel drums), including chromium trioxide (234 tonnes in 1,100 steel drums) (Class 5.1: oxidizing substances, subsidiary risk – corrosive) and sodium dichromate (180 tons in 700 steel drums). All drums had removable heads. Except 27 drums stowed on deck, the chemicals were stowed inside the holds. During the storm, the ship experienced machine failure. She received immediate towing assistance. But, during the towing the ship listed, capsized and subsequently sank (i.e. a typical marine accident - foundering) ca. 2 km north of the island of Öland, at a water depth 17 m. During the towing, the ship lost overboard 10 of 27 on-deck-stowed drums. Two drums were never found. The responsible Swedish authorities carefully and continuously monitored the situations from the day one of the accident until the ship was salvaged.

Figures 4.17~4.21 show the release, dispersion and concentration modelling of chemicals into the sea water. Both chemicals are solids, which when in contact with water dissolve forming chromic acid (Class 8: corrosive substances) that is corrosive and toxic. The analysis of water samples showed the presence of chromic acid in the sea water suggesting that the sea water had penetrated drums, dissolved and released chemicals (in the form of chromic acid) into the sea (see Figures 4.17~4.21). The investigation after the recovery operations showed that of 27 on-deck-stowed drums, 4 drum were empty and 7 drums were leaking. Due to impact or compression several drums had breached. The removable heads on the drums were not completely tightened. For six days, an estimated amount of 1-2 tonnes of chromium dissolved, released, dispersed and concentrated into the sea, as shown in Figures 4.17~4.21. The process was a function of several influencing factors, including the extent of damage/breach of drums, the amount and the rate of release, chemical properties of chromium (in particular solubility in water), and the compounded water currents (strength and directions). In the first two days after the ship sank, because of the small amounts of chemicals diluted into the water and probably in the absence of detectable water currents, the dispersion and concentration of chemicals were confined in the vicinity (15-20 m) of the sunken ship (see Figure 4.17). As more chromium diluted into the water and because of stronger water currents, chemicals dispersed and concentrated in the sea water column, mainly in the lower levels, as far as 1 km away form the sunken ship (see Figures 4.18~4.21).

The natural chrome concentration in the sea water column of the Baltic Sea was 1µg/l. The analysis results of the sea water samples showed that the levels of chrome concentrations in the sea water column in the vicinity and around the ship wreck far exceeded the natural level (see Figures 4.17~4.21). The acute toxic effect concentration in fish varied between 1-100 mg/l. The non-immediate lethal, but long-effect, concentration in fish varied between 0.02-0.2 mg/l. High levels of chrome concentration, which exceeded the aforementioned levels, were also found in marine organisms such as fish, mussels and algae. Many dead jellyfishes and a few fishes were observed in the site of the wreckage. In order to minimise the effects of chemicals on the environment and its organisms, three days after the accident, the wreckage site was treated with 11 tons of ferrosulfate. The latter reacts with chromic acid forming a less dangerous solution. The ship was salvaged in day six. The total costs of the search and recovery operations amounted to ca. $ 600,000.

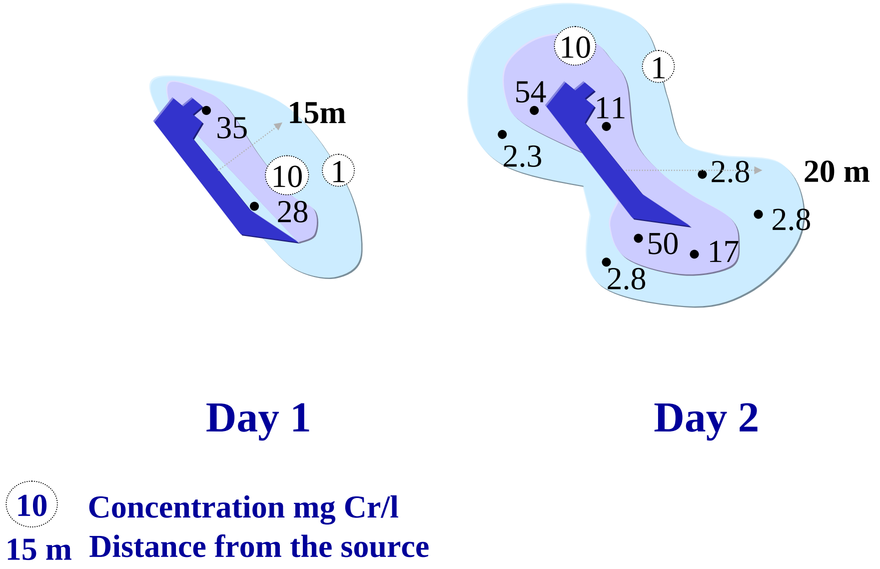


Figure 4.17: Chemicals release, dispersion and concentration – day 1 and 2 (from SNV, 1974)

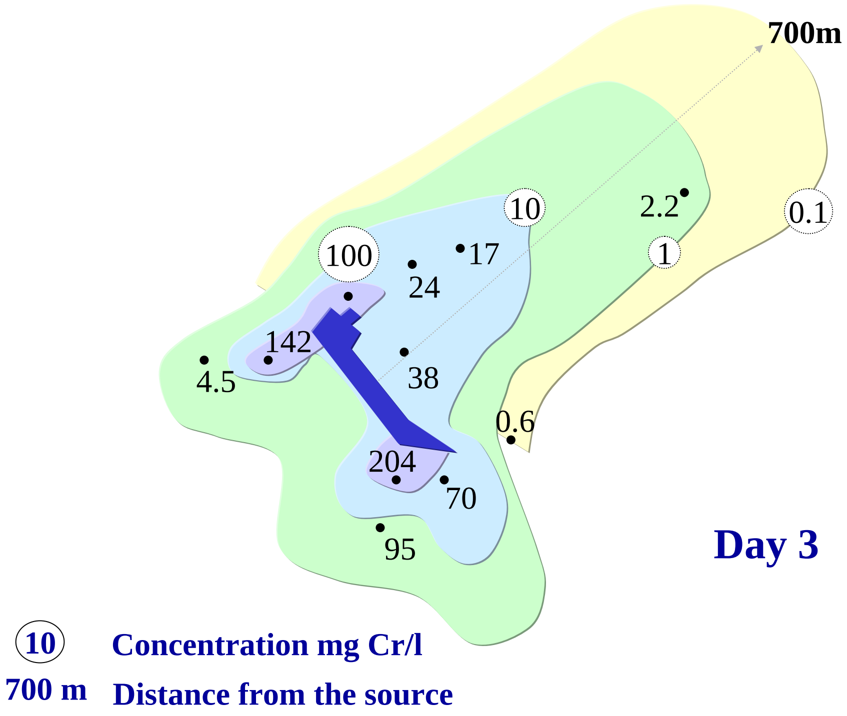


Figure 4.18: Chemicals release, dispersion and concentration – day 3 (from SNV, 1974)

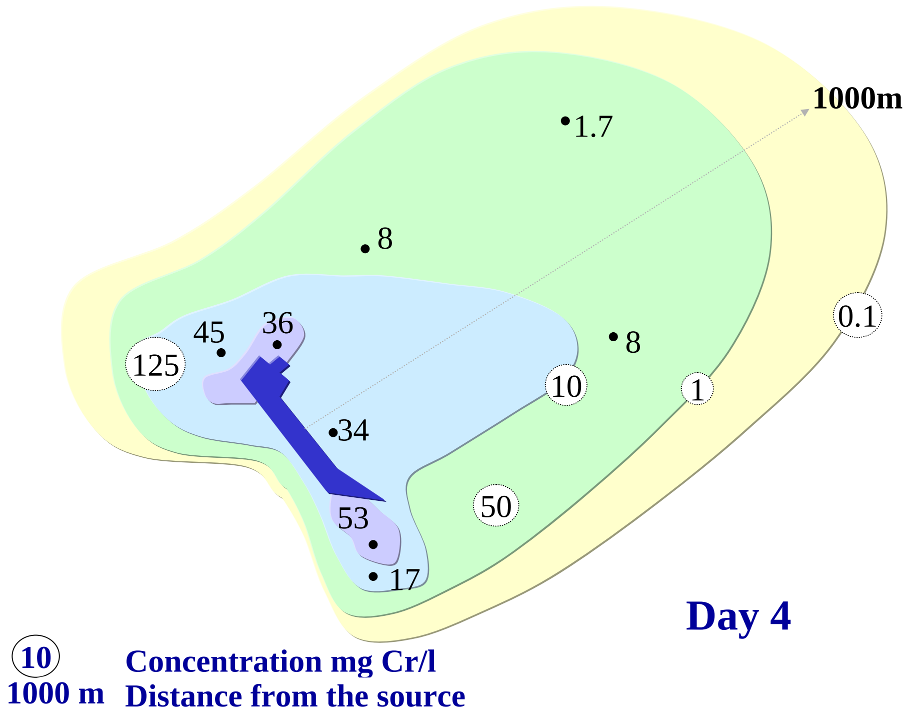


Figure 4.19: Chemicals release, dispersion and concentration – day 4 (from SNV, 1974)

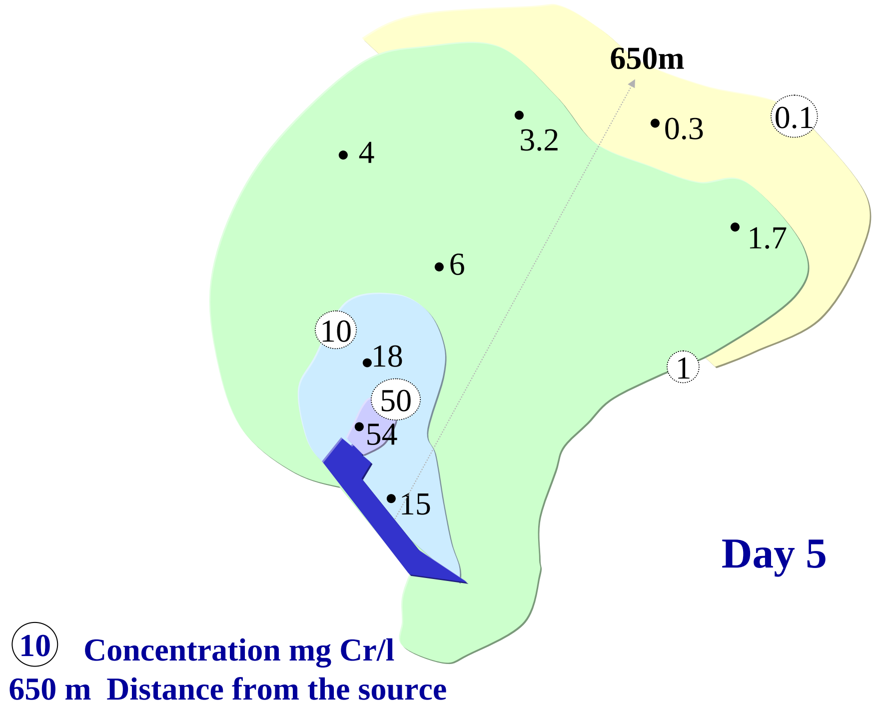


Figure 4.20: Chemicals release, dispersion and concentration – day 5 (from SNV, 1974)

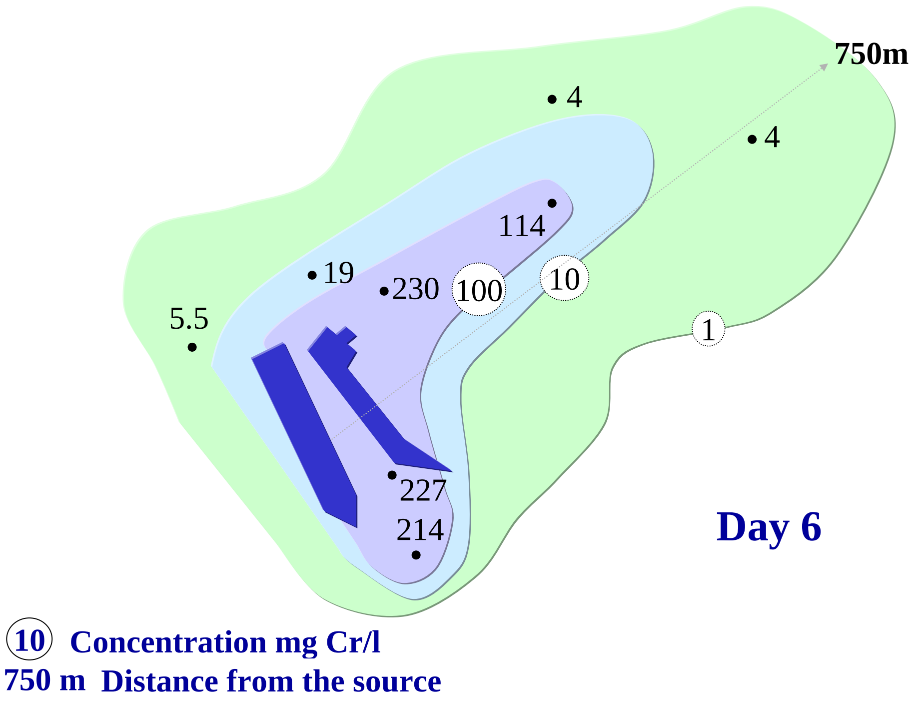


Figure 4.21: Chemicals release, dispersion and concentration – day 6 (from SNV, 1974)

4.1.4. Risk receptors exposure

Questions: What types/categories of risk receptors were exposed to dangerous goods? How many? How were they exposed?

Tasks: Explore and quantify risk receptors exposed to dangerous goods. Explore circumstances and sequences of exposure events (see the **highlighted areas** in Figure 4.22).

The following sections explore the main categories of risk receptors and the circumstances in which they were exposed to arsenic trioxide and magnesium phosphide hazards (Table 4.4). The numbers/amounts of risk receptors exposed to dangerous goods were not available, except for the number of crew.

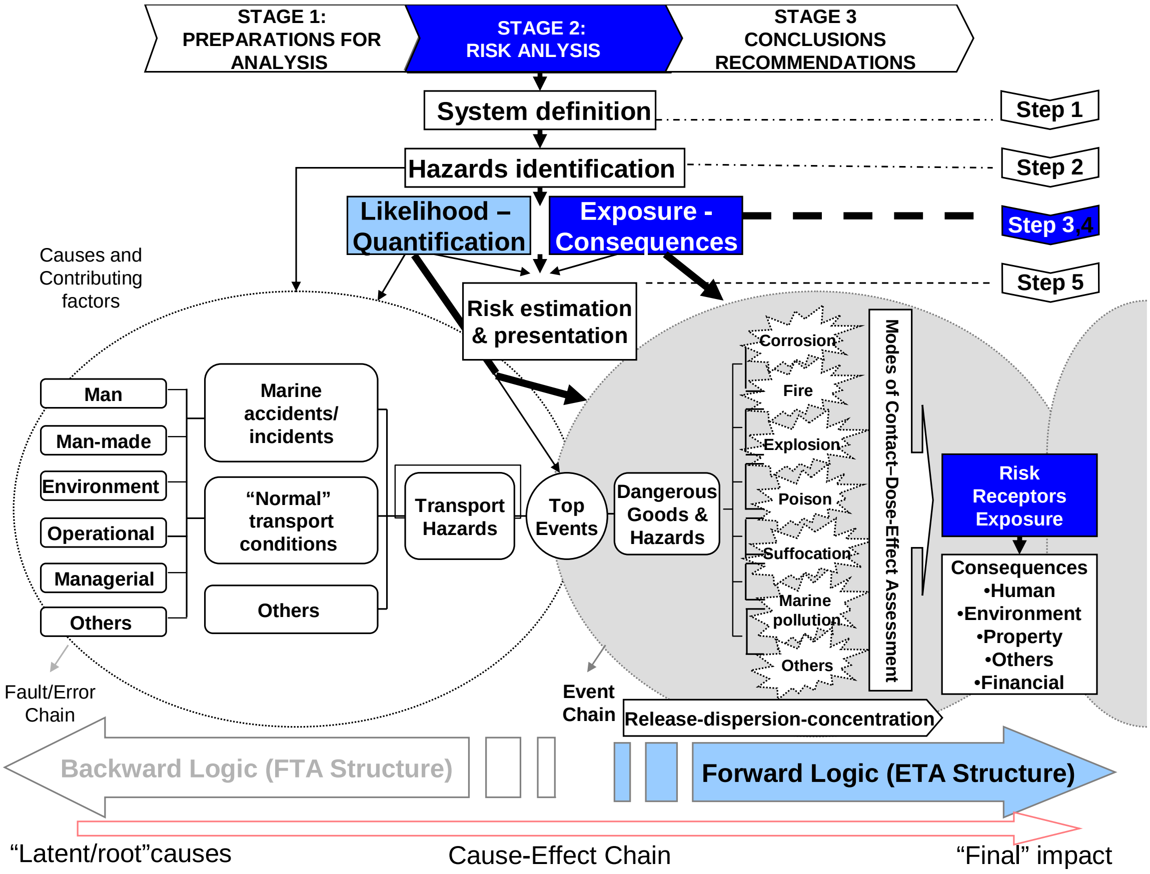


Figure 4.22: Stage 2 – Risk Analysis; Step 3 – Exposure and consequences analysis, risk receptors exposure (continued from Figure 1.2)

Table 4.4: Categories of risk receptors and circumstances of exposures

No.	**Main categories and sub-categories of risk receptors exposed**	**Circumstances of exposure: where and how risk receptors were or could have been exposed**	**Number/ amount**
1	***Human***		
1.1	• *Crew of the m/v SCI*: - AB seamen - Bosun - Chief mate - Deck officers - Master - Other crew • *Crew of other ships*	• Cargo/ship securing and re-securing • Cargo inspection • Preparing the ship for loading, discharging and navigation • Mooring/ un-mooring of the ship • Other activities • Living aboard the ship	28
1.2	• *Stevedores* in ports of Baltimore and Charleston: - Stevedores working aboard the m/v SCI - Stevedores working aboard other ships and in other port areas • *Supervisors*	• Loading/discharging cargo onboard the m/v SCI • Supervising cargo operation • Cargo operations in other ships and port territories in the vicinity of the m/v SCI • Other activities in port	N/A*
1.3	• *Cleanup workers*	• Local contractors who worked with: - Recovery and cleanup of chemicals onboard the ship - Deactivation of magnesium - Overpacking and disposal of chemicals	N/A
1.4	• *Search, rescue and response personnel*: - Maryland Department of the Environment's emergency response team - Local hazardous material response teams - Divers trained for hazardous materials - Specialised salvage and diving companies	• Cargo/ship inspection • Diving in search of arsenic drums on the sea floor • Recovering arsenic drums from the sea floor • Loading and discharging drums of chemicals • Overpacking or repacking damaged drums • Transport and disposal of chemicals	N/A
1.5	• *Authorities and representatives* - Port authorities - Police authorities - U.S. Coast Guard authorities - Fire department personnel	• Authorities and representatives boarded the contaminated ship/ cargo to perform: - Port formalities - Cargo and ship inspections - Monitoring and supervision of recovery and cleanup operations	N/A

No.	Main categories and sub-categories of risk receptors exposed	Circumstances of exposure: where and how risk receptors were or could have been exposed	Number/ amount
	- Representatives of cargo receiver - Representatives of shipping company - Representatives of SCI's insurers		
1.6	- *Fishermen*	• Exposure to arsenic trioxide drums caught in nets – one fisherman recovered an arsenic trioxide drum caught in his net • Consumption of fish contaminated by arsenic trioxide	N/A
1.7	• *Local community* - Ports of Baltimore and Charleston - Delaware Bay and coastlines	• Damaged magnesium phosphide drums were left on the apron outside a stevedore shed • The chemical would have reacted violently with water (rain), producing phosphine gas, which is a highly poisonous and flammable gas • Large amounts of poisonous gas and fire and explosions would have exposed the port, workers, other ships, property and the local community to hazard • Consumption of fish and shellfish contaminated by arsenic trioxide • Exposure to un-recovered arsenic trioxide drums landed on the coastlines	N/A
1.8	• *Others* - Cargo surveyor	• Cargo/ship surveying - taking photos of spilled chemicals and other damaged dangerous goods onboard	N/A
2	***Marine environment***		
2.1	• *Marine environment* of the area of Delaware Bay and the New Jersey southern coast: - Seawater - Fauna and flora - Sediments - Coastlines - Amenities - Others	• Four arsenic trioxide containers were lost overboard • An estimated amount of 200 kg of arsenic trioxide was released from damaged drums into the sea • An unknown amount of spilled arsenic trioxide on deck might have been blown by winds or washed by rain or green waters into the sea • Many drums were not found and, therefore, not recovered from the sea • Possible exposure to un-recovered arsenic trioxide drums stranded on the coastline	N/A
3	***Property***		
3.1	• *Cargo*	• Different types of general cargo aboard the	N/A

No.	Main categories and sub-categories of risk receptors exposed	Circumstances of exposure: where and how risk receptors were or could have been exposed	Number/ amount
	- Cargo of the m/v SCI - Cargo of other ships	m/v SCI were exposed to spilled chemicals, including freight containers, trucks, lumber, cartons of wine, cotton and others • Cargo in other ships in the vicinity was exposed to chemical dust and gas, potential fire and explosion	
3.2	• *Ship* - The m/v SCI - Other ships in the vicinity	• Almost the entire m/v SCI was contaminated: - No.1 hold – tweendeck: magnesium phosphide - No. 2 hatch and deck: arsenic trioxide - Other holds and decks: arsenic trioxide, magnesium phosphide and other dangerous goods • Other ships were exposed to chemical dust and gas, potential fire and explosion	N/A
3.3	• *Property ashore* - Property within the port territory - Property of the local community	• Property ashore was exposed to chemical dust and gas and potential fire and explosion, including: - Stevedore shed - Warehouses - Terminals - Others - Private and public property of the local community	N/A
4	**Activity**		
	• *Disruption of activities* - Ship - Port - Local community - Maritime- related activities – fishing - Coastlines	• The m/v SCI was put out of operation (laid-up) for several days • Cargo operations related to the m/v SCI were suspended	N/A

*N/A – Not Available or Assessed

4.1.5. Sequences of risk receptors exposure events

The conditions for exposure to dangerous goods were present onboard the m/v SCI and the marine environment, including:

- Many arsenic trioxide containers/drums that were lost overboard;
- Many arsenic trioxide drums that were damaged, spilling their contents on deck;
- A large amount of magnesium phosphide that had spilt from damaged drums in no. 1 hold, and phosphine gas emitted from magnesium phosphide that had built up in the hold at high levels of concentration.

Many risk receptors were unknowingly exposed to arsenic trioxide and magnesium phosphide. The following section explores the sequences of exposure events as well as failure modes to warn against and avoid the exposure to dangerous goods, prevent the escalation of events, and mitigate the consequences. Specific causes and factors contributing to failure in time and space are explored by means of *forward logic* analysis. As this analysis will show, the causes, contributing factors and failures are multiple and interlinked in a complex way. The *highlighted areas* indicate the exposure events and when/where the risk receptors were exposed to dangerous goods. The triangle **(*continued*)** denotes that that particular box is linked to the next, or to another, sequence of events, which will be indicated accordingly. The analysis follows (*forward logic*) the sequences of exposure events shown in Figure 4.23.

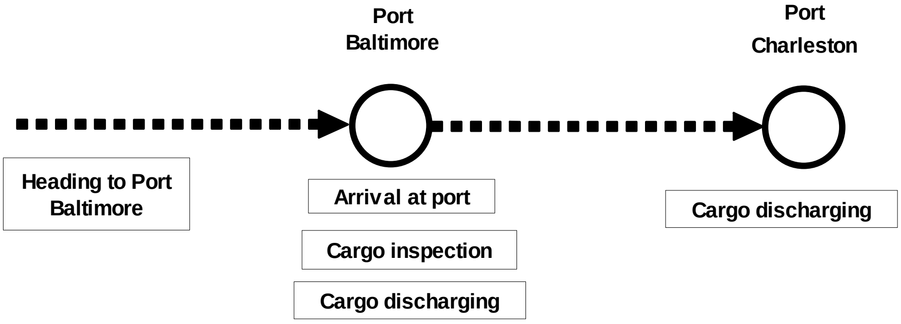


Figure 4.23: Sequences of exposure events – in time and space

The analysis is organised on the basis of the following locations and activities, which are sequences of events as they occurred:

Heading to/prior to arrival at Port Baltimore

A) Arrival at Port Baltimore
B) Cargo inspection in Port Baltimore
C) Cargo discharging in Port Baltimore
D) Cargo discharging in Port Charleston
E) Accident responses in both ports

A. Heading to/prior to arrival at Port Baltimore

At 0603 hrs on January 4, the ship arrived at Delaware Bay, where the Delaware Bay pilot boarded it. The ship headed towards Port Baltimore (Figure 4.24).

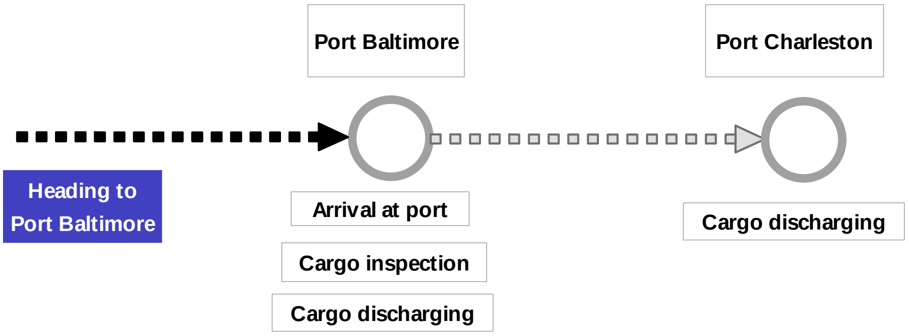


Figure 4.24: Ship heading to/prior to arrival in Port Baltimore

The pilot reported to the ship's bridge that a container was hanging overboard. The pilot also noticed pools of a white liquid on deck. The liquid was leaking from damaged drums. He probably discussed the white liquid with the master. The *forward logic analysis* (Figure 4.25), which presents a qualitative analysis of failure modes of exposure to dangerous goods prior to arrival at Port Baltimore, follows *from left to right*.

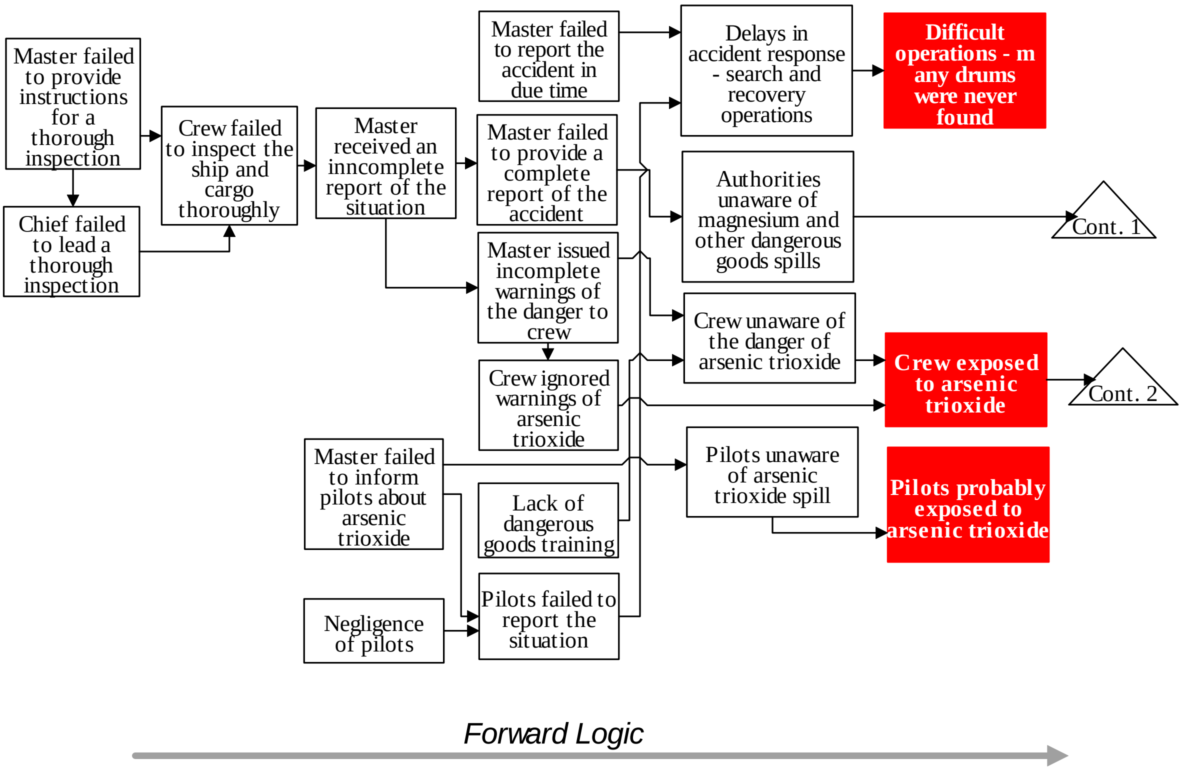


Figure 4.25: Exposure to dangerous goods prior to arrival at Port Baltimore

The master failed to provide instructions for a thorough inspection: After the pilot's report, the master instructed the chief mate to inspect the cargo on deck only. There was no indication that he provided instructions for a thorough inspection inside the holds.

The chief failed to conduct a thorough inspection: The chief mate should have made a thorough inspection. Given his responsibilities as the chief mate, he did not need any instruction from the master.

The crew failed to inspect the ship and cargo thoroughly: The chief mate and several crewmembers went down on deck to inspect the damage. There was no indication that they were wearing any special protective suit. After the inspection, the chief mate reported the blue drums and the white powder on deck and on the hatch cover. By visual observation of the labelled drums and with reference to the IMDG Code, the master confirmed that they contained arsenic trioxide, which was a toxic substance. The crew did not carry out a thorough inspection of the ship and cargo, where accessible, including the cargo in the UTD of the no.1 hold. Subsequently, ***the master received an incomplete report of the situation*.** At this point, the master was probably unaware of the situation inside the holds.

The master failed to provide a complete report of the accident: At 13.55 hrs, on the basis of the inspection report and visual observation on deck, the master informed the ship’s agent in Port Baltimore about the loss of arsenic trioxide containers, damage and spills on deck only. He did not report the magnesium phosphide spill inside the no.1 hold or other dangerous goods spills in other holds. This is supported by the fact that the master requested arrangements for a cleanup of arsenic trioxide on the no.2 hatch only. The agent informed the relevant local authorities and parties in port Baltimore. The ***authorities were unaware of magnesium phosphide and other dangerous goods spills*** (see the next Section – *continued 1*). The master also informed the shipowner.

The master failed to report the accident in due time: In accordance with the relevant regulations, the master should have reported the accident (the loss overboard of cargo) to the relevant authorities when it occurred. According to the master, due to heavy rains and poor visibility, the situation was “first” noticed at 0603 hrs on January 4, when the pilot boarded the ship at Delaware Bay and reported damage and spills. At 1355 hrs, approximately eight hours after the “first” observations and 12 hours after the accident occurred, the master reported it to the ship’s agent. Given the following facts, the account of the master was not quite reliable. Massive losses and damage on deck are unlikely to go unnoticed just a few metres away with an open view. Nearly the entire stow in hatch no.2 (21 of 25 containers and the piece of machinery) was lost overboard. The remaining containers stowed on deck were badly damaged. Shifting, damage and loss overboard of heavy cargo produce noticeable noises and vibrations. Some containers were fully loaded, weighing approximately 20 tons. The machinery weighed 21 tonnes. Unusual noise due to impacts, breakings, shifting, rollings, sliding, banging of heavy cargo is quite noticeable. One container was still hanging (see Figure 2.16) and probably banging on the portside when the ship arrived at Baltimore Bay. Seasoned seafarers can detect vibrations including those caused by impacts, rollings, sliding, banging of heavy cargoes. The degree of visibility was not reported. According to the SMA database (SMA, 1985-1999), the worst degree of restricted visibility was around 100 m or less. In the case of the m/v SCI accident, because of strong winds, the visibility was probably beyond 100 m, which is beyond the no.2 hatch. Given the ship's overall length of 146 m, the aft part of the no. 2 hatch and the front of the bridge were only 60 m apart (see Figure 4.26).

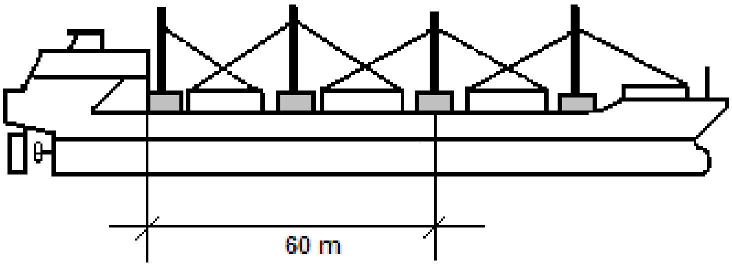


Figure 4.26: Cargo losses and damage occurred just 60 m away on an open view

Delays in accident response: Delays in reporting the accident led to delays in accident response, i.e. the search and recovery operations, which subsequently contributed to ***difficulties in operations***. The search and recovery teams made large efforts and spent considerable time and resources to locate arsenic trioxide containers and drums on the sea floor. Many drums were never found and, therefore, not recovered. These drums posed future threats to the marine environment and the local community (see Section 4.2.3.2). If the master had reported the accident in due time and if information about the cargo had been correct, the authorities in charge and the parties involved in the rescue and recovery operations might have:

- Pinpointed precisely the initial positions where containers/drums fell;
- Predicted the drifting of containers/drums faster and more accurately;
- Determined and informed the areas dangerous for navigation in due time; and
- Conducted search and recovery operations effectively (for a discussion in greater detail, see Section 4.2.7.1).

The master issued incomplete warnings of the danger: Because of the danger posed by the arsenic trioxide, the master issued danger warnings ordering every one off deck forward of the house until the ship reached Port Baltimore. It was uncertain whether these warnings reached all the crewmembers.

Some crewmembers ignored the warnings of arsenic trioxide hazards: Some crewmembers ignored the warnings and freely wandered about the deck contaminated by arsenic trioxide. ***Unaware of the danger,*** one crewmember reported taking some arsenic trioxide powder in his hands and smelling it. These facts suggest that the master's warnings were inadequate, and that the crew ***lacked training in dealing with dangerous goods***. Consequently, the ***crew was exposed to arsenic trioxide*** *(see Figure 4.25, continued 2).*

The master failed to inform pilots about arsenic trioxide: The master warned the crew about the danger of arsenic, but not the pilots. Although they were aware of the dangerous nature of the liquid on deck, the master, chief mate and deck officers did not inform the Delaware Bay pilot that the white liquid was arsenic trioxide. The pilot became aware of the arsenic trioxide several hours later, when he arrived home. The USCG, USEPA and other state officials from Delaware and Maryland called him and asked whether he knew anything about the leaking arsenic trioxide (Klein and Nugent, 2004). Other pilots (Delaware River and other pilots) might not have been informed of the danger of arsenic trioxide. Being unaware of the danger, ***pilots may have been exposed to arsenic trioxide*** while boarding or leaving the ship.

Pilots failed to report the situation: Although the master did not inform them and it might have not been their direct responsibility, none of the pilots reported the situation onboard the m/v SCI to the pilot station or the relevant authorities. U.S. Federal Law requires reporting of oil and chemical spills to the National Response Center (NRC).

Negligence of pilots: Given their experience and the visible damage and spills on deck, the pilots (even as private citizens) should have reported the situation, regardless of whether there was any chemical involved, but they neglected to do so. According to the USCG, a good rule of thumb for when to fill out the accident notification (Report of Marine Accident) is: "When in doubt, fill it out" (USCG, 2005). As mentioned above, after boarding the ship, the Delaware Bay pilot informed the master of the damage and the white liquid leaking from damaged drums on deck.

Summary

Due to various combinations of all these failures, the risk receptors (the crew and pilots) were exposed to arsenic trioxide. The authorities and other parties in Port Baltimore were unaware of the magnesium phosphide and other dangerous goods spills.

B. Arrival at Port Baltimore

At 1525 hrs on January 4, the m/v SCI arrived at the pier in Port Baltimore (see Figure 4.27). No one predicted the full potential danger brought along by the m/v SCI.

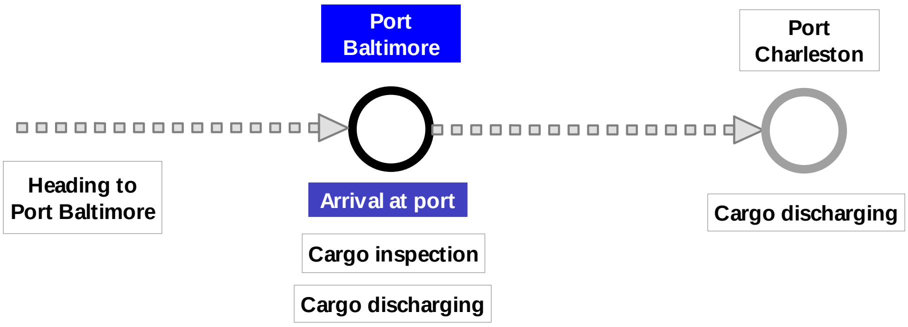


Figure 4.27: Arrival at Port Baltimore

Figure 4.28 shows the *forward logic analysis* (*from left to right*) of the failure modes as the ship arrived at port Baltimore.

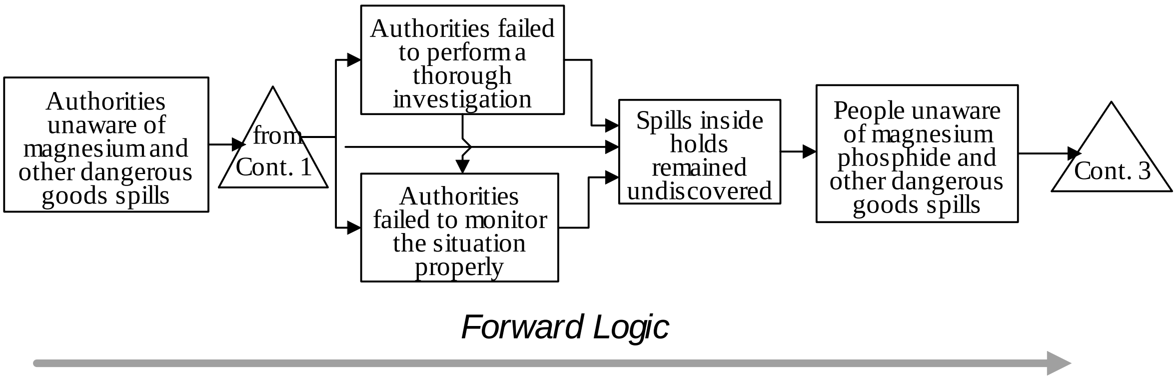


Figure 4.28: Exposure to dangerous goods on arrival at Port Baltimore

Authorities unaware of magnesium phosphide and other dangerous goods spills *(from* ***continued 1****)*: Over the next several hours after the ship's arrival, numerous authorities and representatives boarded the ship, including the Maryland Port Authority police, emergency response teams, the fire department, the USCG, and representatives of the shipping company. The members of the Maryland Department of the Environment's emergency response team, assisted by the local hazardous-materials teams, conducted the initial response and the boarding of the ship. After inspecting the ship and cargo and unaware of the situation inside the holds, the authorities concluded that there was no immediate danger. Consequently, the situation progressed into the post-emergency phase.

Authorities failed to perform a thorough investigation: The conclusions, decisions and actions taken by the authorities were inadequate. The sequence of events indicated that all the authorities and representatives mentioned failed to perform a thorough investigation. They inspected losses, damage and spills on deck only, but failed to investigate the situation below deck, particularly inside the no.1 hold. The situation on deck clearly indicated that the ship had had a rough time at sea. However, none of the experts thought that cargo damage and spills would probably have occurred inside the holds. A careful investigation of the shipping documents would have shown that the m/v SCI was loaded with other dangerous goods than arsenic trioxide, which had also been damaged and spilled. The later accident investigation carried out by the USCG (U.S. DOT, 1992), which was triggered by public concern and the incident in Port Charleston, left nothing (no "stone") unturned.

Authorities failed to monitor the situation properly: The responsible authorities mentioned failed to monitor the situation properly. They may have left the ship soon after the situation progressed into the post-emergency phase, or prior to the start of cargo discharging. This is supported by the fact that, on January 5, between 09.00 and 10.30 hrs, four damaged drums with magnesium phosphide were discharged from the no.1 hold. The hold was covered with the toxic powder, but no one from the authorities or expert teams was present to observe the labelled damaged drums and the spill.

Summary

At this point, the ***spills inside holds remained undiscovered*** and, subsequently, ***people*** *(crew, authorities, and stevedores)* ***were still unaware of the danger of magnesium phosphide and other dangerous goods spills*** *(continued 3, Figure 4.28)*.

C. Cargo inspection in Port Baltimore

In Port Baltimore, the chief mate, the bosun and at least four crewmembers entered each hold to inspect and re-secure the cargo that was not scheduled for discharge in Port Baltimore (Figure 4.29). In addition, for the purpose of cargo and ship insurance, the shipowner hired a cargo surveyor to examine the condition of the cargo aboard the m/v SCI. The timing of the cargo inspection was unclear. It may have taken place prior to, or during, cargo discharging.

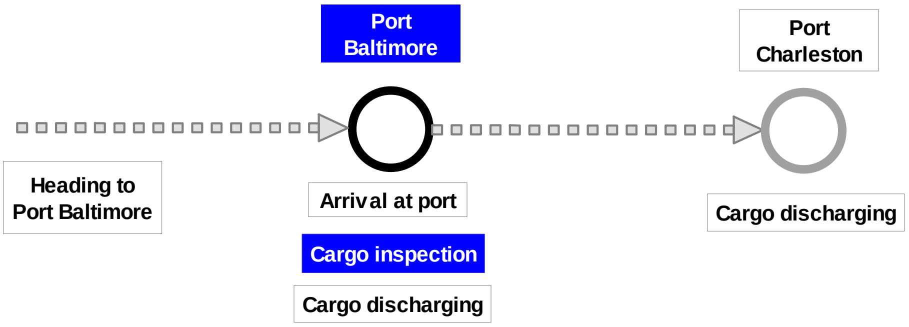


Figure 4.29: Cargo inspection in Port Baltimore

Figure 4.30 shows the *forward logic analysis* (*from left to right*) of the failure modes in cargo inspection in Port Baltimore.

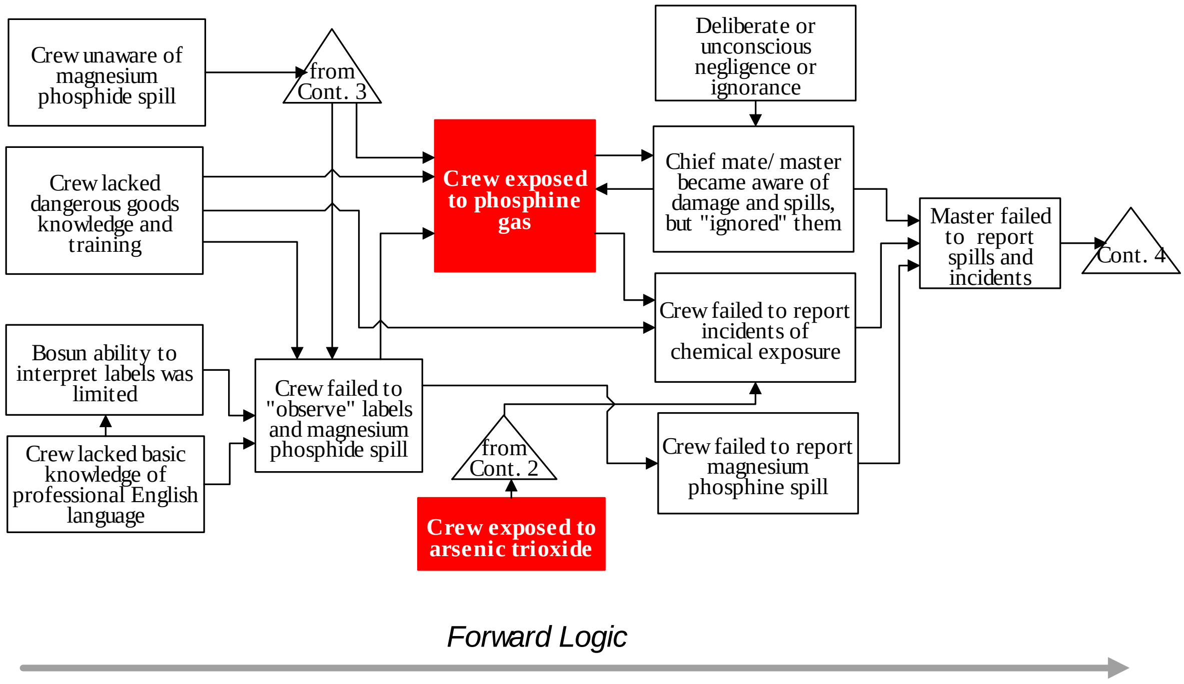


Figure 4.30: Exposure to dangerous goods during cargo inspection in Port Baltimore

The crew failed to "observe" labels on drums and the magnesium phosphide spill: The crew entered the UTD of the no.1 hold and found two pallets of magnesium phosphide upset, their drums and contents mixed with other cargo. The drums were properly and clearly labelled. These labels were very hard to miss (see Figure 4.31). However, according to the crew's statements, none of them "recalled" any hazard labels. The crew denied knowledge of any spilled dangerous goods other than arsenic trioxide on deck. In other holds, the crew also found that several containers, trucks, and breakbulk packages had broken lose and been damaged. At least two other dangerous types of cargo were similarly set adrift and spilled.

Figure 4.31: "Toxic" and "dangerous when wet" labels

The crew lacked knowledge of and training in dangerous goods: The crew lacked basic knowledge and training in identifying dangerous goods. When interviewed by the Board of Inquiry, two crewmembers stated that they knew nothing about dangerous goods labels, and that they relied completely on the bosun for direction (U.S. DOT, 1992). The crewmembers may have seen the labels but did not know what they meant. However, it does not require any special knowledge and training to recognise the danger associated with a very common sign shown in the "toxic" label (see Figure 4.31 – the label on the left).

The bosun's ability to interpret labels was limited: The bosun was "familiar" with dangerous goods labelling, but his ability to interpret labels was limited. He could not read labels in English. During the accident investigation, the bosun stated that when he saw pictures, it was a good indication of the problem, but if it was written in English, he could not read it (U.S. DOT, 1992). The Delaware Bay pilot found that the m/v SCI's crew barely spoke any English (Klein and Nugent, 2004). These facts suggest that the ***crew lacked basic knowledge of the English language of their profession***.

The crew failed to report magnesium phosphine spill: According to the investigation report (U.S. DOT, 1992), no one reported the magnesium phosphine spill and the hazardous conditions in the no.1 hold or the spills of other dangerous goods in other holds, to the master.

The chief mate and master became aware of damage and spills, but "ignored" them: The statements of the crew that "they did not recall any hazard labels or spill" were not very convincing, particularly that of the chief mate. The chief mate is supposed to have the formal education and training and extensive experience, including the carriage of dangerous goods. The spill (393 kg of magnesium phosphide) and damage inside the no.1 hold were quite visible. One important task of the ship management onboard, including the chief mate, is to safeguard the safety, health, and well-being of the ship's crew. The chief mate should have exercised due diligence prior to entry in the no.1 hold, in accordance with the relevant IMO recommendations and guides for entering enclosed spaces, particularly cargo spaces loaded with dangerous goods. In addition, once he became aware of damage and spills in the hold, he should have ordered everyone out of the hold immediately. Another important task of the chief mate is to take care of the cargo. He should have taken notes and investigated cargo damage and spills thoroughly. If the chief mate really did not recall any hazard label and spill, this would be very serious ***negligence or ignorance*** on his part. Most probably, the chief mate, including other crewmembers, observed the spill, knew exactly the nature of the chemical spilled and reported it to the master. However, the chief mate and the master may have decided to "ignore" the incidents and not to inform people about the danger.

The most compelling evidence of the master's and chief mate's knowledge of damage and spill of magnesium phosphide aboard the ship is the cargo survey in Port Baltimore. For two days, the ship remained at the pier in Port Baltimore. A cargo surveyor, who was hired by the shipowner or the P&I Club for the purpose of cargo and ship insurance and the shipowner's limited liability, examined the conditions of the cargo and ship. He witnessed extensive cargo damage and spillages inside the holds. The surveyor produced a large volume of photos. The photos taken before the no.1 hold was unloaded clearly showed the spill of magnesium phosphide and the "toxic" and "dangerous when wet" labels on the damaged drums. Additional photos showed spills of dangerous substances in other holds. As a matter of practice, the cargo surveyor is usually accompanied during the inspection by at least one of the ship's crew, for example the chief mate, deck officer, bosun or AB seaman, who also observed the damage and spills. After the examination, the surveyor may have discussed the conditions of the cargo with the master and the chief mate. They may also have seen the photos taken by the surveyor. Even a month after the incident, attorneys for the shipowner were unwilling to allow the Board of Inquiry to interview the surveyor. The unwillingness of the attorneys for the shipowner suggests that the interview with the supervisor (including his photos) would have compromised the statements of the master, the chief mate and other crewmembers to the effect that "they did not recall any hazard labels or spill."

The crew exposed to phosphine gas: Being ***unaware of the danger*** (from *continued 3, Figure 4.28*) and due to the failures mentioned above, the crew entered the no.1 hold without wearing special protecting suits and were exposed to phosphine gas. Two crewmembers showed symptoms of gas intoxication.

The crew failed to report the incidents of chemical exposure: According to the investigation report (U.S. DOT, 1992), two incidents of chemical exposure (arsenic trioxide – from *continued 2*, and phosphine gas) were not reported to the ship's medical officer or the master. The chief mate and bosun may have been present at one or both incidents, but they failed to report them. Some of the possible reasons why these incidents were not reported are the following:

- The crewmembers were really unaware of the danger and exposure to chemicals.
- The crewmembers deliberately ignored the incidents.
- The incidents may have been reported to the medical officer or the master, or they may have become aware of them somehow, but:
  - they may have ignored the incidents and failed to investigate their causes; or
  - they may have been well aware of the spill and the causes of the incidents, but for fear of complicating the situation, they decided not to inform the people concerned, including the crew, stevedores, port authorities and the Board of Inquiry.

The master failed to report spills and incidents: For the reasons just mentioned, the master failed to report the ships and incidents. According to the investigation report (U.S. DOT, 1992), no one reported the hazardous conditions in the no.1 hold to the USCG captain of Port Baltimore, as required by the relevant U.S. regulations (49 CFR Parts 171 and 176.) The master also failed to inform other parties concerned, including stevedores in Port Baltimore and Port Charleston.

Summary

Because of the lack of knowledge and training and deliberate or unconscious failures, the crew were exposed to chemicals. The incidents of spills and exposure were not reported to the master or the ship’s medical officer. The magnesium phosphine spill from damaged drums, which were properly and clearly labelled, was quite visible, but neither the master nor the chief mate warned the people concerned, including the crew, stevedores and the relevant authorities of the danger inside the holds. The possibility that the master and chief mate were aware of the nature of the spills and the incidents cannot be excluded.

D. Cargo discharging in Port Baltimore

At 02.00 hrs on January 5, a local cleanup contractor, who was hired and directed by the m/v SCI’s insurers, began recovering and cleaning up arsenic trioxide from the no.2 hatch cover and deck. The operation took nearly one whole day. The large container with cotton was removed in order to gain access to the deck area. Stevedores discharged other damaged containers from the no.2 hatch cover and deck. Then, discharging the cargo scheduled for Port Baltimore began (Figure 4.32).

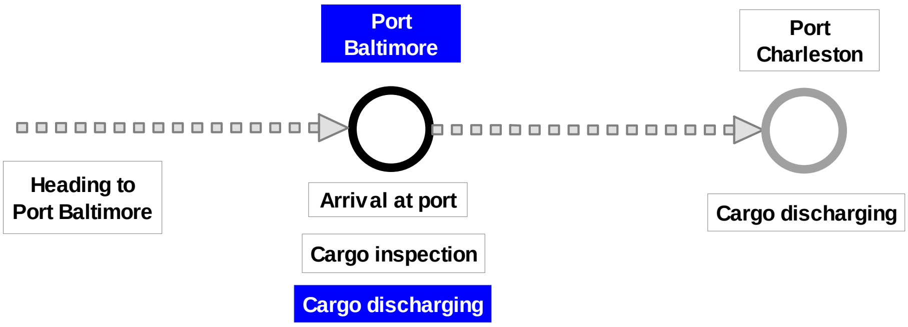


Figure 4.32: Cargo discharging in Port Baltimore

The case history provides conflicting information about discharging cargo from the no.1 hold. According to Merrick (1993), the local cleanup contractor directed by the m/v SCI's insurers overpacked four damaged drums of magnesium phosphide. The master requested arrangements for cleaning up dangerous goods on the no.2 hatch only (U.S. DOT, 1992). No request for cleaning up in the no.1 hold was mentioned. The fact that loose magnesium phosphide remained inside the no.1 hold until arrival at the next port (U.S. DOT, 1992) indicates that no overpacking, recovery or cleaning up took place. A review of stevedoring records in Port Baltimore indicated that, sometime between 09.00 and 10.30 hrs on January 5, the cargo described as "three skids of steel drums and four loose damaged drums" was discharged from the m/v SCI's no.1 hold (Merrick, 1993). According to the investigation report (U.S. DOT, 1992), stevedores discharged all the magnesium phosphide drums.

Figure 4.33 shows the *forward logic analysis* (*from left to right*) of the failure modes in discharging cargo in Port Baltimore.

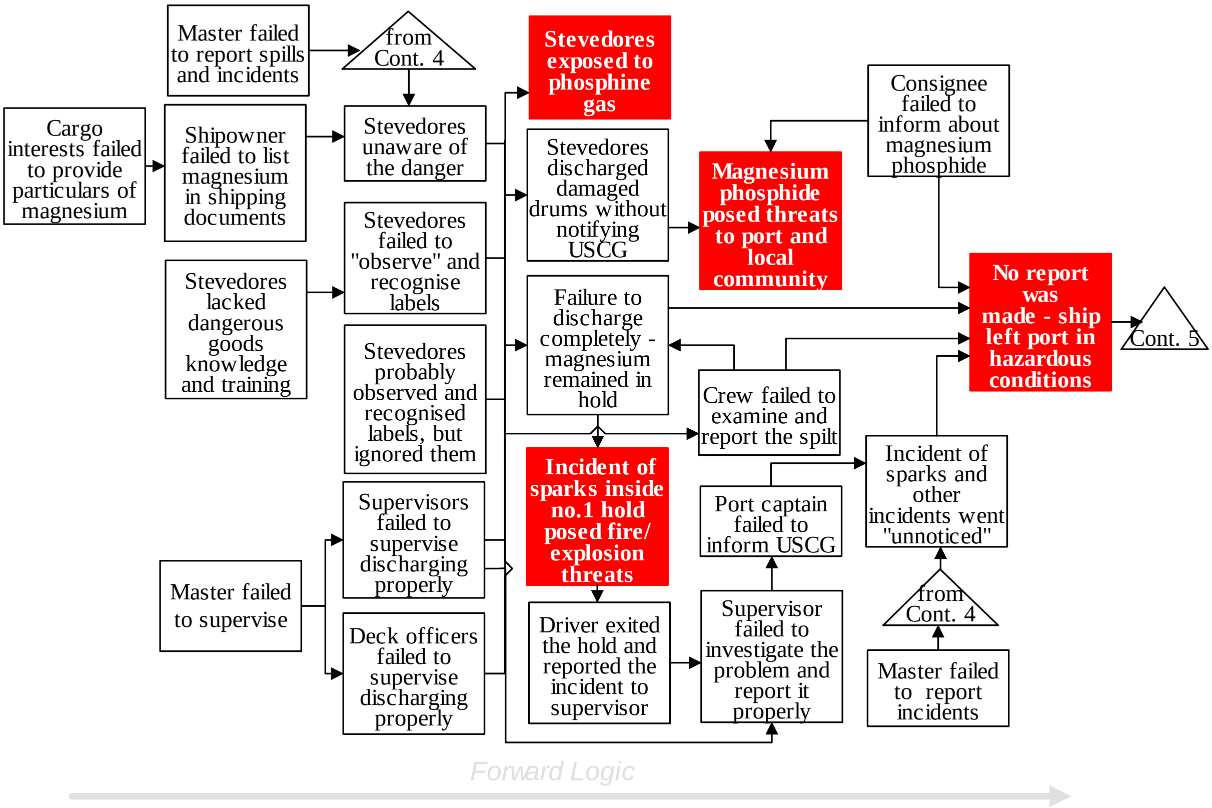


Figure 4.33: Exposure to dangerous goods during cargo discharging in Port Baltimore

Prior to and while discharging cargo, for the reasons mentioned earlier, ***the master failed to inform the parties concerned*** (form *continued 4*), including the stevedores, the USCG and the port authorities of the danger of chemicals spilt inside the holds. The master should have made arrangements for cleaning up the no.1 hold as well as other holds with the same local cleanup contractor. But, the chain of failures continued.

The shipowner failed to list magnesium in the shipping documents: Magnesium phosphide is regulated under the U.S. regulations (49 CFR) and the IMDG Code for carriage by sea, with stowage permitted “on deck or under deck.” In accordance with these regulations, the chemical is labelled both “toxic/poison” and “dangerous when wet.” Although classified as a dangerous substance and clearly and properly labelled, magnesium phosphide was not identified in the shipping documents (i.e. the precursor of the Dangerous Goods Manifest – DCM) as dangerous cargo, as required by the relevant regulations. According to McGowan (1993), the shipowner and the master failed to list the drums of magnesium phosphide in the shipping documents. The case history does not specify whether magnesium phosphide was identified in such documents as bills of lading, cargo manifests and cargo loading/discharging plans.

Cargo interests may have failed to provide particulars of magnesium phosphide: The bills of lading (i.e. the documents containing full particulars of goods shipped or to be shipped and the cargo manifests, which are prepared by the shipowner or his representatives, are based on the cargo documents forwarded by cargo interests or their representatives. The parties involved in the shipment of the chemical, including the shipper, consignor, seller, shipping agents, freight forwarders or other third party logistics, may also have been responsible for the failure. A cross examination of all the shipping documents would have shown the origin of the failure. The case history shows that such an examination was not carried out in the course of the accident investigation. The bills of lading are issued to the shipper in sets of three or four, one copy is retained by the master, and two copies are dispatched, usually by express mail, to the buyer or to any other addressee of cargo or consignee (Gaskell et al., 1992). In the case of the m/v SCI, if the bills of lading contained full particulars of magnesium phosphide drums, which is quite possible, then the buyer, consignee or their representatives in Port Baltimore were very much aware of the nature of the contents of the damaged drums.

Stevedores were exposed to phosphine gas: No one in Port Baltimore informed the stevedores of the dangerous contents of the drums. ***Being unaware*** of the chemical and unprotected, the stevedores entered the no.1 hold and began discharging the cargo. As they entered the hold, they were all exposed to phosphine gas. The fact that two crewmembers who entered the same hold showed symptoms of phosphine gas intoxication indicates that magnesium phosphide had emitted phosphine gas. However, the dose of gas inhaled was not sufficient to cause any detectable symptoms of intoxication, as the level of concentration may have been low. The level of toxic gas exposure is, among others, a function of the duration of exposure. Although initially unaware, the stevedores had still the opportunity to discover the danger, suspend work and leave the hold immediately, thus avoiding a longer exposure to toxic gas and fire/explosion threats.

Stevedores failed to “observe” and recognise hazard labels: Although drums were properly and clearly labelled with “toxic” and “dangerous when wet” labels, the stevedores failed to “observe” and recognise these labels. They neither showed any concern nor reported the spill but discharged all the magnesium phosphide drums.

Stevedores lacked knowledge of and training in handling dangerous goods: Failure to recognise labels and discharging damaged drums without any notification indicate that the stevedores lacked adequate knowledge of and training in handling dangerous goods.

Stevedores probably observed and recognised labels, but ignored them: The labels (as shown in Figure 4.31) are quite large and visible. The stevedores probably observed and recognised the labels, but they may have ignored them. They handled the drums with their hands. Someone among the stevedores may have had the experience and knowledge of dangerous goods required to identify hazards. The very common sign shown in the "toxic" label (see Figure 4.31), which it does not require any special knowledge and training to recognise, clearly indicates the danger. The stevedores' mother tongue was English, and they read and understood the words "toxic" and "dangerous when wet."

Stevedores discharged damaged magnesium phosphide drums without notifying the USCG: The stevedores discharged all the magnesium phosphide drums ashore, including damaged drums. This was done without notifying the U.S. Coast Guard.

Magnesium phosphide posed threats to the port and the local community: All ten drums were transported and stored in open air at the terminal, on the apron outside a stevedore shed. Given its chemical properties and the proximity of the shed to the populated area, the magnesium phosphide posed threats to the port and the local community.

Failure to discharge the cargo completely - loose magnesium phosphide remained aboard: After all ten drums had been discharged, an amount of 393 kg of loose magnesium phosphide remained inside the no.1 hold. The course of events showed that loose magnesium on deck was a very dangerous situation. Regardless of the crew's knowledge of the nature of the cargo, in principle, the loose cargo (i.e. magnesium phosphide) should have been collected, repacked and discharged ashore either as part of the cargo or as waste. If accepted, the loose cargo also belongs to the consignee. However, both the ship and shore personnel failed to do so. The hold should have been cleaned thoroughly to remove any residues.

The incident of sparks inside the no.1 hold posed fire/ explosion threats: After discharging the magnesium phosphine drums, one stevedore working a forklift on the UTD of the no.1 hold noticed sparks as the rubber tires on the forklift spun on the grey, granulated chemical on deck. The ***driver promptly exited the hold and reported the incident to the supervisor***. Given the chemical properties of phosphine gas, this incident could have turned into a disastrous fire/ explosion scenario (for more information, see Section 4.2.1).

The supervisor failed to investigate the problem and report it properly: One of the supervisors reported to the port captain that he had a problem (U.S. DOT, 1992). He simply reported that he had a problem, nothing else. He failed to go down inside the hold, suspend the discharging of the cargo and make a thorough investigation. This fact suggests that he did not take the situation very seriously. The supervisor should have made a detailed and complete report of the incident. Although the chain of communication was unclear, the supervisor could also have informed other relevant authorities directly, including the USCG.

The port captain failed to inform the USCG: The port captain failed to report the incident to the USCG. The failure to report the incident after being informed by the supervisor suggests that the port captain did not take the situation very seriously either.

The incident of sparks and other incidents went "unnoticed": No one reported the incident of sparks in the no. 1 hold as well as other incidents (from *continued 4*) to the USCG (U.S. DOT, 1992) or any other relevant authority.

Supervisors failed to supervise the discharging of cargo properly: The primary task of supervisors is to supervise cargo operations. The fact that no one knew about hazardous conditions inside the hold and discharging damaged drums without any notification indicates that the supervisors did not perform their task properly. Probably, none of them was on the deck of the m/v SCI to observe the situation inside the no.1 hold, including the damaged drums, the spill and the incident of sparks. If they had been present, had observed the situation and had done nothing, this would have been very serious negligence and ignorance on their part.

The chief mate and deck officers failed to supervise the discharging of cargo properly: The primary task of the chief mate as well as of the deck officers on duty in port is to supervise cargo operations. None of them was present when the incident of sparks occurred. Furthermore, no one expressed any concern about the damaged drums discharged ashore and the loose powder remaining on deck. As mentioned earlier, the chief mate and the crew stated in the inquiry that "they did not recall any hazard labels or spill." If they really did not recall anything even in broad daylight and with open hatch covers, which was very unlikely, the chief mate and deck officers seriously failed to supervise the discharging of cargo in Port Baltimore.

The master failed to supervise: The master is also responsible for the failure, since his main task was to supervise and manage every activity onboard the ship. This task includes the supervision of cargo operations, his subordinates and the shore personnel. Given massive cargo damage, losses, and spills on deck, the master should have inspected the situation inside the holds thoroughly for himself.

The consignee or his representatives failed to inform about the chemical: In every part of the world, the cargo loaded or discharged from a ship is checked and counted by one or several parties. The case history does not indicate whether the magnesium phosphide drums discharged in Port Baltimore were checked and counted. However, in principle, the consignee, his representatives or any other third party should have checked and counted the cargo in Port Baltimore. In accordance with the contract of sale and the shipment documents, the buyer or consignee should have received from the m/v SCI all ten drums (or 10x179.6 kg=1,796 kg) in good condition. In fact, the ship delivered six drums in good condition (or 6x179.6 kg=1,077.6 kg) and four damaged drums containing 325.4 kg of magnesium phosphide (4x179.6 kg=718.4 kg – 393 kg=325.4 kg). In total, the consignee received an amount of 1,403 kg instead of 1,796 kg of product as specified in the documents, i.e. a shortage or short lading of 393 kg. This amount had been spilled on deck of the no.1 hold, which was not discharged, and remained onboard until the ship arrived at the next port of destination. Depending on the contact of sale, the buyer may want to reject the goods if they are not in the specified condition, or the buyer may be entitled to claiming damage, normally in the form of paying a reduced price or replacement of goods (Gaskell et al., 1992). In the case of the m/v SCI, the consignee or his representatives should have received partly damaged cargo after compensations or a signed document entitling the consignee to compensations for the shortage and damage. This document should have contained, among other things, particulars (e.g. type/class and amount) of the cargo involved, i.e. magnesium phosphide. If these procedures were performed, which is very likely, and then the consignee as well as all the parties involved including the supervisors, the master and the chief mate, were well aware of the nature of the contents of the damaged drums and the spill. The consignee or his representatives should have informed the relevant authorities of the danger. Furthermore, he/she should have taken all the necessary measures to avert any incident or threat posed by a “toxic” and “dangerous when wet” chemical stowed in the open air and close to a populated area.

The crew failed to examine and report the spill: No further cargo work was done in the UTD of the no.1 hold in Port Baltimore. As mentioned earlier, a considerable amount of loose magnesium phosphide remained on deck inside the no.1 hold. Again, the ship personnel, including the master, the chief mate, deck officers, bosun and AB seamen, failed to examine the toxic powder spilled in the hold, take the necessary measures and report the conditions to the relevant authorities. As a matter of good seamanship, prior to departure, the crew should at least have prepared the hold for cargo operations in the next port, including cleaning up and fixing the mess in the no.1 hold (as seen in Figures 4.97 and 4.98, Section 4.2.4).

No report was made - the ship left the port in hazardous conditions: At 0645 on January 6, the ship completed discharging the cargo and left Port Baltimore, bound for Port Charleston (South Carolina, U.S.). No report of any spill, hazardous conditions inside the no.1 hold or incident was made to the USCG in Port Baltimore as required by U.S. regulations (49 CFR Parts 171 and 176). The m/v SCI left Port Baltimore in hazardous conditions.

Summary

Being unaware of the danger, stevedores entered the no.1 hold and discharged all ten magnesium phosphine drums, including four damaged drums, without notifying the USCG. A considerable amount of loose magnesium remained on deck, posing fire/explosion threats. Three incidents in Port Baltimore were “a wake-up call” for everyone concerned, which would have prevented the incident in Port Charleston. However, neither the ship nor the shore personnel paid any attention to the spill and incidents of human exposure. The ignorance and negligence of all parties concerned were major failures that led to the incident in Port Charleston. The ship left Port Baltimore in hazardous conditions.

E. Cargo discharging in Port Charleston

At 22.20 hrs on January 7, the m/v SCI arrived at Port Charleston in ***hazardous conditions*** (from *continued 5, Figure 4.33).* During the voyage, in contact with moisture or water, the magnesium phosphide that was spilt on deck of the no. 1 hold reacted and emitted toxic and flammable gas. The gas concentrated inside the hold at a high level. The next day, on January 8, the hatch covers were opened and the work began onboard the ship (Figure 4.34).

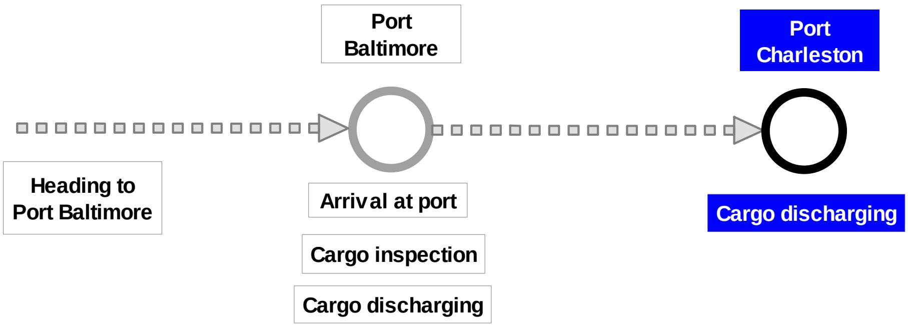


Figure 4.34: Cargo discharging in Port Charleston

Figure 4.35 shows the *forward logic analysis* (*from left to right*) of the failure modes in discharging cargo in Port Charleston.

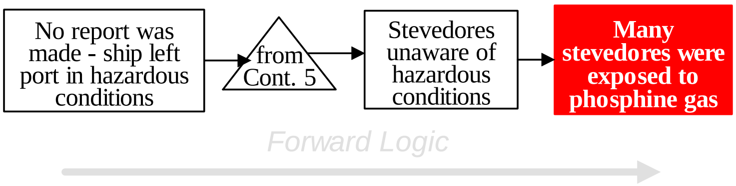


Figure 4.35: Exposure to dangerous goods during cargo discharging in Port Charleston

Stevedores were unaware of hazardous conditions: Unaware of hazardous conditions, the stevedores entered the no. 1 hold, which was filled with phosphine gas, unprotected in order to discharge the cargo scheduled for Port Charleston.

Many stevedores were exposed to phosphine gas: On the same day, on January 8, many stevedores were sent to hospital for examination after exposure to phosphine gas.

According to Merrick (1993), the information provided in the m/v SCI’s cargo manifest showed that arsenic trioxide was the only dangerous cargo onboard. This was believed to have been the case until a large amount of loose chemical was discovered in the hold in the port of Charleston (Merrick, 1993). However, according to the accident investigation report (U.S. DOT, 1992), the ship carried other dangerous goods. The spilt chemical “turned out” to be magnesium phosphide.

The case history provides no answers to the following questions: Why was magnesium phosphide “discovered” in Port Charleston? How was it “discovered”? Who made the “discovery”? Although not listed in the cargo manifest, the magnesium phosphide drums that had already been discharged in front of many people in Port Baltimore several days before were properly and clearly labelled. In Port Charleston, only an “unknown” loose powder with no label and shipping document remained inside the no.1 hold. One plausible explanation is that, in response to symptoms of toxic gas exposure observed in stevedores, Port Charleston authorities made the “discovery” of magnesium phosphide after the investigation. Someone informed the authorities. According to the 1992 accident records (NRC, 2005 – see Table 2.2), an anonymous caller reported that he had discovered the incident on 8 January 1992, and that he would notify the Department of Health. It was unclear how this “discovery” was made.

Summary

One major failure was the casual manner in which dangerous goods were handled. Repeated instances of ignorance and negligence associated with the handling of dangerous goods and in the response to its loss, damage and spills were occurred onboard the m/v SCI and in ports. The course of events showed that the spills were not sufficient conditions for the dangerous goods to cause harm to the people involved. Although dangerous goods were spilt aboard the ship, there were still plenty of opportunities and measures, including last-minute measures, to interrupt the chain of events and prevent human beings from exposure and its consequences. However, neither the ship personnel nor the shore personnel identified and/or reported the spills, hazardous conditions and incidents. Due to their deliberate or unconscious failures, the ship and shore personnel involved put other people, the ship, the marine environment, ports and local communities at risk. The analysis in this section showed that the failures were due to a combination of human, operational and managerial factors (Table 4.5). The number in each item indicates the incidence of failures.

The list of causes and contributing factors (see the summary in Table 4.5) explored in this section as well as in other subsequent sections can be added to the list of causes and contributing factors in the m/v SCI accident explored in hazard identification (see Chapter 3, Vol. II). Altogether, they form an “open” complex cause-effect chain, in which the effects of one, or more, event become the causes for other events.

Table 4.5: Exposure events: causes and contributing factors

Exposure events: causes and contributing factors				
Human/Man (17)	**Man-made (0)**	**Environmental (1)**	**Operational (19)**	**Managerial (9)**
1. Ship personnel (8) ***1.1 Master/chief mate (1)*** • Master and chief mate became aware of damage and spills, but "ignored" them (1) ***1.2 Crew: AB, bosun (7)*** • Crew unaware of the danger (1) • Crew ignored warnings of arsenic trioxide hazards (1) • Crew lacked knowledge and training in handling dangerous goods (2) • Crew failed to "observe" labels and the spill (1) • Bosun's ability to interpret labels was limited (1) • Crew lacked basic knowledge of the professional English language (1) **2. Shore personnel (9)** ***2.1 Stevedores (6)*** • Stevedores unaware of hazardous conditions (2) • Stevedores failed to "observe" and recognise hazard labels (1) • Stevedores lacked dangerous goods knowledge and training (1)		**1. Weather conditions (1)** • Poor weather conditions hampered search and recovery operations (1)	**1. Dangerous goods communication – reporting accidents/spills (13)** ***1.1 Ship personnel (9)*** *1.1.1 Master (5)* • Master failed to provide a complete report of the accident (1) • Master failed to report the accident in due time (1) • Master failed to inform pilots about arsenic trioxide (1) • Master failed to report spills and incidents (2) *1.1.2 Crew (4)* • Crew failed to examine and report the spill (1) • Crew failed to provide an complete report of the situation (1) • Crew failed to report magnesium phosphine spill (1) • Crew failed to report incidents of chemical exposure (1) ***1.2 Shore personnel (4)*** *1.2.1 Consignee (1)* • Consignee or his representatives failed to inform about the chemical (1) *1.2.2 Port captain (1)* • Port captain failed to inform the USCG	**1. Instruction – ship/cargo inspection and monitoring accident response (3)** • *Master* failed to provide instructions for a thorough inspection (1) • *Master* issued incomplete warnings of the danger (1) • *Chief mate* failed to instruct and lead a thorough inspection (1) **2. Monitoring accident response (1)** • *Port authorities* failed to monitor the situation properly (1) **3. Supervision of cargo operations (3)** ***3.1 Ship personnel (2)*** • *Master* failed to supervise activities and personnel (1) • *Chief mate and deck officer*s failed to supervise cargo discharging properly (1) ***3.2 Shore personnel (1)*** • *Supervisors* failed to supervise cargo discharging properly (1) **4. Compliance with regulation – reporting of accidents/spills (2)** • *Supervisor* failed to investigate the problem and report it properly (1) • No one (*ship/shore personnel*) reported chemical spills and incidents in accordance with regulations (1)
		Other (0)		

Exposure events: causes and contributing factors				
- Stevedores observed and recognised labels, but ignored them (1) - The incident of sparks and other incidents went “unnoticed” (1) ***2.2 Pilots (2)*** - Pilots unaware of the danger (1) - Negligence of pilots (1) ***2.3 Authorities (1)*** - Port authorities unaware of magnesium phosphide and other dangerous goods spills (1)			(1) *1.2.3 Pilots (1)* - Pilots failed to report the situation (1) *1.2.4 Stevedores (1)* - Stevedores discharged damaged magnesium phosphide drums without notifying the USCG (1) **2. Ship/cargo inspection (1)** - *Crew* failed to inspect the ship/cargo thoroughly (1) **3. Accident response and investigation (2)** - Delays in accident reporting and response made recovery operations difficult (1) - *Port authorities* failed to perform a thorough investigation (1) **4. Dangerous goods documentation (2)** ***4.1 Shipowner (1)*** - Shipowner failed to list magnesium in the shipping documents (1) ***4.2 Cargo interests (1)*** - Cargo interests failed to provide particulars of magnesium phosphide (1) **5. Cargo discharging (1)** - Stevedores failed to discharge cargo completely (1)	

F. Accident responses in both ports

Cleanup, deactivation and disposal of magnesium phosphide

The “discovery” of magnesium phosphide inside the no.1 hold of the m/v SCI shook up the Port Charleston authorities and sent shock waves back to Port Baltimore, where ten drums were still sitting at the terminal. After that, the authorities in both ports, Port Charleston and Port Baltimore, took the situation very seriously.

Port Charleston

On January 8, on the day of the “discovery”, due to the threats posed by toxic gas to the crew and stevedores, the USCG in Port Charleston suspended cargo operations and ordered that the ship should be evacuated. Then, due to the threats posed by toxic gas to other ships, the port and the local community, the m/v SCI was taken with a skeleton of the crew to the anchorage area in the Port Charleston harbour for cleanup and deactivation operations of magnesium phosphide. With continuous mechanical ventilation of the hold, a specialised cleanup team (the U.S. National Strike Force personnel) spent several weeks in delicate operations. Every single kilogram of chemical was deactivated carefully (alternatively dry and then wet) at a time. In Port Charleston, the cleanup operations were completed on February 8 (U.S. DOT, 1992). The entire amount of magnesium phosphide spilt was recovered and deactivated.

Port Baltimore

On January 11, three days after the first “discovery”, the long process of magnesium phosphide response began in Port Baltimore. Initially, all ten drums of magnesium phosphide were removed from the stevedore shed and sent to another, more remote, location at the terminal, area 98. The consignee inspected and accepted six undamaged drums, which were then shipped to the intended destination. Four damaged drums remained in area 98 for deactivation and disposal.

The U.S. Federal On-Scene Coordinator and other authorities reviewed several deactivation and disposal plans. The contractor who was hired by the m/v SCI insurers to remove the damaged drums submitted an initial plan. This plan involved first the deactivation of the magnesium phosphide by allowing the chemical to react with the moisture in the ambient air. Then, the chemical was to have been immersed in water to react any residuals. This plan was not accepted by the authorities because of the risks involved in the on-site deactivation in the densely populated terminal (Merrick, 1993). The contractor was asked to submit another plan. The second plan involved the deactivation of a limited quantity of magnesium on site. This plan would have required two permits from the state of Maryland, which was reluctant to issue these permits unless there was no other option available. Therefore, the authorities invited additional contractors to bid for the deactivation and removal of drums. The contractors were asked to submit plans that would involve the repacking and off-site transportation of the magnesium phosphide, rather than on-site treatment. A new contractor was selected on the basis of a draft plan calling for a repacking of the chemical in a nitrogen-inserted atmosphere.

The authorities asked the contractor to submit a detailed plan, including a remedial action plan and a site-specific health and safety plan. The Atlantic Strike Team and Maryland Department of the Environment recommended some amendments to the plan. During this time, the site preparations and the construction of an inert enclosure were underway in area 98.

On June 26, the on-scene coordinator gave the contractor the green light to proceed with the repacking and deactivation of the chemical according to the approved plans. The contractor repacked the first three drums without incident. While a remote puncturing device was used on the fourth drum, the phosphine gas that had built up inside the drum exploded, propelling the drum into the overhead of the inert enclosure. The drum landed in the original overpacking after releasing about 38 litres of magnesium phosphide into the inert enclosure. After the atmosphere in the inert enclosure had stabilised, decontamination was conducted and the loose magnesium phosphine was repacked. At 08.00 hrs on June 30, the magnesium phosphide was repacked and sent to the final disposal site in Arkansas.

Cleanup on the ship was initiated in Port Baltimore on January 5 and was completed in Port Charleston on February 8, 1992.

Recovery and disposal of arsenic trioxide drums

After the debris of arsenic trioxide containers and drums was found, numerous ways to recover the drums were explored. Prior to the recovery operations, the authorities considered the development of a plan in accordance with the U.S. relevant dangerous goods regulations necessary (29 CFR 1910). The Multi-Agency Local Response Team (MALRT), a body of federal, state and local agencies, was called in for consultation on how best to proceed and deal with the situation. Parallel to the HAZMAT response procedures of Recognition, Evaluation, and Control, the team developed a master plan involving several operational phases. At the same time, the authorities reviewed several proposals and options, and decided to employ specialised salvage and diving companies, which were hired by the P&I Club representing the shipowner. The U.S. federal dangerous goods regulations (29 CFR 1910.1018) require appropriate training for people involved in search and recovery operations of dangerous goods. The companies were equipped with ROVs and dangerous goods trained divers outfitted with one-atmosphere diving suits. None of them was reportedly exposed to or affected by arsenic trioxide.

On April 8 1992, the recovery operations began. Some of the drums were damaged. By means of mechanical arms drums were placed into overpacking drums that were filled with grout (sand) material. Some 320 drums were recovered from the sea floor by means of RVOs with mechanical arms. They were brought on deck and stored in containers, then offloaded onto another ship and taken to port. They were loaded onto a trailer and sent to a disposal facility. Because of the water contamination, the arsenic trioxide was considered a hazardous waste.

On May 19, a final extensive sonar and ROV search was made in the environmentally critical areas, but no more drums were found. Many arsenic trioxide drums remained un-recovered on the sea floor. The m/v SCI accident case was formally closed on October 5, 1992. The authorities issued instructions to the maritime community on what to do in cases when drums were located or caught in nets.

Summary

After the “discovery” of magnesium phosphide, the situation aboard the m/v SCI and ashore was taken very seriously. Deactivation, repacking and disposal of magnesium phosphide and recovery and disposal of arsenic drums were carried out in an orderly and well planned fashion in accordance with the relevant regulations and expert evaluations. No one was reported to have been exposed to or affected by the chemicals.

4.1.6. Modes of contact – routes of exposure

Questions: How were risk receptors exposed to dangerous goods? How did they come in contact with dangerous goods?

Task: Explore the modes of contacts – routes of exposures to dangerous goods (see the **highlighted areas** in Figure 4.36).

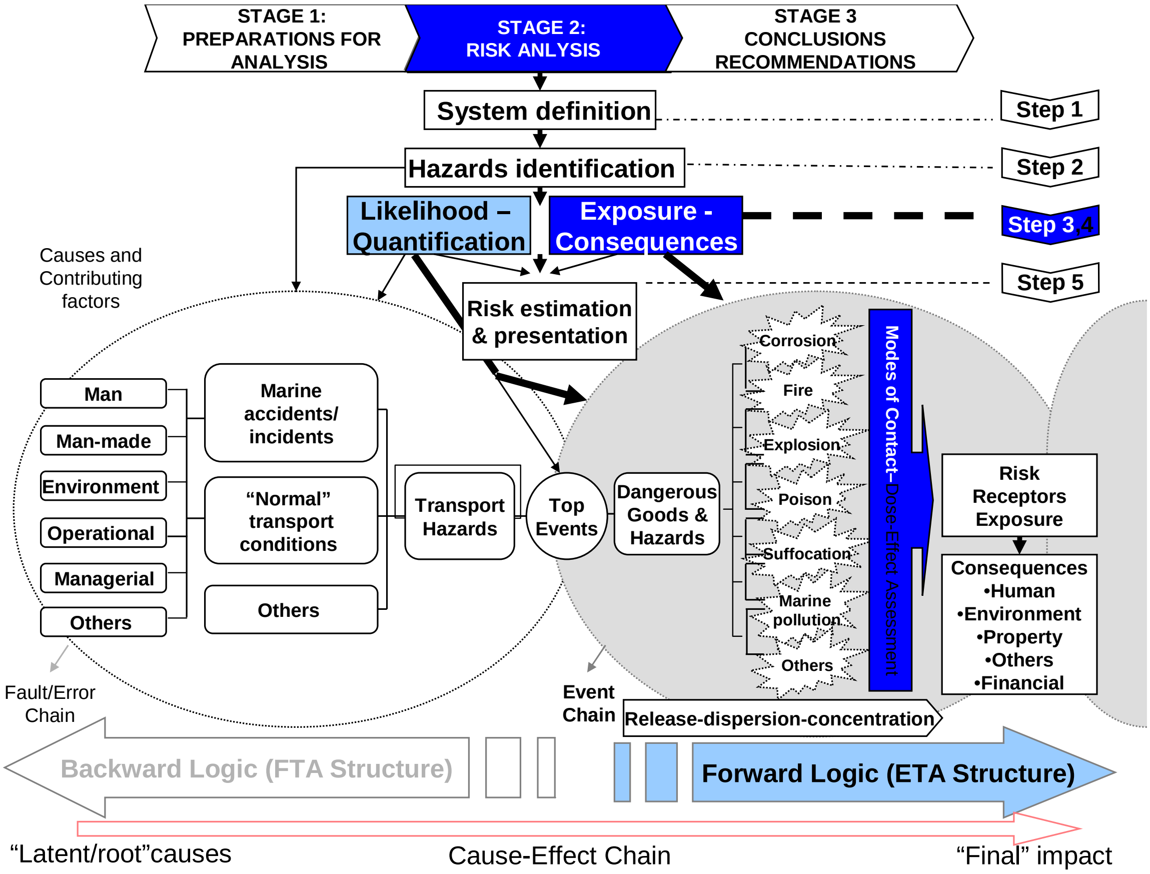


Figure 4.36: Stage 2 – Risk analysis; Step 3 – Exposure and consequences analysis, modes of contacts or routes of exposure to dangerous goods (continued from Figure 1.2)

In the case of the m/v SCI accident, the release, dispersion and concentration of dangerous substances were necessary, but not sufficient, conditions for the dangerous substances to cause harm to the risk receptors. The dangerous substances had to come in contact with the risk receptors in order to cause harm. The route of exposure was an important factor in consequences and response to arsenic trioxide and magnesium phosphide spills. Given their chemical properties (see Appendixes 1 and 2, Vol. II), the routes of exposure in which arsenic and phosphine may have come in contact with human as well as other living organisms include: *inhalation, ingestion, and skin/eye contact*. In terms of bioaccumulation, for arsenic, exposure via ingestion of the aquatic food chain is more important than exposure from ingestion of water (USEPA, 2003). Arsenic can be absorbed to a much lesser degree through skin contact than inhalation or ingestion (Kamrin, 2005). Levels of arsenic or its metabolites in blood, urine, hair, nails or other parts of the body are used as biomarkers of arsenic exposure, each of which may be used as indicators of the duration, routes of exposure, and the absorbed dose of arsenic. However, the case history provides no information as to whether such examinations were conducted on people exposed to arsenic trioxide. Human exposure to phosphine and metal phosphide may occur via the skin, the eyes, or the respiratory tract. Significant absorption of phosphine occurs via the lungs (IPCS, 2005).

The type and extent of consequences caused by arsenic trioxide and magnesium phosphide hazards depended, among other things, on the route of exposure. Inhalation is the commonest route of phosphine poisoning (IPCS, 2005). In the m/v SCI accident, most likely, all people reportedly affected by arsenic trioxide and phosphine gas were exposed to chemicals through *inhalation*. A number of people unaware and unprotected were exposed to the toxic hazards of phosphine gas by inhalation when they entered the no.1 hold. One crewmember felt sick after smelling arsenic trioxide powder. Other modes of contact, such as ingestion, eye and skin contact with chemical vapours, mists or dusts are not to be excluded. Airborne arsenic trioxide and magnesium phosphide particles may have reached a harmful concentration. Inhaled magnesium phosphide dust deposited on the moist surfaces of the respiratory tract release phosphine. In order to avoid chemical exposure and for extra personal protection, the people should have worn complete special protective equipment, including self-contained breathing apparatus (IPCS and EC, 2001) (as those seen in Figure 4.37) or they should have altogether avoided entering within the hazard range. However, they were apparently unaware of the danger.

Arsenic trioxide released at sea, including water column, sediments and flora, comes into contact with and accumulates in aquatic organisms. Increased phosphate significantly decreases the uptake of arsenic in microorganisms (Yamaoka et al., 1988). All routes of exposure are important in chemical accumulation in aquatic organisms. Arsenic accumulation by fish and shellfish takes place through ingestion of arsenic contaminated seawater, sediments and foods. Plants may come in contact with and accumulate inorganic arsenic by root uptake from the sediments or by adsorption of arsenic deposited on leaves or stems. Arsenic trioxide can be transferred to humans when they consume (ingest) contaminated fish and shellfish.

Figure 4.37: Chemical response operation – specialised hazardous material response personnel equipped with special suits to avoid chemical exposure by skin contact, ingestion and inhalation (U.S. DOT, 1992)

Summary

The release and concentration of arsenic trioxide and magnesium phosphine (phosphine gas) were not sufficient conditions for the dangerous goods to cause harm. The dangerous substances had to come in contact with risk receptors through various routes, including inhalation, ingestion, skin/eye absorption, and skin/eye contact. All people reportedly affected by arsenic trioxide and phosphine gas were most likely exposed to chemicals through inhalation. However, other routes of exposure are not to be excluded. The statistical data available (HMIS and NRC databases) contain no information about the modes of contacts with dangerous goods. However, many case histories and other data sources do contain explicit and/or implicit information about modes of contact.

4.1.7. Dose-effect assessment

Questions: How much/long were risk receptors exposed to dangerous goods? What were, or could be in the future, the effects of dangerous goods to risk receptors?

Tasks: Explore and assess dose-effect relationships (see the **highlighted areas** in Figure 4.38).

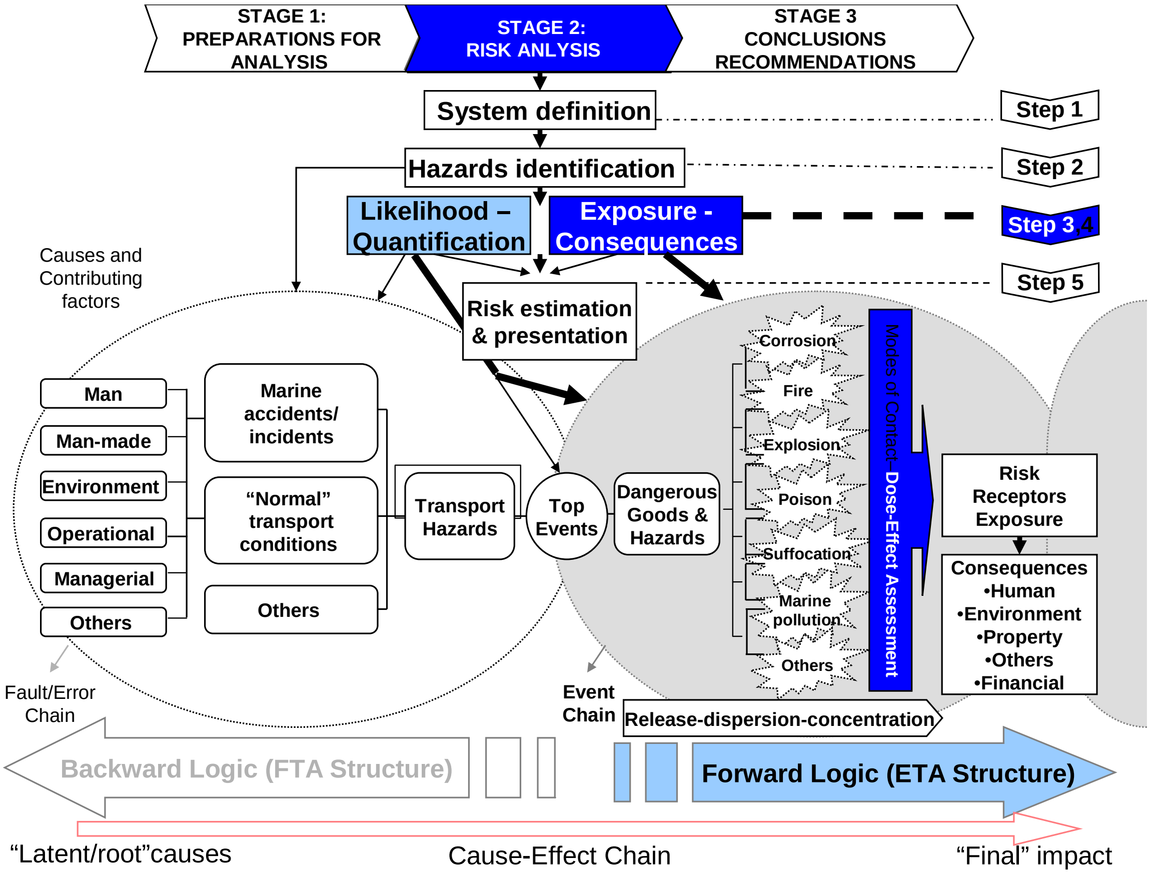


Figure 4.38: Stage 2 – Risk analysis; Step 3 – Exposure and consequences analysis, dose-effect assessment (continued from Figure 1.2)

In the m/v SCI accident case, coming into contact with the risk receptors was a necessary, but still not a sufficient condition for dangerous goods to cause harm. Effects of dangerous goods on risk receptors can only occur after a certain level of exposure is exceeded. Thus, the m/v SCI accident case history showed that the stevedores in Port Baltimore might have been exposed to phosphine gas when they entered the no.1 hold. However, the dose of gas inhaled was not sufficient to cause any acute intoxication, as the level of gas concentration inside the hold was apparently low. The biological, physical, chemical and other effects of arsenic and phosphine to the risk receptors depend on a variety of different factors, including:

- Duration and extent of exposure
- Chemical and biological processes
- Properties of chemicals
- Mechanism of uptake of the chemicals by the organisms
- The environment
- Features of the risk receptors exposed

Thus, the data have shown that inorganic arsenic is more toxic than organic arsenic. The mechanism of arsenic uptake by organisms differs significantly across different organisms. In addition, different organisms respond differently to different arsenic compounds. For example, bio-concentration factors (BCFs) in freshwater invertebrates and fish for arsenic compounds are lower than for marine organisms (IPCS, 2001). There is laboratory and field evidence indicating that organisms living in much higher concentrations have become adapted to high inorganic arsenic levels (IPCS, 2001).

The effects of dangerous substances largely depend on the dose-effect or exposure-response relationships, in which all the aforementioned factors play different roles. Living organisms including human bodies contain many different chemicals. Over time, for different reasons and from different sources, human bodies have absorbed and still can absorb substances present in the environment, including arsenic. For example, according to a study released by the U.S. Environmental Working Group, some 200 industrial chemicals and pollutants were found in the blood of newly born babies (Zwillich, 2005).

Arsenic trioxide (*As_2O_3*): Arsenic is found in its natural form in soil, water, air, plants and animals. Arsenic is a normal constituent of the human body (NJDEP, 2001). It is also further released and elevated to high levels of concentrations into the environment due to natural and human activities. Many studies, including (Chilvers and Peterson, 1987), (Wewerka et al., 1978) and (EC, 2000), have shown that human activities are significant sources of arsenic contamination. Arsenic contaminations are linked to human activities such as application of arsenical pesticides in agricultural areas (Vowinkel et al., 2001). Through underground and surface waters, the marine environment receives a portion of land-based arsenic. The case of the m/v SCI accident is also a good example of arsenic contamination from human activities. Arsenic continually cycles through all elements of the environment. Humans are exposed through various routes to certain levels of arsenic because very low levels of arsenic are always present in nature. The daily intake of the total arsenic (inorganic and organic arsenic - approx. 25% consists of inorganic arsenic depending on food ingested) ingested through food and beverage is generally between 20 and 300 µg/day (IPCS, 2001). Marine organisms naturally contain and accumulate considerable amounts of organic arsenic compounds. Ingestion of seafood exposes human to arsenic compounds. In summary, the human as well as other living organisms contain arsenic.

They are daily exposed to arsenic. Living organisms have the capacity to withstand the intake of certain levels (threshold doses) of arsenic.

However, a small dose of arsenic trioxide exceeding the threshold doses may be lethal or cause chronic health problems to humans and other living organisms. The size of the lethal dose depends, among other things, on the type of arsenic compound involved, the route of exposure, and the dose-effect mechanism. Arsenic compounds exhibit different toxicities. According to the dangerous substances information sheet provided by the Chemical Hazardous Response Information System (CHRIS, 1992; Whipple et al., 1993), the acute lethal concentration (LC) of arsenic trioxide to humans through inhalation (continuous inhalation for one hour) is 2 mg/m^3. This means a concentration of 2mg arsenic in one m^3 would be acute or lethal for people within the hazard range (i.e. the space in which the concentration is 2mgAs/m^3). The lethal dose (LD) of arsenic trioxide to humans through ingestion is LD_{050} – 45mg/kg (CHRIS, 1992), which is a concentration of 45mg arsenic trioxide per kg of body mass. Acute fatal arsenic trioxide poisonings would have occurred to people exposed (crew, stevedores or others) after oral exposure to an estimated dose (a single intake) of 3.15g (45 mg/kg x 70 kg=3.150 mg) for persons with an average weight of 70 kg. The total amount (459,270 kg) of arsenic trioxide carried aboard the m/v SCI would have been sufficient to kill 145.8 million people (adults 70 kg). Acute fatal inorganic arsenic poisonings have been reported in doses as low as 0.12 g (Baldwin and Marshall, 1999; Bartolome et al., 1999; Hu, 1998). According to CHRIS (1992), there was no data available for the lethal dose for skin/eye contact and absorption. The *inhalation* of an acute or lethal dose of arsenic trioxide may be significantly lower than the *ingestion*, which is why the inhalation of the chemical may be more lethal than ingestion.

The m/v SCI accident case history provides no data for the dose of arsenic trioxide taken up by the people exposed. The fact that no acute fatality was reported suggests that arsenic trioxide uptake did not exceed the acute lethal dose. However, exposure to non-acute lethal doses is not excluded. A cumulative process can also achieve a lethal dose of arsenic over a period of time. The duration of exposure, i.e. the period of time during which the ship and shore personnel were exposed to arsenic trioxide spilt on deck, was limited to less than 48 hours. This was the time space between the occurrence of the arsenic spill (approx. at 02.00 hrs, January 4th) and the completion of cleanup operations (afternoon, January 5th), assuming a complete cleanup with no residues remaining.

***Magnesium phosphide*:** According to medical analyses, the level of phosphine concentration in the stevedores' bodies, i.e. the accumulative dose of phosphine taken up, was 400 ppm. This level was twice the level of "immediately dangerous to life and health" (i.e. 200 ppm or 282 mg/m^3) (IPCS, 1989; U.S. DOT, 1992). The phosphine dose taken up by the people exposed depended on the level of phosphine gas concentration in the air inside the no.1 hold, the amounts of the gas inhaled, the duration of exposure and physical conditions of the people exposed. The case history provides no data for these parameters. However, the medical examinations and the course of events suggest that:

- The level of gas inside the hold was too high, probably at a lethal concentration.
- The amount of gas inhaled by the people was also too high, in particular for those who showed symptoms of intoxication or were sent to the hospital.
- Given toxic properties of phosphine gas and activities carried out inside the no.1 hold, the duration of exposure may have ranged from several minutes to a few hours.

Although some of the people were exposed to very high doses (400 ppm) of phosphine, no acute fatality was reported. This may be attributed to immediate responses and medical treatment after detection of symptoms of exposure to toxic gas. Other people who did not show symptoms of acute intoxication might have also been exposed to smaller doses of phosphine gas. The extent of exposure to lower doses was unknown, as not all the people (the crew, stevedores in Port Baltimore, and other people) underwent medical examinations and treatments.

Summary

Living organisms have the capacity to withstand certain levels of chemical exposure as they contain many different chemicals, including arsenic. Living organisms are also daily exposed to arsenic from various sources. The effects of dangerous substances to risk receptors depend very much on dose-effect relationships, in which different factors play different roles. The acute lethal concentration of arsenic trioxide to humans through continuous inhalation for one hour is 2mg/m^3. The lethal dose (LD) of arsenic trioxide to humans through ingestion is LD_{050} – 45mg/kg. The fact that no acute fatality was reported indicates that arsenic trioxide uptake did not exceed the acute inhalation and ingestion lethal doses. The medical analysis showed that the stevedores in Port Charleston were exposed to high levels of phosphine, namely twice the level of “immediately dangerous to life and health” (i.e. 200 ppm or 282 mg/m^3). Due to immediate response and medical treatment, no acute fatality was reported. Exposures to smaller non-acute lethal doses of arsenic and phosphine are not to be excluded.

The statistical data available (HMIS and NRC databases) contain no information about the doses and effects of dangerous goods to risk receptors. However, injuries, fatalities and other consequences due to hazards of dangerous goods/hazmat, for example, suggest that, in these cases, dose exposures have exceeded threshold doses. Many case histories and other data sources contain explicit and/or implicit information for assessing the doses-effects relationships for a wide range of dangerous substances.

4.1.8. Combined causes and contributing factors

The m/v SCI accident, and consequences and threats associated with it, were attributed to a large menu of causes and contributing factors. Table 4.6 shows the main category, with respective numbers of incidences, of individual and combined causes and contributing factors. These include: a) causes and contributing factors of losses and damage of containers/cargo (Table 3.4); and b) causes and contributing factors of exposure events, which is the exposure of risk receptors after the loss and release of dangerous goods (Table 4.5). The combined causes and contributing factors include both (a) and (b) (Table 4.6). They constitute causes and contributing factors of the entire chain of events, i.e. the cause-effect chain (see Figure 1.2). The ship as well as shore personnel had plenty of opportunities and measures at their disposal to interrupt this chain of events.

Table 4.6: Incidences of the main categories of combined causes and contributing factors of the m/v SCI accident

Nr	**Category**	**Combined causes and contributing factors**			
		Accident: losses and damage	Exposure to dangerous goods	Total	
				N	%
1	Human/Man	23	17	40	21.4
2	Man-made	28	0	28	15.0
3	Operational	42	19	61	32.6
4	Managerial	17	9	26	13.9
5	Environment	15	1	16	8.6
6	Other	9	0	9	4.8
	Total	134	46	181	100.0

Figure 4.39 shows ranking of the main categories of combined causes and contributing factors of the m/v SCI accident by number of incidences/percents. Approximately one third of all causes and contributing factors explored in the m/v SCI accident case are of an operational character (top ranking). The causes and contributing factors related to the human factor and its interactions with the systems (operational and managerial factors/elements) constituted the vast majority of the list of causes and contributing factors.

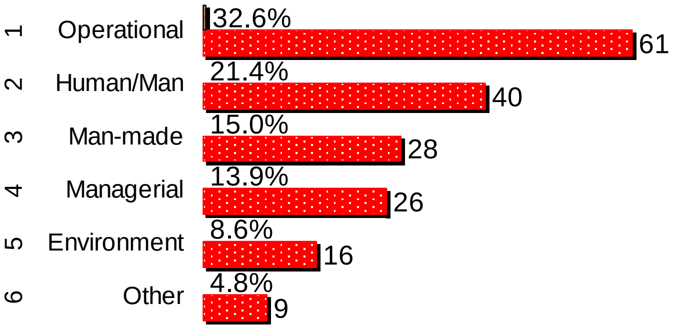


Figure 4.39: Ranking of combined causes and contributing factors of the m/v SCI accident

Paradoxically, the human factor is responsible for everything – but not always. The human, who consists of individuals, groups, and the entire society, is responsible for almost everything as it is involved in every activity, including design, construction, operation and management of all system elements and activities. The human element affects directly and indirectly, in various degrees, the system elements and their outcomes. For example, customers (supply chain actors – groups or organisations) and consumers (individuals, groups and the society) affect the system by requiring products and services of the right quality, amount, time and place. However, given the limitations and constraints surrounding the human factor, in particular individuals, the human factor is not always and entirely responsible for everything. In the case of the m/v SCI accident, the environmental factors, including heavy weather conditions (high winds, heavy seas, green waters, rain and poor visibility) and effects associated with them (forces exerted in heavy ship's motions) were, to a considerable extent, beyond the control of the master and other ship's personnel. However, the master was primarily responsible for taking the ship out to sea despite warnings of heavy weather conditions. The master could have avoided the accident if he had taken a reasonable decision by waiting in Port Elizabeth until weather conditions improved. In addition, the master's navigational skills and tactics considerably exacerbated the effects of the weather conditions. However, the combination of different factors, including individual and industry prejudices and business (costs and time) constraints, hampered the master's decision. The pressure to meet the schedule in Port Baltimore, which was due to the chain of pressures including the pressure from the shipowner's customers, caused the master to take an unfortunate and skewed decision. Despite deteriorating weather conditions, he was anxious to get the ship loaded and underway (U.S. DOT, 1992). Probably, if the master had acted otherwise, the shipowner would have warned, if not fired, him. The shipowner, in turn, would have been responding to pressure from his customers' complaints.

4.1.9. Exposure analysis – statistical data

The risks can be estimated as consequences relative to a wide range of attributes of systems, including means of transport/vessels, commodities/ hazmat flows, transport economy performances and population. In addition, by comparing risk elements, such as incidents and their consequences, against the attributes of the systems exposed, and comparisons among systems' attributes themselves, certain properties can be explored. They can provide supporting explanations for changes, differences and similarities in risks and systems elements. The aforementioned elements cannot be analysed on the basis of one (i.e. the m/v SCI accident case) or a few case histories. Further, the exposure analysis requires other types of data and information than incident data. Therefore, in order to provide a full demonstration and test external validity, the demonstration of the framework (see the **highlighted areas** in Figure 4.40) is extended to the analysis of quantitative data and other systems.

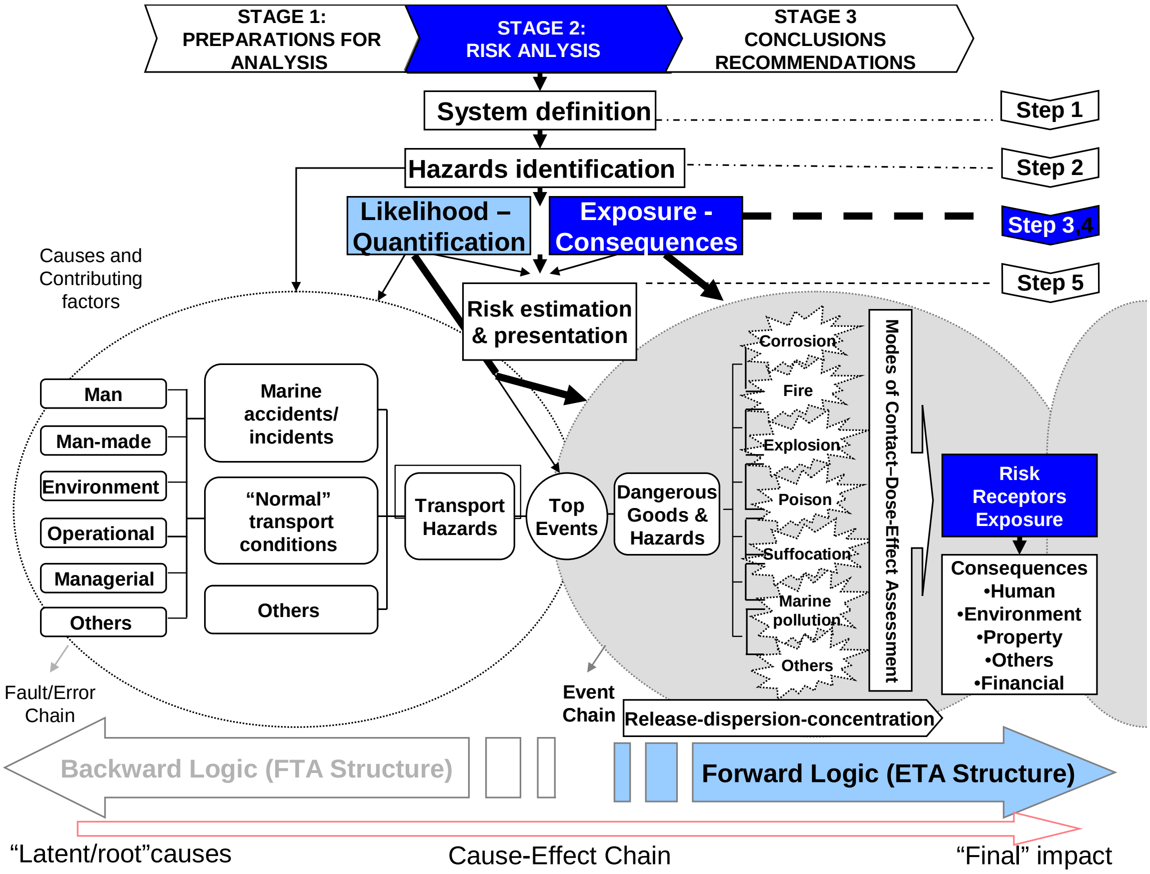


Figure 4.40: Stage 2 – Risk analysis; Step 2 – Exposure and consequences analysis, risk receptors exposure (continued from Figure 1.2)

4.1.9.1. Means of transport: vessels – types, calls and capacity

The vessel is an important element of the maritime/water transport system. The properties of the vessel and vessel traffic, such the number of vessels, calls and capacity (measured in deadweight tonnage – dwt), are some of the exposure measures. The risks can be measured as consequences averaged over the mentioned exposure measures per year. The following section presents statistical data collected from the U.S. DOT concerning vessel traffic in U.S. ports during the period 2001-2004. The data include vessel calls and capacity for all types of vessels (see the list in Table 4.7). For more information about definitions and concepts concerning vessel types, see Chapter 3, Vol. I, and Mullai 2006a.

The types of vessels listed below carry freight, including hazmat in bulk and in packaged form. Vessel capacity is estimated as the sum of vessel calls weighted by vessel dwt, which is an approximate measure of goods traffic by water. The U.S. DOT (2001-2004) records contain data only for ocean-going self-propelled vessels of 10,000 dwt or larger. According to the source, in 2003, these vessels accounted for 98% of the total vessel capacity calling at U.S. ports. On average, approximately 57,900 ocean-going self-propelled vessel calls, including all seven main categories of vessel types as shown in the list below, with a total capacity of approximately 2.8

billion dwt, have been made each year at U.S. ports – on average, 48,337 dwt per call. The nationality of vessels calling at U.S. ports is not reported, nor is the number of vessels in operation in the U.S. A vessel may call at U.S. ports only once or several times a year. Vessel calls and capacity have shown increasing trends (see Figures 4.41~4.43). Larger numbers of larger vessel sizes are calling at U.S. ports. During the period 2001-2004, ships carrying PDG, such as dry cargo ships, including container ships, dry bulk ships, ro-ro ships and general cargo ships, accounted for 65.7% and 50.6% of all vessel calls and capacity respectively (Figures 4.44 and 4.45).

According to another source (U.S. DOT 2001a, from LMIS 2001), in the year 2000, the number of vessel calls (including tankers, dry bulk, container and other vessels over 1,000 dwt) at U.S. ports amounted to 71,548 calls, which is a larger number than the figures provided in U.S. DOT (2001-2004).

Table 4.7: Vessel types calling at U.S. ports (U.S. 2001-2004)

Main categories and sub-categories of vessel types	
1. Tanker:	5. General Cargo:
1.1 Petroleum Tankers	*5.1 General Cargo Carriers*
1.1.1 Product	*5.2 Partial Containerships*
1.1.2 Crude oil	*5.3 Refrigerated Ships*
1.2 Chemical Tankers	*5.4 Barge Carriers*
2. Gas Carrier:	*5.5 Livestock Carriers*
2.1 LNG Carriers	6. Container:
2.2 LNG/LPG Carriers	*6.1 Container Carriers*
2.3 LPG Carriers	*6.2 Refrigerated Container Carriers*
3. Combination:	7. Ro-Ro:
3.1 Ore/Bulk/Oil Carriers	*7.1 Ro/Ro Vessels*
3.2 Bulk/Oil Carriers	*7.1 Ro/Ro Containerships*
4. Dry Bulk:	
4.1 Bulk Vessels	
4.2 Bulk Containerships	
4.3 Cement Carriers	
4.3 Ore Carriers	
4.4 Wood-chip Carriers	

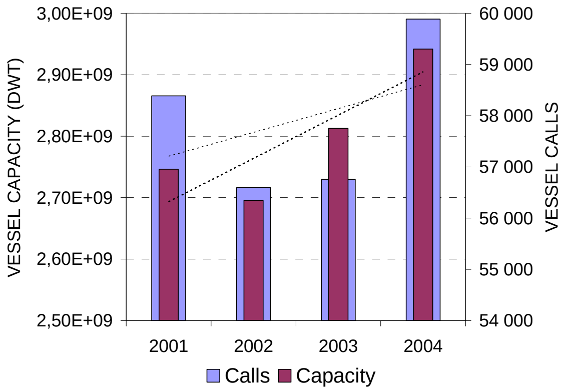


Figure 4.41: Vessel calls and capacity (U.S. DOT, 2001-2004)

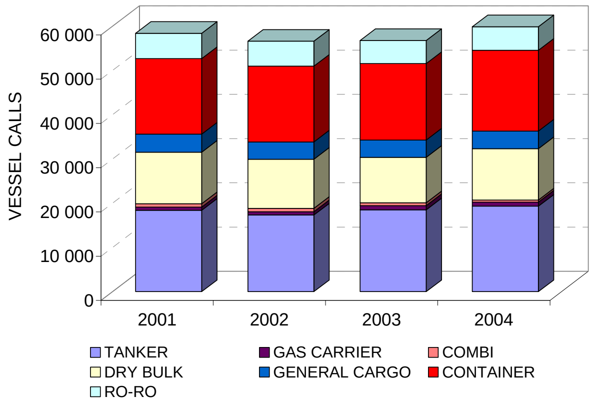


Figure 4.42: Vessel calls by vessel type (U.S. DOT, 2001-2004)

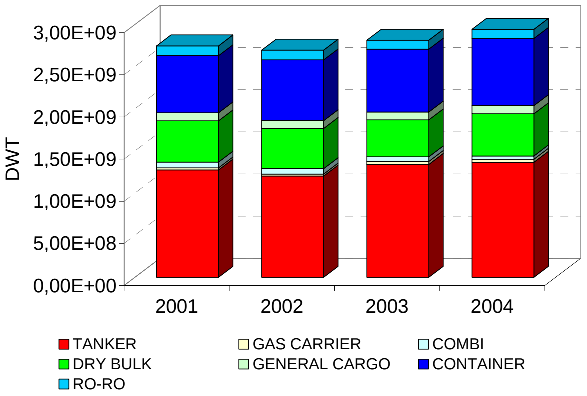


Figure 4.43: Vessel capacity by vessel type (U.S. DOT, 2001-2004)

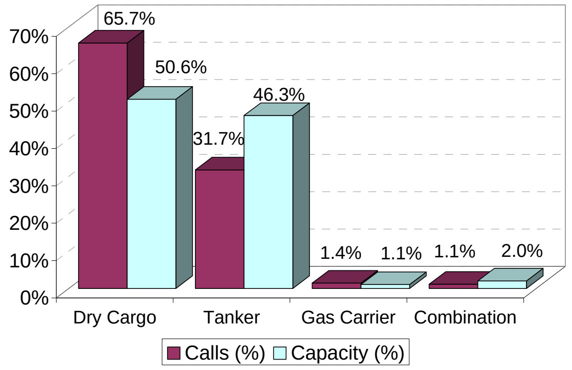


Figure 4.44: All vessel types calls and capacity on average per year (U.S. DOT, 2001-2004)

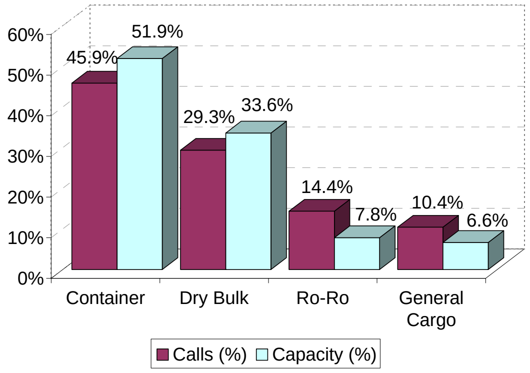


Figure 4.45: Dry cargo vessel calls and capacity on average per year (U.S. DOT, 2001-2004)

U.S. flagged vessels by type

In 2003, the total number of vessels flying the U.S. flag was 39,983 (U.S. DOT, 2005b). Figure 4.46 shows the shares (in %) of vessel types. The data include all types of vessels in operation in the U.S. The total number of vessels in the U.S. fleet also includes vessels whose age and classification are unknown. Offshore support vessels include crew boats. A large portion of the U.S. flagged vessels, such as dry and tanker barges, towboats, offshore support vessels and small-size dry cargo, tanker and passenger vessels, operate within and around U.S. waters, i.e. coastal and inland water vessel traffic. Vessels such as dry cargo vessels, dry barges as well as offshore supply vessels may carry packaged dangerous goods.

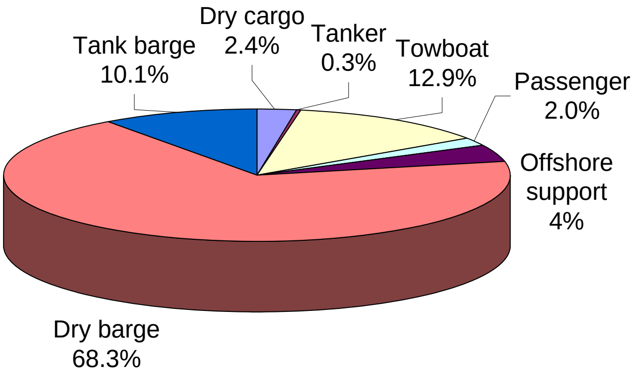


Figure 4.46: U.S. flagged vessels by type: 2003 (U.S. DOT 2005b)

4.1.9.2. Commodity Flow Surveys (CFS) – hazmat transportation

For a number of interrelated purposes, including the assessment of *safety and environmental risks,* the relevant U.S. authorities conduct Commodity Flow Surveys (CFSs) on a regular basis. CFSs are undertaken through cooperation among different organisations and authorities, e.g. the U.S. DOT, the U.S. Census Bureau, the U.S. DOC, and the Bureau of Transportation Statistics (BTS). The CFSs, which have been conducted as part of an integrated programme at 5-year intervals since 1954, capture data on commodity flow characteristics. This section of the report combines some of the key data from the three latest surveys, namely the 1993, 1997 and 2002 CFS reports. Unless otherwise cited, the commodity/ hazmat flow data are collected from these sources: (U.S. DOT, 1996, 1999, 2000, 2004a, 2004b).

The CFSs contain specific data on hazmat transportation shipments, which have been defined in accordance with the UN and U.S. classification systems. The key commodity and hazmat shipments characteristics include type of commodity/hazmat, number, value, weight (tons), and weight/ length of haul or distance shipped (ton-miles), mode of transportation, and origin and destination of shipments.

The CFSs cover a wide range of U.S. business establishments. The 2002 CFS, for example, covers business establishments listed in the 1997 North American Industry Classification System (NAICS). This system contains five main establishments, which are manufacturing, mining, wholesale, retail and service or auxiliaries' establishments, and more than 25 sub-categories of business establishments. In the 1993 and 1997 CFSs, establishments are classified on the basis of the 1987 Standard Industrial Classification System (SIC). The surveys are carried out by means of the survey methodology of multi-stage probabilistic sampling design. The sample sizes for each respective survey are relatively large: the 1993 CFS- 200,000/790,000 (i.e.

approximately 200,000 establishments selected from a universe of about 790,000 in-scope establishments); the 1997 CFS – 100,000/770,000 establishments and the 2002 CFS- 50,000/760,000 establishments.

Transportation and the U.S. economy**:** For statistical purposes, the U.S. GDP is classified into GDPs from services, goods, and structures (U.S. DOC, 2004). Goods include all goods consumed as final demand. The service category includes U.S. government consumption expenditures for service purposes, such as education and national defence, and produced by the government. Services also include services provided by the transport industry. The structure category includes infrastructures and other fixed assets such as roads, railroad tracks, airports, power plants and medical buildings. For the last three decades, the U.S. GDP has increased significantly – from 100 in 1970 to 267 in 2002 (Figure 4.47). Transport performance indicators, such as freight ton-miles and ton-miles per capita, have also increased accordingly (Figure 4.47). The GDP from services has shown a steady increase (Figure 4.48). The transport industry is a large contributor to the U.S. economy. In 2001, transport-related goods and services accounted for 10.4% ($ 1.05 trillion) of the overall U.S. GDP ($ 10.05 trillion) (Table 4.8). Transport risks can be measured relatively as the aggregated consequences (measured in monetary units $) due to transport incidents averaged over GDP ($) generated by the transport industry as well as the GDP from all services and the overall U.S. GDP.

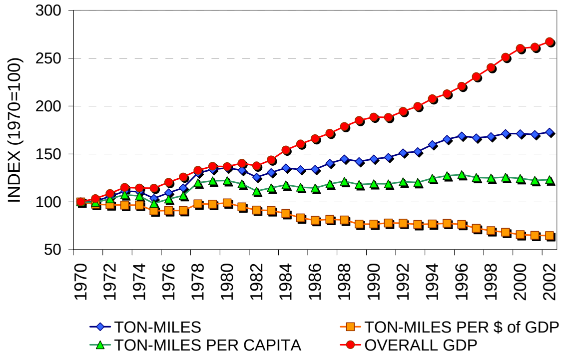


Figure 4.47: Freight ton-miles and U.S. GDP (U.S. DOC, 2004 and U.S. DOT, 2004a, 2004b)

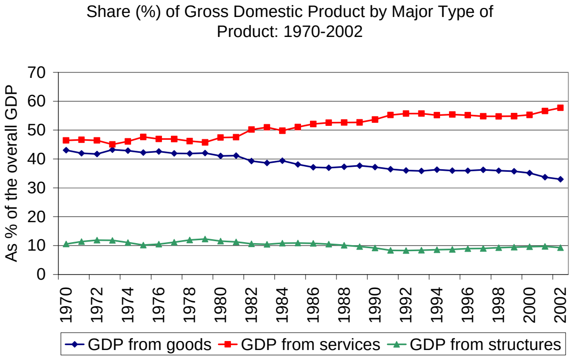


Figure 4.48: Shares (%) of U.S. GDP by products (U.S. DOC, 2004)

Table 4.8: Transport in relation to the U.S. GDP in 2001 (U.S. DOT, 2002a)

Transportation in relation to GDP	**2001**
Overall GDP ($ trillion[10])	10.05
Transportation-related goods and service purchases ($ trillion)	1.05
Transportation's share of GDP (%)	10.4%

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[10] In the U.S. and Canada, the number is represented as one followed by twelve zeros (10^{12} or 1.0E+12) (CED, 1992).

Commercial freight shipments – all types of goods combined: Large amounts of different types of goods are exposed to incidents. Figures 4.49~4.51 present data on U.S. commercial freight shipments for the years 1993, 1997 and 2002, including the estimations of the U.S. Bureau of Transportation Statistics of out-of-scope categories of goods shipments.[11] These estimations cover logging, farm-based truck shipments, truck imports from Canada and Mexico, rail imports from Canada and Mexico, air cargo imports and exports, water imports and exports, and pipeline crude and petroleum products shipments. They exclude other out-of-scope categories of goods movements for which, according to the data sources, no reasonable basis for an estimate exists, including government shipments, the service sector, the retail sector, the construction sector, transportation service providers, household goods movement, and municipal solid waste. Large amounts of different goods are moved in the U.S (Figure 4.49). In 2002, approximately 15.8 billion tons (or 10.5 trillion ton-miles) freight shipments, with a total value $ 10.5 trillion, were moved in the U.S (Figure 4.49). In terms of tons (15.5%) and ton-miles (20%), water or maritime transport is the third largest mode of transportation in the U.S. (Figure 4.50). During the period 1993-2002, U.S. commercial freight shipment characteristics (value, ton and ton-miles) of all modes of transport combined increased by 45.3%, 18.4% and 23.8% respectively (Figure 4.51). The value of freight shipments is inflation-adjusted[12] with the goods GDP deflator for the year 2000 dollars. The carriage of freight shipments by water increased both in value (39.9%) and tons (10.2%), which was lower than for transports overall**,** but decreased in ton-miles (by 16.9%) (Figure 4.51). In 2002, goods were moved by water over shorter distances as compared to 1993 (Figure 4.51).

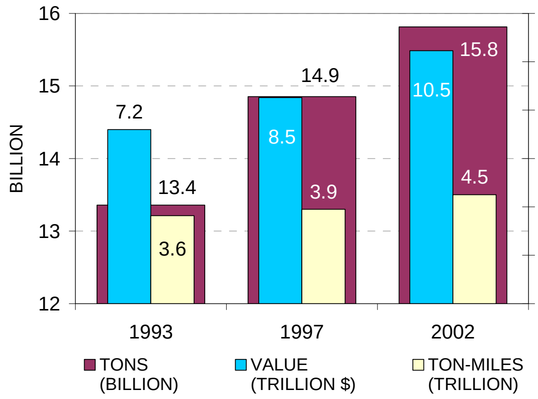

Figure 4.49: Freight shipment characteristics (value, tons and ton-miles) (U.S. 1993-2002) (U.S. DOT, 1996, 1999, 2000, 2004a, 2004b)

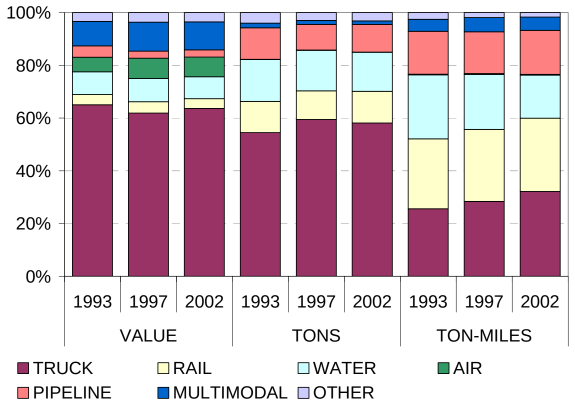

Figure 4.50: Modal shares (in %) of freight shipment characteristics (value, tons and ton-miles) (U.S. 1993-2002) (U.S. DOT, 1996, 1999, 2000, 2004a, 2004b)

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[11] Criteria for within and out-of-scope categories of goods movements are established in the U.S. Industrial Classification Systems.

[12] Adjusted by the U.S. Department of Transportation, Bureau of Transportation Statistics.

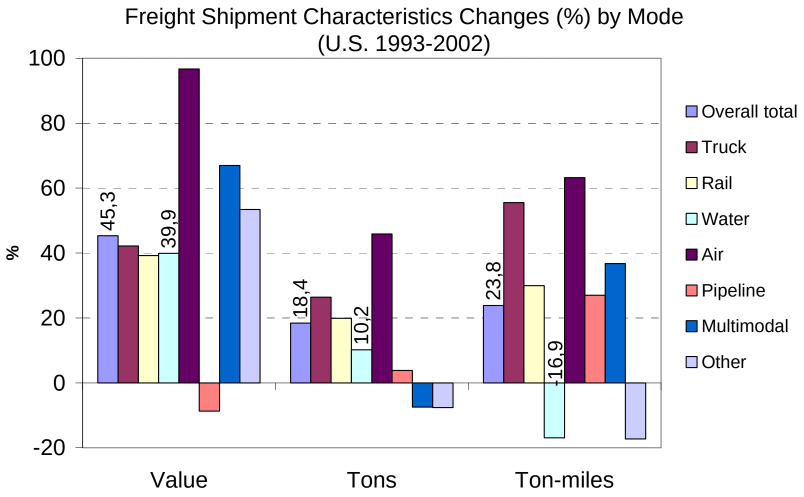

Figure 4.51: Freight shipment characteristics (value, tons and ton-miles) changes (in %)[13] by mode of transport (U.S. 1993-2002) (U.S. DOT, 1996, 1999, 2000, 2004a, 2004b)

Hazardous versus non-hazardous material shipments – hazmat shipment characteristics by mode of transportation: By virtue of their inherent properties, large amounts of goods are hazardous to organisms and the environment. Hazmat not only contribute to incidents and their consequences, but they are also affected by incidents. Hazmat as well as non-hazmat shipment characteristics (value, tons and ton-miles) can serve as exposure measures. The data show that large amounts of freight shipments involve hazmat. In 2002, hazmat shipments in the U.S. accounted for 18.8% and 10.4% of the total freight shipment (hazmat and non-hazmat) tons and ton-miles respectively (Table 4.9). Approximately 33.5% and 25.0% of freight shipments, in tons and ton-miles respectively, moved by water in the U.S. are hazmat (Table 4.9). Figures 4.52~4.52 show the characteristics of hazmat and non-hazmat shipments (in value, tons, and ton-miles) by mode as percentages of the total for the year 2002.[14] In 2002, truck or road transport dominated hazmat shipments in all characteristics – in value (63.6%), tons (52.9%) and ton-miles (41.1%) (Figures 4.53, 4.56 and 4.58). In terms of hazmat shipment tons (10.4%) and ton-miles (26.4%), water transport is the third largest mode (Figures 4.53 and 4.56), whereas pipeline transport, excluding shipments of crude petroleum, is the second largest mode by hazmat shipment value (22.0%) and tons (30.2%). Because of high sampling variability or poor response quality, hazmat shipment ton-miles for pipeline transport have not been estimated by the relevant authorities. Compared to other modes, air transport of hazmat shipments is insignificant (0.03-0.2%) or equal to zero in all three shipment characteristics. Compared to 1997, hazmat shipments by all modes of transportation combined increased in 2002 – in value (25.3%), tons (22.9%) and ton-miles (10.8%) (Table 4.10 and Figure 4.59). Except for the air and pipeline transport modes, in certain hazmat shipment characteristics, all individual modes have shown increasing trends (Figure 4.49). For the same period, water transport of hazmat shipments has also shown a considerable increase – in value (41.7%), tons (36.1%) and ton-miles (12.0%) (Table

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[13] Comma (,) in figures should be read full stop (.).

[14] Values equal to zero or very small ones are not shown.

4.10 and Figure 4.49), which are higher than the respective average increases for all modes combined (Figure 4.49).

Because of the discrepancies in the statistical data recording systems, the data on shipment characteristics differ among the data sources.

Table 4.9: Hazardous versus non-hazardous material shipment characteristics by mode of transportation: for 2002 (U.S. DOT, 2004a)

Mode of transportation	Tons					Ton-miles				
	Total (,000)	Hazardous		Non-hazardous		Total (millions)	Hazardous		Non-hazardous	
		(,000)	%	(,000)	%		(millions)	%	(millions)	%
Single modes[15]	***11 086 660***	***2 158 533***	***19.5***	***8 928 127***	***80.5***	***2 867 938***	***311 897***	***10.9***	***2 556 041***	***89.1***
Truck[16]	7 842 836	1 159 514	14.8	6 683 322	85.2	1 255 908	110 163	8.8	1 145 745	91.2
For-hire truck	3 657 333	449 503	12.3	3 207 830	87.7	959 610	65 112	6.8	894 498	93.2
Private truck	4 149 658	702 186	16.9	3 447 472	83.1	291 114	44 087	15.1	247 027	84.9
Rail	1 873 884	109 369	5.8	1 764 516	94.2	1 261 612	72 087	5.7	1 189 525	94.3
Water	**681 227**	**228 197**	**33.5**	**453 030**	**66.5**	**282 659**	**70 649**	**25.0**	**212 011**	**75.0**
Air[17]	3 760	64	1.7	3 696	98.3	5 835	85	1.5	5 751	98.5
Pipeline[18]	684 953	661 390	96.6	23 563	3.4	S[19]	S	S	S	S
Multiple modes[20]	***216 686***	***18 745***	***8.7***	***197 941***	***91.3***	***225 715***	***12 488***	***5.5***	***213 228***	***94.5***
Parcel, U.S.P.S., courier	25 513	245	1.0	25 268	99.0	19 004	119	0.6	18 885	99.4
Other multiple modes	191 173	18 500	9.7	172 673	90.3	206 712	12 369	6.0	194 343	94.0
Other/unknown modes	364 573	14 241	3.9	350 332	96.1	44 245	2 342	5.3	41 903	94.7
Total - all modes	**11 667 919**	**2 191 519**	**18.8**	**9 476 400**	**81.2**	**3 137 898**	**326 727**	**10.4**	**2 811 171**	**89.6**

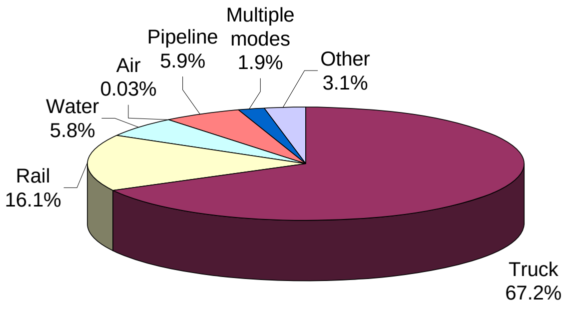

Figure 4.52: Freight shipment (hazmat and non-hazmat tons by mode of transportation for 2002 (U.S. DOT, 2004a)

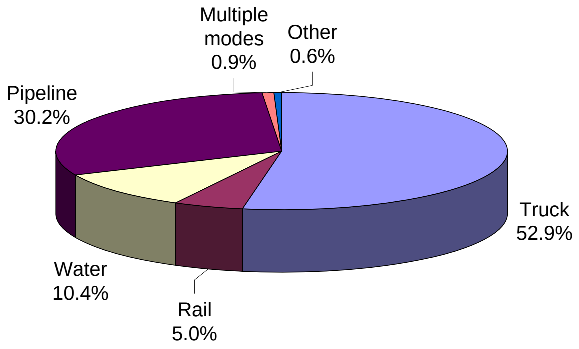

Figure 4.53: Hazmat shipment tons by mode of transportation for 2002 (U.S. DOT, 2004a)

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[15] "Single mode" includes individual modes: truck/road, rail, water, air and pipeline transport.

[16] "Truck" or road transport (a single mode) includes shipments that were made by private and for-hire trucks, or a combination thereof.

[17] "Air" includes combined truck and air transport.

[18] Estimation of hazmat shipments for pipeline excludes shipments of crude petroleum.

[19] Estimate does not meet publication standards because of high sampling variability or poor response quality.

[20] "Multiple modes" includes parcel, U.S. Postal Service or courier and other multiple modes.

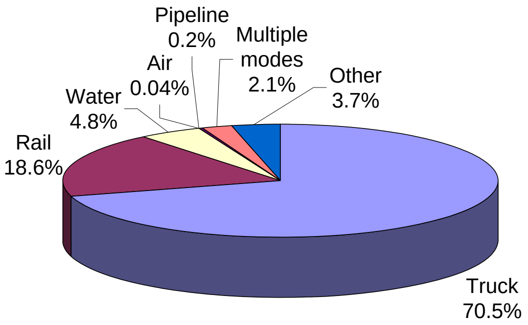

Figure 4.54: Non-hazmat shipment tons by mode of transportation for 2002 (U.S. DOT, 2004a)

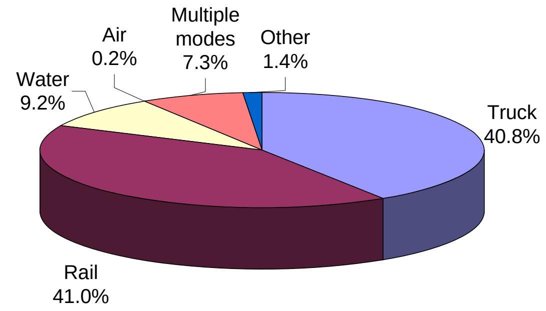

Figure 4.55: Freight shipment (hazmat and non-hazmat) ton-miles by mode of transportation for 2002 (U.S. DOT, 2004a)

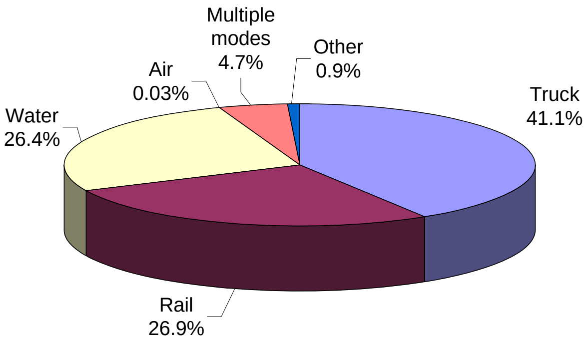

Figure 4.56: Hazmat shipment ton-miles by mode of transportation for 2002 (U.S. DOT, 2004a)

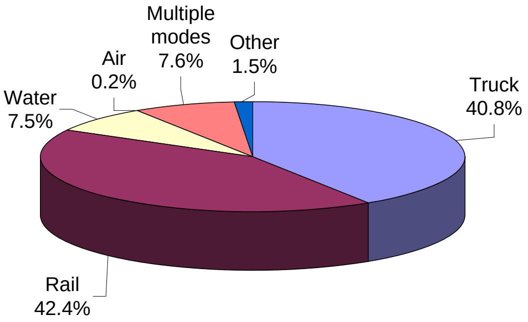

Figure 4.57: Non-hazmat shipment ton-miles by mode of transportation for 2002 (U.S. DOT, 2004a)

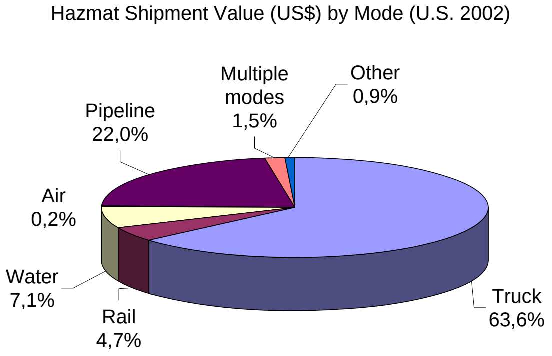

Figure 4.58: Hazmat shipment value ($) by mode of transportation for 2002 (U.S. DOT, 2004a)

Table 4.10: Hazmat shipments by mode of transportation for 2002 and 1997 (U.S. DOT, 2000, 2004a)

Mode of transportation	Value ($ million)		Tons (,000)		Ton-miles (millions)	
	2002	1997	2002	1997	2002	1997
Truck	419 630	325 166	1 159 514	959 199	110 163	82 211
Rail	31 339	34 937	109 369	102 508	72 087	78 619
Water	46 856	33 071	228 197	167 716	70 649	63 089
Air	1 643	8 591	64	74	85	100
Pipeline	145 021	108 653	661 390	522 560	S	S
Multiple modes	9 631	7 203	18 745	12 266	12 488	S
Other	6 061	9 058	14 241	19 298	2 342	1 885
Total - all modes	**660 181**	**526 679**	**2 191 519**	**1 783 620**	**326 727**	**294 823**

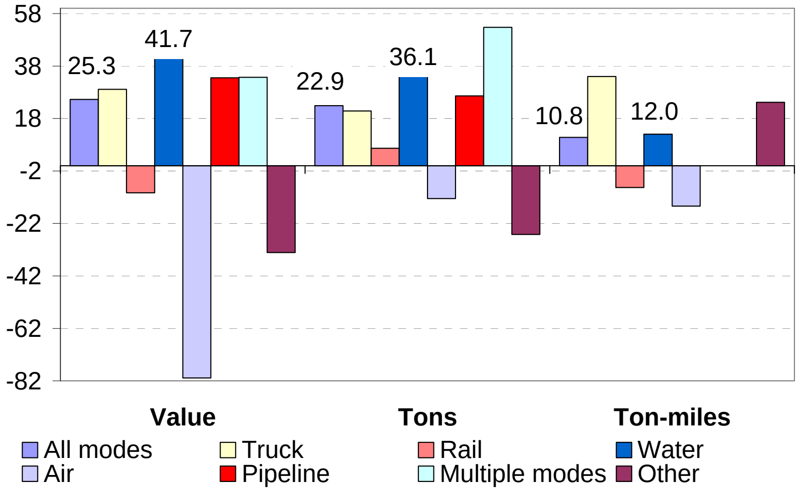

Figure 4.59: Hazmat shipments changes (in %) by mode of transport (U.S. 1997-2002) (U.S. DOT, 2000, 2004a)

Hazmat shipment characteristics by class: Tables 4.11 and 4.12 and Figure 4.60 show hazmat shipment characteristics (value, tons and ton-miles) and changes in them by hazard class for the period 1997-2002. The data show that hazmat shipments of Class 3 (flammable liquids) accounted for the vast majority of hazmat shipments, including all shipment characteristics, moved in the U.S. (1997-2002). In 2002, shipments of Class 3 were (in % of the total shipments) in value (74.3%), tons (81.6%) and ton-miles (66.9%) (Tables 4.11 and 4.12). Other important classes (in % of total shipment tons) are: *Class 2* (gases – 9.7%), *Class 8* (corrosive materials – 4.1%) and *Class 9* (miscellaneous dangerous goods – 2.1%) (Tables 4.11 and 4.12). During the period 1997-2002, some classes have shown increases and some decreases (Figure 4.60). The most significant changes are observed in the increase of shipment tons of Class 1 (explosives – 191%) and shipment value of Class 7 (radioactive materials – 114.9%). This may be attributed to increasing military expenditures and demand for nuclear energy resources.

Table 4.11: Hazmat shipments by hazard class for 2002 & 1997 (U.S. DOT, 2000, 2004a)

Hazard class	**Value ($ million)**		**Tons (,000)**		**Ton-miles (millions)**	
	2002	1997	2002	1997	2002	1997
Class 1	7 901	5 584	5 000	1 718	1 568	S
Class 2	73 932	47 288	213 358	137 138	37 262	26 002
Class 3	490 238	386 994	1 788 986	1 450 591	218 574	184 824
Class 4	6 566	4 238	11 300	14 832	4 391	9 735
Class 5	5 471	4 485	12 670	9 239	4 221	4 471
Class 6	8 275	10 085	8 459	6 366	4 254	2 824
Class 7	5 850	2 722	57	87	44	48
Class 8	38 324	41 336	90 671	98 331	36 260	42 918
Class 9	23 625	23 946	61 018	65 317	20 153	22 727
Total	**660 181**	**526 679**	**2 191 519**	**1 783 620**	**326 727**	**294 823**

Table 4.12: Hazmat shipments by hazard class for 2002 & 1997 (U.S. DOT, 2000, 2004a)

Hazard class	**Value (%)**		**Tons (%)**		**Ton-miles (%)**	
	2002	**1997**	**2002**	**1997**	**2002**	**1997**
Class 1	1.2	1.1	0.2	0.1	0.5	S
Class 2	11.2	9.0	9.7	7.7	11.4	8.8
Class 3	74.3	73.5	81.6	81.3	66.9	62.7
Class 4	1.0	0.8	0.5	0.8	1.3	3.3
Class 5	0.8	0.9	0.6	0.5	1.3	1.5
Class 6	1.3	1.9	0.4	0.4	1.3	1.0
Class 7	0.9	0.5	—	—	—	—
Class 8	5.8	7.8	4.1	5.5	11.1	14.6
Class 9	3.6	4.5	2.8	3.7	6.2	7.7
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

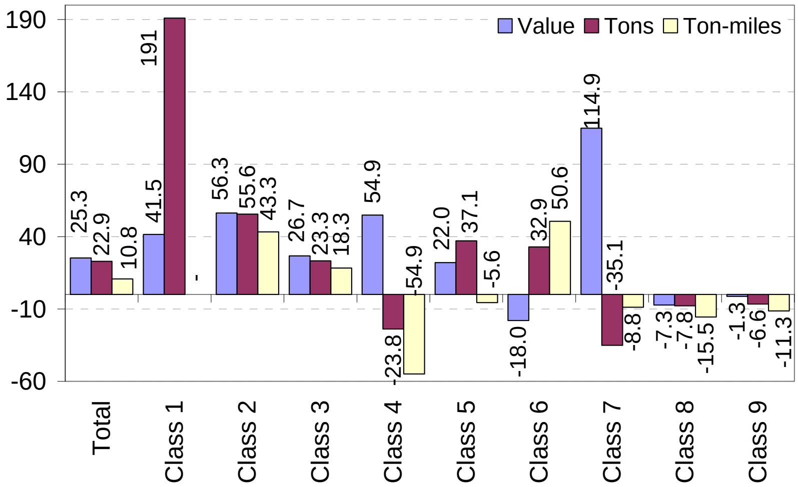

Figure 4.60: Hazmat shipment characteristics (value, tons and ton-miles) changes (in %) by hazard class (U.S. 1997-2002) (U.S. DOT, 2000, 2004a)

Hazmat shipment characteristics by state of origin and destination: The states of New Jersey and Pennsylvania, which are two of five states in the area of the m/v SCI accident site, were ranked (by tons) respectively: a) 5th and 12th in the list of the top 20 selected states of origin of hazmat shipments (accounting for 82% of the total hazmat shipments in all states); and b) 7th and 10th in the list of the top 20 selected states of destination of hazmat shipments (accounting for 81% of the total hazmat shipments in all states). In 2002, both states combined accounted for approximately 6.3-6.5% of all the origins/destinations of hazmat shipments (in tons) in the U.S. (Tables 1.13 and 1.14).

Table 4.13: Hazmat shipments by state of origin for 2002 (U.S. DOT, 2004a)

State of Origin	**Value**		**Tons**		**Ton–miles**	
	($ million)	%	(,000)	%	(million)	%
New Jersey	22 161	3.4	92 133	4.2	11 131	3.4
Pennsylvania	24 885	3.8	51 191	2.3	5 633	1.7
Total – all states	**660 181**	**100.0**	**2 191 519**	**100.0**	**326 727**	**100.0**

Table 4.14: Hazmat shipments by state of destination for 2002 (U.S. DOT, 2004a)

State of Destination	**Value**		**Tons**		**Ton–miles**	
	($ million)	%	(,000)	%	(million)	%
New Jersey	23 071	3.5	85 470	3.9	16 218	5.0
Pennsylvania	18 554	2.8	52 390	2.4	5 245	1.6
Total – all states	**660 181**	**100.0**	**2 191 519**	**100.0**	**326 727**	**100.0**

4.1.9.3. Resident population and transportation occupational employment

The employees/employers, passengers and general public are, to various degrees, exposed to incidents involving hazmat. During the period 1990-2000, the U.S. resident population increased by 13.2% (Figure 4.61). In 2000, the U.S. resident population reached 285.2 million. In 2002, 19.9 million people, or 15.6% of the total U.S. labour force (127.5 million), were employed in transportation and related- industries or jobs (Table 4.15). Water transport employment accounts for approximately 0.05% and 0.3% of the overall U.S. labour force and transport employment respectively. Figures 4.62 and 4.63 show employment in the U.S. water transport by occupation category and year (1998-2005). The main categories of occupation in water transport employment, which are set according to the U.S. Standard Occupational Classification (SOC) code, and their respective average (1988-2005) shares (in %) are: *sailors* (43%), *captains, mates and pilots* (38%), *motorboat operators* (5%), and *ship engineers* (14%). For more information about categories of ship personnel in the shipping industry, see Mullai 2006a. These estimates do not include self-employed workers. Compared to 1998, the number of people employed in the U.S. water transport industry has increased (Figure 4.62). The people working in the transport industry, including water transport as well as the general population are, to various degrees, directly and indirectly exposed to hazmat incidents in the transport system. The human (fatality/injury) risks can be measured as consequences (fatalities/ injuries) averaged over the number of people employed in all modes of the U.S. transport industry, waterborne transport and the resident population.

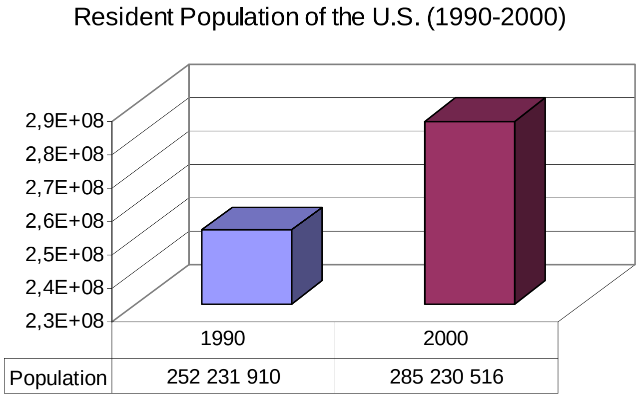

Figure 4.61: U.S. resident population (1990-2000) (U.S. DOC, 2000; U.S. DOT, 2002b)

Table 4.15: Occupational employment: transport for 2002 (U.S. DOT, 2002b)

Nr.	**In relation to employment**	**2002 (million)**
1	**Total U.S. occupational employment**	**127.5**
2	***Total transportation***	***19.9***
2.1	Transportation and related industries	10.7
2.1.1	For-hire transportation industry, total	4.4
2.1.2	Equipment manufacturing (transportation only)	1.7
2.1.3	Other related industries (e.g. automotive repair, service stations, car dealers, auto supplies, and highway construction)	4.5
2.2	Transportation occupations in non-transportation industries (e.g. truck drivers employed by retail and grocery chains and wholesale shipping clerks)	9.2
	Transportation and related jobs: share of total U.S. labour force	***15.6%***

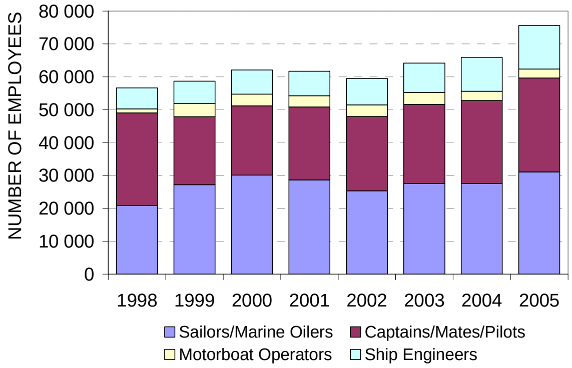

Figure 4.62: U.S. water transport employment by occupation category and year (U.S. 1998-2005) (U.S. BLS, 2006)

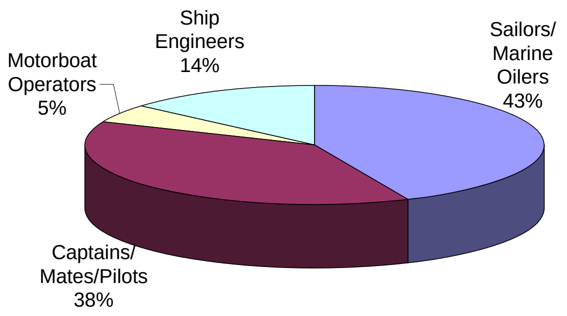

Figure 4.63: U.S. water transport employment by occupation category (U.S. 1998-2005) (U.S. BLS, 2006)

4.1.9.4. The U.S. economy and transport characteristics and incidents

Figures 4.64~4.69 present some illustrative examples of comparisons between the U.S. economy (GDP) and transport performance characteristics and incidents. Supply chain incidents, which include all transport modes combined and vessel incidents, have shown increasing trends largely similar to those in the U.S. economy (GDP) and transport performance characteristics. Thus, as the U.S. GDP and subsequently freight shipment (hazmat and non-hazmat) characteristics (in value, tons and ton-miles) increased, so did the number of incidents (see Figures 4.64~4.66). During the period 2001-2004, the fluctuations in vessel incidents matched vessel calls better than vessel capacity fluctuations (see Figures 4.67 and 4.68), which means that the vessel calls variable may have a stronger impact than the vessel capacity variable in the number of vessel incidents. The results of comparisons suggest that the U.S. economy (GDP) and transport performance characteristics may have considerable influencing powers on the trends or patterns of supply chain incidents, including transport and vessel incidents. They may have offset or diminished the effects of the preventive risk management strategies and measures.

If hazmat shipment characteristics had been the only important influencing factors in transport incidents, then the expected deviations or differences (in %) between hazmat shipment characteristics (as % of the total value, ton and ton-miles) (see Tables 4.11 and 4.12) and the number of incidents by class (as % of the total number of incidents) (see Figure 4.66) would have been nearly zero or equal to zero for all classes and shipment characteristics. The data show that deviations for the following classes are insignificant or equal to zero: Classes 1, 4, 7 and 9 (-3.0% to 0.7%), and, to some extent, Class 5 (2.0 to 2.9%) (Figure 4.69). Deviations for Classes 2 and 6 do not exceed the -10% + 10% band - they are Class 2 (-4.9% to -6.3%) and Class 6 (5.5% to 6.7%) (Figure 4.69). However, deviations for Class 3 and Class 8 are very significant – they are significantly underrepresented and overrepresented respectively (Figure 4.69). Some plausible explanations of these deviations include the number of shipments and packages and hazardous properties of the hazmat. Substances of Class 8 differ from other hazmat classes because their primary hazardous property is corrosion, which affects packaging performance considerably. In addition, compared, for example, to Class 3 (flammable liquids – oil and oil products), Class 8 shipments may consist of large numbers of smaller packages containing smaller quantities. The correlation analysis also showed that the "hazmat releases" variable is positively related to the "number of packages" variable.

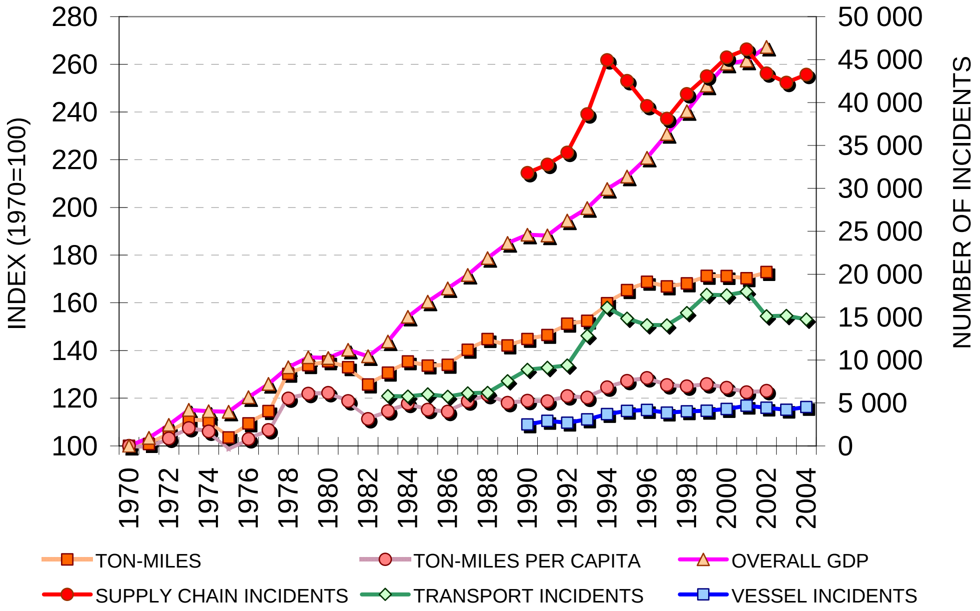

Figure 4.64: Comparison between the U.S. economy and transport characteristics and incidents (U.S. 1970-2004) (U.S. DOC, 2004; U.S. DOT, 2004a, 2004b, 2005a; NRC, 2005)

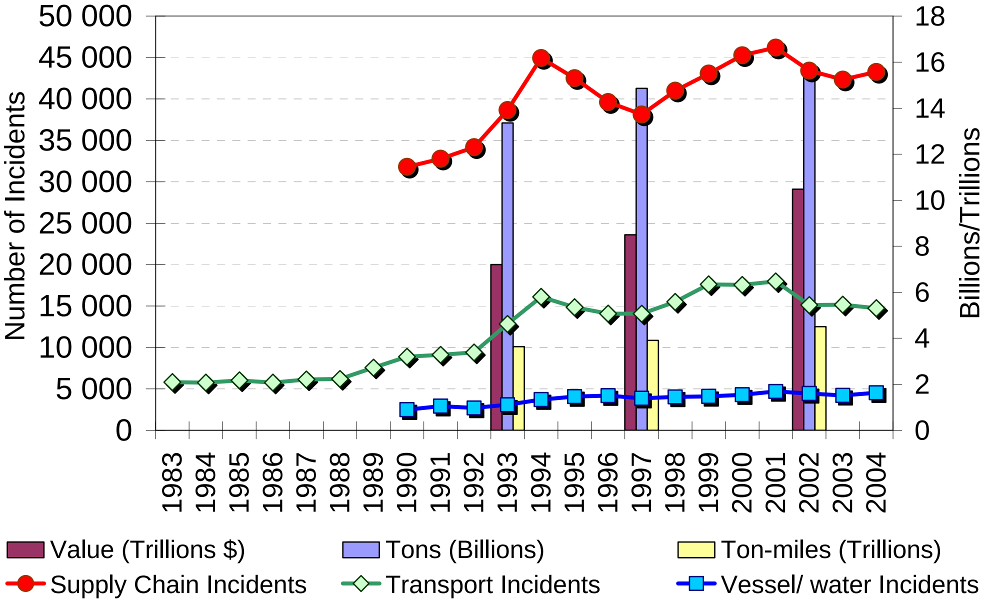

Figure 4.65: Comparison between freight shipment characteristics and incidents (U.S. 1983-2004) (U.S. DOT, 1996, 1999, 2000, 2004a, 2004b, 2005a; NRC, 2005)

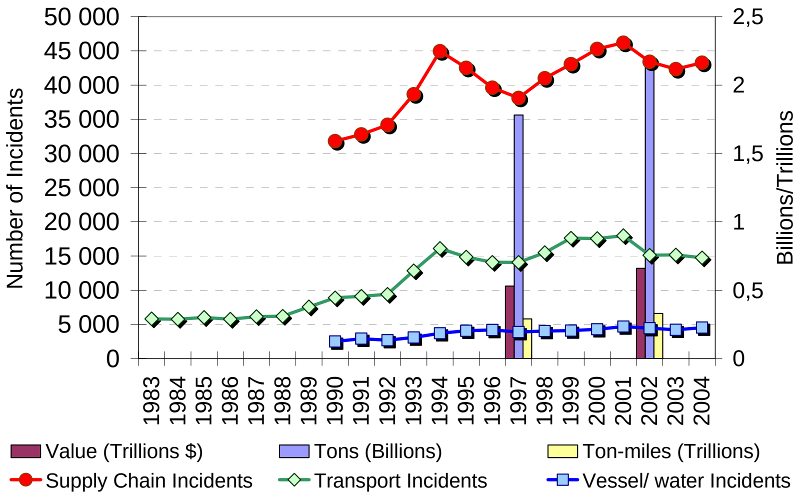

Figure 4.66: Comparison between hazmat shipment characteristics and incidents (U.S. 1983-2004) (U.S. DOT, 2000, 2004a, 2005; NRC, 2005)

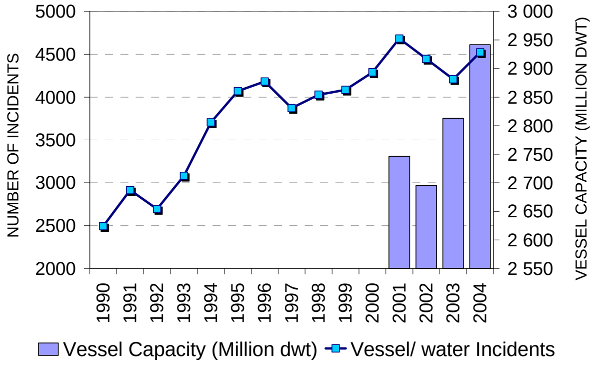

Figure 4.67: Comparison between vessel calls and vessel incidents (U.S. 2001-2004) (U.S. DOT, 2001-2004; NRC, 2005)

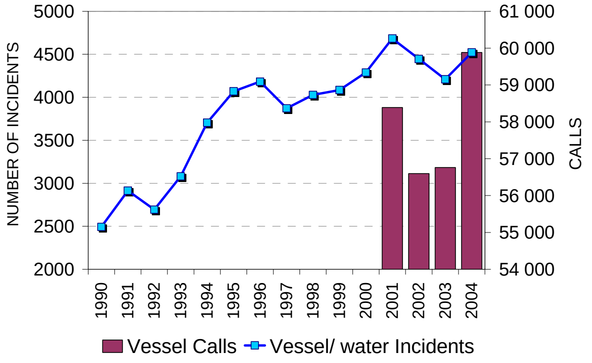

Figure 4.68: Comparison between vessel capacity (dwt) and vessel incidents (U.S. 2001-2004) (U.S. DOT, 2001-2004; NRC, 2005)

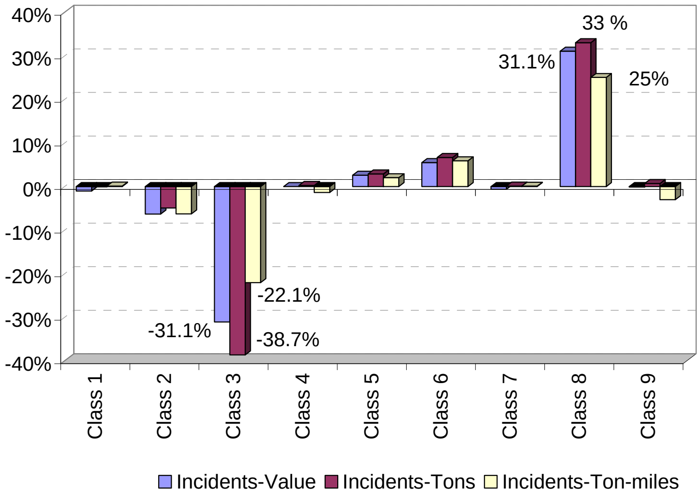

Figure 4.69: Comparison between hazmat incidents and hazmat shipment characteristics by class (U.S. DOT, 2000, 2004a, 2005a; NRC, 2005)

4.2. Consequences of dangerous goods incidents

Questions: What were the consequences? How often, many/much?

Tasks: Explore and quantify consequences to the risk receptors (see the **highlighted areas** in Figure 4.70).

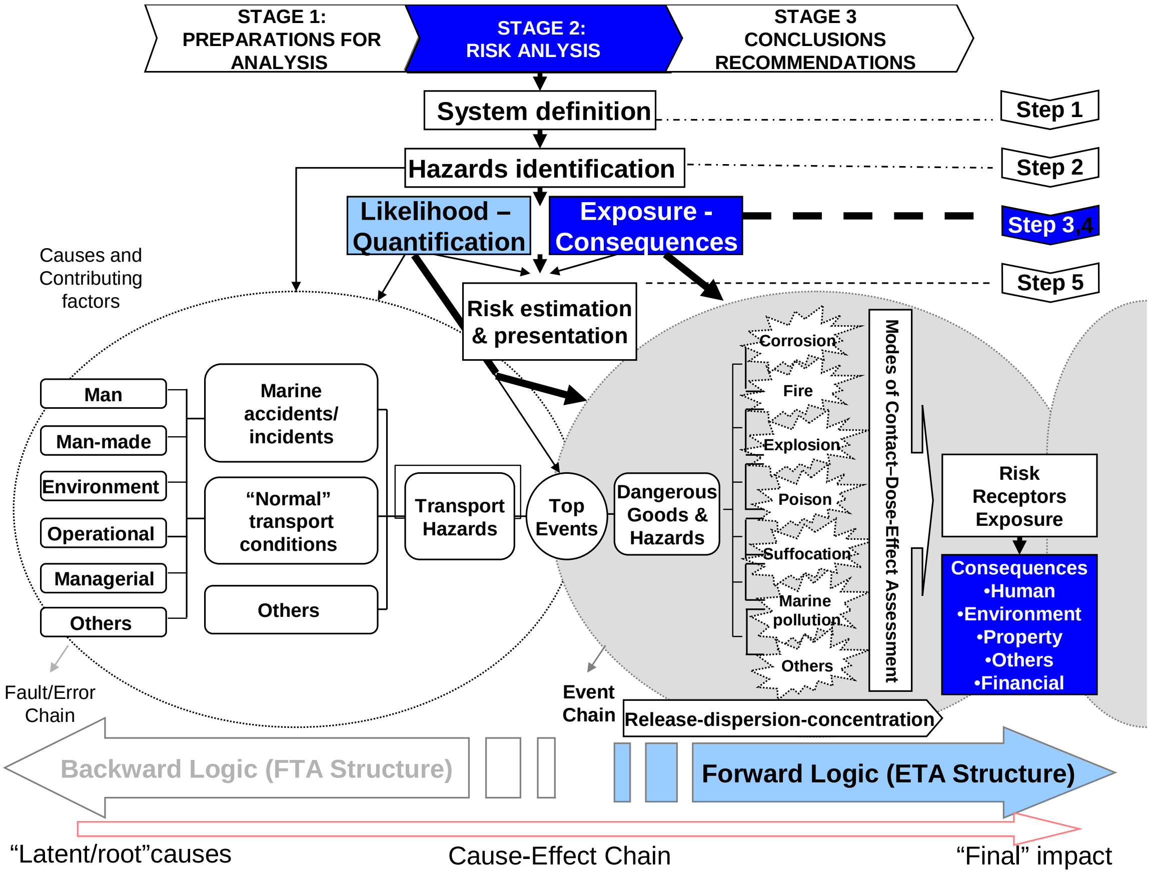

Figure 4.70: Stage 2 – Risk Analysis; Step 2 – Exposure and consequence analysis, consequences to risk receptors (continued from Figure 1.2)

The m/v SCI and her cargo sustained severe damage and losses in heavy weather conditions. The case history provides very limited data for the consequences due to the inherent hazardous properties of dangerous goods. Based on the combination of the case history and several other sources, this section explores the actual consequences and potential threats of arsenic trioxide and magnesium phosphide. Some consequences were the results of concerns, threats and responses to hazards of dangerous goods (domino or knock-on effects). Threats and consequences to human beings, the marine environment, property, activities and others are presented first. The costs of the accident, or the economic consequences, are also explored.

4.2.1. Fire/explosion and toxicity threats

In addition to toxic hazards, magnesium phosphide posed serious fire/explosion and toxicity threats to the crew, stevedores, ships, cargo, ports and the local communities.

Given its chemical properties, magnesium phosphide might have been responsible for a spontaneous fire or combustion. In contact with water or atmospheric moisture inside the ship's hold, magnesium phosphide might have given off flammable phosphine gases in dangerous quantities. Flammable gases form an explosive mixture with air at concentrations greater than 1.8% by volume (or 18,000 ppm) (U.S. DOT, 1992; IPCS, 1989). This mixture might easily have been ignited by any ordinary source of ignition, such as naked lights, sparking, defective electric installations, and unprotected light bulbs. The auto-ignition temperature of pure phosphine is 38°C, but the presence of impurities often causes the technical product to ignite spontaneously at room temperature (IPCS, 1989). Contact with hot surfaces in the absence of oxygen causes phosphine to break down into phosphorus and hydrogen. Consequently, high concentrations of phosphine gas inside the no.1 hold could have led to spontaneous combustion or explosion. The level of phosphine gas concentration was too high, particularly during the voyage between Port Baltimore and Port Charleston and prior to discharging in Port Charleston. The following pieces of evidence indicate that the situations aboard the ship and ashore were seriously dangerous:

- In Port Charleston, one stevedore working with a forklift observed sparks when rubber tires on the forklift spun on the grey granular chemical on deck. The stevedore acted wisely by stopping work and exiting the hold immediately. The situation might have escalated to a worst-case scenario if he had continued working with the forklift's tires spinning and sparking.
- A high level of phosphine concentration (400 ppm) was found in the stevedores' bodies, which is an indication of a high level of gas concentration inside the hold.
- Stevedores discharged all ten magnesium phosphide drums (6 + 4 damaged drums) and stored them in open air at the terminal, on the apron outside a stevedore shed. The damaged drums, which were placed in the vicinity of property and inhabited areas, were exposed to weather conditions such as rain, water and moisture. In Port Baltimore, recognising the threats to the densely populated terminal, the authorities rejected the initial plan submitted by the cleanup contractor for deactivation of magnesium phosphide on-site.
- In Port Baltimore, during devastation operations, phosphine gas that had built up inside of one of the drums exploded, propelling the drum into the overhead of the inert enclosure when a remote puncturing device was used on the drum. The same phenomenon might have happened aboard the ship or ashore.

Based on the experiences of other marine accident case histories, the situation aboard the m/v SCI might have escalated to the worst-case scenario, if all necessary and sufficient conditions had been present:

- Fire could have broken out due to sparks and high concentrations of flammable gases inside the no.1 hold. Fire could have spread quickly to the entire hold/cargo, other holds/cargoes or even engulfed the entire ship/ cargo.
- Explosion could have occurred inside the no.1 hold, other holds or the entire ship; the m/v SCI was also loaded with other dangerous goods than arsenic and magnesium.
- Fire could have spread to other ships and port properties in the vicinity.

- Stevedores and crew working in the hold/ship, who may not have managed to escape, could have been trapped inside the holds/ship and died.
- Toxic clouds, smoke and explosions could have threatened the port and the local community around the port area.
- The severely damaged ship might have sunk, resulting in severe marine environment pollution; the m/v SCI contained large amounts of arsenic trioxide and other dangerous goods.
- The port and surrounding areas could have been declared prohibited zones.
- Due to toxic clouds and smoke carried by prevailing winds, the local community might have been urged to evacuate the area, or stay inside with all doors and windows closed; large-scale evacuations might have caused chaos and panic.

In order to illustrate some of threats mentioned above, the following provides a summary of a marine accident case history that involved a dangerous substance with hazardous properties similar to those of magnesium phosphide. The summary of the incident is based on these data sources (Spices, 1984; Gould et al., 1986; Looström, 1991a).

Example: Explosion in a container with aluminium phosphide

On July 27th, 1984, an explosion occurred in the no.2 hatch of the Argentine flag m/v ‘Rio Neuquen’ during discharging of containers in the port of Houston, Texas (U.S.). Flying container doors killed one longshoreman, and toxic fumes overcame four others. Further explosions and toxic gas releases posed serious threats to the port and the local community. The explosion occurred in a 20-foot container loaded with 10 tons of aluminium phosphide packaged in cardboard boxes, each containing 14 aluminium flasks. The aluminium phosphide (similar to magnesium phosphide) is class 6, which reacts with water or atmosphere moisture and emits *phosphine gas*. The cargo was packed in a poorly ventilated container. Storage under deck further complicated the situation, because the phosphine gas released from the container was heavier than air and not readily ventilated. A large amount of phosphine gas accumulated inside the container before the explosion occurred. There were signs that the container was dragged along the ship’s deck and punctured by the forklift. Phosphine gas spontaneously ignites at a temperature of about 38^{o}C. The temperature inside the hold may have reached or even exceeded this limit, as the ambient temperature was 32^{o}C. The accident investigation concluded that the cause of explosion was the ignition of accumulated phosphine gas inside the container. Flasks packaged inside the container were not hermetically sealed, constantly generating gases. In response to the accident, the USCG assumed responsibility and took several preventive measures, including the evacuation of the immediate port area, diversion of vessel traffic away from the area and controlling access to the area. The total expenses amounted to approximately $ 485,000.

Summary

Given the seriousness of the situation, magnesium phosphide posed serious threats to people onboard and ashore, the ship, properties in ports and the local community. The situation might have escalated to a worst-case scenario similar to or even worse than that described above.

4.2.2. Human consequences – health effects

Table 4.16 shows the categories and the number of people exposed and reportedly affected by toxic hazards of arsenic trioxide and magnesium phosphide.

Table 4.16: Human consequences – the categories and the number of people affected by toxic hazards of arsenic trioxide and magnesium phosphide

Nr	Category	Number of people exposed	People health affected by toxic hazards			
			Arsenic trioxide	Magnesium phosphide	Total	
					Nr.	%
1	Crew	28	1	2	3	7.5
2	Stevedores	N/A	-	37	37	92.5
	Total	**28+**	**1**	**39**	**40**	**100**

Crew: All crewmembers (28) were potentially exposed to chemicals spilled onboard the ship. Some of them were exposed several times directly to both chemicals by skin contact or inhalation. Three (out of 28) crewmembers were reportedly affected by chemicals. Some crewmembers entered into the enclosed space in the UTD of the no.1 hold to re-secure cargo. Two crewmembers felt dizziness and one of them vomited, which is a typical reaction to phosphine gas exposure. Another crewmember reported taking some of the spilled powder in his hands and smelling it, after which he felt sick. The symptoms of arsenic acute poisoning appear 1/2 to 1 hour after exposure, or may even be delayed for several hours (IPCS and EC, 2001). Once the people inhaled, ingested or came into contact with the chemicals or they were suspected to suffer chemical poisoning, they should have been sent for immediate medical care. They should have received fast and adequate treatment in order to prevent or mitigate toxic effects.

Stevedores: The deadly powder (i.e. magnesium phosphide) piled several inches deep in some areas. In Port Baltimore, although drums were clearly and properly labelled as “toxic” and “dangerous when wet”, stevedores failed to recognise hazards and unloaded magnesium phosphide drums. Subsequently, on January 8th, in Port Charleston, 37 stevedores were sent to the hospital for observation after exposure to toxic gas while working inside the no.1 hold. They were unaware of the danger of phosphine gas. The gas is not visible. The "garlicky" odour of technical phosphine depends on the presence of odoriferous impurities and is usually detectable at concentrations in the range 0.14-7 mg/m^3 (IPCS, 1989). The case history does not indicate whether the stevedores smelled any "garlicky" odour. The gas may have shown toxic effects within a short period of time. The medical analyses (Draeger readings) showed a high level of phosphine concentration in their bodies, up to 400 ppm. According to the U.S. NIOSH guidelines (U.S. DOT, 1992), this was twice the level of “immediately dangerous to life and health” (IDLH). The stevedores were released from the hospital after observations. The case history provides no information about the effects of their exposure to high levels of phosphine and the time they remained in the hospital. They may have been off the job for at least one day.

Accidental exposure to dangerous goods might also have occurred from wearing inadequate or damaged clothing when carrying out search, recovery, cleanup, decontamination and disposal operations. No acute fatality or immediate and future chronic health implications were reported due to exposure to arsenic trioxide, particularly to high doses of phosphine gas.

A review of the U.S. DOT statistics including incident records of the HMIS (2005) and NRC (2005) databases showed that health effects on the m/v SCI's crew and stevedores were not recorded in both databases. The number of water transport injuries involving non-bulk hazardous material related accidents was zero for 1992 (HMIS, 1975-2004). Probably these health effects did not satisfy the definitions or thresholds for reporting and, therefore, they were not reported and/or recorded as injuries. Case histories have shown that marine incidents, including fatal accidents, may go unreported. According to Dickinson (2000), official USCG records (during the period 1994-1997) indicated that as many as several hundred boating fatalities had been systematically unreported, and had never shown up in annual boating safety reports. However, serious and very serious accidents involving multiple fatalities and serious injuries are unlikely not to have been reported in the U.S.

The following is an illustrative example of what can happen, even after many years, after the exposure to dangerous goods. The incident involved the exposure of four seamen to arsine gas released from damaged cylinders. This is an arsenic compound that shares similar hazardous properties with arsenic trioxide, involved in the m/v SCI accident. The example also illustrates numerous points mentioned earlier in this report. The example is based on the accounts of an officer who was onboard the ship at the time of the incident. The incident has been anonymously reported (report no. 99040) to Marine Accident Reporting Scheme (MARS, 1999).

> **Example: An arsine incident - delayed heath effects due to arsine exposure**
>
> The officer recalled, "*...The ship was sailing across North Atlantic towards Europe. On approaching the south west coast of England, four seamen were sent to check lashings and they were all overcome by the fumes in one of the holds. Their condition was very severe and they were taken ashore by helicopter. This happened in 1974, eighteen years later I heard that two of these men were still very ill and a couple of years after that they died. The incident happened because two cylinders of arsine gas, which were properly marked and labelled, were placed inside a freight container without any markings or placards on the outside. The arsine gas was not declared to the ship. The result of the non-declaration was that the container had been stowed in the hold instead of on deck. I am not sure whether they had been initially secured inside the container but, if there had been any lashings, they broke and two cylinders were rolling around inside the container. The result was that the valves were damaged and the gas was released.*" (MARS, 1999)

The gas is heavier than air and, subsequently, the released gas sank in the hold atmosphere. Arsine gas is a stowage category D. If the container had been marked or placarded on the outside, it would have been correctly stowed on deck. The released gas would have escaped into the air and four seamen would not have been exposed to the gas. The failure of a shipper or his representatives to comply with dangerous goods transport regulations costs other people lives. Even after many years, the exposure to dangerous goods can cause serious chronic health problems or even death.

4.2.2.1. Fatality and injury equivalence

Analysis of marine accidents shows that fatalities and injuries are positively correlated (e.g. U.S. DOT, 2005a; NRC, 2005) (Table 4.18). Therefore, measures to prevent or reduce fatalities may prevent and reduce injuries as well.

The IMO has introduced a straightforward conversion approach suggesting an equivalence ratio between fatalities, major injuries and minor injuries, which are: a) 1 fatality equals 10 severe injuries; and b) 1 severe injury equals 10 minor injuries (IMO, 1997b and IMO, 2004a). These conversions are employed in the IMO Risk Matrix for ranking risks and hazards. For the purpose of evaluation and lacking precise data, the equivalence between injuries (health effects) and fatalities is estimated for some scenarios of the m/v SCI accident based on the above ratios (Table 4.17).

Table 4.17: Equivalence between injuries and fatalities for the m/v SCI accident

Nr.	Scenarios of human effects	Equivalent to:		
		Severe injuries	Severe injuries/ fatalities	Fatalities
1	40 minor injuries	4		0.4
2	30 minor/ 10 severe injuries	13	3/1	1.3
3	20 minor/ 20 severe injuries	22	2/2	2.2
4	10 minor/ 30 severe injuries	31	1/3	3.1
5	40 severe injuries	40		4

Scenarios 1 (40 minor injuries equivalent to 4 severe injuries) and 5 (40 severe injuries equivalent to 4 fatalities) are respectively the optimistic (the lower limit) and worst (the upper limit) scenarios of human effects of the m/v SCI accident.

Example: Correlations between "fatality" and "injury" variables

Based on the incident data contained in the NRC database (U.S. 1990-2004), the linear association between "fatality" and "injury" variables has been measured for vessel incidents and all types of supply chain incidents combined (Table 4.18). The values of the correlation coefficient[21], which ranges on a scale from negative very strong (-1) to positive very strong (+1), for vessel incidents and all supply chain incidents combined are respectively 0.689 and 0.230. The positive sign of the

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[21] Based on the Pearson Correlation Coefficient, which is the linear association between two variables

coefficient indicates that the direction of the relationship is positive, which means that any increase/decrease in the fatality number is associated with increase/ decrease in the number of injuries. The larger absolute value of the correlation coefficient for vessel incidents indicates that the relationship between "fatality" and "injury" in vessel incidents is (approx. three times) stronger than the relationship between respective variables for all types of incidents combined. One plausible explanation may be that the number of the crew, which is largely exposed to hazmat hazards, serving onboard the ships is larger than the crew of other means of transport as well as some facilities and terminals. This factor increases the probability of simultaneous occurrences of fatalities and injuries in a single accident.

Table 4.18: Correlations between fatalities and injuries (U.S. 1990-2004) (NRC, 2005)

	Types of incidents	Correlation coefficient: fatality-injury
1	Vessel incidents	0.689
2	All supply chain incidents combined	0.230

Summary

In total, some 40 people, including crewmembers and stevedores, were reportedly affected by both dangerous goods, of which 39 (or approx. 98%) were affected by exposure to phosphine gas only. This is largely attributed to chemical properties of the gas and unawareness of people exposed. The vast majority of the people affected (37 of 40 or 92.5%) were stevedores, who were exposed to twice the level of "immediately dangerous to life and health". Given their job specifications, stevedores were within the most dangerous hazard range of phosphine gas concentrations. They handled magnesium phosphine drums. No acute fatality was reported. Other people, for example stevedores in Port Baltimore, may also have been exposed and their health affected by dangerous goods. Depending on the routes, duration and extent of exposure, arsenic trioxide can cause acute and chronic effects in humans and other living organisms at concentrations ranging from a few micrograms to milligrams per unit (liter/kg/m^3). People who might have been exposed or are likely to be exposed in the future to high doses of arsenic trioxide may suffer from chronic health problems or diseases, or may even die. For more information about definitions and concepts concerning human consequences, see Chapter 3, Vol. I, and Mullai 2006b.

4.2.2.2. Human consequences – statistical data

Human consequences are key elements for measuring and expressing risks. The data show that incidents have been associated with various types of human consequences or effects (e.g. fatality, injury, hospitalisation, and evacuation) at various degrees of magnitude (e.g. the number of fatalities and injuries in a single event, major and minor injuries) on different categories of people exposed (e.g. employees, employers, passengers and the public). The human consequences can be compared or related to a wide range of variables representing the elements of systems and risks. They may include properties of modes and means of transport, other supply chain systems and activities, hazards/classes of hazmat, packaging systems, distribution/transport hazards, causes and contributing factors, incident locations and time. The variables representing the categories of consequences can also be related among themselves. The consequences, including human consequences, to the risk receptors solely attributed or affected by hazardous properties of hazmat are unclear. Neither database (NRC and HMIS databases), nor many other databases reviewed, contains variables for measuring directly and explicitly the effects of hazardous properties of hazmat. However, the review of many case histories shows that inherent hazardous properties of hazmat have contributed to and/or generated additional and severer consequences. The following presents and discusses some key results from the NRC and HMIS databases concerning human consequences and their relations to some variables.

Human consequences of supply chain incidents

NRC database (1990-2004): Table 4.19 shows some key indicators of human consequences, including fatalities, injuries, hospitalisations and evacuations, due to all categories of supply chain incidents combined as reported to the NRC (U.S. 1990-2004). On average, 751 fatal incidents have been reported every year in the U.S. involving 928 fatalities. Approximately 1.236 and 0.031 fatalities are expected respectively per fatal incident and incident. The probability of a supply chain incident turning into a fatal incident is 0.025, i.e. 2.5 fatal incidents are expected in 100 incidents. The probability is higher for the transport system, in particular for the railroad. Many incidents have been associated with combinations of consequences. The data show that some catastrophic incidents have generated large numbers of consequences. Except hospitalisations, the number of human consequences per year has fluctuated during the period 1990-2004, reaching their respective maximum and minimum values as shown in Figures 4.71, 4.72 and 4.74. The high values are attributed to one or a very few severe incidents involving large numbers of fatalities or evacuations in a single incident. For example, one catastrophic aircraft incident, which involved 229 fatalities, contributed to the large number of fatalities reported in 1996. And the large number of evacuations is attributed to a single evacuation incident reported in 1990 in water transport, which involved the evacuation of 99,999 people. Compared to 1990, supply chain fatalities and injuries have shown generally increasing trends (Figures 4.71 and 4.72). Meanwhile, hospitalisations (2000-2004) and evacuations (after 1998) have shown generally declining trends (Figures 4.73 and 4.74).

Table 4.19: Some indicators of human consequences due to supply chain incidents reported to the NRC (U.S. 1990-2004)

Category	**Fatality**	**Injury**	**Hospital.**	**Evacuation**
Total number (1990-2004)	13 914	34 338	9 168	908 100
Mean per year	928	2 289	611	60 540
Number per incident	0.031	0.076	0.020	2.004
Fatal, injury, hospital., evacuation incidents	11 258	14 309	4 291	5654
Fatal, injury, hospital., evacuation incidents per year	751	954	286	377
Fatality, hospital., evacuation incidents per incident	0.025	0.032	0.009	0.012
Per fatal, injury, hospital. and evacuation incident	1.236	2.399	2.136	160.612
The largest number in a year	1 377	3 189	2 104	119 312
The largest number in a single incident	229 (***1***)	300	100	99 999 (***2***)

Examples: Extractions from the NRC database (1990-2004)

The following examples are two of the worst cases of fatal and evacuation incidents.

1. Aircraft Incident - fatality

- Description: 747 airplane fuel tanks/explosion
- Incident type: Aircraft
- Cause: Unknown
- Time: 1996-07-17 20:40
- Location: Meriches Inlet, 10-12 miles south, Meriches
- City/State: NY, Suffolk
- Fatality: 229 passengers and crew
- Medium: Water, Atlantic Ocean
- Response: Cleanup crew notified and enroute
- Spill: Sheen size::1/4 mile X 2 miles
- Material CHRIS Code: JPO
- Material name: Jet fuel, JP-1, (kerosene)
- Amount: Unknown

2. Vessel Incident - evacuation

- Description: M/v Marine Chemist: two chemicals mixed by accident in a tank
- Incident type: Vessel
- Cause: Operator error
- Time: 1990-05-29
- Location: Dow Chemical, Dock A-4, Freeport
- City/State: Brazos, TX
- Evacuation: The ship and the area around evacuated (99,999 people)
- Medium: Air
- Response: The tank cooled down
- Material CHRIS Code: Unknown
- Material name: Unknown - unknown vapours
- Amount: Unknown

The human consequences can be related, for example, to the incidents in supply chain systems and activities, including modes of transport. As the direct outcomes of incidents, the patterns of fatalities and injuries have, to some extent, followed or matched the pattern of incidents (Figures 4.75 and 4.76). However, the data show that this match is not perfect. For example, since 1996-1997, despite the general tendency of the increasing numbers of incidents, the number of fatalities has generally declined up until 2003 (Figure 4.71 and 4.75). Some of the reasons for imperfections include: a) the probability of an incident turning into a fatal and/or injury incident as incidents are not always associated with human consequences; and b) after the initial events, the courses of incidents are associated with a wide range of other causes, contributing factors and situations. For example, the severity of consequences depends very much on the efficiency and timely response of operations. After exceptional years, the numbers of fatalities and injuries reported per year have shown tendencies of declines for several years in a row (Figures 4.71, 4.72, 4.75 and 4.76). In general, in many organisations, industries and countries, including the U.S., different measures are taken for reducing consequences in response to severe incidents, such as legal or regulatory, technical and economic measures. They might have taken serious measures to enhance safety after learning lessons from tragic accidents.

Transport fatalities

NRC (U.S. 1990-2004) and HMIS (U.S. 1993-2004) databases: Figures 4.77 and 4.78 show that, during the period 1990-2004, the vast majority of fatalities reported to the NRC is attributed to the transport system (92.1%), in particular rail transport. The transport fatalities include fatalities reported to the NRC under the category of “railroad non-release” (NR) incidents. As mentioned earlier, this category consists of a large number of fatal as well as injury incidents due to accidental failures, negligence and deliberate acts or reckless behaviour. This type of incident has, in many cases, caused disruptions in the system. Compared to the shares of the supply chain and transport system incidents, fatalities in the transport system, in particular in rail transport, are significantly overrepresented (see Figures 4.71, 4.77, 4.78 and 4.79), while fatalities in plants and vessel transport are significantly underrepresented ((see Figures 4.71, 4.77, 4.78 and 4.79). Some plausible explanations for the large number of fatalities in the transport system include:

- The mobility and frequency of activities
- Exposure to distribution/transport hazards
- The numbers and categories of people exposed to hazmat hazards
- The vicinity of people to hazardous sources
- The number and density of people within the hazmat hazards boundaries
- Factors affecting the course of events and response operations
- Discrepancies in the incident reporting and recording systems.

The modal shares (in %) of incidents and fatalities vary considerably between the two databases – NRC and HMIS databases. The number of transport fatalities reported to the HMIS database (total 252 or on average 21 fatalities per year) is significantly lower compared to the number of fatalities reported to the NRC (see Table 4.19 and Figure 4.71). Railroad fatalities reported to the NRC are excessively overrepresented, whilst, the number of vessel incidents reported to the HMIS database is significantly smaller as compared to other transport modes. These differences between records of two databases could be explained by discrepancies in the incident reporting and recording systems and procedures in both databases.

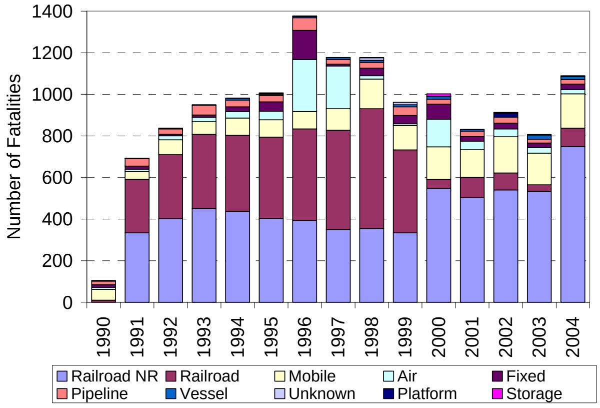


Figure 4.71: Supply chain fatalities by system and year (U.S. 1990-2004)

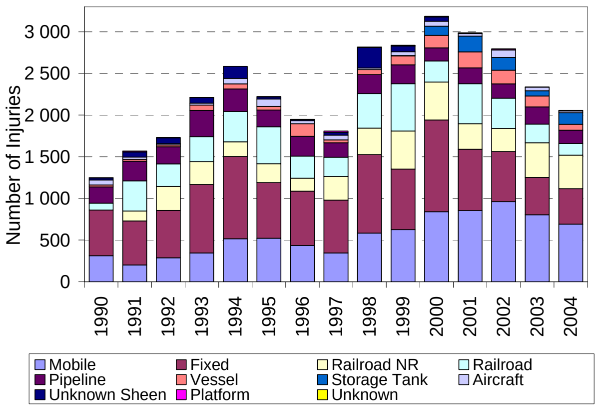


Figure 4.72: Supply chain injuries by system and year (U.S. 1990-2004)

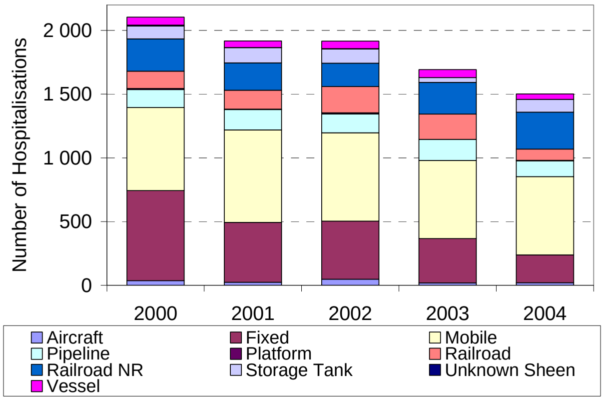


Figure 4.73: Supply chain hospitalisations by system and year (U.S. 1990-2004)

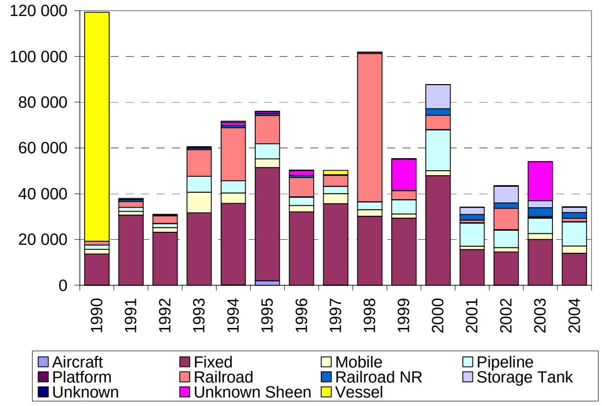


Figure 4.74: Supply chain evacuations by system and year (U.S. 1990-2004)

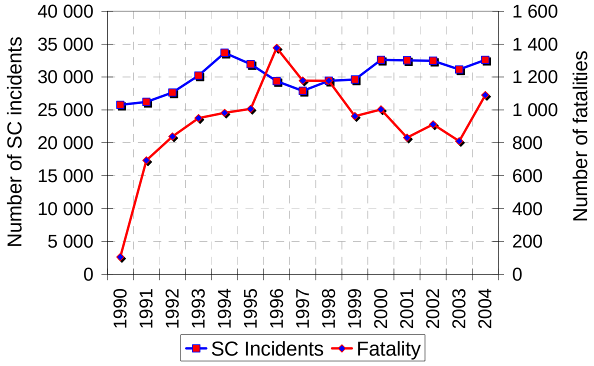


Figure 4.75: Comparison between supply chain incidents and fatalities (U.S. 1990-2004)

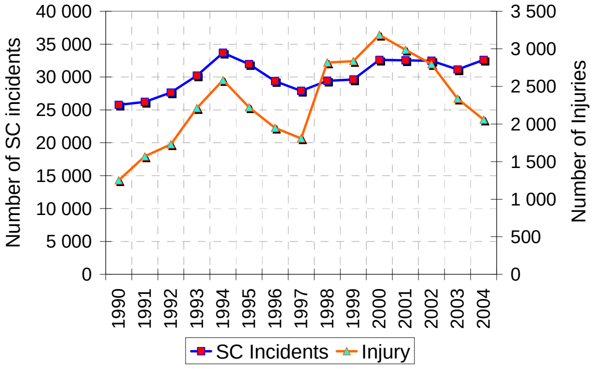


Figure 4.76: Comparison between supply chain incidents and injuries (U.S. 1990-2004)

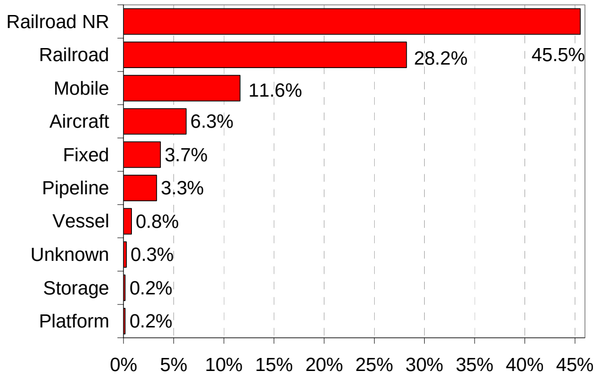
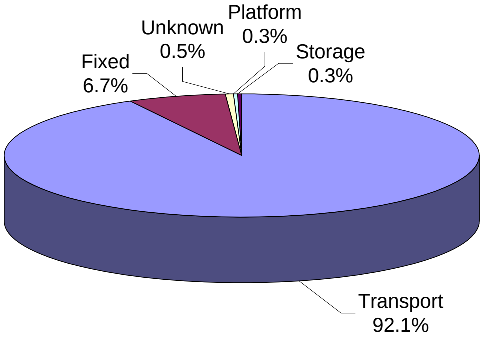


Figure 4.77: Ranking of supply chain fatalities (U.S. 1990-2004)



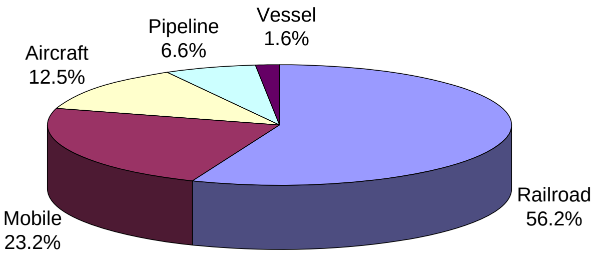
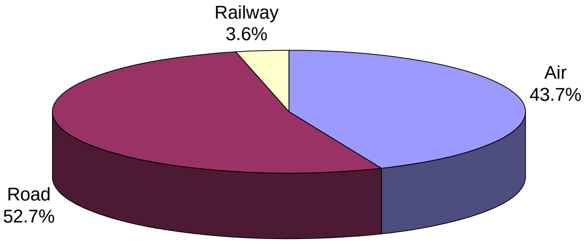


Figure 4.78: Supply chain fatalities by system, excluding railroad NR fatalities (U.S. 1990-2004)

Figure 4.79: Transport fatalities by mode, excluding railroad NR fatalities (U.S. 1990-2004)



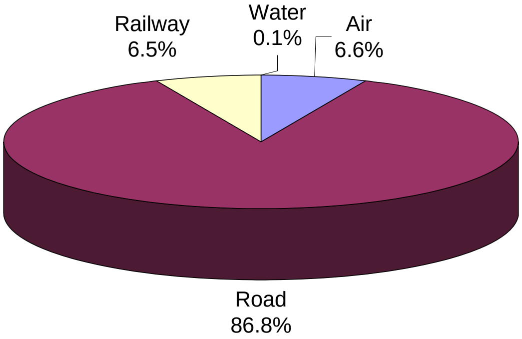


Figure 4.80: Transport fatalities by mode (U.S. 1993-2004)

Figure 4.81: Transport incidents by mode (U.S. 1993-2004)

Human consequences of vessel incidents

NRC database (U.S. 1990-2004): Vessel incidents have been associated with human consequences. With some fluctuations, vessel fatalities and injuries have generally increased during the period 1990-2004 (Figures 4.82 and 4.83). However, since 2001, the number of injuries per year has declined. The number of evacuations per year has fluctuated considerably, reaching its maximum values in 1990 (99,999 people) and 2003 (4,361 people) (Table 4.21). The pattern of fatalities and injuries also matches, to some extent, the pattern of vessel incidents (Figures 4.85 and 4.86). Single vessel incidents have been associated with one or combinations of categories of consequences. The extent of the match can be explained by the fact that the vast majority of fatal, injury and hospitalisation incidents have involved one or a few people. The imperfect match can be explained by the effects of a wide range of factors, including: a) types of incidents; b) classes of hazmat involved; c) the number of people within the boundary of hazards; and d) many circumstances and conditions affecting the courses of incidents after the initial events and response operations. The data show that not all types of vessel incidents inevitably lead to human consequences. Human consequences due to certain types of vessel incidents, for example minor spills, are remotely probable. Although at a lower probability, some severe incidents have involved large numbers of consequences. Fatalities due to vessel incidents accounted for 1.6% of all supply chain fatalities combined as reported to the NRC (U.S. 1990-2004), excluding railroad NR fatalities (Figure 4.81). The number of fatalities in packaged hazmat maritime transport reported to the HMIS database is zero (see Figure 4.105), which is largely consistent with the number of incidents. As mentioned earlier, the number of incidents in the packaged hazmat maritime transport reported to the HMIS database is significantly lower than the number of incidents reported in other transport modes (see Figure 4.81).

Table 4.20 shows the relations between the number of fatalities and incidents. The probability of a vessel incident reported to the NRC turning into a fatal incident is 0.0019, or approximately 2 fatal incidents expected in 1,000 vessel incidents. On average, every fatal vessel incident and vessel incident have respectively been associated with 1.67 (or more than one fatality per incident) and 0.0012 fatalities, or 1.2 fatalities expected in 1,000 vessel incidents. These figures are lower than supply chain fatalities shown in Table 4.20.

Table 4.20: An example of relations between the number of vessel fatalities and incidents

Fatal incidents per incident: 0.0019 or 2 fatal incidents expected in 1,000 incidents
Fatalities per fatal incident: 1.67or 17 fatalities expected in 10 fatal incidents
Fatalities per incident: 0.0012 or 1.2 fatalities expected in 1,000 incidents

The majority of fatal and injury incidents were single-fatality (45 of 66) and injury (335 of 593) incidents. The majority of fatal vessel incidents are attributed to the following categories of causes: equipment failure (34.6%), operator error (15.4%), and other causes (16.4%). Causes and contributing factors of a large number of fatal incidents were recorded in the NRC database as unknown (30.8%). The data suggest that any random or untargeted reduction in the number of vessel incidents may not necessarily be followed directly or in the near future by the same margin of reduction in the number of fatalities, injuries, hospitalisations and evacuations.

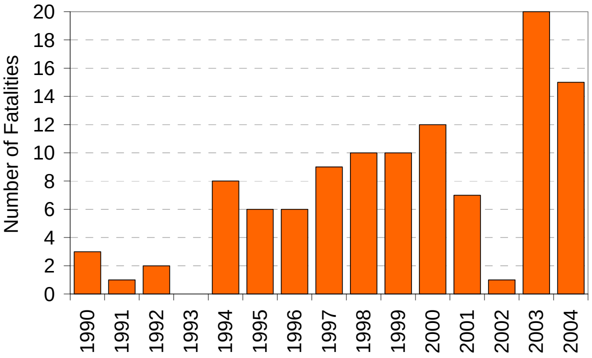


Figure 4.82: Fatalities of vessel incidents by year (U.S. 1990-2004)

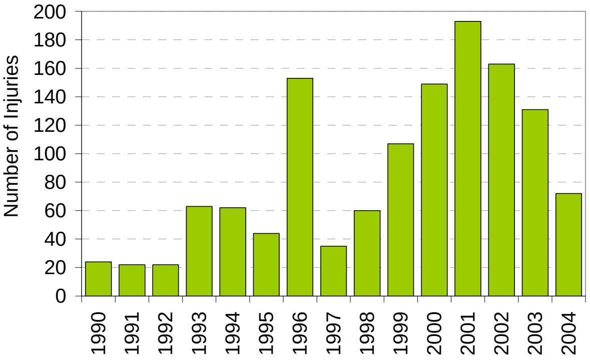


Figure 4.83: Injuries of vessel incidents by year (U.S. 1990-2004)

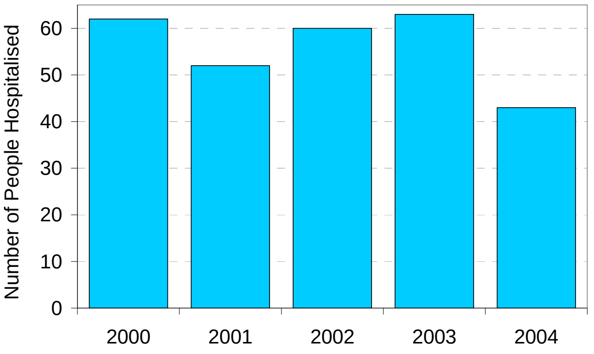


Figure 4.84: Hospitalisation of vessel incidents by year (U.S. 1990-2004)

Year	Number of People Evacuated
1990	99,999
1991	410
1992	49
1993	70
1994	515
1995	192
1996	166
1997	1,918
1998	18
1999	78
2000	67
2001	140
2002	286
2003	84
2004	187
Total	104,179
Mean per year	6 ,945

Table 4.21: Evacuations of vessel incidents by year (U.S. 1990-2004)

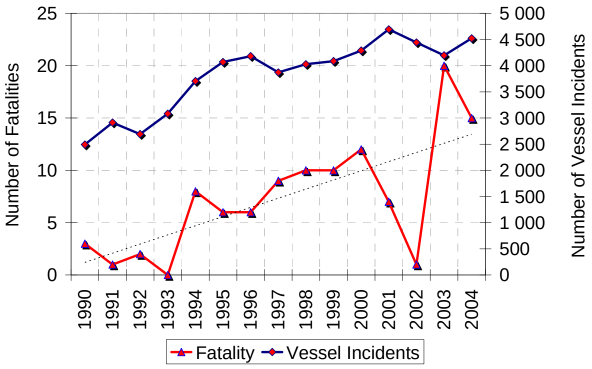


Figure 4.85: Comparison between vessel incidents and fatalities by year (U.S. 1990-2004)

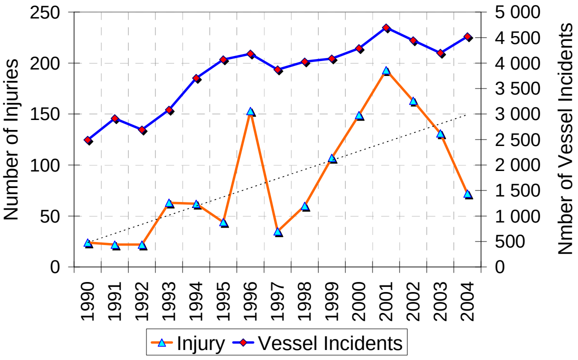


Figure 4.86: Comparison between vessel incidents and injuries by year (U.S. 1990-2004)

4.2.3. Marine environment consequences

On January 4th, 1992, the m/v SCI lost overboard a large portion of its containerized cargo of arsenic trioxide during a severe storm some 30 miles off the coast of Cape May, New Jersey (U.S.), in 40 meters of water, near to the entrance of Delaware Bay (Figure 4.87).

Figure 4.87: Approximate location of arsenic trioxide loss site

Some important parameters for assessing environmental consequences caused by arsenic are the amount and type of dangerous substances, the sensitivity and importance of the area, and the extent of arsenic contamination and accumulation in the marine environment.

As mentioned earlier, the m/v SCI was loaded with 25 containers of arsenic trioxide, 19 containers in the no.2 hold and 6 containers on the no.2 hatch cover. Each container was packed with 108 palletised drums, each of which contained approx. 170 kg product. Table 4.22 shows the estimated amounts (drums/kg) of arsenic trioxide stowed on deck, lost at sea and spilt aboard the m/v SCI. A total number of 648 arsenic trioxide drums (or 110,225kg) were stowed on deck. During the storm, *all six* on-deck-stowed arsenic trioxide containers were damaged or broke loose. *Four* of these containers, together with other cargo, were lost overboard.

In addition, many drums broke loose on the no.2 hatch cover and deck. In Port Baltimore, of the total number of 648 drums on-deck-stowed containers, *234 drums* (or 39,803 kg) were recovered inside the two remaining containers or on deck (U.S. DOT, 1992) (Whipple et al., 1993). Some *13 drums broke open* spilling their contents. An estimated amount of *two tons* of loose arsenic trioxide spread on deck (Merrick, 1993). An unknown amount of spilled arsenic trioxide may have been blown by strong winds, diluted by rains and green waters and ended up in the sea.

According to the USEPA, more than 400 drums of arsenic trioxide were lost overboard (USEPA, 1992). Based on the mentioned sources, the number of drums lost overboard is estimated to be *414* (or approx. 70,421 kg.). However, according to 1992 incident records in the NRC database (2005), the number of drums lost overboard is larger, i.e. 441 drums (Table 4.22). The sources of the case history are considered more reliable, and, therefore, the estimation in this section is based on the information provided by these sources. The responsible authorities launched a massive search and recovery operation. Based upon its proximity to a sensitive ecological zone, the section nearest to the entrance of Delaware Bay was targeted as the first search area. For several months, a large area was searched. On May 19th, after extensive sonar and ROV search of the areas determined as environmentally critical areas was made with no drums found. On October 5th, 1992, the case was formally closed. At the end of search and recovery operations, only *320 of the lost drums* were recovered. An amount of approximately *200 kg* of arsenic trioxide was estimated to have been released from 320 drums recovered. According to estimations, some *94 arsenic trioxide drums* (or 15,990 kg) were never found; subsequently they remained unrecovered on the sea floor.

Table 4.22: Amounts of arsenic trioxide lost at sea and spilt aboard the m/v SCI

Location	**Amounts of arsenic trioxide involved – on deck**		**Arsenic trioxide recovered**						**Un-recovered arsenic**		**Arsenic lost/ spilt at sea and on deck**
			Intact		Damaged		Total				
	c[22]/d[23]	kg	d	kg	d	kg	d	kg	d	kg	kg
Lost at sea	4/414	70 421	n/a[24]	n/a	n/a	n/a	320	54,232	94	15,990	200
On deck	2/234	39,803	221	37,592	13	211	234	37,803	-	-	2,000
Total	6/648	110,225					554	92,035	94	15,990	2,200

All the lost arsenic trioxide containers/drums sank and scattered in a vast area in the sea floor close to the entrance of Delaware Bay. The area is a sensitive and important ecological, economical and recreation zone for the local community. The area is heavily used by commercial clammers (bivalve molluscs) and recreational fishermen (NOAA, 1992b). For more information about the sensitivity and importance of the area, see Section 2.4.

In summary, some 94 drums were never found. An amount of approximately 200 kg arsenic trioxide was released from breached drums (320) recovered from the sea floor. In addition, some of 2,000 kg arsenic spilt on deck from damaged drums that remained onboard may have also ended up in the sea due to winds, rains and green waters. In total, an amount of approximately 16 tons of arsenic trioxide was lost overboard in the environmentally sensitive area and never found.

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[22] Container

[23] Drum

[24] Not Assessed or Available

4.2.3.1. Assessment of environmental consequences by the U.S. authorities

In response to the loss of arsenic trioxide drums at sea, the responsible authorities conducted an assessment of the environmental hazard posed by arsenic trioxide drums on the ocean floor. The data sources provide some conflicting information concerning which and how many authorities were involved in the assessment. According to the sources, the assessment may have been prepared by one or several authorities, including the U.S. National Marine Fisheries Service (NMFS) (Whipple et al., 1993), the U.S. National Oceanic and Atmospheric (NOAA) (U.S. DOT, 1992; NOAA, 1992a), and the U.S. Food and Drug Administration (FDA) (NOAA, 1992a).

In order to assess any possible arsenic contamination and accumulation in the marine environment, numerous samples of the seawater column, bottom sediments, and shellfish (clam) tissue were collected in and around the debris site for analysis. According to Whipple et al. (1993), samples were taken between February and April (1992). The data sources available provide a very short qualitative assessment, with no exact figures for arsenic levels. According to NOAA's initial assessments, *the absorption of arsenic trioxide by algae and clams could be significant, but it does not have any bio-effects on other marine life or birds* (U.S. DOT, 1992). *Effects of arsenic trioxide outside the immediate vicinity of the spill were viewed as unlikely* (U.S. DOT, 1992). The analysis results of samples were (NOAA, 1992a):

- *Seawater column*: The seawater column contained only background levels or naturally occurring arsenic. Dispersion of unconfined arsenic trioxide (approx. 200 kg) was expected over a period of a few days to a week after the release.
- *Sediments*: The sediments contained only background levels of arsenic.
- *Aquatic life*: Arsenic levels in the shellfish (calms) tissues were within normal concentrations.

An amount of arsenic trioxide released into the sea (200 kg + a part of 2000 kg) was dispersed into the water. This amount was too small compared to the massive body of the Atlantic Ocean water. Some arsenic may have been dissolved into the water, and the rest may have been spread in a wide area on the sea floor, which is why the samples of the seawater, sediments and organisms showed only background levels of arsenic.

No other reports have been found on the marine environment assessment after the m/v SCI accident case was closed. The following section explores potential threats posed by unrecovered arsenic trioxide drums.

4.2.3.2. Threats from unrecovered arsenic trioxide drums

As mentioned above, some 94 drums containing approx. 16 tonnes arsenic trioxide were never found. The case history does not contain information concerning the fate and threats posed by unrecovered arsenic trioxide drums. Unbreached drums may remain intact on the sea floor for many years. Case histories have shown that containers with toxic substances are accidentally recovered intact from the sea floor after many years, in some cases after a half-century. Arsenic trioxide drums lost from the m/v SCI may pose future threats to the marine environment and the local community. Based on inferences from accident case histories and other data sources mentioned in this report, the following explores some scenarios.

Drums washing ashore: Case histories (HCB, 1986-2003) have shown that many packaged goods are lost overboard each year. Due to combined effects of water currents and circulation induced by wind, waves, and tides, and sediment transport, packages including drums are washed ashore (like those drums seen in Figure 4.88). If arsenic trioxide drums have the same fate, their contents may expose people, coastlines (as shown in Figures 4.89 and 4.90) and their habitats. Arsenic may be released from disintegrated drums and dispersed into the environment. However, given the long distance (the accident site was some 30 miles off the coast of Cape May, New Jersey) and the negative buoyancy of the drums, the occurrence of this scenario is remotely likely.

Figure 4.88: Drums washed ashore - salvage drums (on the left) can be seen in the background (IMO, 1992)

Figure 4.89: Sea Isle City, New Jersey, west of the m/v SCI accident site (USNA, 2005)

Figure 4.90: Cape May, New Jersey, west of the m/v SCI accident site (USNA, 2005)

Drums getting snagged in nets: There may be possibilities of un-recovered drums (94) getting snagged in nets, particularly in bottom-fishing gear. Due to compression forces, corroded drums may be breached, possibly contaminating the catch or directly exposing fishermen. Prior to the recovery of 320 drums, a fisherman reported catching an arsenic trioxide drum in his net. This incident suggests that the possibility of drums being caught by net existed and arsenic trioxide posed health hazards to the fishing communities. In order to prevent incidents, the relevant authorities issued broadcasts to inform fishermen of steps when arsenic trioxide drums were sighted or recovered. Had the 320 drums not been recovered, the probability of drums being caught by nets and the subsequent exposure to arsenic would have been higher.

Release of arsenic trioxide from disintegrated drums: Unless all drums are recovered (either accidentally or planned) from the sea floor or arsenic is solidified into rocks, which are, from the marine environment point of view, the most optimistic scenarios, the occurrence of this scenario is quite likely. Due to the combination of moisture inside drums, seawater and temperature differences, drums will be corroded. Under hydrostatic pressure and other mechanical forces, the corroded drums will disintegrate to the point at which arsenic trioxide will be released into the seawater column, sediments and marine biota.

Contamination of the seawater column: Due to low solubility of arsenic in water, the massive body of the Atlantic Ocean water and water disturbances in the area, the contamination of the seawater column may be insignificant. However, due to the large amount of arsenic (approx. 16 tons or 16E+12 µg), concentration of arsenic in the seawater over the contaminated sediment areas may exceed the general seawater background concentrations (*1–2 µg/l*). For example, if it had been diluted entirely into the seawater at a concentration 3µg/l above the background concentration, the amount of unrecovered arsenic of the m/v SCI would have contaminated approx. 5.3E+09 m^3 (or 5.3 km^3 = 132.5 km^2 x 40m depth) of seawater. The amount of arsenic lost at sea in the m/v SCI accident case would have contaminated a large portion of the body of water of the Öresund area (i.e. the strait between Sweden and Denmark). Arsenic concentrations in the seawater over the contaminated sediments area may even reach the lowest lethal concentrations for marine organisms.

Contamination of sediments: Arsenic released from drums will settle and seep into the sediments. The arsenic life and the degree of penetration into the sediments depend on various factors, including the contents and structural properties (e.g. porosity) of the sediments, the solubility and other properties of arsenic, water currents and sediment transport. The coastal area is predominately sandy sediments. Delaware has sandy shores (University of Delaware, UD, 2003). Because of its very low solubility, (water 1.82g/100g) arsenic is expected to persist in the sediments at toxic levels for some time. However, water currents and circulations close to the sea bottom may affect the duration of arsenic on the sediments by increasing the rate of dilution. The sediment transport may affect changes in configurations and locations of arsenic-contaminated sites. The sediment transport on a shoreline depends on the incident waves (height and direction).

The size and the extent of the arsenic-contaminated sediments area are important parameters that indicate the extent of the marine environment consequences. Lacking hard data, the sizes of the sediments areas that may be potentially contaminated by arsenic trioxide are estimated (Figures 4.91~4.96) on the basis of the following assumptions and facts:

- Type of sediments: sandy
- The specific gravity of wet sand: 1.93 grams per cm^3 or 1.93 tons/m^3 (Reade, 2005).
- Some relevant arsenic concentration levels that are taken into account include: Background arsenic concentrations in aquatic sediment for the state of *New Jersey* (U.S.) range from *<1 to 12 mg/kg* (NJDEP, 2000). The state's sediment arsenic concentration criteria for marine/estuarine are: Effects Range-Low (ER-L) = *8.2 mg/kg*; and Effects Range-Median (ER-M) = *70 mg/kg* (NJDEP, 2000). Sediment arsenic concentrations in *Maurice River*, (*Delaware River Basin, New Jersey*) range between 25.3-515 mg As/kg dry weight (Faust et al., 1987a). In some locations in the inland waters of *New Jersey* arsenic concentrations far exceed (as much as 8 fold) the concentration level of 515 mg/kg. The latter is not taken into account.
- The amount of arsenic trioxide not recovered from the sea: 94 drums containing approx. 16 tonnes or 1.60E+10 mg.

Some assumptions are:

- No drum is recovered; the amount of arsenic remains the same
- Arsenic is not solidified into rocks
- The amount of arsenic is simultaneously released from un-recovered drums
- Insignificant dilution and degradation or changes to arsenic in the seawater and sediments by biological and abiotic factors
- Uniform distribution of arsenic in sediments.

Some scenarios of arsenic penetration into the sediments are: 1 cm, 2 cm, 3 cm, 5 cm, 10 cm, 15 cm and 20 cm. The arsenic-contaminated sediment area is estimated by the formula:

$$S = \frac{Q}{10CGD}$$

Where

S - Arsenic contaminated sediments area (m^2)
Q - Quantity (mg) of arsenic trioxide released
C - Concentration (mg/kg) of arsenic trioxide in the sediments – deviation from background concentrations
G - Specific gravity of wet sand (1.93 tons/m^3)
D - Depth (cm) of arsenic trioxide penetration in the sediments
10 - Coefficient

The contamination level of the sediments as well as the entire ecosystem can be viewed as the deviation values from the existing concentrations prior to the release of arsenic. The existing state of concentrations may include "natural" or background concentrations.

$$C_{\text{Deviation}} = C_{\text{Actual}} - C_{\text{Existing}}$$

Where

$C_{\text{Deviation}}$ - Deviation values of actual arsenic concentrations from existing concentrations

C_{Actual} - Actual arsenic concentrations after the release of arsenic

C_{Existing} - Existing arsenic concentrations prior to the release of arsenic

Some results of the estimations are (see Figures 4.91~4.96):

- The estimated size of the sediments area that may be contaminated at an arsenic concentration level exceeding 1 mg/kg the lowest limit (*<1 mg/kg*) of the background concentration, may range from approx. 8.33E+08 m^2 (830 km^2) (for arsenic penetration at a depth of 1 cm) to approx. 0.42E+08 m^2 (42 km^2) (for arsenic penetration at a depth of 20 cm).
- The estimated size of the sediments area that may be contaminated at an arsenic concentration level exceeding existing concentrations by the state of *New Jersey* sediment arsenic concentration criterion for marine/estuarine of Effects Range-Low (ER-L = *8.2 mg/kg*), may range from approx. 1.02E+08 m^2 (102 km^2) (for arsenic penetration at a depth of 1 cm) to 5.08E+06 m^2 (5 km^2) (for arsenic penetration at a depth of 20 cm). At a concentration level exceeding existing concentrations by the criterion of Effects Range-Median (ER-M = *70 mg/kg*), the size of the contaminated area may range from 1.19E+07 m^2 (12 km^2) (for arsenic penetration at a depth of 1 cm) to 5.95E+05 m^2 (0.6 km^2) (for arsenic penetration at a depth of 20 cm).
- The estimated size of the sediments area that may be contaminated at an arsenic concentration level exceeding existing concentrations by the upper limits (515 mg/kg) of sediment arsenic concentrations in *Maurice River*, (*Delaware River Basin, New Jersey*), may be approx. 1.62E+06 m^2 (1.6 km^2) (for arsenic penetration at a depth of 1 cm). One of the worst-case scenarios may be the contamination of the sediments at a concentration level exceeding existing concentrations by 515 mg/kg, in which arsenic seeps into the sediments to a depth of 20 cm. In this scenario, the arsenic-contaminated area is estimated to be 8.09E+04 m^2 (0.0809 km^2 = 8.09 ha).

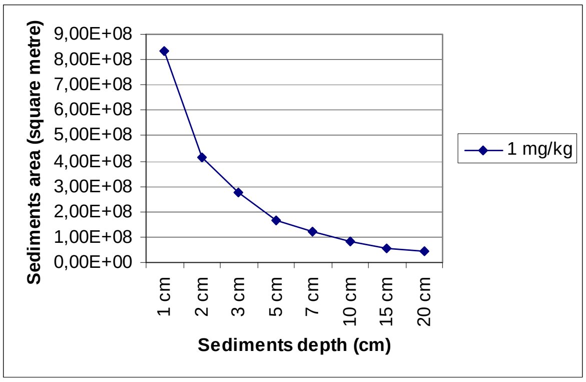

Figure 4.91: Estimated arsenic-contaminated sandy sediments (area and depth) at a concentration level exceeding existing concentrations by 1 mg/kg.

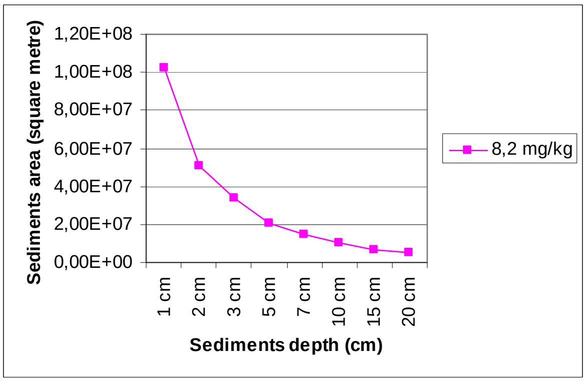

Figure 4.92: Estimated arsenic-contaminated sandy sediments (area and depth) at a concentration level exceeding existing concentrations by 8.2 mg/kg.

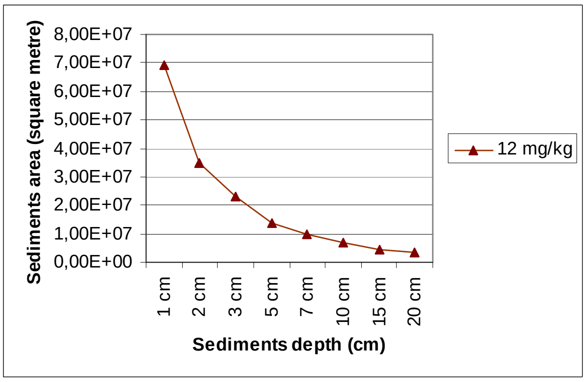

Figure 4.93: Estimated arsenic-contaminated sandy sediments (area and depth) at a concentration level exceeding existing concentrations by 12 mg/kg.

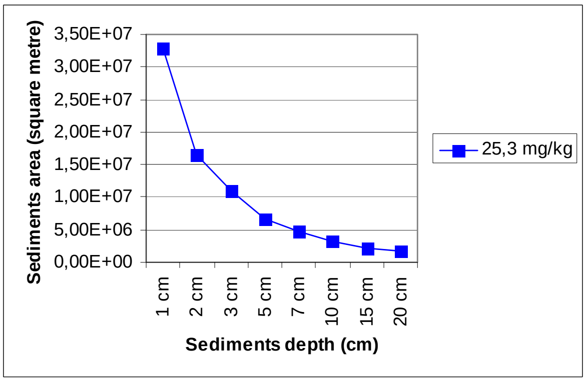

Figure 4.94: Estimated arsenic-contaminated sandy sediments (area and depth) at a concentration level exceeding existing concentrations by 25.3 mg/kg.

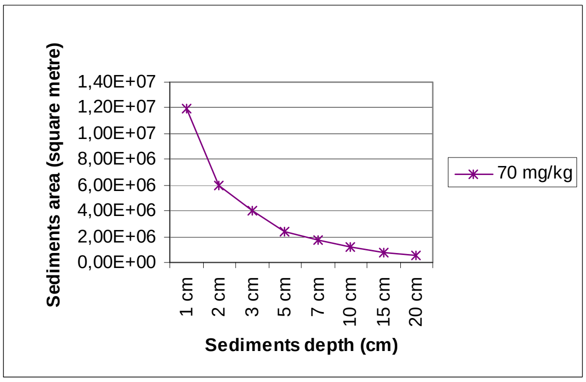

Figure 4.95: Estimated arsenic-contaminated sandy sediments (area and depth) at a concentration level exceeding existing concentrations by 70 mg/kg.

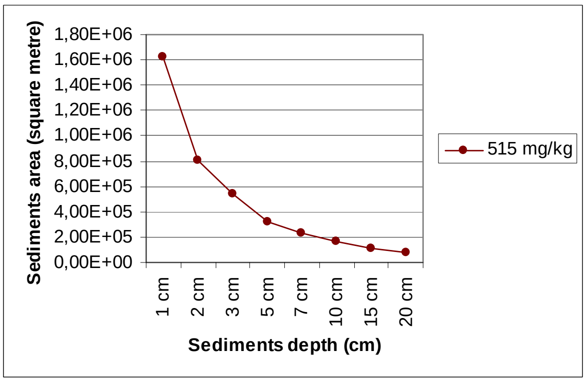

Figure 4.96: Estimated arsenic-contaminated sandy sediments (area and depth) at a concentration level exceeding existing concentrations by 515 mg/kg.

The size (the amount and diversity) and the severity of the marine organisms' contamination depend largely on the size of arsenic contaminated sediments area and deviation values of arsenic concentrations. In the later case scenarios, the sediments areas will be considerably or seriously contaminated. For more information about the concentrations, processes and transformations of arsenic in the marine environment see Appendix 2, Vol. II.

Threats to marine biota: Because of the intimate food chain connection to sediments, arsenic is transferred from sediments to marine biota (fauna and flora). Marine invertebrates and vertebrates that inhabit or swim through the arsenic-contaminated areas and through food web transfers may, to various degrees, be contaminated. The sediments in the southern coastlines of the state of New Jersey and the area in the vicinity of Delaware Bay are largely inhabited by clams. Arsenic trioxide is harmful to marine organisms as well as coastal organisms including algae, fish, shellfish, birds, and mammals, in very low concentrations. Exposure to arsenic compounds can cause acute and chronic effects in marine habitats at low concentrations ranging from a few micrograms to milligrams per litre. Conventionally, generic assessment would apply uncertainty factors to the lowest reported chronic effects concentration (IPCS, 2001). For marine micro-organisms, invertebrates and vertebrates the lowest acute lethal concentrations of arsenic compounds are reported respectively 5 µg As(V)/litre, 11 µg As/litre, and 12.7mg As (III)/litre (IPCS, 2001). Because of general low exposure and undeveloped tolerance, marine algae are extremely sensitive to inorganic arsenic. For plant tissue, the lowest critical concentration is approximately 1 mg/kg (PCS, 2001).

For marine organisms inhabiting the New Jersey coastlines and the area in the vicinity of Delaware Bay, the acute arsenic toxicity ranges from approximately 250 µg/l for crabs and copepods, which is an important constituent of plankton, to greater than 1500 µg/l for *bivalve molluscs*, shrimps and fish (USEPA, 1985). The lowest lethal or critical concentrations of arsenic can be reached in the contaminated areas. The effects of exposure to arsenic include: *lethality*, *inhibition of growth*, *photosynthesis, survival* and *reproduction impairment*, *alterations* and *behavioural* effects (Lima et al., 1984; Sanders, 1986). The arsenic-contaminated marine environment is characterized by *limited species quantity* and *diversity*. Only species exhibiting resistance to arsenic may be present in an arsenic-contaminated environment with relatively high levels of arsenic concentrations. Arsenic concentrations in marine organisms (fish and shellfish - clams) inhabiting the contaminated area may reach higher levels than the permissible level for human consumption. For more information about arsenic consequences in the marine environment, see Appendix 2, Vol. II.

Threats to humans: There may be potential threats to human health through the consumption of arsenic contaminated fish and shellfish. Due to arsenic trioxide spilt from breached drums, fish and shellfish inside or in the vicinity of the contaminated areas may absorb high levels of arsenic that may be harmful to humans. The consequences of consuming arsenic contaminated fish and shellfish will depend on the amount of fish and shellfish eaten and the levels of arsenic in the fish and shellfish. For more information about human consequences of arsenic exposure, see Appendix 2, Vol. II.

In summary, the large amount of arsenic trioxide still unrecovered may pose real threats to the marine environment and the local community.

Summary

A large number of 414 on-deck-stowed arsenic trioxide drums (or approximately 70,421 kg) were lost overboard in a sensitive and important ecological, economic and recreational zone for the local community. The area is used by commercial clammers and recreational fishermen. After massive search and recovery operations, only 320 of the lost drums were recovered. An estimated amount of 200 kg of arsenic trioxide was released from those drums. In addition, part of the arsenic spilt on deck may also have ended up at sea. The results of samples taken at the accident site showed that the seawater column, sediments and shellfish (clams) contained only background levels of arsenic. Some 94 arsenic trioxide drums (or 15,990 kg) were never found. The analysis showed that unrecovered arsenic may pose real threats to the marine environment and the local community.

4.2.3.3. Environmental consequences – statistical data

Hazmat releases can cause a wide range of effects to the environment and its populations, which can be measured by different measurement units, including: a) the amounts of hazmat released; b) the area affected; c) the duration and irreversibility of damage; d) bioaccumulation and persistency of the substance involved; e) damage in monetary units including cleanup and other costs. For more information and examples, see Sections 4.2.3 and 4.2.7.1.

The amount of hazmat involved is a very important factor and, consequently, indicator that can serve as a measure of the severity of environmental consequences. Case histories, including the m/v SCI case, have shown that the amount is positively related to the consequences – the larger the amount of pollutants involved the larger and more severe consequences to the environment are expected. However, the extent of consequences is also affected by many other factors, including: a) types and properties of pollutants; b) forms of hazmat containment; c) properties, sensitivity and conditions of the environment and its habitats; and d) the efficacy of response operations. The following presents data concerning the environmental consequences due to arsenic incidents in terms of amounts of arsenic compounds involved/released into the environment in the U.S. (1990-2004).

NRC database (1990-2004): Table 4.23 shows that, on average, 24 arsenic release incidents, which in many cases have involved large amounts of different types of arsenic compounds, are reported each year in the U.S. (1990-2004) from different sources. These incidents have involved arsenic contaminated soil, liquids/waters and objects; arsenic compounds and mixtures; and arsenic liquid and solid wastes. The amount of arsenic involved per incident varies considerably. In many cases (42% of 353 cases), the amounts of arsenic involved have not been reported. Based on the extrapolations of the reported amounts, an amount of 1497 tons or m^3 arsenic per year or 62.4 tons or m^3 arsenic per incident per year is estimated to have been involved. The largest amounts of arsenic involved per year and per incident/year are reported for 2004 (Table 4.23). The amount of arsenic lost at sea from the m/v SCI (approx. 70 tons), which was one of the largest amounts involved in a single incident, exceeded the mean amount of arsenic involved per incident per year during the period 1990-2004.

Table 4.23: Arsenic incidents and amounts of arsenic released into the environment (U.S. 1990-2004)

Year	Reported amounts (kg/l)	Total nr. of events	Nr. of events - amounts unknown	Nr. of events - amounts known	Amounts per event - known amounts	Amount estimated for events -unknown amounts	Total estimated amounts (kg/l)
1990	13 431	27	10	17	790	7 900	21 331
1991	4 219	23	5	18	234	1 172	5 391
1992	207 071	23	10	13	15 929	159 285	366 357
1993	195 998	27	16	11	17 818	285 088	481 085
1994	8 965	23	6	17	527	3 164	12 129
1995	572 824	25	13	12	47 735	620 559	1 193 383
1996	7 044	19	7	12	587	4 109	11 153
1997	994	12	5	7	142	710	1 704
1998	404	18	9	9	45	404	809
1999	100 397	14	9	5	20 079	180 715	281 112
2000	9 981	27	15	12	832	12 476	22 457
2001	959	24	8	16	60	480	1 439
2002	6 849	31	15	16	428	6 421	13 270
2003	429 712	27	13	14	30 694	399 018	828 730
2004	15 142 100	33	7	26	582 388	4 076 719	19 218 819
Total	**16 700 948**	**353**	**148**	**205**	**718 289**	**5 758 221**	**22 459 169**
Mean	**1 113 397**	**24**	**10**	**14**	**47 886**	**383 881**	**1 497 278**

4.2.4. Damage to properties

During the storm, the m/v SCI and her cargo sustained significant damage due to a combination of green waters and heavy motions. In addition, many arsenic drums were recovered from the sea floor. Initially, the USCG and USEPA agreed to consider arsenic trioxide as a hazardous product as opposed to hazardous waste. Attempts were made to ship the chemical back to the manufacturer, but this was unsuccessful. The arsenic trioxide was damaged by water and, subsequently it was considered as hazardous waste.

Due to their inherent hazardous properties, dangerous goods carried onboard the m/v SCI caused additional damage and threats to properties aboard the ship and ashore. The following explores those properties that were contaminated or threatened by hazardous properties of arsenic trioxide and magnesium phosphine.

Cargo and ship contamination: The m/v SCI was loaded with a large amount of different types of general cargoes including freight containers, trucks, cotton, lumber, household goods and cartons of wine. Parts of the ship and her cargo were considerably contaminated. The main deck and several hatches were literally awash with arsenic trioxide (Figure 4.97). In the upper tweendeck of the no.1 hold, in which two pallets with drums of magnesium phosphide had turned over and broken loose, the contents (393 kg) had spilled and mixed with other cargoes, including loose lumber and broken cartons of wine (Figure 4.98). Given the toxic properties of arsenic trioxide and magnesium phosphide, some goods, such as foodstuffs, are disposed of or discarded regardless of the extent of contamination. Packages with dangerous goods were also broken loose in other holds. Several containers, trucks, and breakbulk packages below deck were found broken, loose and damaged. At least two other dangerous cargoes were similarly set adrift in other holds, but their effects were not reported.

Figure 4.97: No.2 hatch/deck contaminated by the white powder (arsenic trioxide) (U.S. DOT, 1992)

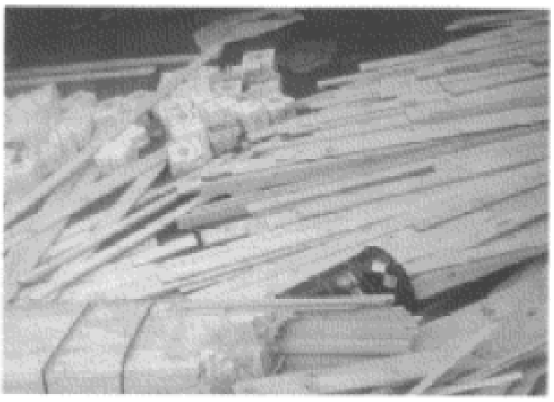

Figure 4.98: Broken cartons of wine and lumber in the no.1 hold contaminated by magnesium phosphide (U.S. DOT, 1992)

Other ships and cargoes: In both ports (Port Baltimore and Port Charleston), other ships in the vicinity and their cargoes were threatened by contamination and fire/explosion. In Port Charleston, due to potential contamination and fire/ explosion threats to other ships and their cargoes, the m/v SCI was sent to the anchorage area.

Port territory and properties: In both ports, the port territory and properties were also threatened by potential contamination and fire/ explosion.

Summary

Arsenic trioxide, magnesium phosphide and other dangerous goods contaminated large parts of the m/v SCI and her cargo. Potential fire/explosion also threatened the ship and her cargo. Contamination and fire/explosion hazards threatened other properties in the vicinity.

4.2.5. Disruption of activities

In the wake of the m/v SCI accident, due to involvement and threats posed by dangerous goods, numerous activities were disrupted:

Ship activities – cargo discharging suspended, ship arrested: After the “discovery” of magnesium phosphide inside the no.1 hold in Port Charleston, the regular schedule of the m/v SCI was interrupted. On January 8th, because of contamination and potential threats to other ships, activities and the local community, the USCG in Port

Charleston ordered ship evacuation. National Strike Force personnel took the m/v SCI out of the berth and sent her to a more isolated area in anchorage for decontamination. The ship’s crew was evacuated, except for a skeleton emergency team of 10 crewmembers. Cleanup operations onboard the ship began in Port Baltimore on January 5th and completed in Port Charleston on February 8th, 1992. Because of contaminations and related cleanup operations, the ship was put out of operation (laid-up) – the ship was out of service for some 30 days. In addition, the ship remained under arrest in the harbour at Port Charleston for an unspecified time after the completion of cleanup on February 8th. The lawsuit filed by the U.S. Department of Justice against the shipowner and operator prevented the ship’s departure (USEPA, 1992).

Port activities – stevedores suspended cargo discharging: Due to hazards of dangerous goods involved, ship and port activities were interrelated. In Port Baltimore, cargo operations began after arsenic trioxide spilt on deck was cleaned up. In Port Charleston, stevedores suspended cargo operations as the ship was taken to anchorage due to contamination and potential threats posed by the m/v SCI to other ships, activities and the local community. In addition, in Port Charleston, some 37 stevedores suspended their work as they were sent to hospital for examination after exposure to toxic gas.

Maritime related activities - fishing banned: The U.S. Department of Commerce closed to fishing some four square miles of the Atlantic Ocean off the coast of the resort town of Cape May, New Jersey (U.S.). The authorities issued an emergency declaration after 414 drums of arsenic trioxide were lost overboard from the m/v SCI on January 4th. Arsenic trioxide posed threats to human and marine life. Immediately after the accident, NOAA sent notices to all surf clam and ocean quahog (known on the Atlantic coast of North America as hard-shell clam or round clam) permit holders warning them of potential dangers of exposure to arsenic trioxide (U.S. DOT, 1992). The fishing ban stayed in effect for approximately four months (January-April, 1992) until arsenic trioxide drums were found and removed, and samples analysis and assessment of the seawater, sediments and marine organisms were completed.

Other activities: Numerous organisations, authorities and individuals involved in the m/v SCI accident interrupted their daily routines.

Summary

Due to dangerous goods involvement, threats, concerns and responses to arsenic trioxide and magnesium phosphide spills, many activities, such as ship activities, port activities, fishing activities and other activities, were disrupted. Many organisations and individuals also interrupted their daily routines. The costs of activity disruptions were unknown. However, the aforementioned facts suggest that these costs could have been very high.

4.2.6. Bad publicity and legal implications

Two other ships and a barge reported containers losses in the same severe storm. However, they may not have received the same attention as the m/v SCI accident. Probably these incidents went unnoticed and the public knew nothing about them. Because of the involvement of arsenic trioxide, the SCI accident remained at the centre of the media, congressional and legal debates for two months in the U.S. (McGowan, 1993). The shipowner's attitude and response to the accident seriously aggravated the situation. Initially, the shipowner neither took any action nor reported the situation to the responsible authorities. The analysis showed that the shipowner was well aware of the gravity of the situation.

The following are some of the facts mentioned earlier indicating the knowledge of the shipowner about the situation. In Port Baltimore, the cargo surveyor, who was hired by the shipowner, examined the condition of the cargo. He witnessed extensive cargo damage and spillages below the ship's decks. The surveyor produced a volume of photos, which clearly showed the spillage of magnesium phosphide and the "toxic" label on the damaged drums. Additional photos taken by the surveyor in other cargo holds showed the spillage of other dangerous substances. The shipowner as well as the master and chief mate have seen the photos. Initially, the shipowner was unwilling to step forward and call attention to the gravity of the situation. When interviewed, crewmembers denied knowledge of any spilled dangerous substance other then arsenic trioxide. Even a month after the incident, attorneys for the shipowner were unwilling to allow the Board of Inquiry to interview the surveyor. Since no report was filed of any additional spillage with the USCG or other authorities, the ship left Port Baltimore in extremely hazardous conditions, placing its crew, and Port Charleston and its citizens at risk.

Against the aforementioned background, the USCG's Board of Inquiry recommended criminal actions against the shipowner and the crew of the m/v SCI (McGowan, 1993). However, the U.S. Department of Justice declined criminal prosecution of the crew. Crewmembers were granted immunity to require them to testify in a civil action against the shipowner to recover the costs of the accident. The U.S. Department of Justice, on behalf of the USEPA, filed a lawsuit against the m/v SCI (i.e. the shipowner) for the loss of arsenic trioxide drums off the coast of Cape May, New Jersey, and Delaware Bay (USEPA, 1992). Under the rules of the "Superfund" law (U.S.), the shipowner and the ship operator involved in the release of a dangerous substance into the marine environment are liable for the costs of recovery actions and for any damage to natural resources (USEPA, 1992). The m/v SCI remained anchored in the harbour at Port Charleston (USEPA, 1992). The lawsuit prevented ship departure, thereby making it possible for the USEPA to recover the costs of search and recovery operations of the drums.

The search of 1992 records of the NRC database (2005) showed that the m/v SCI had changed her name to the m/v Santa Mercedes (see Table 2.2). Approximately 4 ½ months after this accident, the m/v SCI, under another name "Santa Mercedes", was involved in another incident in the same port - Port Baltimore (Maryland, U.S.).

Probably, after the accident, because of the bad publicity and legal implications, the shipowner changed the ship's name or sold her to another owner.

Summary

Initially, although well aware of the situation, the shipowner did not report the situation and was unwilling to take appropriate actions. This attitude of the shipowner further aggravated the situation in many respects. The Board of Inquiry recommended criminal actions against the shipowner and the crew for the loss of arsenic trioxide containers. In order to recover costs incurred during search and recovery operations, the U.S. Department of Justice filed a lawsuit against the shipowner. The costs of bad publicity and legal implications may be substantial, and may far exceed all other costs combined. Bad public and business image is very difficult, if not impossible, to repair.

4.2.7. Costs of the m/v SCI accident – economic consequences

Except for the expenses related to the search and recovery of arsenic trioxide drums, the case history does not indicate the extent of consequences and threats of arsenic trioxide and magnesium phosphide in terms of monetary values. Based on the inferences from the data available and other case histories and data, Table 4.24 explores the main categories of costs related to human, environment, and property consequences, threats and related implications due to inherent hazardous properties of dangerous goods.

Table 4.24: Costs related to dangerous goods hazards

Nr.	Main categories of costs	Description of costs occurrences
1	*Human*	• Human health problems or diseases: compensation payments resulting from chronic diseases, temporary or permanent disabilities • Medical treatments: hospital examinations and treatments, and future treatments
2	*Marine environment*	• Marine environment damage/ contamination: sediments and aquatic organisms • Losses and damage to the fishery industry and recreation
3	*Property*	• Ship and cargo contamination • Short lading • Discarded goods • Replacement of goods • Delays in delivery
4	*Activity disruption*	• Port operations • Ship activities: demurrage or detention • Maritime related activities: fishing banned • Loss of businesses • Lost incomes resulting from delays or interruptions

Nr.	Main categories of costs	Description of costs occurrences
5	*Search, recovery, cleanup and disposal operations*	• At sea: search, recovery, repacking, transport and disposal of arsenic trioxide drums ($ 2.2 million) • Aboard the m/v SCI: cleanup, repacking, transport and disposal of arsenic trioxide spilt aboard • Aboard the m/v SCI: cleanup, destruction, repacking, transport and disposal of magnesium phosphide • Ashore – Port Baltimore: cleanup, destruction, repacking, transport and disposal of magnesium phosphide • Discharging, transport and disposal of contaminated goods • According to the P&I Club (1998), costs related to the aforementioned operations account for up to 15% of the club's cargo losses claims
6	*Accident investigation and assessment*	• Management and clerical time and expenses to investigate the accident and process information • Sampling, analysis and assessment of the seawater, sediments and marine organisms
7	*Legal*	• Legal costs: legal procedures are complicated, time and labour intensive and very expensive • Third party liabilities: claims and compensations arising due to consequences and threats related to human, environment, property and activities • Possible fines or penalties • Legal implications: possible negligence or failure charges, which may even lead to imprisonments
8	*Other costs*	• Bad reputation/PR: poor service quality, unreliable, not environmentally friendly. Bad publicity can be more damaging than monetary sanctions. • Future employment implications • Increase in the insurance premium • Decrease in the value of the company's shares, if quoted on the stock market • Social costs: public concerns, protests, aversions • Other short and long term implications

The only reported costs were those ($ 2.2 million) incurred in search and recovery operations of arsenic trioxide containers/drums. The costs listed above may be viewed as direct and indirect costs. Direct costs are those that are more tangible and easily measured. These costs are explicitly attributable to the m/v SCI accident in terms of the impact on the parties concerned, such as compensations resulting from health effects, costs of cargo contamination, and costs related to search, recovery and cleanup operations. Indirect costs are less tangible and more difficult to measure, for example, impacts on public image, business losses and future implications. However, costs are interrelated and there is no clear cutoff among them. The m/v SCI accident case history showed that search and recovery operations of arsenic trioxide drums from the sea floor were labour intensive, complicated and expensive.

4.2.7.1. Costs of search and recovery of arsenic drums

The m/v SCI's arsenic trioxide drums search and recovery was a very large-scale operation. In response to the accident, the U.S. Environment Protection Agency (USEPA), Region III headquarters, was contacted and requested funding under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) for the search and recovery of arsenic trioxide drums. The initial expenditure-ceiling request was $ 250,000. The USEPA agreed and opened the so-called "Superfund." Given the extent of the expenditure for operations the ceiling was increased to $ 1 million. The actual expenditure exceeded the granted expenditure ceiling as the operations progressed.

The m/v SCI operations involved many different authorities, agencies, organisations and individuals across the U.S. The operations required many sophisticated tools. The diversity and the number of parties involved and equipment and devices deployed indicated the scale of operations.

Authorities, agencies and organisations involved

- U.S. Coast Guard
- U.S. Environment Protection Agency
- Multi-Agency Local Response Team (MALRT), a body of federal, state and local agencies
- District Industry Hygienist
- Federal Aviation Administration
- National Oceanographic Atmospheric Administration
- Navy's Helicopters Mine Countermeasure Squadron Fourteen
- Navy Supervisor of Salvage
- Marine Research Center
- National Marine Fisheries Service
- Port Administrations
- Port Committee Association
- Steamship Trade Association
- U.S. Maritime Administration (MARAD)
- MSO Baltimore
- Maritime Institute of Technology and Graduate Studies in Linthicum, Maryland
- International Longshoreman's Association
- Private Sector Port Committee
- Others

Equipment and devices deployed

- Helicopters fitted with equipment for locating waterborne mines
- Specialised vessels equipped with:
  - Side Scanning Sonar Systems (SSS)

  - Class I Remotely Operated Vehicles (ROV)
  - Remotely controlled mechanical arms
  - Global Positioning Navigation System (GPS)
- Numbers of searching platforms
- A specialized barge equipped with 4 mooring systems
- Others

The operations required detailed preparations, planning, reviews, meetings, and coordination of several different agencies and organisations and their resources. The On Scene Coordinator (OSC) coordinated operations by employing HAZMAT response strategy of Recognition, Evaluation and Control. The Atlantic Strike Team consisted of some 20 members representing different agencies involved in the operations.

The helicopter searches covered 305 nm of the ship's tracking line and 98.5 square miles of ocean search. Salvage crews spent almost two months scouring a huge stretch of ocean (60 x 1 km) before the debris was found. The team spent another month using another ROV to load the arsenic trioxide drums. *Poor weather conditions hampered the search and recovery operations*. The operations lasted for 5 months and 15 days.

The total federal costs of search and recovery operations amounted to $ 2.2 million. According to U.S. law, the USEPA had the right to file lawsuits and claim the costs incurred in search and recovery operations of the drums. Table 4.25 shows the costs per unit (drum/kg/ton) of arsenic trioxide lost at sea and recovered. These costs ($ 31,240/ton) far exceeded (many fold) the average claims per unit (approx. $ 1,900/ton or $ 3,000/ton, adjusted for the price inflation for 2001) of nine major world oil spills between 1967-1996, excluding the "Exxon Valdez" accident (Mullai and Paulsson, 2002).

Table 4.25: Costs of search and recovery operations per unit of arsenic trioxide involved

Nr.	**Arsenic lost and recovered from the sea**	**Drums/ amounts (kg) of arsenic**		**Costs per unit – expenses for search and recovery operations ($ 2.2 million)**		
		drums	kg	$/drum	$/ton	$/kg
1	Arsenic lost at sea	414	70 421	4 989	31 240	31.24
2	Arsenic recovered	320	54 432	6 875	40 420	40.42
3	Arsenic not recovered	94	15 989			

The search and recovery operations related to accidents involving PDG may be very expensive because they are generally specialised, labour and time intensive operations. Many countries may lack the required human and technical expertise and financial resources to deal with these types of accidents.

4.2.7.2. Estimated costs of human consequences

Human consequences can also be measured in monetary terms based on the economic value of a human life. In a wide range of sciences and disciplines including economics, health care, insurance, accident prevention and safety, environmental impact assessment, it has been necessary to put an economic value on a human life. “Costs per fatality” and “costs of averting a fatality” are interrelated concepts employed in risk management. These costs vary across countries and industries. For example, a Swedish study (Lund Institute of Technology) (Trawen et al., 2000) carried out in some developed countries showed that costs of a traffic fatality (for 1999) varied from less than $ 1 million in Austria to approximately $ 3.7 million in the U.S. Based on Persson and Cedervall (1991) and SIKA[25] (1999), Trawen et al. (2000) have estimated costs of a traffic fatality in Sweden for 1999 to be SEK 14.345 million[26], including medical costs, lost productivity capacity, human costs or value of a statistical life (VOSL = SEK 13 million[27]) and other costs.

In the shipping industry, the IMO (2004a) has proposed Costs of Averting a Fatality (CAF), which is the cost of reducing the average number of fatalities by one. The proposed value of GCAF (Gross Cost of Averting a Fatality) for injuries and ill health is $ 1.5 million (IMO, 2004a). Based on the IMO’s GCAF, the costs of human consequences scenarios of the m/v SCI accident are estimated. The GCAF ($ 1.5 million per injury) is applied for severe injuries (Table 4.26). Table 4.26 shows that the estimated costs of human consequences of the m/v SCI accident may range between $ 6-60 million, for the optimistic and worst-case scenarios respectively.

Table 4.26: Estimated costs of human consequences of the m/v SCI accident

Nr.	Scenarios of human effects	Equivalent severe injuries	Estimated costs of equivalent severe injuries ($ million)
1	40 minor injuries	4	6.0
2	30 minor/ 10 severe injuries	13	19.5
3	20 minor/ 20 severe injuries	22	33.0
4	10 minor/ 30 severe injuries	31	46.5
5	40 severe injuries	40	60.0

Summary

The exact costs of the accident were unknown, except for the expenses for search and recovery of arsenic trioxide drums ($ 2.2 million). These expenses may have been only a portion of the total costs incurred due to involvement and threats of dangerous goods. The costs of operations may be a small portion of potential consequences of arsenic to the marine environment and the local community. The costs of the

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[25] Statens Institut för Kommunikationsanalys (SIKA) – Swedish Institute for Transport and Communications Analysis

[26] SEK 14.345 millions = $ 1.849 million for October 2005 with an exchange rate 7.8 SEK/$

[27] SEK 13 million = $ 1.667 million for October 2005 with an exchange rate 7.8 SEK/$

optimistic scenario of human consequences are estimated at $ 6 million. Any cost-benefit assessment based solely on the reported cleanup and direct costs may be invalid and unreliable. Unreported hidden and indirect costs may constitute a large portion of the total costs of the accident. The costs of the m/v SCI accident far exceeded the costs (perhaps some $ 6,000) if the master had decided to wait in Port Elizabeth for one or two days until weather conditions improved or if he had avoided the storm by returning to Port of New York for shelter.

4.2.8. Damage to the environment and properties – statistical data

Incidents have caused damage or consequences[28] to different risk receptors, including the environment and properties belonging to individuals, organisations and communities. Damage is measured by different measurement units. One of the commonest measurement units is a monetary unit, for example, $. As mentioned earlier, environmental damage is measured by a wide range of different measurement units, including monetary units. Properties included means of transport, cargo/ packages, and business, private and local community properties. Damage to properties is usually measured in monetary units. The following presents and discusses some key results from the NRC and HMIS databases concerning damage associated with incidents.

NRC database (U.S. 1990-2004): Damage incidents are those incidents that have been reported associated with damage (in $) to the risk receptors. Many incidents have involved combinations of consequences. Table 4.27 and Figures 4.99~4.102 provide some key figures concerning damage due to the supply chain and vessel incidents reported to the NRC (U.S. 1990-2004). The number and extent of damage solely attributed to hazardous properties of hazmat are unclear. As mentioned earlier, the NRC database contains no variable for explicitly specifying the categories of damage and measuring their relationships. However, the review of many incident cases shows that damage mainly consists of damage to the environment and properties and costs related to responses to incidents. Other categories of damage and other related costs are not to be disregarded.

During the period 1990-2004, a total number of 3,069 damage incidents were reported in the U.S., amounting to approximately $ 649 million, of which 1.9% and 1.27% of damage incidents and amounts of damage respectively have been reported in the maritime transport system (Table 4.27). Compared to vessel incidents, as % of the supply chain incidents (12.6%) (Table 4.27), these figures are underrepresented.

Both the number and extent of damage is underreported and underestimated. The number of reported damage incidents (in $) is only a very small fraction (less than

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[28] The term “damage” is used in the NRC database, and it shares similar meaning with the terms “consequence” or “effect”.

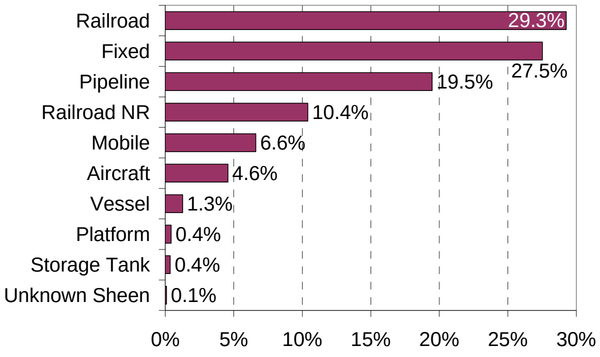
0.7%) of the total number of incidents reported to the NRC (Table 4.27). The costs of damage may be preliminarily estimated and reported. Except in certain cases such as near-miss incidents, incidents are largely associated with damage or other related costs or implications. The review of the NRC incident records shows that, in the case of the m/v SCI accident, no property and environmental damage (in $) have been reported.

Vessel damage incidents are ranked (in %) far down in the list of supply chain damage incidents as shown in Figure 4.99. However, accident case histories have shown that vessel or marine accidents can lead to excessive damage. For example, the costs of the Exxon Valdez accident alone (see Mullai and Paulsson, 2002) far exceed the costs of all supply chain incidents combined reported to the NRC database during the period 1990-2004.

Figures 4.100~4.102 show that the number and amounts per year of damage incidents in the U.S. supply chain and water transport have considerably fluctuated, in particular for the later. However, the general tendency shows an increase (Figures 4.101 and 4.102). Since 2000/ 2001, however, both the number and amounts per year of damage incidents have declined. The largest amount of damage ($ 147.3 million) was reported in 2001. In 2004, no damage incident was reported in the water transport system. Some explanations for the mentioned changes and differences may include specific properties of the constituent systems of the supply chain, types of hazmat handled or carried, distribution/transport hazards, the regulatory frameworks governing the systems, and incident reporting systems and procedures in the industries.

Table 4.27: Damage incidents reported in the supply chain and water transport

Category	**Damage incidents and amounts**		
	Supply Chain (SC)	Water transport (WT)	WT as % of SC
Total number of incidents (1990-2004)	453 129	57 274	12.6%
Number of incidents per year	30 209	3 818	
Total damage incidents (1990-2004)	3 069	58	1.89%
Number of damage incidents per year	205	4	
Damage incidents as % of all incidents	0.68	0.1	
Total amounts ($) of damage	649 070 241	8 260 481	1.27%
The largest amount ($) in a year	147 247 110	2 206 000	
The largest amount ($) in an single incident	100 000 000	1 000 000	
Amounts ($) per year	43 271 149	550 699	1.28%
Amounts ($) per damage incident	211 492	142 422	



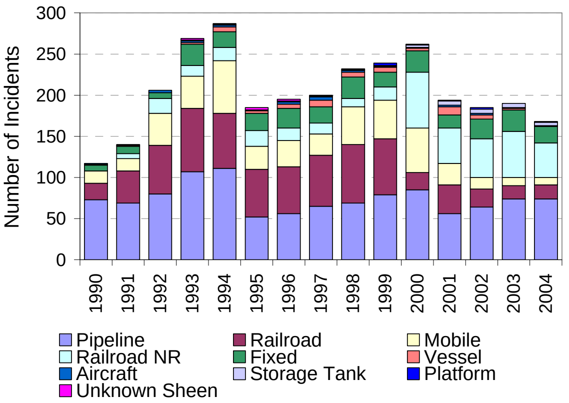
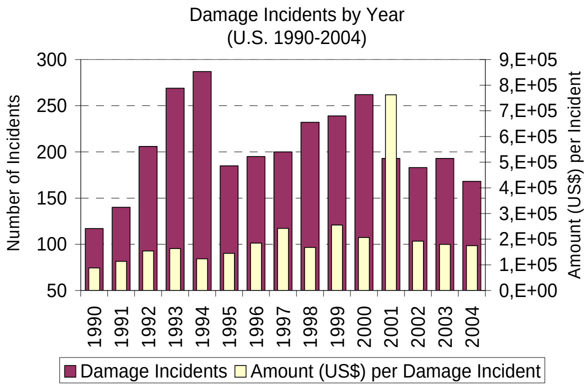


Figure 4.99: Ranking of supply chain damage incidents by system (U.S. 1990-2004)

Figure 4.100: Supply chain damage incidents by system and year (U.S. 1990-2004)



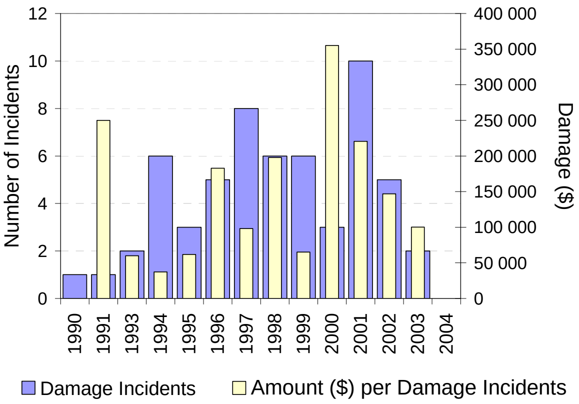


Figure 4.101: Supply chain damage incidents and amounts ($) per damage incident by year (U.S. 1990-2004)

Figure 4.102: Vessel damage incidents and amounts ($) per damage incident by year (U.S. 1990-2004)

Example: Extraction from the NRC database

Vessel Incident

- Description: Vessel “Pacific Pearl” collided with a jetty on entering Anaheim Bay.
- Incident type: Vessel
- Cause: Unknown
- Time: 2000-07-04 21:30, occurred
- Location: Anaheim Bay, naval weapons station
- City/State: Seal Beach, CA
- Fatality/Injury: One occupant of the vessel was injured
- Damage: $ 1 million
- Medium: Water, Pacific Ocean
- Response: Vessel has been salvaged. Three fuel tanks and one engine remained submerged on site. Plans for removal will occur on 06-JUL-00.
- Hazmat CHRIS Code: ODS
- Hazmat name: Diesel oil
- Amount: 20 gallons

HMIS database (U.S. 1993-2004): Figure 4.103 shows the shares (in %) of damage (in $) to the environment, carriers, public and private properties and others consequences associated with hazmat transport incidents. The costs of environmental damage, including cleanup, decontamination and other costs, accounted for more than a half (53.7% of the total amount $ 490 million) of the total costs due to transport incidents during the period 1993-2004, excluding human consequences such as fatalities, injuries, evacuations and hospitalizations. Environmental damages have become very expensive. The HMIS incidents records show that the highest reported costs of environmental damage in two cases reached $ 5 million and in eight cases $ 2 million. In the case of the m/v SCI accident, search and recovery operations only amounted to $ 2.2 million, which is similar to eight worst-cases reported to the HMIS database (U.S. 1993-2004).

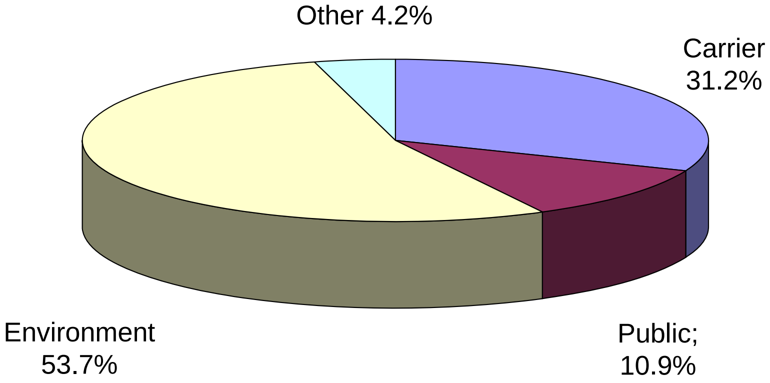


Figure 4.103: Economic consequences of transport incidents (U.S. 1993-2004)

4.2.8.1. Estimation of aggregated consequences

In certain conditions and for different purposes, incidents and their consequences, and consequently the risks, are related or aggregated[29] in connection to many different system and risk elements (Figure 4.104). The review of many incident databases shows that many databases are specifically designed for recording incidents occurring in a given system, activity, or industry (e.g. maritime transport and/or combinations of other modes) in a location, country/state, or region. For example, in order to measure the risks of the entire transport system, which are the aggregated risks of all modes of transport combined, the risks of individual modes are estimated and aggregated based on data from various databases. The estimation of aggregated risks is based on the estimation of aggregated consequences. In addition, even when the scope of a database encompasses the entire system, in order to measure the contributions and relations of individual constituent systems or elements the consequences can be related to many different elements (Figure 4.104).

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[29] Aggregate means: a) *adjective*: formed of separate units collected into a whole; collective; corporate; b) *noun*: a sum or assemblage of many separate units; sum total; c) *verb*: to combine or be combined into a body; to amount to (a number) (CED, 1992).

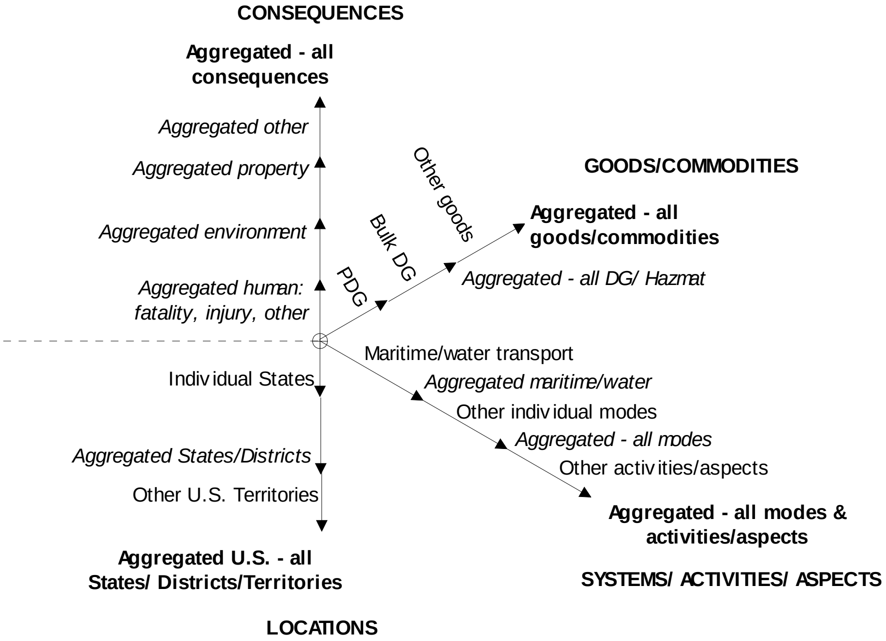
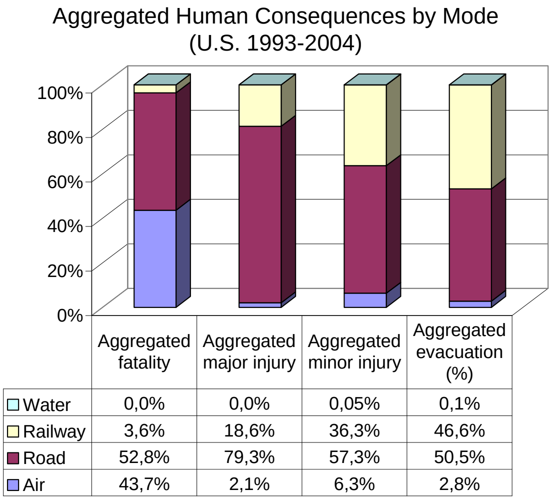


Figure 4.104: Examples of elements for aggregating and relating consequences

4.2.8.2. Aggregated human consequences by transport mode

The following example demonstrates estimation of aggregated human consequences by transport mode.

HMIS database (U.S. 1993-2004): The same types of consequences that are measured by the same measurement units can be readily aggregated. For example, individual human consequences, such as fatality, injury and evacuation, can be individually aggregated by mode of transport (Figure 4.105). The aggregation cannot be performed across various types of human consequences as they cannot be directly added together. Figure 4.105 shows human consequences attributed to hazmat transport incidents reported to the HMIS database (U.S. 1993-2004). Road transport is the largest contributor to all categories of human consequences of transport incidents, followed by rail transport, except the category of fatalities. In terms of the number of fatalities, air transport is the second largest contributor (43.7%). This figure is remarkably high compared to other categories of human consequences in air transport, rail transport fatalities and modal shares of hazmat shipment characteristics (ton and ton-miles). The large number of fatalities in air transport is attributed to a very few tragic accident cases, where large numbers of people have lost their lives in single incidents. Case histories have shown that, given the very specific properties of the system, in air transport an insignificant incident, which may be insignificant for other modes of transport, may turn into a catastrophic accident. As mentioned earlier, compared to other modes, the number of vessel incidents reported to the HMIS database is insignificant (0.1% of all transport incidents combined).



	Aggregated fatality	Aggregated major injury	Aggregated minor injury	Aggregated evacuation (%)
Water	0,0%	0,0%	0,05%	0,1%
Railway	3,6%	18,6%	36,3%	46,6%
Road	52,8%	79,3%	57,3%	50,5%
Air	43,7%	2,1%	6,3%	2,8%

Figure 4.105: Aggregated transport human consequences by mode (U.S. 1993-2004)

4.2.8.3. Aggregated human consequences and damage

The illustrative example presented below demonstrates the estimation of aggregated human consequences and damage.

NRC database (U.S. 1990-2004): Different individual consequences, as shown above, that are measured by different measurement units cannot be readily aggregated. Incidents have caused different types of consequences to different risk receptors that are measured by different measurement units. For example, fatalities cannot be directly aggregated with injuries and damage. In order to aggregate various types of consequences, they have to be converted into consequences that are measured by the same measurement unit. The illustrative examples (Figures 4.106 and 4.107) show the estimation of the aggregated consequences of incidents based on the IMO's conversion approach and CAF (Costs of Averting a Fatality). The IMO's conversion approach suggests equivalence ratios between fatalities, major injuries and minor injuries, namely a) one fatality equals 10 severe injuries, and b) one severe injury equals 10 minor injuries (IMO, 1997b; IMO, 2004a). For the purpose of demonstration, injuries reported to the NRC are assumed to be severe injuries (i.e. the worst-case scenario). The costs of human life in the U.S. are very high compared to many countries. However, for the purpose of demonstration, the proposed value of the IMO's CAF of $ 1.5 million per fatality, injury or ill health (IMO, 2004a) is taken into consideration. The costs of a traffic fatality in Sweden, which are estimated (1999) as approximately SEK 14.345 million[30], are largely consistent with the IMO's CAF. The review of many risk studies shows that, to a large extent, assessments and subsequently decision-making and measures for managing risks focus primarily on the estimation of the number of fatalities alone as the key indicator of risks. Figure 4.106 shows that the actual number of the aggregated fatalities of supply chain incidents in the U.S. (1990-2004), combining fatalities and equivalent fatalities of injuries[31] and reported damage

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[30] SEK 14.345 millions = $ 1.435 millions with an approximate exchange rate 10.0 SEK/$ (year 2000-2002)

[31] For the purpose of demonstration assuming serious injuries – worst-case scenarios

to properties and environment, are considerably higher (on average, as high as 28%) than the number of fatalities alone.

Fatality is a very useful, but not perfect, indicator for measuring the extent of risks. The human life is priceless and the dearest thing for individuals. However, the data show that, given the large number of injuries per year and the same value of CAF for both fatalities and injuries, the estimated injury costs of incidents to society may be higher than the fatality and damage combined (Figure 4.107). Injuries, in particular injuries due to dangerous goods hazards, may be very expensive. Sometimes a severe injury, for example a permanent and painful disability, may be worse than death for the injured individual him/herself and members of his/her family. The estimations show that the aggregated costs of supply chain incidents in the U.S. (1990-2004), which combine equivalent $ of fatalities and injuries and damage ($), here not including a wide range of other and unreported costs, have amounted to approximately $ 4.87 billion per year (Figure 4.107) or, on average, $ 10,744 per incident. Compared to costs of human consequences (fatalities and injuries), damage (in $) reported to the NRC are insignificant (Figure 4.107). The other category of costs includes those costs incurred by evacuations, disruptions or suspensions of activities or systems, losses to business, fines and legal implications and other costs due to short and long term and hidden implications to the risk receptors. As mentioned earlier, the review of the NRC incident records (1990-2004) shows that the number and the extent of damage incidents are underreported and underestimated.

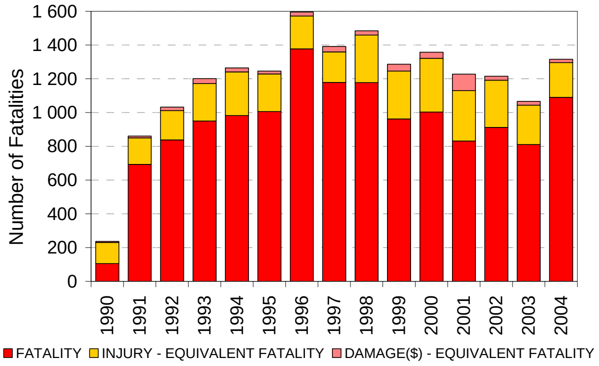

Figure 4.106: Aggregated consequences (fatalities and equivalent fatalities of injuries and damage) of supply chain incidents (U.S. 1990-2004)

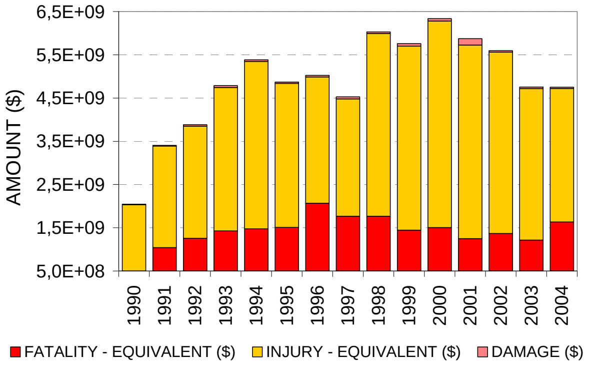

Figure 4.107: Aggregated consequences (damage and equivalent ($) of fatalities and injuries) of supply chain incidents (U.S. 1990-2004)

Depending on the system of the country and the industry, the costs of incidents are born by individuals, groups, organisations and the entire society or combinations thereof. The costs of the hidden, unknown and long-term effects of the wide range of chemicals, in particular those related to the ecosystem and humans could be very high. They will be borne by the future generations, and by services and industries directly related to health care systems and the ecosystem.

5. Step 4 – Likelihood/Frequency Estimation, Evaluation and Quantification

Questions: How often, many/much? How likely is it?

Tasks: Estimate the likelihood – quantify risk and system elements. In absence of quantitative data, evaluate the severity and frequency of consequences against relevant risk criteria available (see the **highlighted areas** in Figure 5.1).

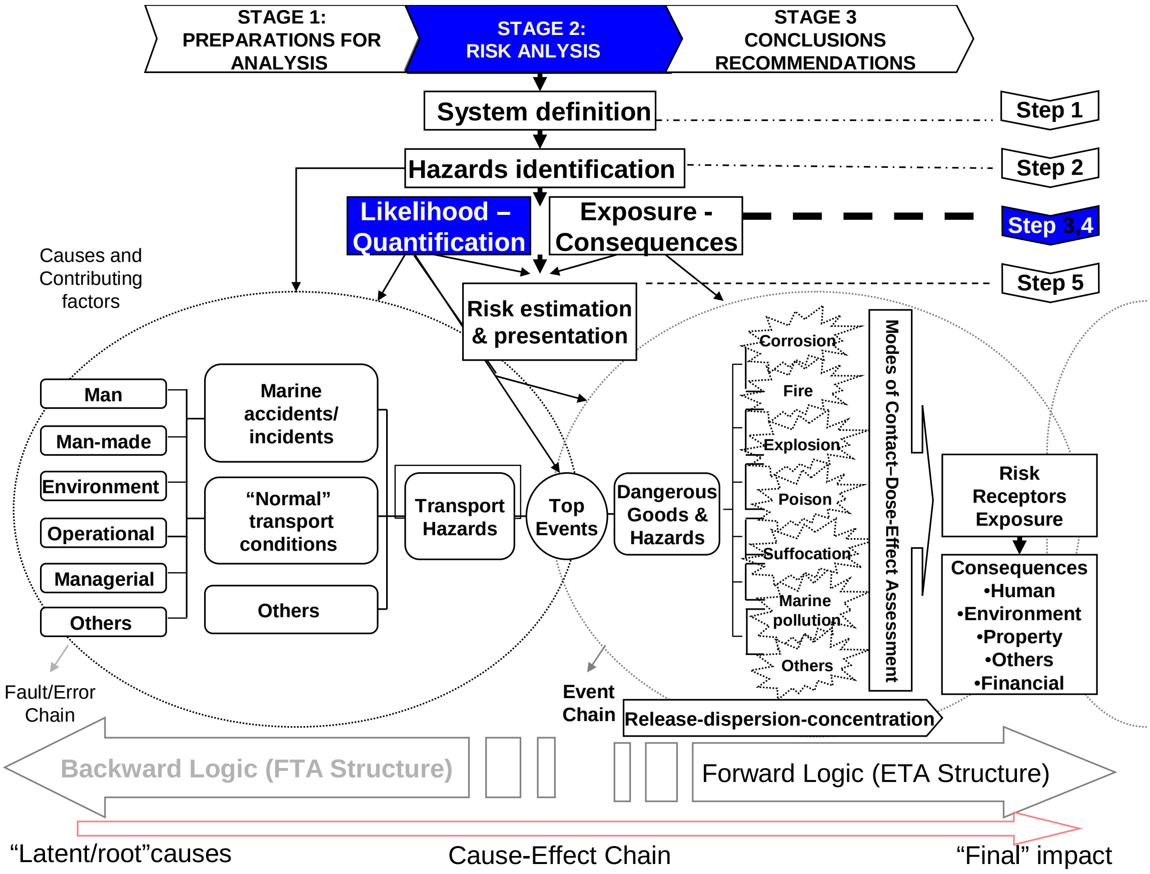

Figure 5.1: Stage 2 – Risk Analysis; Step 4 – Likelihood/frequency estimation, evaluation, quantification (continued from Figure 1.2)

The purpose in this step is to quantify and/or evaluate risk and system elements. As the risk analysis of the m/v SCI accident case has demonstrated so far, exploration and quantification are inseparable procedures. For more information about evaluation, estimation or quantification of the risk and system elements, see Chapter 5, Vol. I.

Based on the data available in the m/v SCI case history, in the course of the risk analysis of the m/v SCI accident case, numbers of the risk and system elements are quantified, including:

- *Causes and contributing factors*: the incidences of causes and contributing factors (see Table 4.6).

- *Dangerous goods*: the number of packages (drums, pallets, containers) and quantities of dangerous goods carried aboard the m/v SCI (see Table 4.1).
- *Human exposure*: the number of crew likely exposed to dangerous goods (see Table 4.4).
- *Human consequences*: the number of people (the crew and stevedores) whose health was affected by respective dangerous goods (see Table 4.16)
- *Marine environment consequences*: the amounts of arsenic trioxide lost overboard, spilt on deck, recovered and unrecovered from the sea floor (Table 4.22).
- *Threats of unrecovered arsenic trioxide drums*: estimations of the amount of seawater and sediments areas that may be potentially contaminated by arsenic released from un-recovered drums (see Figures 4.91~4.96).
- *The costs of the m/v SCI accident – economic consequences*: costs of search and recovery operations per unit of arsenic trioxide involved (see Table 4.25) and estimated costs of human consequences (see Table 4.26).

Quantification encompasses a wide range of quantitative or statistical data analysis procedures. In the risk analysis based on a single or a few case histories, quantification is very limited, if not impossible, for many system and risk elements. In qualitative risk analysis, risk elements are evaluated or benchmarked against relevant risk criteria available. However, the support of quantitative data and experts' judgments are still required to facilitate sound and reliable evaluations. Without this support, the analysis may be incomplete and end there.

In the case of the risk analysis of the m/v SCI accident, the aforementioned quantifications were very limited. The data available in the case history did not allow any bivariate or multivariate statistical analysis of the system and risk elements. The relationships among elements cannot be statistically analysed.

In addition, by definition, risk is a function of frequency or exposure and consequences. The risk estimation may combine a) the likelihood (frequency/ probability) (F) and consequences (C); or b) consequences (C) averaged over or divided by exposed populations (E), that is estimated for one year. Quantification of the risk and system elements cannot be performed with a single or a few case histories.

As mentioned in Chapter 2, Vol. I, maritime risk studies are largely based on the case history methodology that makes use of large amounts (as many as thousands) of case histories (DNV, 1995; Carol et al., 2001). The case history methodology has become one of the prevailing forms for acquiring and representing accident knowledge (Brigitte and Carsten, 1997). In order for a quantitative analysis to make sense, a certain minimum number of cases is required. A general rule in statistical analysis is that the ratio of cases (i.e. marine accident case histories) or observations to independent variables should never fall below 5 to 1 (Hair et al., 1998). This means that in a multivariate analysis there should be at least five cases or observations for each independent variable. However, the desired level of this ratio is 15-20 to 1 (Hair et al., 1998). This ratio may be even higher for univariate and bivariate analysis. A single or even a few case histories do not satisfy the mentioned condition. For more information about quantitative analysis, including exposure, consequence and likelihood estimation see Chapter 5, Vol. I.

However, in a qualitative risk analysis, risk elements can be qualitatively evaluated. In the context of the m/v SCI accident case history, every reasonable effort has been made to demonstrate the evaluation of consequences and frequency. The review of many risk criteria available shows that criteria are not very comprehensive and specific for the evaluation of the risks involving maritime transport of dangerous goods. A single criterion alone has no capacity to facilitate the evaluation of the wide range of dangerous goods consequences and threats and the frequency. Therefore, the severity of consequences and frequency[32] of the m/v SCI accident category are evaluated or benchmarked against a set of risk criteria available, namely: a) IMO Risk Matrix; b) IMO, LMIS and U.S. DOT criteria; c) Wright and other environmental criteria; and d) ISO Risk Matrix.

Due to limitations of the criteria and incompatibilities between scenarios anticipated in the criteria and the m/v SCI accident case history, rankings of the severity of consequences and threats and the frequency of the m/v SCI accident may not necessarily match descriptions of indexes contained in respective criteria.

5.1. Consequence evaluation

The involvement of dangerous goods in the m/v SCI accident case led to a wide range of consequences and posed threats to the risk receptors. The severity of consequences of the m/v SCI accident is benchmarked against the criteria available shown above. No criterion has been found for threats of dangerous goods to the human being, the marine environment or property.

5.1.1. Severity Index (SI) – IMO Risk Matrix

In recent years, the IMO Risk Matrix has been employed in numerous maritime risk studies. The IMO Guidelines on Formal Safety Assessment (FSA) (IMO, 2002) provides a risk matrix for ranking of risks and hazards. The risk matrix, which is a 4x4 scale matrix for frequencies and effects or consequences[33] respectively, is used only for ranking *combined human and property* (i.e. the ship) risks related to ship operations. Table 5.1 shows the Severity Index (SI) (4 scales) for human (fatality and injury) risks and effects on the ship. The Frequency Index (FI) (Table 5.5) and the Risk Index (RI) (Figure 6.3), which combines both SI and FI, are respectively provided in the frequency and the risk evaluation.

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[32] The frequency is evaluated based on *a*, *c* and *d* criteria, as *b* criteria contain no Frequency Index (FI).

[33] The terms “effect” and “consequence” share similar meanings.

Table 5.1: Severity evaluation of the aggregated (human and ship) consequences of the m/v SCI accident based on the Severity Index (SI) of the IMO Risk Matrix (IMO, 2002)

Severity Index				
SI	**Severity**	**Effects on human safety**	**Effects on ships**	**S (Equivalent fatalities)**
1	Minor	Single or minor injuries	Local equipment	0.01
2	Significant	Multiple or severe injuries	Non-severe ship damage	0.1
3	**Severe**	Single fatality or multiple severe injuries	Severe casualty	1
4	Catastrophic	Multiple fatalities	Total loss	10

Based on the Severity Index of the IMO Risk Matrix, given the following facts (see also Table 5.4), the severity of the human and property consequences of the m/v SCI accident is ranked *SI3 "Severe"* (see the marked area in Table 5.1). The following are some of the facts:

- *Effects on human safety – SI3"Severe"*: The m/v SCI accident did not involve any fatality, but the health of some 40 people was reportedly affected by dangerous goods. Of these, 37 stevedores were sent to hospital after exposure to very high doses of phosphine gas, which was twice the level of "immediately dangerous to life and health." With reference to injury-fatality equivalence (see Table 4.17), 40 minor injuries (health effects), which is the optimistic scenario, are equivalent to 4 severe injuries or 0.4 fatalities. The fatality figure exceeds SI2 (significant).
- *Effects on ships – SI3"Severe"*: The m/v SCI and her cargo were so severely contaminated ("damaged") that it took more than one month to clean up and decontaminate ("fix damage") the ship.
- Taking into consideration the severity of other human and property consequences and threats described in Table 5.4.

Limitations of the IMO Risk Matrix

The Severity Index (SI) of the IMO Risk Matrix is incomplete and vague:

- Criteria are designed for the consequences of marine accidents in general. The matrix provides no specific criteria for the consequences of marine accidents involving dangerous goods.
- Criteria are designed for fatality and injury only; types of injuries are not specified; other effects on humans are not included.
- Combinations of effects on humans and ships are very limited; criteria lack cross-combinations and weighting factors of all elements in combination. For example, the following question may arise: What is the aggregated SI of an accident that has involved a total loss of the ship (SI4 - catastrophic), but no fatality or injury?
- Criteria are designed for ship damage only – types of damage are not specified.
- The matrix provides no criteria for the following consequences:
  - Marine environmental damage or consequences
  - Properties: contaminations and damage, including:

    - Contamination of the ship/cargo, and contaminations and damage to other ships/cargoes and properties ashore
  - Activity disruptions
  - Others: publicity and legal implications
  - Economic consequences
  - Aggregated consequences
- There are no criteria for threats
- There are no criteria for aggregated consequences and threats.

Given the limitations of the Severity Index (SI), in order to facilitate the evaluation of the severity of consequences and threats of the m/v SCI accident, some other available criteria have been employed.

Severity of accidents – IMO, LMIS and U.S. DOT criteria

With respect to the severity of marine accidents, the IMO, Lloyd's Maritime Information Services (LMIS) and U.S. Department of Transportation (U.S. DOT) employ the following criteria.

The IMO's Code of Investigation of Marine Casualties and Incidents defines (IMO, 1996a) *marine accident (casualty)* as an event that has resulted in:

- The death of, or *serious injury* to, a person that is caused by, or in connection with, the operation of a ship
- The loss of a person from a ship, that is caused by, or in connection with, the operation of a ship; or
- The loss, presumed loss or abandonment of a ship; or
- Serious material damage to a ship; or
- The stranding or disabling of a ship, or the involvement of a ship in a collision; or
- *Serious damage to environment* caused by, or in connection with, the operations of a ship.

Given the severity of the consequences and threats, the m/v SCI accident category can be classified as "*marine accident or casualty*."

For the purpose of marine accident reporting, the IMO (1996b) defines:

1. "*Serious*" casualties as casualties to ships that do not qualify as "very serious casualties" and that involve fire, explosion, collision, grounding, contact, heavy weather damage, ice damage, hull cracking, or suspected hull defect resulting in:
   a. Structure damage rendering ship unseaworthy;
   b. *Pollution, regardless of the quantity*; and/or
   c. A breakdown necessitating towage or shore assistance.
2. "*Very serious*" casualties as casualties to ships that involve total loss of ship, loss of life, or *severe pollution*.

Lloyd's Maritime Information Services (LMIS) defines (LMIS, 1995):

1. *Serious casualty*: Accident resulting in at least one of the following consequences:
   a. Total loss;
   b. Breakdown resulting in the ship being towed or requiring assistance from ashore;

    c. Flooding of any compartment; and
    d. Structural, mechanical or electrical damage requiring repairs before the ship can continue trading.
2. *Total loss*: Ship having ceased to exist after a casualty, either due to being irrecoverable (actual total loss) or due to being subsequently broken up (constructive total loss) (LMIS, 1995).
3. *Constructive total loss* occurs when the cost of repair exceeds the insured value of the ship.

A generic "*serious casualty*" for bulk carriers is estimated to cost *$ 5.61 million* and a total loss $ 24.81 million, including cost elements such as cargo and environmental damage (IACS, 2001).

The U.S. Department of Transportation's (U.S. DOT) Office of Hazardous Materials Safety (OHMS), within the Pipeline and Hazardous Materials Safety Administration (PHMSA), has developed a new definition of a hazardous materials "serious incident." Starting with reporting on 2002 incidents, PHMSA (2002) defines "serious incidents" as incidents that involve:

- a *fatality* or *major injury* caused by the release of a hazardous material,
- the *evacuation of 25 or more persons* as a result of release of a hazardous material or exposure to fire, a release or exposure to *fire* which results in the *closure of a major transportation artery*,
- the alteration of an aircraft flight plan or operation,
- the release of radioactive materials from Type B packaging,
- the *release* of over 11.9 gallons (or 45.06 litres) or 88.2 pounds (or 40.01 kilograms) of a severe marine pollutant, or
- the *release* of a bulk quantity (over 119 gallons or 882 pounds) (or over 450.56 litres or 400.07 kg) of a hazardous material.

Summary

Based on the IMO, LMIS and U.S. DOT criteria for the severity of accidents, given the following facts (see also Table 5.4), the m/v SCI accident can be classified as a *serious marine accident or casualty*. The following is a summary of the facts:

- The m/v SCI accident did not involve the ship's total loss or construction loss, but the ship and her cargo were *very seriously* or *severely contaminated* by dangerous goods.
- The m/v SCI accident did not involve any loss of life, but many people (some *40 crewmembers and stevedores*) were reportedly health affected by dangerous goods.
- Due to contamination and fire/explosion threats, the USCG in Port Charleston ordered evacuation of the ship including *20 crewmembers and many stevedores*. The m/v SCI was taken out of the berth and sent to a more isolated area in the anchorage.
- Given the massive body of surrounding water and limited quantity of arsenic trioxide (200 kg+) released from damaged drums recovered from the sea floor (320 drums), there were *no or insignificant contaminations or effects* to the marine environment. However, the large amount of unrecovered arsenic trioxide (94 drums

or *16 tons*) may pose *real serious threats* to the marine environment and the local community.

- The total costs of the m/v SCI accident considerably exceeded the costs of search and recovery operations ("costs of environmental damage") ($ 2.2 million). Based on the IMO (2004a)'s proposed values of Costs of Averting a Fatality (CAF) ($ 1.5million), the amount of $ 2.2 million is equivalent to more than *one fatality*.
- Due to threats of dangerous goods involved in the m/v SCI accident, many activities were disrupted. *The fishing ban stayed in effect for approximately four months* (January-April, 1992).

5.1.2. Severity Index (SI) – Wright and other criteria

Environmental consequences or damage[34] are evaluated on the basis of one or combinations of various parameters, including: a) the area affected; b) the likely duration and irreversibility of damage; c) bioaccumulation and persistency of the substance involved; d) resources affected; e) deviation levels of contamination; f) the value of the site; and cleanup costs. The severity of the environmental consequences and threats of the m/v SCI accident is evaluated against the Wright and other environmental criteria.

Wright criteria

Wright (1993) has suggested criteria for the evaluation of environmental risks of accidental releases. With some adjustments, Table 5.2 presents the Severity Index (types) of environmental consequences contained in the Wright criteria (Wright, 1993). The m/v SCI accident case history does not contain precise data as required in the Wright criteria (e.g. years of recovery). Furthermore, the data available are largely incompatible with possible scenarios described in the criteria. However, attempts have been made to provide a qualitative evaluation. Based on the SI of the Wright criteria, given the following and other aforementioned facts and estimations (see also Table 5.4), the severity of the environmental consequences and threats of the m/v SCI accident is ranked *SI3 ("Serious")* – see the marked area in Table 5.2.

According to the environmental assessment carried out by U.S. authorities after the accident, the marine environment was not affected by arsenic. The seawater column, sediments and shellfish (clams) samples on the accident site showed only background levels of arsenic (U.S. DOT, 1992; NOAA, 1992a). According to the Wright criteria, the Severity Index (SI) of the environmental consequences of the m/v SCI accident matches SI1 ("Not detectable"). However, given the real threats of unrecovered arsenic drums and other mentioned facts and estimations, the SI of the aggregated environmental consequences and threats can be raised to level *SI3 ("Serious").* The following is a summary of facts and estimations:

- *Alteration*: According to numerous sources, arsenic is bioaccumulative.
- *Effects*: Arsenic can persist in the marine environment; due to its properties, arsenic can be transmitted to the food chain and human beings.

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[34] Alternative terms for "consequences" are "effects" and "damage".

- *Sustainability*: There may be losses of the marine biota (resources) within or in the vicinity of the area where drums have landed. However, the overall sustainability of the area may be insignificantly affected.
- *Recovery*: Recovery of the marine biota in heavily arsenic-contaminated sediment areas takes considerable time.
- *Area affected*: The large amount of unrecovered arsenic may contaminate the sediments in the range between the estimated sediment area slightly (830 km^2) and heavily (8 ha) contaminated.

Table 5.2: Severity evaluation of the aggregated environmental consequences and threats of the m/v SCI accident based on the Severity Index (SI) of the Wright criteria (Wright, 1993)

SI	Severity of consequence	Description
1	Not detectable	Alteration or disturbance within natural viability. Effects not transmitted, not accumulating. Resources not impaired.
2	Moderate	Temporary alteration or disturbance beyond natural viability. Effects confined < 5000 m^2, not accumulating. Resources temporarily affected. Recovery < 5 years.
3	**Serious**	Alternation/disturbance of a component of an eco-system. Effects not transmitted, not accumulating or impairment. Loss of resources but sustainability unaffected. Recovery in 10 years.
4	Very Serious	Alteration to one or more eco-systems or component levels, but not irreversible. Effects can be transmitted, and can accumulate. Loss of sustainability of selected resources. Recovery in 50 years. Area affected 50 km^2.
5	Catastrophic	Irreversible alteration to one or more eco-systems or several component levels. Effects can be transmitted, and can accumulate. Loss of sustainability of most resources. Life cycle of species impaired. No recovery. Area affected 100 km^2.

Environmental consequences evaluation based on other criteria

The severity of the environmental consequences and threats of the m/v SCI accident is also evaluated against the following environmental criteria. For more details see Table 5.4. The criteria contain neither the Severity Index (SI), except the Swedish EPA criteria, nor the Frequency Index (FI).

- The perceived "value" and "vulnerability" of the ecosystem are suggested as criteria to assess the significance of damage to the environment (Weigkricht and Fedra, 1993). The m/v SCI accident site is a *sensitive* and *important* ecological, commercial and recreational zone for the local community.
- An accident that results in contamination of 10 km of river or 2 hectares of estuary is considered “a major accident to the environment” (Monnier and Gheorghe, 1996).

The m/v SCI accident occurred some 30 miles off the coast of Cape May, New Jersey (U.S.). However, in the worst-case scenario, the release of the large amount of unrecovered arsenic could *seriously* contaminate a sediment area of approx. 8 hectares.

- The UK Department of Environment (DE) uses the *costs of cleanup and "repair"*, which is an established concept in environmental economics, as criteria for evaluation of environmental damage (UK DE, 1991). No established criteria have been found for environmental damage caused by dangerous goods carried by sea. The m/v SCI accident involved *major costly* search and recovery operations ($ 2.2 million). In terms of costs per unit (drum/kg/ton) of dangerous substances “cleanup”, the costs of the m/v SCI accident (31,240 $/ton) far exceeded (many fold) some of the world’s major oil spills.
- *Irreversibility* is an important parameter for evaluation of environmental damage (Weigkricht and Fedra, 1993). According to numerous sources, arsenic is bioaccumulative; it can persist in the marine environment.
- The Swedish EPA classifies the *deviation levels* of the marine environment contamination into: class 1 (null), class 2 (low level), class 3 (moderate level), class 4 (high level) and class 5 (very high level) (SEPA, 1998). This classification (index) has been applied for pollutants other than arsenic. According to the environmental assessment carried out after the accident, the marine environment was not affected by arsenic (i.e. *class 1 – null*). However, the release of the large amount of unrecovered arsenic may contaminate the seawater, sediments and the marine biota at very high levels of concentration (i.e. *class 5 – very high level*).

5.1.3. Severity Index (SI) – ISO Risk Matrix

The ISO 17776 Risk Matrix (ISO, 1999) is more detailed and comprehensive than the IMO Risk Matrix and other aforementioned criteria. It consists of a 5x5 matrix with consequence and likelihood categories (see Figure 6.5). Table 5.3 shows the SI of the consequences. Unlike the IMO Risk Matrix and other criteria, the ISO Risk Matrix combines different types of consequences that are divided into four main categories: *people, asset, environment and reputation*. The matrix reflects practices in industries in integrating the safety and environmental risks in the total risk decision-making process. However, the matrix is designed for ranking and evaluation of the aggregated risks in petroleum and natural gas industries, including offshore production installations. These industries/ installations and risks associated with them differ, in many respects, from the shipping industry and its risks, in particular maritime transport of dangerous goods. Like the IMO Risk Matrix and other criteria, the ISO Risk Matrix has limitations. Both SI and FI are highly qualitative and combinations are very limited. The ISO Risk Matrix is largely incompatible with other criteria.

Based on the SI of the ISO Risk Matrix, given the mentioned facts and estimations (see also Table 5.4), the severity of the aggregated (human, property, environment and reputation) consequences and threats posed by the m/v SCI accident are ranked *SI4 to slightly higher* (see the marked area in Table 5.3).

- *People - single fatality (SI4)*: The m/v SCI accident did not involve any fatality. However some 40 people were health affected by chemicals. Of these, 37 stevedores were sent to hospital after exposure to very high doses of phosphine gas, which were twice the level of "immediately dangerous to life and health." With reference to injury-fatality equivalence (Table 4.17), 40 minor injuries, which is the optimistic-case scenario, are equivalent to 4 severe injuries or 0.4 fatalities.

- *Assets*: The m/v SCI was so severely contaminated that it took more than one month to clean up and decontaminate the ship. A large part of her cargo was also contaminated. In the no.1 hold, magnesium phosphide was mixed with other cargoes, including loose lumber and broken cartons of wine. Cargo in other holds was also contaminated by other dangerous goods. Cargo, in particular foodstuffs, contaminated with chemicals is discarded.
- *Environment*: Incidents database records show that the amount of arsenic involved in the m/v SCI accident case was among the top largest amounts involved in the U.S. during the period 1990-2004. Approximately, an amount of 70 tons of arsenic was lost at sea in a sensitive and important ecological, commercial and recreational zone for the local community. Approximately, an amount of 16 tons of arsenic was never found and remained unrecovered, posing serious threats to the marine environment and local community. The m/v SCI search and recovery operation was one of the largest operations in U.S. history that amounted to $ 2.2 million. Costs per unit of arsenic lost or recovered far exceeded many major oil spills.
- *Reputation*: The m/v SCI accident remained for two months at the centre of U.S. public, legal, media and congressional debates. The case is also well known in the world's maritime community. The case may have been referred to the IMO by the U.S. representatives. Some of the sources of the m/v SCI accident case history are conference papers.

Table 5.3: Severity evaluation of the aggregated consequences and threats of the m/v SCI accident based on the Severity Index (SI) of the ISO Risk Matrix (ISO, 1999)

Severity Rating/ Index	Consequences			
	People	**Assets**	**Environment**	**Reputation**
0	Zero injury	Zero damage	Zero effect	Zero impact
1	Slight injury	Slight damage	Slight effect	Slight impact
2	Minor injury	Minor damage	Minor effect	Limited impact
3	Major injury	Local damage	Local effect	Considerable impact
4	Single fatality	Major damage	Major effect	Major national impact
5	Multiple fatalities	Extensive damage	Massive effect	Major international impact

Summary

Based on the criteria and data available and judgements, the severity of individual and aggregated consequences and threats of the m/v SCI accident has been qualitatively evaluated and ranked. Table 5.4 provides a summary evaluation. On the scale from zero (SI0) to catastrophic (SI5), the severity of the aggregated consequences and threats posed by the m/v SCI accident is ranked "*Serious*".

Table 5.4: Consequences and threats of the m/v SCI accident

Consequences and threats by the risk receptor		Description of the severity of consequences and threats	Evaluation

Human	Consequences	- *Health effects or injuries*: 40 people (crew and stevedores) reportedly health affected:
		  - Other people may also have been exposed and health affected by dangerous goods.
		  - 37 stevedores (37 of 40) exposed to very high doses of phosphine gas, which was twice the level of "immediately dangerous to life and health."
		1. *Fatality*: no acute fatality was reported, but the people who were exposed to high doses may suffer from chronic health problems in the future or may even die.
			- *Health effects or injuries*: multiple health effects, optimistically equivalent to *4 serious injuries or 0,4 fatalities*
			- *Fatality*: no acute fatality.

	Threats	- Unrecovered arsenic drums may be washed ashore or become snagged in nets, particularly in bottom-fishing gear, exposing fishermen and other people. - People may consume fish and shellfish contaminated at high levels of arsenic trioxide that may be harmful to humans.	- Unrecovered arsenic trioxide drums may pose *real serious threats* to the local community.
Aggregated human consequences and threats		- The involvement of dangerous goods in the m/v SCI accident caused *serious human consequences* and poses *real serious threats*. Therefore, the severity of the aggregated human consequences/threats is ranked *serious*.	- *Serious*

Marine environment	Consequences	- *Amount*: a total amount of approx. 70 tons arsenic was lost at sea; an amount of approx. 200 kg arsenic was released from 320 breached drums recovered, including some arsenic spilt on deck
		- *Marine pollutant*: arsenic is bioaccumulative; it can persist into the marine environment
		- *Contamination/effects*: the samples taken on the accident site showed that the seawater column, sediments and shellfish (clams) contained only background levels of arsenic
		- *Value and sensitivity of the site*: the accident occurred in a sensitive and important ecological, commercial and recreational zone for the local community.
		- *Cleanup and "repair" costs*:
		  - Costs of search and recovery operations of arsenic trioxide drums amounted to $ 2.2 million.
		  - It was one of the largest operations in U.S. history.
		  - Costs per unit (drum/kg/ton) of arsenic trioxide lost at sea and recovered (31240 $/ton) far exceeded (many fold) the average claims per unit of some
			- *Amount*: A considerable amount of arsenic released, but *not very significant* compared to the body of the Atlantic Ocean water.
			- *Marine pollutant*: arsenic can cause *very serious or permanent environmental damage*.
			- *Contamination/effects*: *no or insignificant actual contaminations or effects* to the marine environment
			- *The value and sensitivity of the site*: the site is *valuable and sensitive* for the local community.
			- *Cleanup costs*: *major costly* search and recovery operations ($ 2.2 million).

		major world oil spills. - Search and recovery operations costs were only a portion of the total costs of the accident.	

	Threats	- *Amount:* 94 drums containing approx. 16 tonnes (1.60E+10 mg or 16E+12 µg) arsenic trioxide were never found and recovered.
		- *Marine pollutant:* see above.
		- *Value and sensitivity of the site:* see above
		- *Potential contamination/effects:* the amount of unrecovered arsenic trioxide spilt into the sea has the capacity to contaminate or affect:
		  - *Seawater*: 5.3E+09 m^3 (or 5.3 km^3 = 132.5 km^2 x 40m; or 265 km^2 x 20m depth) seawater at an arsenic concentration level exceeding 3µg/l seawater background concentration (*1–2 µg/l*).
		  - *Sediment slightly contaminated*: An area of 830 km^2 of sandy sediment contaminated at concentration level exceeding 1 mg/kg the lowest limit (*<1 mg/kg*) of the background concentration (for arsenic penetration at a depth 1 cm).
		  - *Sediment heavily contaminated*: An area of 0.0809 km^2 or 8.09 ha of sandy sediment contaminated at a concentration level exceeding existing concentrations by *515 mg/kg*, in which arsenic seeps into the sediments to a depth of 20 cm. This may be one of the worst-case scenarios.
		  - *Marine biota*: acute and chronic effects in marine habitats including shellfish/clams are observed at low concentrations ranging from a *few micrograms* to *milligrams* of arsenic that can be absorbed from the contaminated seawater and sediments. This level of concentration can easily be reached within and in the vicinity of the area of unrecovered drums.
			- *Amount:* given its chemical properties, 16 tons of arsenic is *a very large amount* that can cause *serious environmental damage*.
			- *Marine pollutant:* see above.
			- *Value and sensitivity of the site:* see above.
			- *Potential contamination/ effects:* un-recovered arsenic may pose *real serious threats* to the marine environment (a very high level of contamination).

Aggregated environmental consequences and threats		- Arsenic trioxide caused no or insignificant actual environmental consequences. However, given the aforementioned facts, estimations and the real serious threats posed by unrecovered drums, the severity of the aggregated environmental consequences/threats is ranked *serious.*	- *Serious*

Properties	Consequences	- *M/v SCI contamination*:
		  - The main deck and several hatches were literally awash with arsenic trioxide.
		  - Upper tweendeck of the no.1 hold was contaminated by magnesium phosphide.
		  - Other holds were contaminated by other dangerous goods.
		- *M/v SCI's cargo contamination*:
		  - Magnesium phosphide was mixed with other cargoes, including loose lumber and broken cartons of wine.
		  - Cargo in other holds was contaminated by other dangerous goods.
			- *Ship/cargo*: the m/v SCI and her cargo were *seriously* or *severely contaminated*.

	Threats	- *M/v SCI/cargo:*
		  - The entire ship and her cargo were seriously threatened by fire/explosion.
		- *Other ships/cargo:*
		  - Other ships in the vicinity and their cargoes were seriously threatened by contamination and fire/explosion.
		- *Properties ashore:*
		  - In both ports, the properties in the port territory and in the vicinity were seriously threatened by contamination and fire/ explosion.
			- The m/v SCI and her cargo, other ships/cargoes in the vicinity, and properties ashore were *seriously threatened* by contamination and/or fire/explosion.

Aggregated property consequences and threats		- The m/v SCI and her cargo were *seriously or severely* contaminated (damaged) by dangerous goods. The m/v SCI and her cargo and other properties were also *seriously* threatened by contamination and/or explosion. Therefore, the severity of the aggregated property consequences/threats is ranked *serious*.	- *Serious*
Others			

Activities	Consequences	- *M/v SCI*: the ship lost at least 30 days of service.
		- *In Port Charleston*
		  - Stevedores suspended cargo operations as the ship was taken to anchorage.
		  - 37 stevedores suspended their work as they were sent to the hospital for medial examinations.
		- *Fishing* ban stayed in effect for approx. four months until drums were found and removed, and environmental consequences were assessed.
		- *Others*: numerous organisations, authorities and individuals interrupted their daily routines.
			- Various activities were *seriously interrupted*.

	Threats	Fishing and other activities may be interrupted due to: - Accidental recovery of arsenic trioxide drums by fishermen - Reassessment of the marine environmental impacts, which may confirm high levels of arsenic concentration in the area - Discovery of high levels of arsenic contamination on fish catches or human effects	- Discovery of arsenic may *seriously* threaten fishing and other activities.

Publicity and legal implications	Consequences	- The m/v SCI accident remained for two months at the centre of the U.S. media, congressional and legal debate. - The USCG’s Board of Inquiry recommended criminal actions against the shipowner and the crew. - The U.S. Department of Justice filed a lawsuit against the m/v SCI for losing arsenic trioxide drums.	- *Very bad* publicity or *very serious* public relation implications in the U.S.. - *Very serious* legal implications. - Perhaps *no or insignificant* public and legal implications in the country of origin – the flag state, the country of registration or the shipowner’s country of residence.
	Threats	- It is very unlikely that the future threats of the m/v SCI accident will have any public or legal implication on the shipowner of the m/v SCI.	- *No or insignificant* future public and legal implications.
Aggregated other consequences and threats		- Given the aforementioned facts and judgments, the severity of the aggregated other consequences/threats is ranked *serious*.	- *Serious*
Aggregated consequences and threats		- Given the aforementioned facts, estimations and judgments, the severity of the aggregated consequences/threats of the m/v SCI is ranked *serious*.	- *Serious*

5.2. Frequency evaluation

The Frequency Indexes (FIs) show that frequency estimation and ranking derive from statistical analyses and judgments of large amounts of historical data. It is difficult, if not impossible, to judge the FI solely on a single case. However, based on the combination of the data available in the case history, and *support by the statistical incident data* (e.g. HCB, 1986-2003; HMIS, 1993-2004; NRC, 1990-2004), other case histories and personal judgment, every reasonable attempt has been made to demonstrate the qualitative evaluation of the frequency of the m/v SCI accident. The frequency is evaluated against the following criteria: a) *IMO Risk Matrix*; b) *Wright criteria*; and c) *ISO Risk Matrix*.

5.2.1. Frequency Index (FI) – IMO Risk Matrix

The Frequency Index (FI) with respective definitions (Table 5.5) is a constituent part of the IMO Risk Matrix (IMO, 2002) (Figure 6.3). The FI indicates that the frequency is measured as the ratio between the occurrences of accidents and the number of ships (a fleet) exposed per unit of time. The number of ships owned by the m/v SCI's shipowner and the number of incidents occurring in his fleet were unknown.

Based on the FI of the IMO Risk Matrix, given the following facts, the frequency of the m/v SCI accident category, which is in terms of human and property consequences, can reasonably be ranked *"Remote"* (FI3) (Table 5.5). The m/v SCI accident has not an extremely remote (FI1) probability. The m/v SCI was one of thousands of ships calling at U.S. ports that had been involved in incidents in 1992 (NRC, 2005). However, according to databases (e.g. HMIS, 2005; NRC, 2005; HCB, 1986-2003), an accident of this magnitude (40 hospitalised people and severe contamination of the ship) is a neither frequent (FI7) nor reasonably probable (FI5) accident in U.S. territorial waters.

Table 5.5: Frequency evaluation of the m/v SCI accident based on the Frequency Index (FI) of the IMO Risk Matrix (IMO, 2002)

Frequency Index (FI)			
FI	**Frequency**	**Definition**	**Frequency (ship/year)**
7	Frequent	Likely to occur once per month on one ship	10
5	Reasonably probable	Likely to occur once per year in a fleet of 10 ships, i.e. likely to occur several times during a ship's life	0.1
3	**Remote**	Likely to occur once per year in a fleet of 1000 ships, i.e. 10% chance of occurring in the life of 4 similar ships	10^{-3}
1	Extremely remote	Likely to occur once in 100 years in a fleet of 1000 ships, i.e. 1% chance of occurring in the life of 40 similar ships.	10^{-5}

5.2.2. Frequency Index (FI) – Wright criteria

Without the support of quantitative data and experts’ judgements, frequency evaluation of a single case, i.e. the m/v SCI accident case, based on the frequency index of the Wright criteria (see Figure 6.4), which is shown in Figure 5.3, is an impossible task.

In order to evaluate the frequency, incident records of two databases have been reviewed. According to HMIS database records, 22 vessel incidents had been reported in the area during the period 1993-2004, occurring at a frequency of approximately two incidents per year. Half of these incidents (11) have been reported in the state of New Jersey waters only, which is the site where the m/v SCI lost arsenic containers, occurring at a frequency of approximately one incident per year. The HMIS database (U.S. 1993-2004) records have shown that no arsenic incident was reported during the mentioned period.

The incident records of the NRC database (U.S. 1990-2004) show that an incident of the m/v SCI accident magnitude, that is in terms of the amount of arsenic involved (approximately 75 tons) has, at worst, a frequency 0.0667 (6.67E-02) per year, or approximately one incident in 15 years (Figure 5.2). Subsequently, the frequency of the m/v SCI accident category lands on the FI 10^{-1}-10^{-2} per year (Figure 5.3). However, the incident records show that several (on the average, 24 incidents per year) arsenic incidents of lesser or larger magnitudes (amounts) than the m/v SCI accident were reported each year from various sources in the U.S (1990-2004) (Figure 5.2).

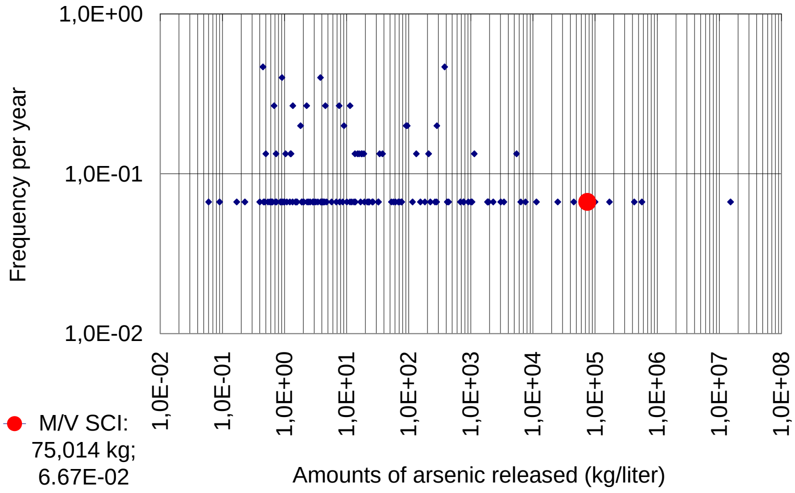


Figure 5.2: Arsenic release incidents (U.S. 1990-2004) – frequency per year and the severity (amount of arsenic released in kg/l)

Frequency per year
1
10^{-1}
🟥
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

Figure 5.3. Frequency evaluation based on the Wright criteria (Wright, 1993)

5.2.3. Frequency Index (FI) – ISO Risk Matrix

Table 5.6 shows the FI of the ISO Risk Matrix (Figure 6.5). As mentioned earlier, the ISO Risk Matrix is specially designed for the petroleum and natural gas industries, including offshore production installations. The ISO FI is highly qualitative, vague, inaccurate and incompatible with the FI of the IMO Risk Matrix and other criteria. The question is: How many is "several times"? The frequency ranking based on the location and operating company is not entirely accurate. The ISO's FI may not correctly measure and rank the frequency of marine accidents. For example, the frequency of marine accidents in a given location, which corresponds to the FIE – "happened several times per year in location", may be lesser than the frequency of marine accidents occurring in a mega carrier with a very large fleet of very large ships, which corresponds to the FID, i.e. "happened several times per year in operation company." Based on the data available, the m/v SCI accident category is evaluated against the FI of the ISO Risk Matrix (see Figure 6.5).

The FI of the ISO Risk Matrix is not a very specific index. It is a highly qualitative index with a low level of precision. In addition, rankings (A, B, C, D and E) are not mutually exclusive. Given the above facts, based on the frequency index of the ISO Risk Matrix, the frequency index of the m/v SCI accident category is reasonably judged *FIB* (*"happen several times per year in the industry"*) and *FIC* (*"has occurred in operating company"*). The review of many case histories shows that, except the FIA, the frequency of many marine accident categories can easily fit in all frequency rankings.

Table 5.6: Frequency evaluation of the m/v SCI accident based on the FI of the ISO Risk Matrix (ISO, 1999)

FI	Frequency Description	Facts
A	Rarely occurred in industry	• Case histories, e.g. HMIS and NRC and HCB, have shown that the m/v SCI accident category is not a rare event in the shipping industry. • See below.
B	**Happened several times per year in industry**	• According to records of several databases, e.g. HMIS, NRC and HCB, marine accidents involving PDG of this magnitude have happened several times per year in the shipping industry. Each year many containers and other CTU with dangerous goods are lost at sea. Many different types of ships carrying PDG have been involved in marine accidents such as foundering, listing/capsizing, grounding, and fire/explosions.
C	**Has occurred in operating company**	• The accident did occur in an operating company. According to databases, one or more incidents of this category/magnitude have occurred per year in the fleet (ships) of some shipping line companies visiting U.S. ports, such as Maersk, Evergreen, P&O Ned Lloyd, Hapag Lloyd and many other large shipping lines.
D	Happened several times per year in operating company	• According to 1992 records of the NRC database, approximately 4 ½ months after this accident, the m/v SCI, under another name – the m/v Santa Mercedes — was involved in another incident in the same port - Port Baltimore (Maryland, U.S.), but the incident was not of this magnitude. The case history provides no information concerning the m/v SCI's shipowner or his company. Incident records of the HMIS and NRC databases suggest that an accident of this magnitude is unlikely to have occurred several times per year in the company of the m/v SCI. However, for large companies operating in the U.S. and worldwide it is not ruled out.
E	Happened several times per year in location	• During the same storm (on January 3-4th, 1992) other ships reported cargo/ container losses in the same location where the m/v SCI lost arsenic trioxide containers. According to the HMIS and NRC databases, vessel incidents happen several times per year in the area including the states of New Jersey, Delaware, Maryland, South Carolina and Pennsylvania. However, the case history and statistical records indicate that an accident of this magnitude, particularly environmental consequences and threats, is unlikely to have occurred several times per year in the location of the m/v SCI accident.

6. Step 5 – Risk Estimation and Presentation

Tasks: Estimate and present risks. Evaluate risks against the relevant risk criteria available (see the **highlighted areas** in Figure 6.1).

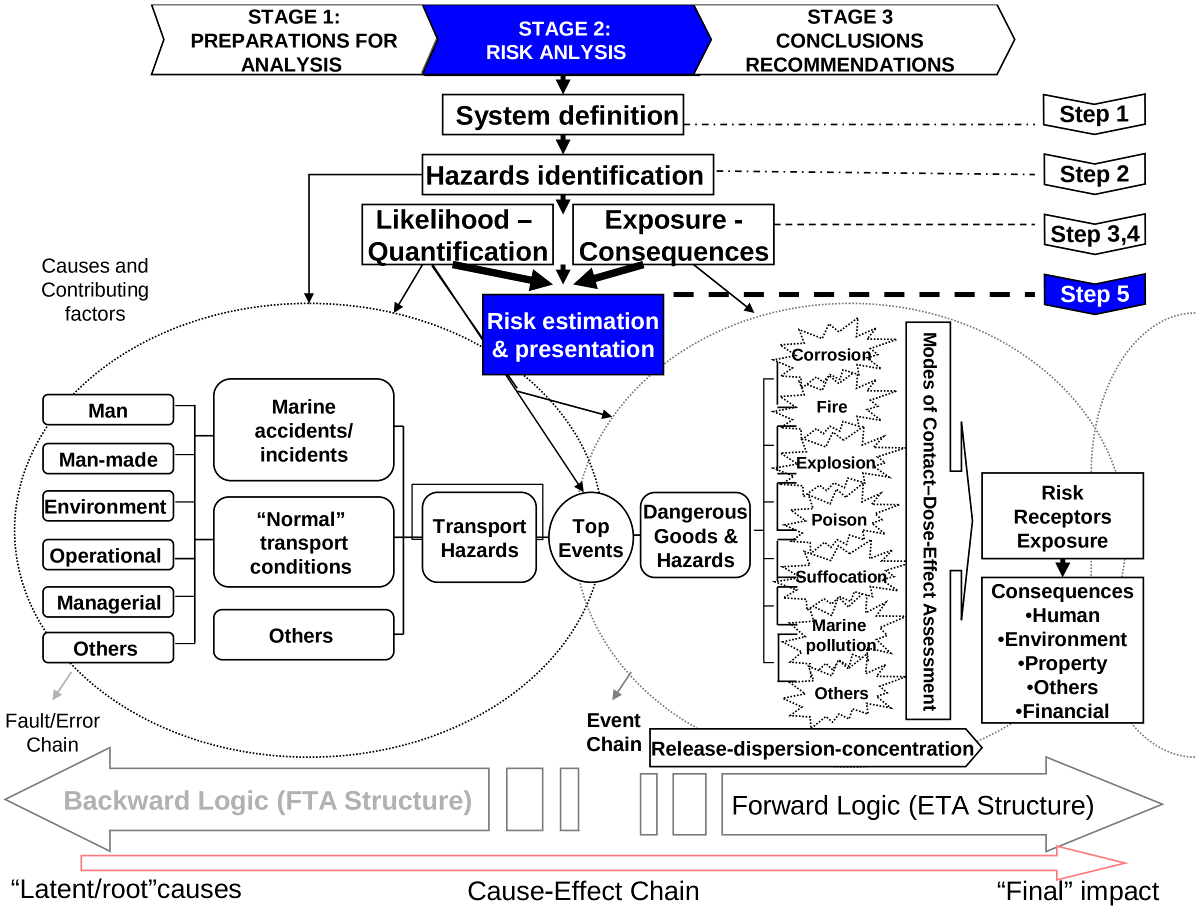


Figure 6.1: Stage 2 – Risk analysis; Step 5 - Risk estimation and presentation (continued from Figure 1.2)

As mentioned in Chapter 3, Vol. I, and Mullai, 2006a, risks are subdivided into *statistically verifiable and non-verifiable risks* (Hammonds, 1992). Statistically verifiable risks are those that can be determined from direct observations. Hence, these risks can be compared to each other. Given the amount of data availability, dangerous goods risks are statistically verifiable. In principle, in order to enhance the validity and reliability of the results, the most ideally desirable situation is to study the entire population of marine accidents/incidents in one country, which is in this case the U.S., a region or worldwide within a period of time, one or more years. However, when the study of the entire population is neither feasible nor practicably possible, a representative sub-population of marine accidents is studied in order to estimate and evaluate risks. From the statistical point of view, a single case may not represent the risks of thousands of marine accidents/incidents. The results of the analysis of a single case may not provide meaningful statistical inferences for risks involving large numbers of events. For more information about definitions and concepts of risks and risks analysis, see Chapter 3, Vol. I, and Mullai 2006a, 2006b.

Risk is a function of combinations of frequency, consequences and exposure. None of the mentioned risk elements can be quantified based on a single or a few cases. Therefore, the risks of vessel incidents in the U.S. during 1992 cannot be estimated and evaluated based on this single case, i.e. the m/v SCI accident case. The m/v SCI accident is one of thousands of vessel incidents occurring each year in the U.S. (Figure 6.2). Given the large number of events, any statistical inference for the risks of the entire population of vessel incidents based on a single case history is highly probabilistic and inconclusive.

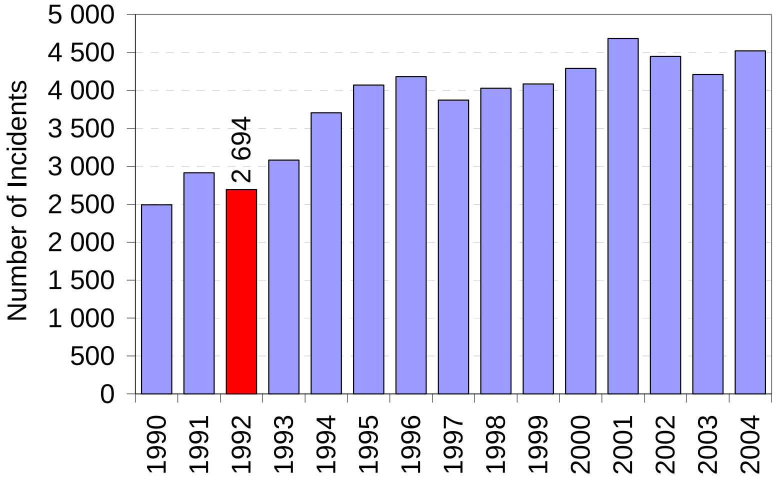


Figure 6.2: Vessel incidents in the U.S. (1990-2004) (NRC, 2005)

6.1. A qualitative risk evaluation of the m/v SCI accident

The aforementioned risk estimation procedures are "purely” technical procedures. However, risk analysis does not exclude “relaxed” qualitative evaluation of the events. In addition to technical aspects, risk evaluation takes into account a number of interrelated non-technical aspects, such as perceptions, concerns, socio-economical and political considerations. Case histories have shown that, due to the severity of the accident as well as the influencing power of parties involved or affected by accidents, individual marine accidents, such as “Exxon Valdez”, “Braer”, “Amoco Cadiz”, “Torrey Canyon”, “Sea Express”, “Aegean Sea”, “Herald Free Enterprise”, “Erica” and many more, have significantly affected shipping and other related industries. Not least, they have affected the maritime transport system of dangerous goods and the regulatory system governing this transport. Many important international and national decisions in the shipping industry have been based on qualitative assessments and in response to single cases of marine accidents. For more information about risk evaluation see Chapter 5, Vol. I.

Based on the analysis of the data and risk criteria available and judgments, the following is a qualitative evaluation of the m/v SCI accident. Risk evaluation combines the evaluated Severity Index (SI) and Frequency Index (FI) of the m/v SCI accident: RI = FI x SI. The risks are evaluated on the basis of the aforementioned risk criteria containing both the SI and FI. Risks are presented in each respective risk matrix.

6.1.1. Aggregated risk evaluation and presentation - IMO Risk Matrix

Figure 6.3 shows the IMO Risk Matrix (IMO, 2002). Given the Severity Index *"Severe" (SI3)* of the *aggregated human safety and property* (ship) consequences (Table 5.1) and the Frequency Index "*Remote*" (FI3) (Table 5.5), the m/v SCI accident is placed in the area shown in Figure 6.3 (RI = SI3 x FI3). The risks of the m/v SCI accident lay in the area between "Low Risk" and "High Risk". The level of aggregated human and property risks posed by the m/v SCI accident can be judged as a *medium risk level*.

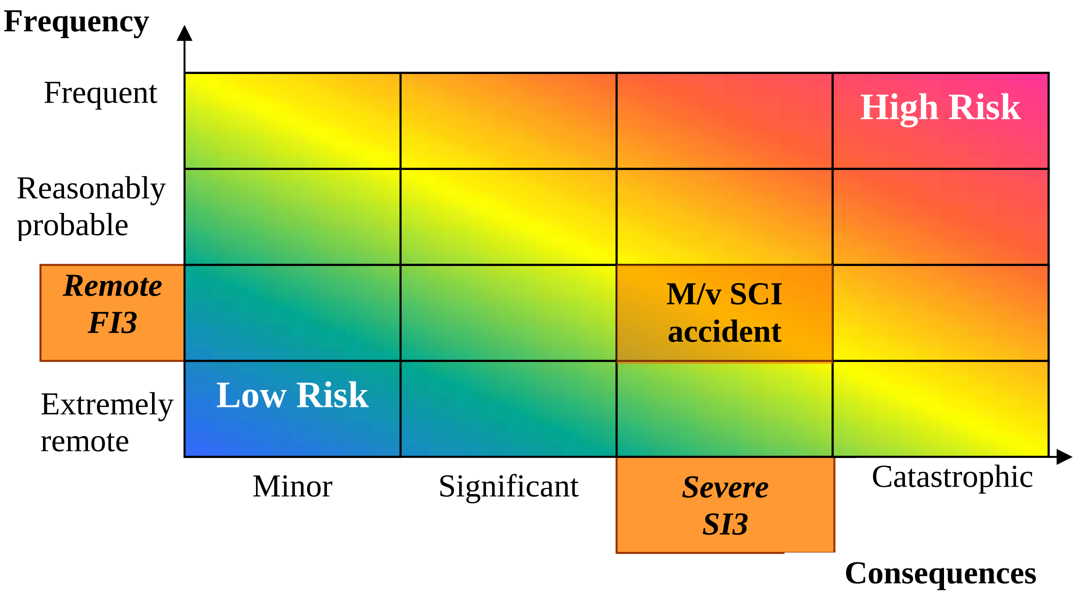


Figure 6.3: Aggregated (human and property) risks evaluation and presentation of the m/v SCI accident based on the IMO Risk Matrix (IMO, 2002)

6.1.2. Environmental risk evaluation and presentation – Wright criteria

Figure 6.4 shows Wright criteria (Wright, 1993). Given the severity of environmental consequences and threats (*SI3-"Serious"*) and the frequency (between 10^{-1}-10^{-2}), the m/v SCI accident category lies in the area shown in Figure 6.4. This is an area on the border between the upper boundary of the "As Low As Reasonably Practicable" (ALARP) or "Tolerable" Region and the lower boundary of the "Intolerable Risk Level" Region. The level of aggregated environmental risks posed by the m/v SCI accident can be judged as a relatively *high or intolerable risk level*. Major public, media and congressional and legal debates and large and expensive search and recovery operations suggest that the m/v SCI accident was perceived as a high-risk incident, which is also consistent with the above evaluation.

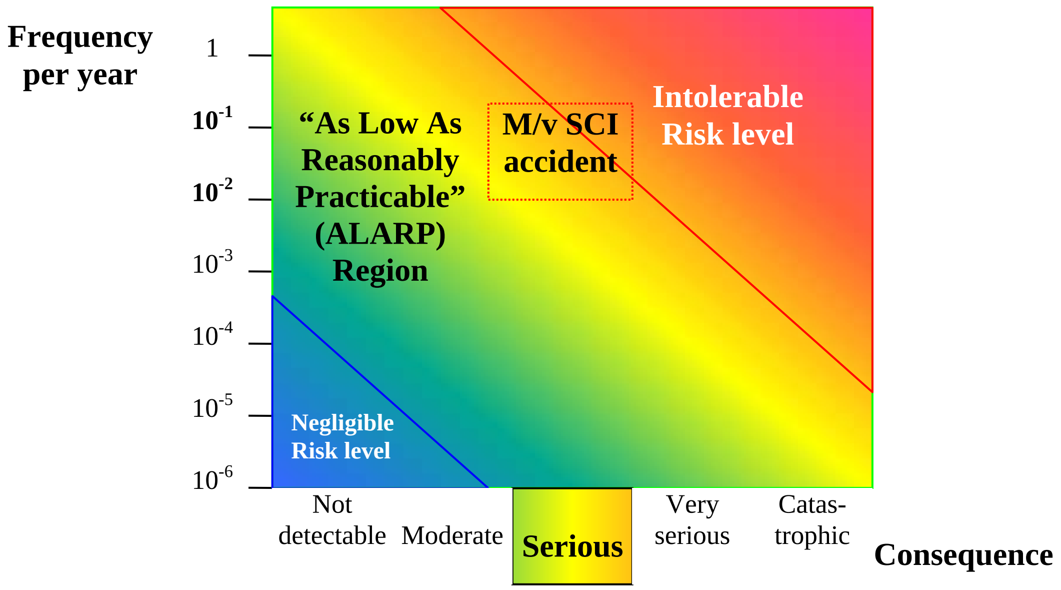
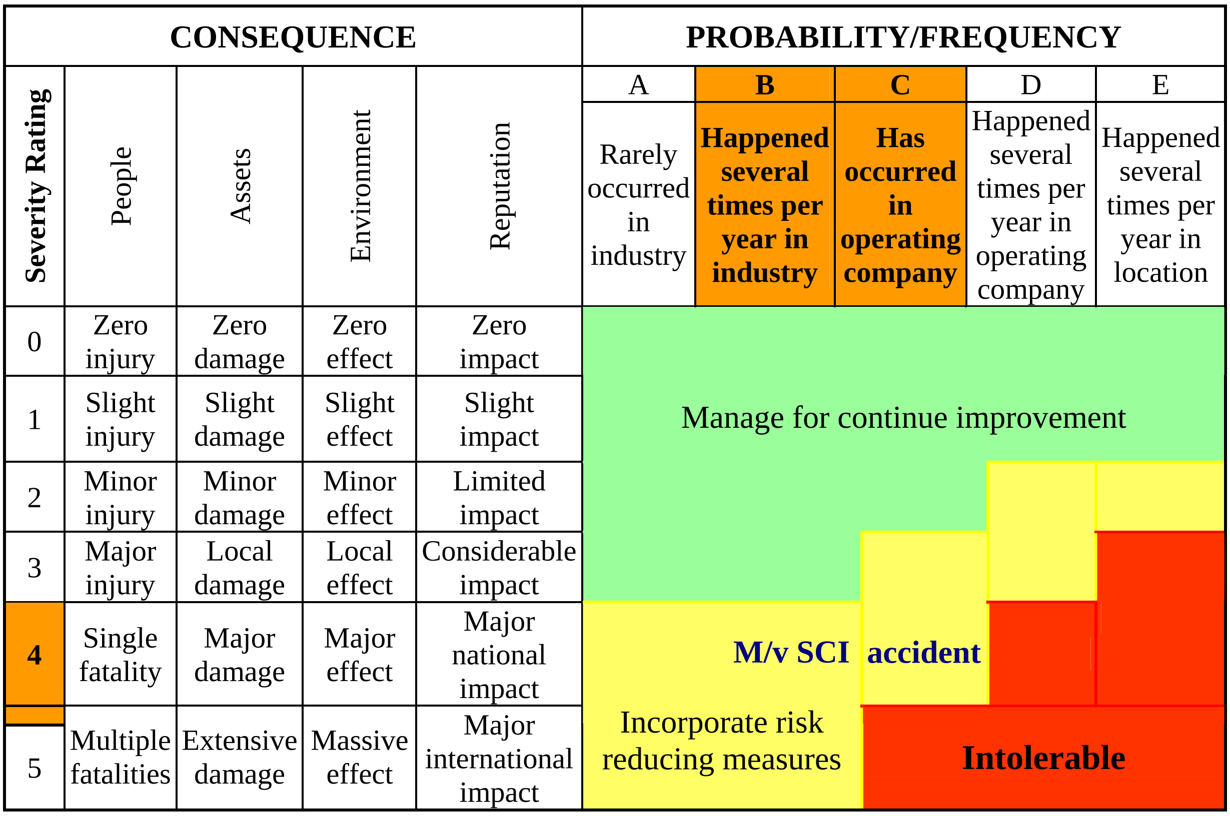


Figure 6.4: Environmental risks evaluation and presentation of the m/v SCI accident based on the Wright criteria (Wright, 1993)

6.1.3. Aggregated risks evaluation and presentation – ISO Risk Matrix

Figure 6.5 shows the ISO Risk Matrix (ISO, 1999). Given the Severity Index (*SI4 or higher*) of aggregated consequences and Frequency Indexes (*FIB and FIC*), the aggregated risks posed by the m/v SCI accident lay in the *ALARP Region or the medium risk level*, with a tendency towards the *Intolerable Region or high risk level* – as shown in Figure 6.5. The latter is mainly attributed to extensive contamination damage, bad publicity and legal implications in a country like the U.S. that is the world's largest economy. In particular, this is due to the very large-scale response operations and the marine environment threats posed by the large quantity of unrecovered arsenic trioxide.



CONSEQUENCE					PROBABILITY/FREQUENCY				
					A	**B**	**C**	D	E
Severity Rating	People	Assets	Environment	Reputation	Rarely occurred in industry	**Happened several times per year in industry**	**Has occurred in operating company**	Happened several times per year in operating company	Happened several times per year in location
0	Zero injury	Zero damage	Zero effect	Zero impact	🟩	🟩	🟩	🟩	🟩
1	Slight injury	Slight damage	Slight effect	Slight impact	🟩	🟩	🟩 Manage for continue improvement	🟩	🟩
2	Minor injury	Minor damage	Minor effect	Limited impact	🟩	🟩	🟩	🟨	🟨
3	Major injury	Local damage	Local effect	Considerable impact	🟩	🟩	🟨	🟨	🟥
4	Single fatality	Major damage	Major effect	Major national impact	🟨	🟨 **M/v SCI**	🟨 **accident**	🟥	🟥
5	Multiple fatalities	Extensive damage	Massive effect	Major international impact	🟨 Incorporate risk reducing measures	🟨	🟥	🟥 **Intolerable**	🟥

Figure 6.5: Aggregated risks evaluation and presentation of the m/v SCI accident based on the ISO Risk Matrix (ISO, 1999)

6.2. Risk perception of the m/v SCI accident

Risk perception is an important factor in shaping the understanding of risks and risk-related decision-making processes. The experts and scientists involved in the m/v SCI accident case assumed that, since arsenic trioxide was non-bioaccumulate in the food chain, there were "little risks" to the human life outside the immediate vicinity of arsenic trioxide drums on the sea floor (U.S. DOT, 1992). However, because of the danger posed by arsenic trioxide drums washing ashore or getting caught in fishing nets and the public demand for immediate actions, the responsible authorities launched a massive search and recovery operation. The m/v SCI operation was one of the largest offshore operations in U.S. history. The massive operations and engagements suggest that responsible authorities and other parties involved considered the loss overboard of arsenic trioxide containers as a "high risk" marine accident. According to the Board of Inquiry (U.S. DOT, 1992), dangerous goods carried aboard the m/v SCI posed serious threats to U.S. coasts and ports. The view of the USCG Atlantic Strike Team was that the m/v SCI accident posed serious threats to the Mid-Atlantic State fishing industry (Whipple et al., 1993). In addition, the public concern, which was further fuelled by the media, also indicates that the public perceived the loss of arsenic trioxide containers at sea as a "high risk" accident. The public perception was probably one of the main driving factors behind concerns and demands for immediate actions, which subsequently led to the enormous response to the m/v SCI accident.

The analysis of the m/v SCI case history showed that the main concern of the authorities and public was the loss overboard of arsenic trioxide drums/containers. However, the most obvious and "serious risk" was not perceived as the "highest risk". Probably the public knew nothing about the incident in Port Charleston. Within the context of this case history, in terms of actual and immediate human consequences and potential threats to humans and properties, phosphine gas emitted from magnesium phosphide spilt inside the no.1 hold posed "higher risks" than arsenic trioxide. The analysis showed that some 39 people (crewmembers and stevedores), or approximately 98% of the total number of people affected, were health affected due to exposure to high levels of phosphine gas only (see Table 4.16). Given its toxic and flammable/ explosive properties, phosphine gas posed serious threats to the ship, crew and stevedores, ports and local communities. The situation might have escalated to a worst-case scenario.

6.3. The m/v SCI accident – out of and in context of the overall risks

The following section demonstrates the important role that the view of maritime risks in context of the overall risks plays in integrated risk management. A detailed description of the context is provided in the "System definition" – for more information, see Section 2.4. Firstly, the m/v SCI accident and responses to it are viewed in the context of maritime risks only, which is out of context of the overall arsenic risks.

Out of context

Some of the key points describing concerns, decisions, actions and measures taken in response to the m/v SCI accident are recalled and summarized as follow:

- **Massive operations**: In response to arsenic trioxide container loss and because of the danger of the drums being washed ashore or getting caught up in fishing nets, and the general public demand for immediate actions, the responsible authorities launched a massive search and recovery operation. The m/v SCI operation was one of the largest offshore operations in U.S. history. Helicopter searches covered 305 nm of the ship's tracking line and 98.5 square miles of ocean search. Salvage crews spent two months scouring a huge strength stretch of ocean 60 km long and 1 km wide. The operations required detailed preparations, planning, reviews, meetings, and coordination of several different agencies and organisations and their resources. A large team of experts (Atlantic Strike Team) consisted of some 20 members representing different agencies involved in the operations. The operations lasted for 5 months and 15 days. Of the total number of 414 arsenic trioxide drums (70.4 tons) lost at sea, 320 drums (or 54.4 tons) were recovered from the sea floor and dumped ashore. The search and recovery operation of arsenic trioxide drums cost $ 2.2 million.

- **Fishing banned**: Immediately after the accident, fishing was banned in the vicinity of the m/v SCI accident site. The NOAA sent notices to all clam fishing permit holders warning them of potential dangers of exposure to arsenic trioxide. The fishing ban stayed in effect for approximately four months (January-April, 1992).

- **Wide attention**: The SCI accident remained at the centre of U.S. media, congressional and legal debates for two months. The public demanded immediate actions.

- **Legal actions**: The USCG's Board of Inquiry recommended criminal actions against the m/v SCI's shipowner and crew. The U.S. Department of Justice, on behalf of the USEPA, filed a lawsuit against the m/v SCI for the loss of arsenic trioxide drums. The lawsuit prevented the ship from departure.

In context of the maritime risks only, the aforementioned decisions and actions are valid for the marine environment protection and safety and health of people who were directly related to the marine environment and its resources, including fishermen, residents and tourists of coastlines, and fish consumers.

In context

Placing the m/v SCI accident into a wide perspective, that is in the context of the overall arsenic risks to the ecosystem, a question may arise: All the aforementioned concerns, debates, expensive responses, and legal actions, for what? In the following section, which recalls and summarizes some of the facts mentioned earlier in this Chapter (see Section 2.4), the case of the m/v SCI accident is viewed in the context of overall arsenic risks.

- **The m/v SCI's arsenic may have worsened the situation ashore**: Arsenic trioxide carried onboard the m/v SCI may have had the same fate as arsenic described in the "System definition", see Section 2.4. The large amount of arsenic (approximately 459 tons) was destined for direct applications in land-based industries as an insecticide, herbicide or wood preservative chemical. It may have contributed to the elevation of the arsenic concentration level in the environment, making the situation ashore even worse. The amount of the m/v SCI's arsenic was added to the total amount (30,391 tons) of arsenic applied in the area during the period 1900-1980.

- **New York/New Jersey (Y/NJ) Bight – a waste dumpsite**: During the storm, the m/v SCI lost overboard a total number of 414 arsenic trioxide drums (70.4 tons), some 30 miles off the coast of Cape May, New Jersey (U.S.), or approximately 48 km away from people and organisms living ashore. The m/v SCI accident site is located in the southern part of the NY/NJ Bight, which, for many years, has served as an ocean dumpsite for large amounts of many different types of wastes, probably including chemical wastes.

- **Wastes disposal sites contaminate groundwater**: After expensive ($ 2.2 million) and extensive search and recovery operations, a total of 320 arsenic trioxide drums (or 54.4 tons) were recovered from the sea floor. Drums were brought ashore closer to humans and land-based living organisms. Like the entire arsenic shipment, this amount of arsenic was also destined for direct applications in land. However, because of water damage, arsenic was considered as a hazardous waste instead. It was sent for disposal at a toxic waste disposal site ashore. Toxic waste disposal sites have the potential to contaminate ground waters and more. In the late 1970’s, massive toxic contaminations were discovered at Love Canal, in upper New York State, U.S., which is located north of the state of New Jersey. The site was used as a toxic waste disposal site during the 1940’s and 50’s. This discovery was followed by other discoveries of many other sites in various parts of the U.S. For more details about the distributions and concentrations of arsenic in the soil, groundwater, streams and streambed sediments in the state of New Jersey, see Figures 2.11~2.14 in Section 2.4.1.

- **The population of the state of New Jersey is already exposed to arsenic**: For two months, the m/v SCI accident remained at the centre of the U.S.’s media, congressional and legal debate (McGowan, 1993). The public was legitimately concerned and demanded immediate actions. However, as mentioned earlier in Step 1: System definition, Chapter 2, Vol. II, a large portion of the population of the state of New Jersey including those who were concerned about the loss of arsenic trioxide containers from the m/v SCI, has already been, and still is daily, exposed to arsenic from various sources. Approximately 5 million residents of the state of New Jersey are potentially exposed to arsenic in ground water sources (NJDEP, 2001). There have been 4 cases of cancers related to drinking water only (NJDEP, 2001). In addition, incident records of the HMIS database (U.S. 1993-2004) show that considerable amounts of different arsenic compounds enter every year into the environment from a wide range of sources. On average, 24 arsenic incidents, which have sometimes involved large amounts of arsenic compounds, have occurred each year in the U.S. (HMIS, U.S. 1993-2004).

Summary

In the context of ecosystem risks, some decisions and measures taken in response to the m/v SCI accident seem inappropriate, if not counterproductive. The amount of arsenic carried onboard the m/v SCI and involved in the accident was only a small fraction of the large amount of arsenic applied or released in the area. The m/v SCI accident is one of 24 arsenic incidents occurring on average each year in the U.S territory.

6.4. Risks estimation and presentation – statistical data

Risks can be estimated and presented in various forms. By definition, the risk is a function of frequency, consequences and/or exposures. For more information about concepts of risk and risk estimation, presentation, and evaluation see Chapters 3 and 5, Vol. I, and Mullai, 2006a.

The risks can be estimated relative to various exposure measures, such as characteristics of dangerous goods shipments (e.g. tons and ton-km or miles), people, activities, means of transport etc. Some of these exposure measures can serve as common denominators (e.g. tons) for most of the systems of the dangerous goods supply chain, but some others can not (e.g. means of transport). In maritime risk studies, the frequency of the FN-curve of the fatality risk is commonly estimated relative to the number of ships – for example, the frequency of N or more fatalities per ship per year (see IMO, 2004a, 2006).

Risk criteria are established standards employed for benchmarking or evaluating estimated risks. Therefore, in order to evaluate the levels of the risks of incidents in the U.S.'s hazmat supply chain including maritime transport, the risks estimated should, in principal, be compared against the quantitative U.S. risk criteria available. Despite an extensive search and the review of many different sources, no risk acceptance criteria have been found for the U.S.'s supply chain including maritime transport. The risk criteria proposed by the IMO (2004a) (see Chapter 3, Vol. I, and Mullai 2006b) are international criteria intended for the evaluation of the total fatality risk of being onboard a ship only, but not for the evaluation of the wide range of various specific risks involving specific hazards, including dangerous goods/hazmat hazards, such as fire, explosion, and toxic hazards. It is not possible to evaluate and determine the levels of risks in absence of risk criteria. In addition, although samples selected for the purpose of this study (i.e. hazmat incidents reported to the NRC and HMIS databases, 1990-2004) are well representative of sub-populations of the entire population of all hazmat incidents occurring in the U.S., accurate estimation and evaluation of risks against quantitative risk criteria require exhaustive data. Thus, the results of one random test of incident cases reported to the NRC (U.S. 1990-2004) show that the accuracy of the FN-curve of fatality risk increases as the sample size increases (Figure 6.6). Figure 6.6- shows that the FN-curve estimated for 50% of incident cases selected at random approximates more accurately the FN-curve of the aggregated supply chain fatality risks (100% - all cases) than does the FN-curve estimated for 1-10% of cases. Several tests may lead to different results as those shown in Figure 6.6.

For the purpose of demonstration, based on incident data from the NRC database (U.S. 1990-2004) and some of the exposure data available (see Section 4.1.9), risks are estimated and presented as a) FN-curves; and b) annual incident and injury/fatality rates. The hazmat supply chain risks can be compared with each other. Changes over the years in risks estimated and presented graphically as annual incident and injury/fatality rates can also be evaluated.

The FN-curves: The risks in the U.S. hazmat supply chain are estimated and presented as FN-curves[35] showing the relationships between the orders of magnitudes of frequencies and the severities of consequences (U.S. 1990-2004) (see Figures 6.7~6.17).[36] The frequencies are estimated in absolute terms based on the incident data (i.e. historical frequencies) from the NRC database (U.S. 1990-2004). The severities of consequences are estimated as numbers or amounts of consequences, such as fatalities, injuries, hospitalisations, evacuations and damage (in $) for the same period (U.S. 1990-2004) (see Section 4.2.2.2). Both the cumulative frequencies and consequences are combined and plotted as FN curves. The FN-curves provide a comprehensive view of risks. They allow graphical presentation and comparison of various dimensions of risks. The slope[37] and position of the FN-curves of individual risks relative to each other and against the FN-curve of the aggregated supply chain risks depict characteristics of the risks. However, the FN-curves do not show changes in risks over the years.

The risks of incidents resulting in large numbers of consequences to humans (e.g. fatalities and injuries) and the community, and aggregated risks of the supply chain, including maritime transport, are, by definition, societal risks (see Chapter 3 and 5, Vol. I, and Mullai 2006a, 2006b). Figures 6.7~6.17 show that, in absolute terms, risks in the water or maritime transport system are generally well below the aggregated supply chain risks. Furthermore, they are lower than the risks in several systems or activities of the supply chain, but higher than risks in some others. For example, the fatality risk in the water transport system is lower than the fatality risk in rail, road, air and pipeline transport and plants, but higher than the fatality risk in storages and platforms (see Figure 6.7). As mentioned earlier, risk is a function of frequencies, consequences and exposures and, consequently, these factors affect them. The severities of human consequences in rail and road transport have been on a lower order of magnitude, but more frequent than those in air transport and plants/fixed. The most severe fatal incidents have been reported in air transport and plants/ fixed. Given the specific properties of the system, some air transport incidents have been very severe, involving up to 229 fatalities in a single incident. Except for evacuations, the severities of the human consequences of vessel incidents have been on a lower order of magnitude than those in other systems. The most severe case of evacuations reported to the NRC database (U.S. 1990-2004) was due to a vessel incident.

The positions of individual FN-curves relative to each other and the FN-curve of the aggregated supply chain risks, which are presented in Figures 6.7~6.17, will change when the frequencies are estimated relative to the exposed populations or universes. The orders of magnitude of absolute frequencies will decrease by the same orders of the denominators, i.e. the amounts of exposed populations – for example, measured in the numbers of employees and amounts of dangerous goods carried/handled in each respective system. In this form, risks are estimated according to various exposure measurements. This form of risk estimation and presentation also reflects changes in

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[35] Similar terms are “plot” and “diagram”.

[36] Note: In Figures 6.7~6.25, the comma (,) should be read “full stop” (.).

[37] The degree of the FN-curve inclination.

the risks due to changes in the exposed populations. But this is a labour and resource intensive process, which requires accurate and exhaustive incident data and common exposure measurement data. The availability and quality of these types of data vary across industries and countries. In many industries and countries these types of data may be nonexistent.

Annual incident and fatality rates: Risks are also estimated and presented as variables representing consequences or undesirable outcomes (i.e. incidents, fatal and injury incidents, fatalities and injuries and other consequences) of the systems relative to a wide range of exposure measures (i.e. consequences averaged over the exposed populations), per year (see Figures 4.18~4.25). As the undesirable outcomes of the system, incidents may serve as the consequence as well as exposure measure. Ratios are presented in graphic formats. The fatality risks, for example, are estimated as annual fatality rates, which includes fatality rate per fatal incident and incident per year. Fatal incidents are those incidents that are associated with at least one fatality. However, this form of risk estimation and presentation does not show the magnitude of the severities of consequences and the relationship between the orders of magnitudes of frequencies and severities of consequences. Furthermore, this form shows no distinction between the high frequency/low severity of consequences and visa-versa, as all consequences (e.g. fatalities) regardless of the severity are averaged over exposure measures per year. The data show that incident, fatality, and injury risks in the vessel or maritime transport system and the supply chain have generally increased in the U.S. during the period 1990-2004 (see Figures 4.18~4.25), except vessel and transport risks measured as the ratio of incidents over the amount of hazmat shipments. In the latter case, the results suggest that the amount of shipments transport by all modes combined and vessel transport has increase more/faster than the corresponding numbers of transport and vessel incidents. The results of this form of the risk estimation and presentation, which are largely consistent with the other form presented above, also show that the vessel risks are well below, in some cases one order of magnitude below, the aggregated supply chain risks.

However, extra cautions should be exercised in the interpretation and judgement of the results of the risk estimation and presentation, in particular the risks measured as consequences relative to the populations exposed, and subsequently in the decision making process. Thus, although the risks may seem relatively low or declining as the result of faster increases in the size of populations exposed (i.e. the denominators – e.g. hazmat shipments, vessel traffic, population etc.) than the consequences (i.e. the nominators – e.g. incidents, fatalities, injuries, property etc.), still this may not be an adequate indicator. Some risk receptors are variable, replicable or replaceable and the consequences or damage to them may be also replaceable or reversible (e.g. damage to property). But, the marine environment, in particular sensitive sea areas (e.g. the Baltic Sea that has a very low water circulation), may have a limited variability and damage may be irreversible. Furthermore, chemical intakes by other living organisms including humans may be “undetectable”, incremental and slow, but with irreversible serious consequences. These chemicals may change the chemical balance within the living organisms (may be faster that the natural or evolution processes), which, in turn, can cause irreversible undesirable changes in the living organism system. Many studies have shown that the number of chemicals in living organisms, including humans, is growing. From the humanity and the future generation point of view, one of the worst possible scenarios may be the degeneration and/or extinction of living organisms, which is worse than acute deaths and physical injuries.

The community has a greater aversion to infrequent severe incidents, such as aircraft and plant disasters and major pollutions, than to frequent less severe incidents. The measures taken in response to these cases have been much faster and stricter than in other less severe cases. The resources spent in response to major disasters have often been very large. Case histories have shown that the risks (e.g. human, environment, property and economic damage) of some individual catastrophic accidents in industries, such as water transport and nuclear power plants, may far exceed the risks of many incidents in other systems.

The risks of fixed installation incidents, in particular those involving nuclear and radiological activities, may be higher than the level of risks of all other systems of the hazmat supply chain combined. The consequences of nuclear power plant incidents may extend far beyond national borders. Also, the catastrophic consequences of a single incident in a nuclear power plant may far exceed the combined consequences of thousands of incidents in other systems. The Chernobyl catastrophe is a very good example. The pessimistic estimations show that fatalities due to the Chernobyl accident may be very high. According to the most recent Greenpeace report (2006), the number of fatalities in Belarus, Russia and the Ukraine alone during the period 1990-2004 is estimated at 200,000. This figure excludes deaths anticipated in the future due to delayed reactions to the radiation. The estimated fatalities (worst-case scenarios) due to the Chernobyl accident would have been equivalent to fatalities generated by approximately 6 million incidents of the same types of incidents reported to the NRC for a period of 215 years.[38]

Example: The risk of the Chernobyl accident

> Due to a combination of inherent design problems and technical and human failures, in the early hours of 26 April 1986, one of four nuclear reactors at the Chernobyl nuclear power station exploded. The impacts of this catastrophic accident, in particular the number of people who could eventually die as a result of the accident, are highly controversial. Due to the disaster, a very high level of radiation was released in the immediate vicinity. The cloud of radionuclide spread in Belarus, Russia and Ukraine and all over Europe, and beyond to Asia. The Scandinavia countries and Finland were also badly affected. More than 50% of the contaminated areas across 13 European countries were dangerously contaminated at high levels of radiation (Greenpeace, 2006). More than five million people in Ukraine, Belarus and Russia are classified as "contaminated"

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[38] Assuming the number of incidents and fatalities reported each year remain unchanged. On average, approximately 928 fatalities are reported each year to the NRC.

with radionuclide due to the Chernobyl accident (UN Chernobyl Forum[39], 2005). The human impact is very uncertain. However, the Greenpeace report on the Chernobyl accident (2006), which involves 52 scientists from around the world, challenged the UN IAEA Chernobyl Forum report predicting 4,000 – 9,000 additional deaths attributable to the accident as a gross underestimation of the real extent of human impacts. The Greenpeace report (2006), based on Belarus national cancer statistics, predicts approximately 270,000 cancers and 93,000 fatal cancer cases caused by the Chernobyl accident. The report also states that, on the basis of demographic data, during the last 15 years, 60,000 people have additionally died in Russia because of the Chernobyl accident, and estimates of the total death toll for the Ukraine and Belarus could have reached another 140,000 (Greenpeace, 2006).

Summary

For the purpose of the demonstration, based on the data available at hand, the risks are estimated and presented in two forms, (FN-curve and rates), and for the U.S.'s hazmat supply chain and for the period of time specified in respective databases (HMIS, U.S. 1990-2004 and NRC, U.S. 1990-2004). The results of both forms of risk estimation and presentation presented in this chapter (Chapter 6, Vol. II) will contribute to enhancing understanding of the risks of the maritime transport system as well as other systems. Given the size of the data, the results of risk estimation and presentation have a higher degree of validity and reliability than many other studies cited in both volumes. These results will serve as the prediction and interpretation tools. Furthermore, they may also serve as the basis for further study or development of risk acceptance criteria in the field.

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[39] The UN Chernobyl Forum consists of the IAEA, WHO, UNDP, FAO, UNEP, UN-OCHA, UNSCEAR and the World Bank.

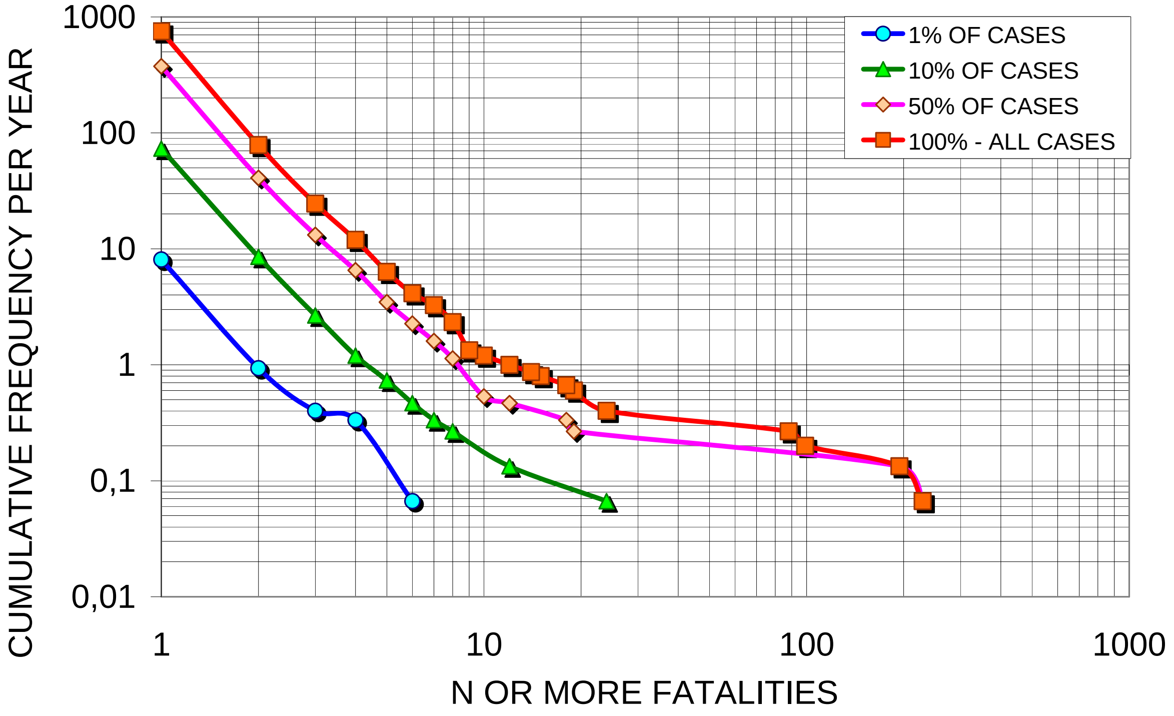

Figure 6.6: Comparison of the analysis results (FN-curves) of supply chain fatality risks (U.S. 1990-2004)

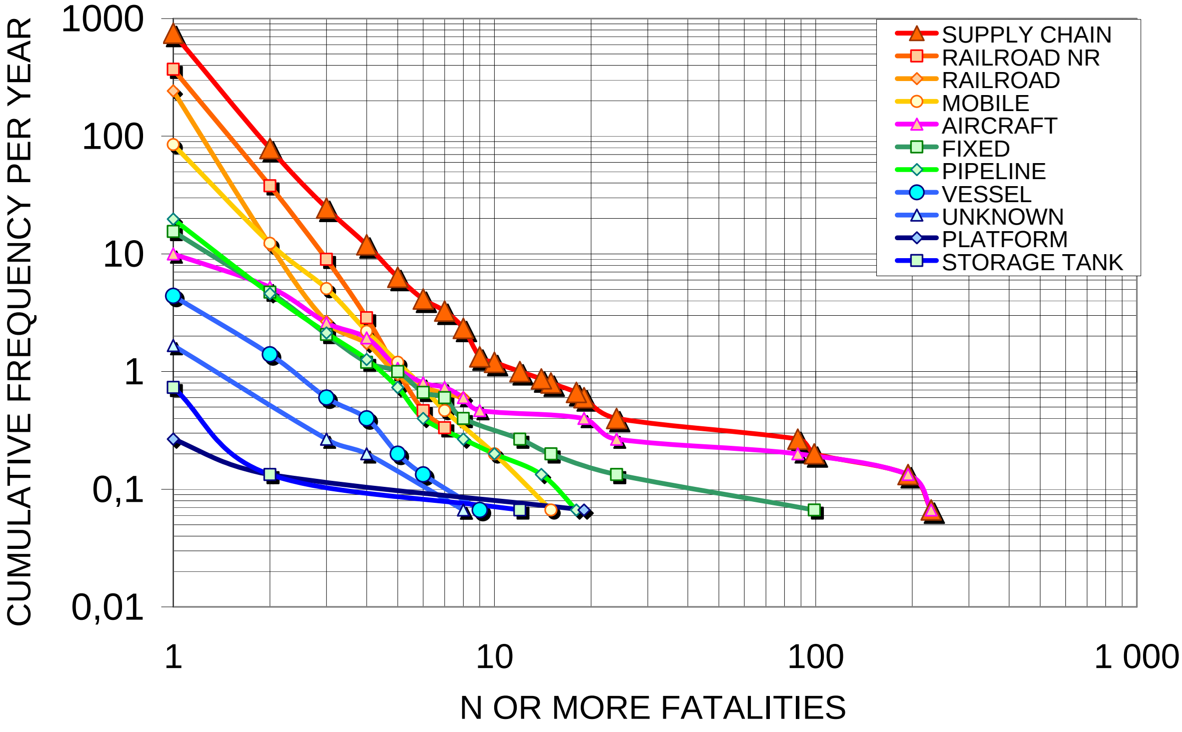

Figure 6.7: FN-curves of supply chain fatality risks by system (U.S. 1990-2004)

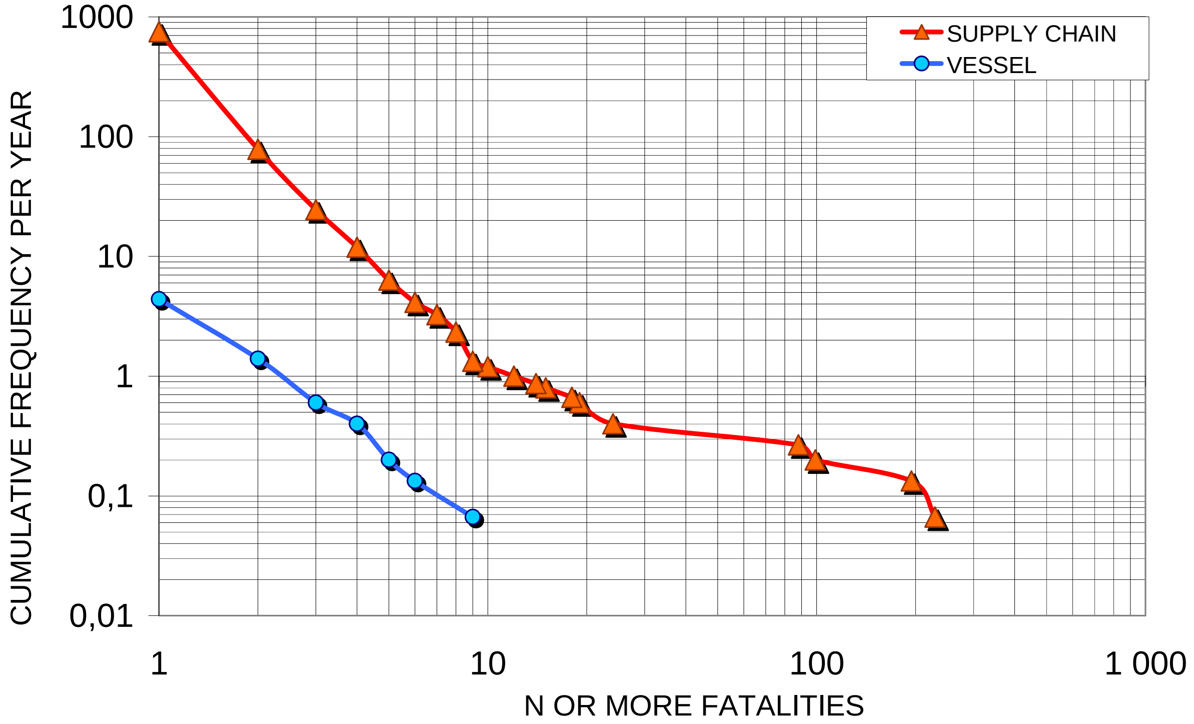

Figure 6.8: FN-curves of vessel and supply chain fatality risks (U.S. 1990-2004)

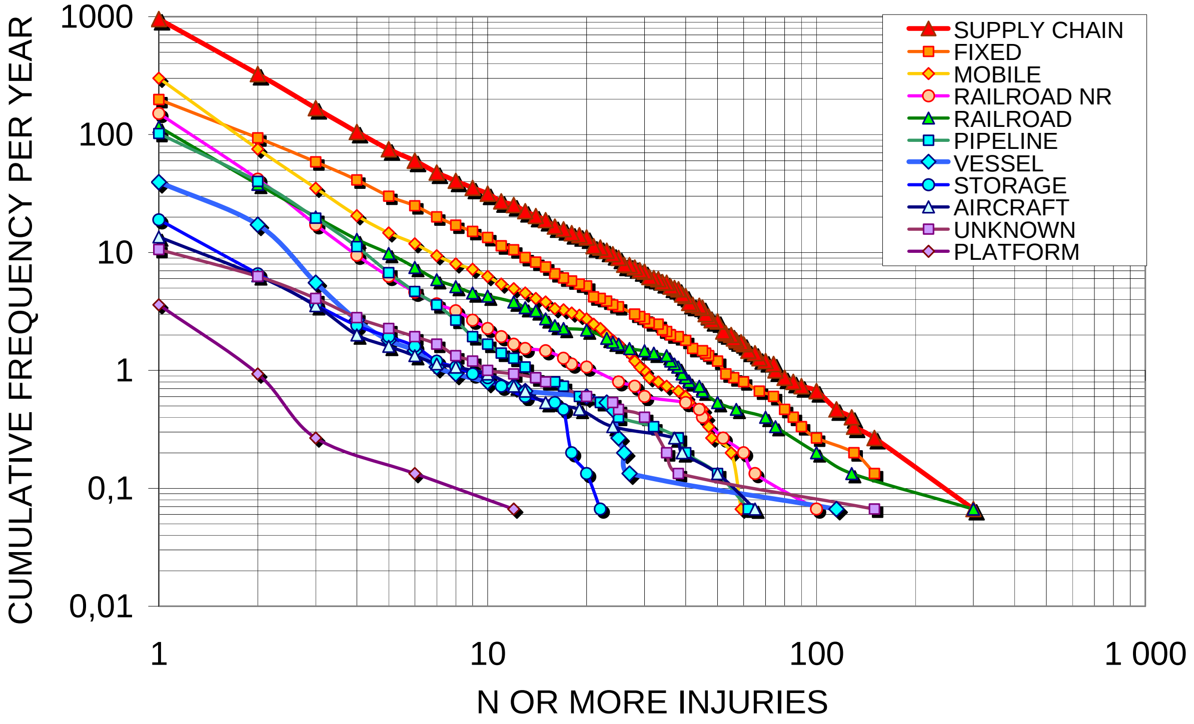

Figure 6.9: FN-curves of supply chain injury risks by system (U.S. 1990-2004)

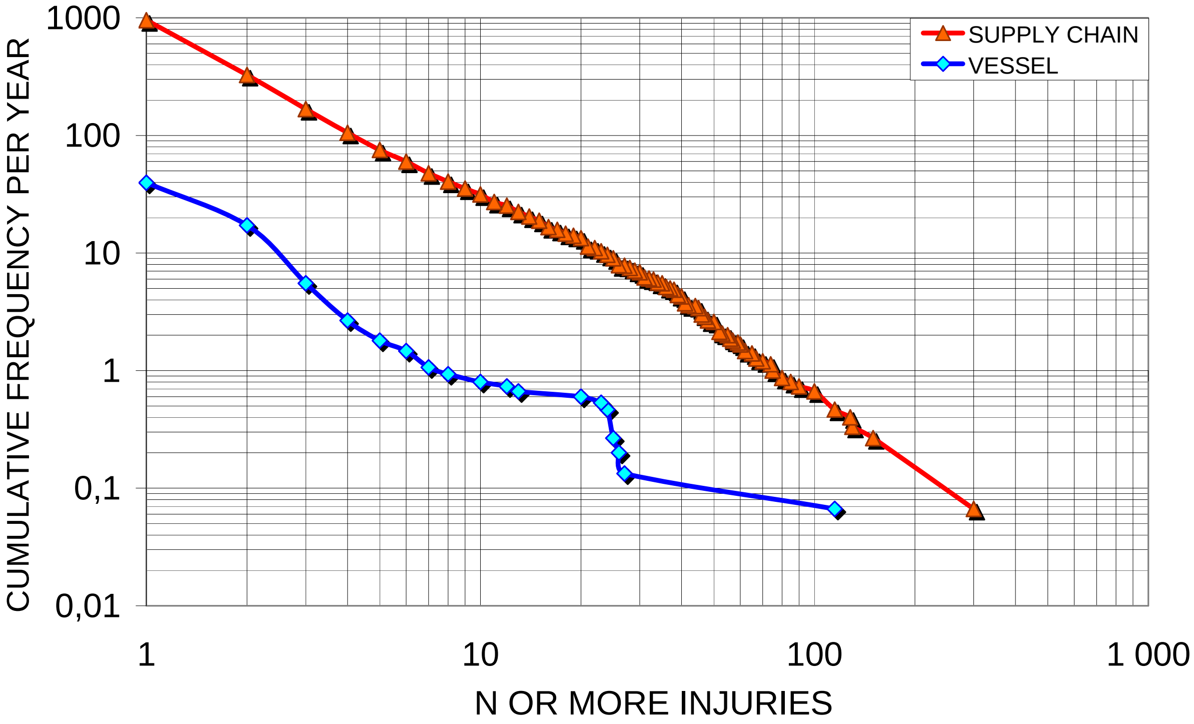

Figure 6.10: FN-curves of vessel and supply chain injury risks (U.S. 1990-2004)

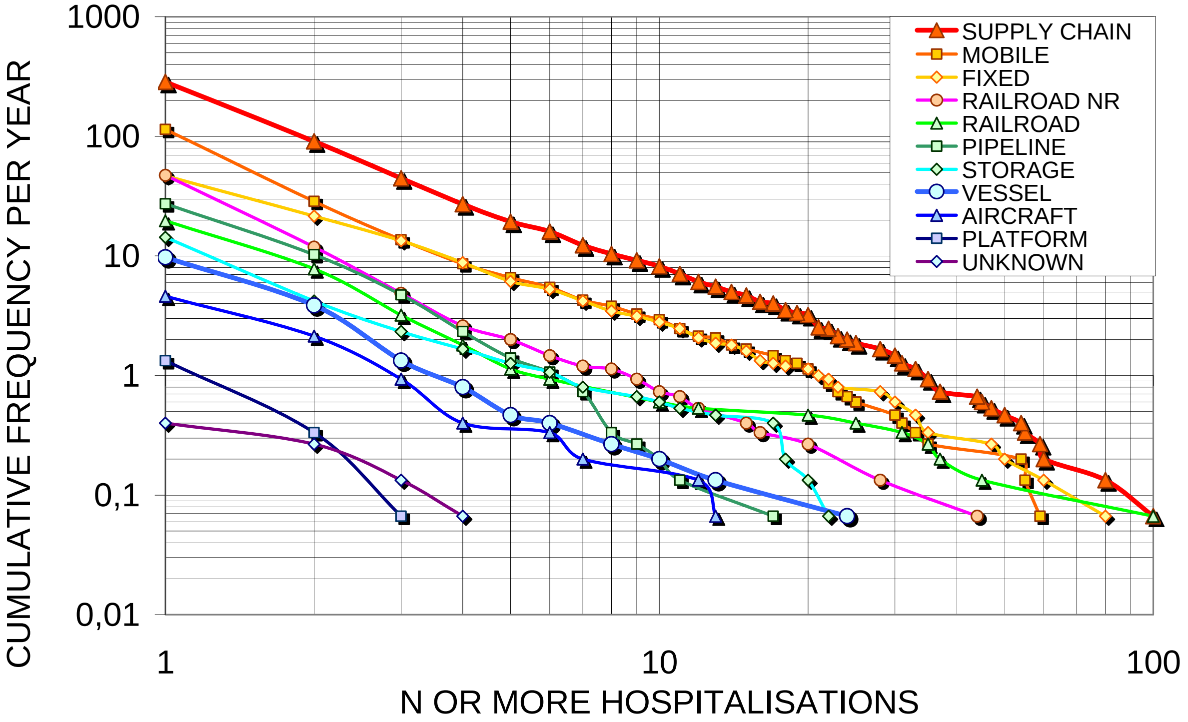

Figure 6.11: FN-curves of supply chain hospitalisation risks by system (U.S. 1990-2004)

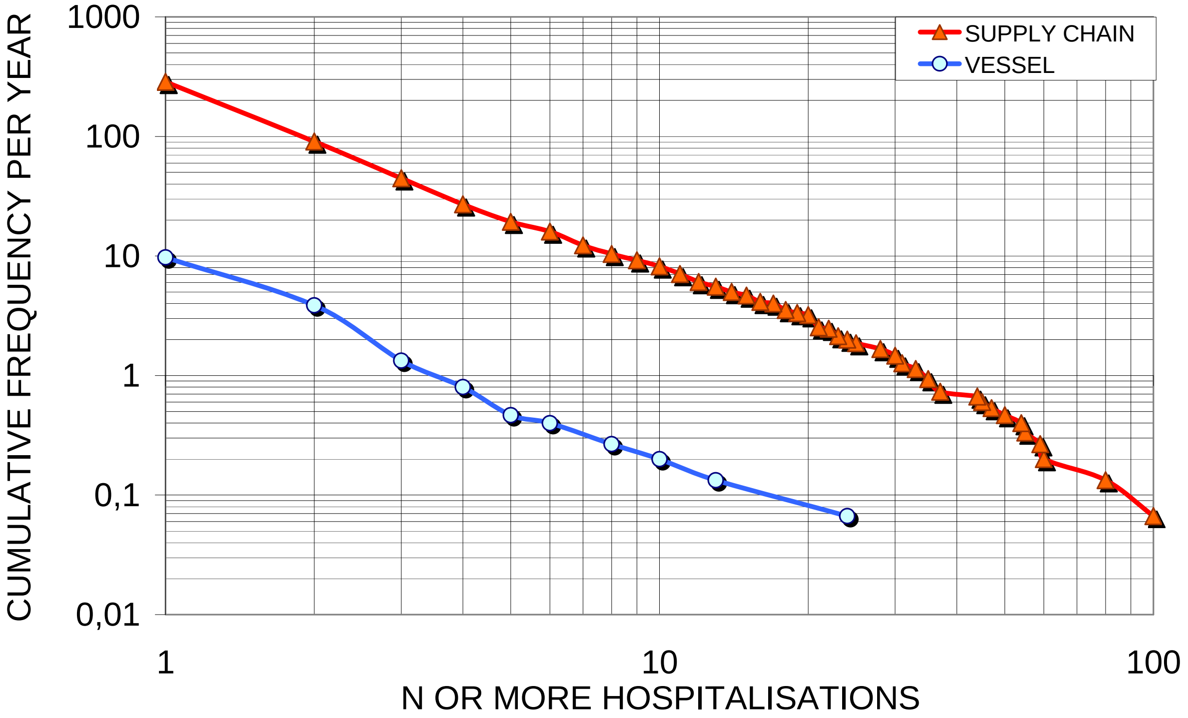

Figure 6.12: FN-curves of vessel and supply chain hospitalisation risks (U.S. 1990-2004)

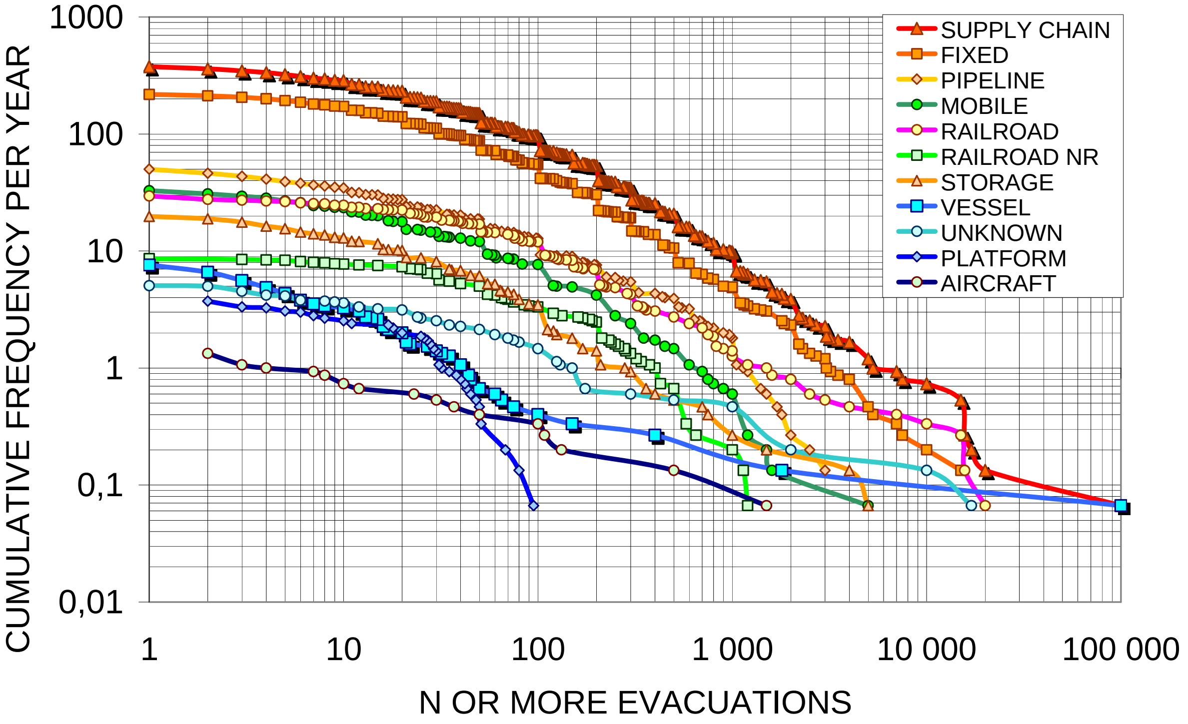

Figure 6.13: FN-curves of supply chain evacuation risks by system (U.S. 1990-2004)

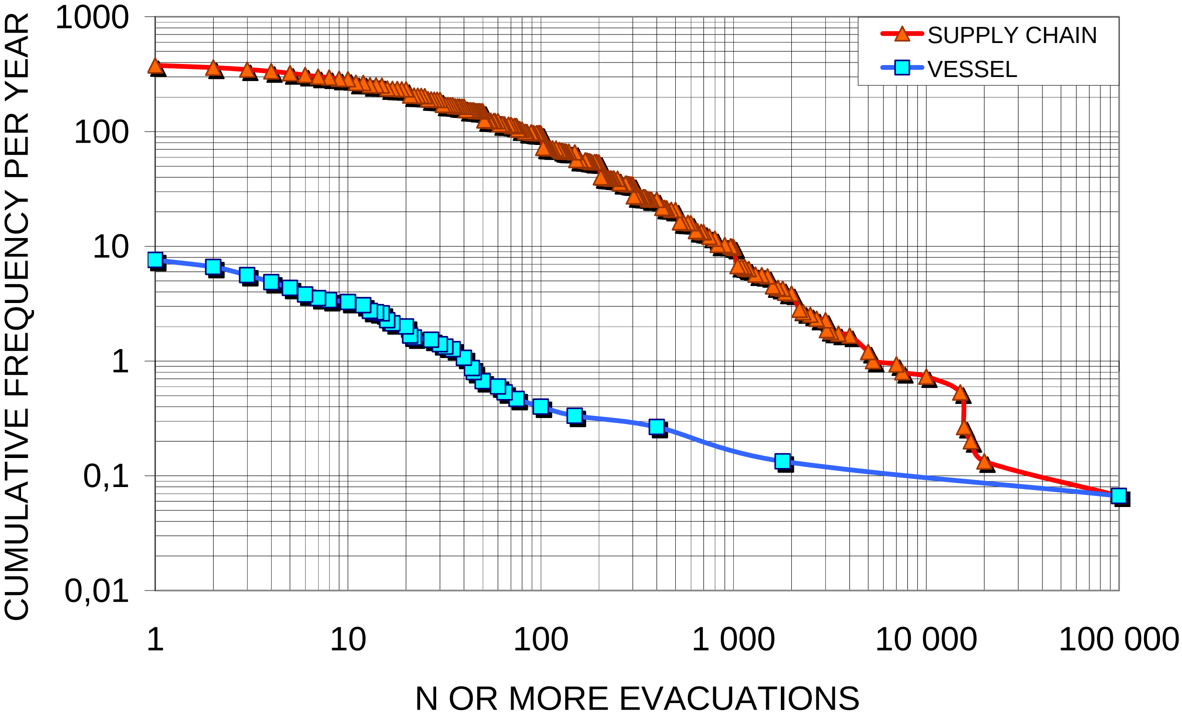

Figure 6.14: FN-curves of vessel and supply chain evacuation risks (U.S. 1990-2004)

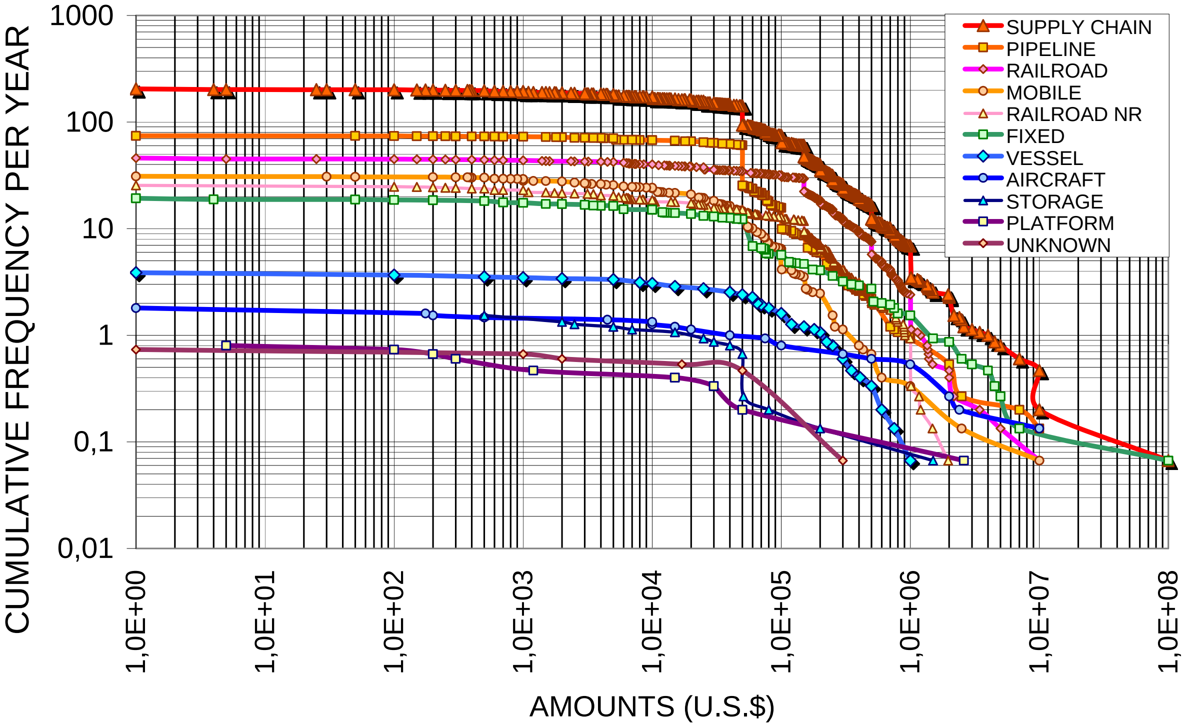

Figure 6.15: FN-curves of supply chain damage risks by system (U.S. 1990-2004)

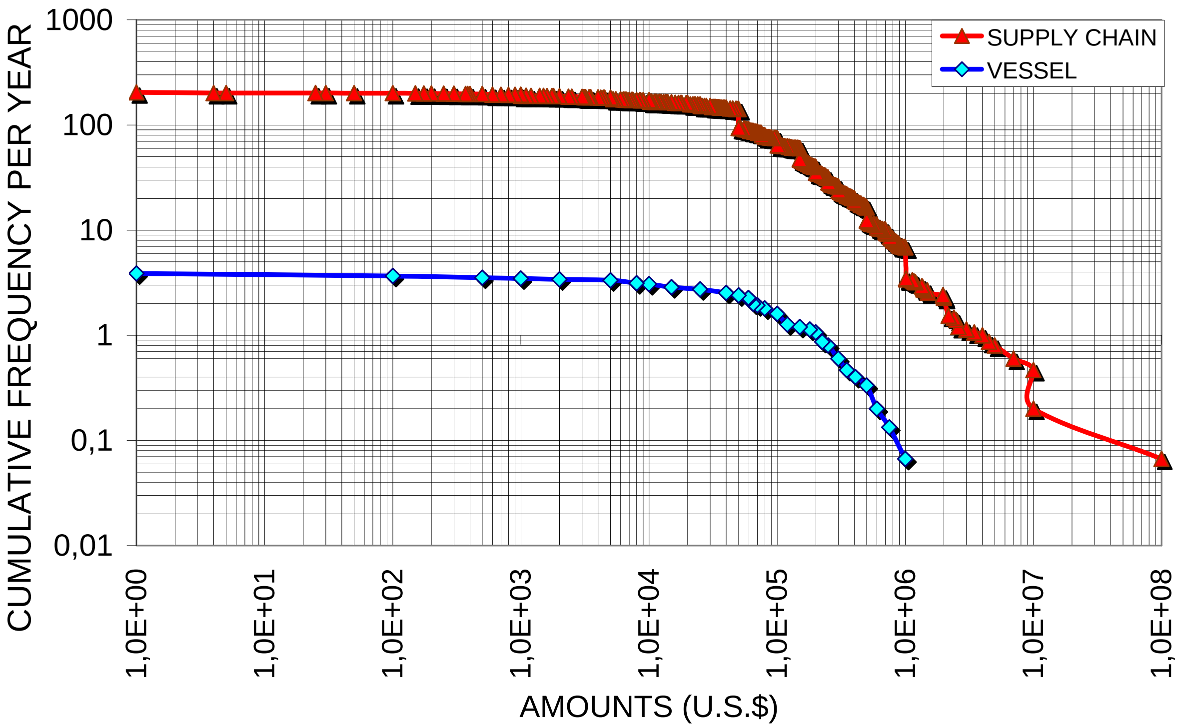

Figure 6.16: FN-curves of vessel and supply chain damage risks (U.S. 1990-2004)

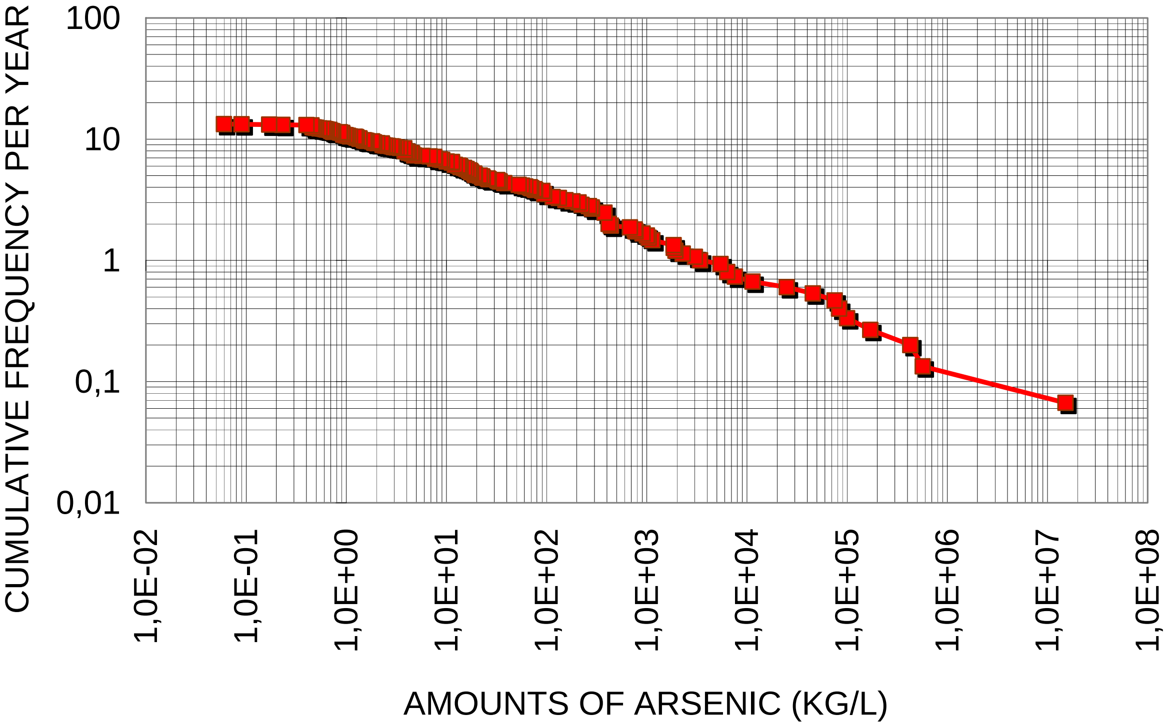

Figure 6.17: FN-curves of supply chain environmental (arsenic) risks (U.S. 1990-2004)

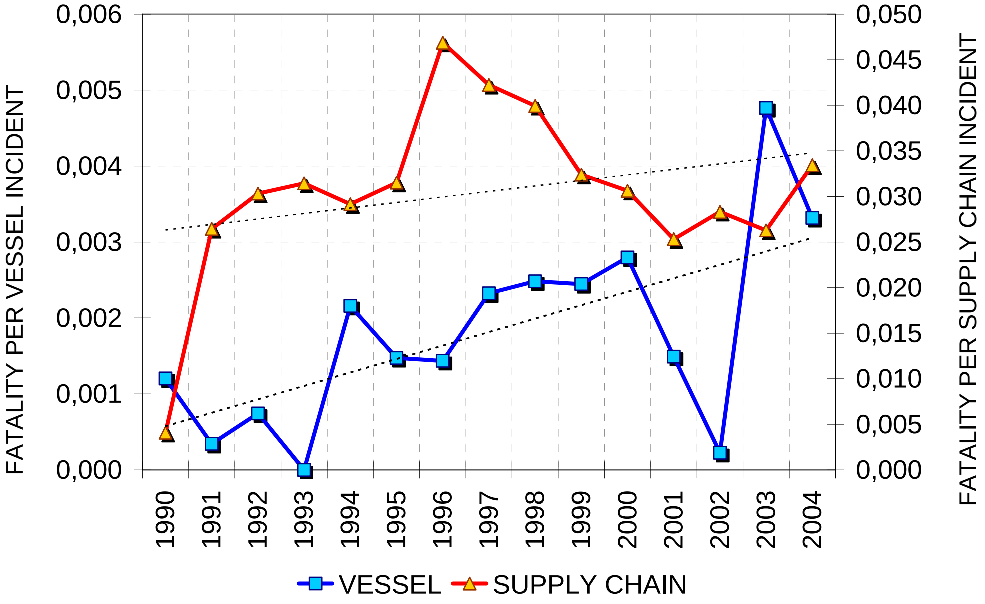

Figure 6.18: Vessel and supply chain fatality risks measured as the ratios between fatal incidents and fatalities and incidents (U.S. 1990-2004)

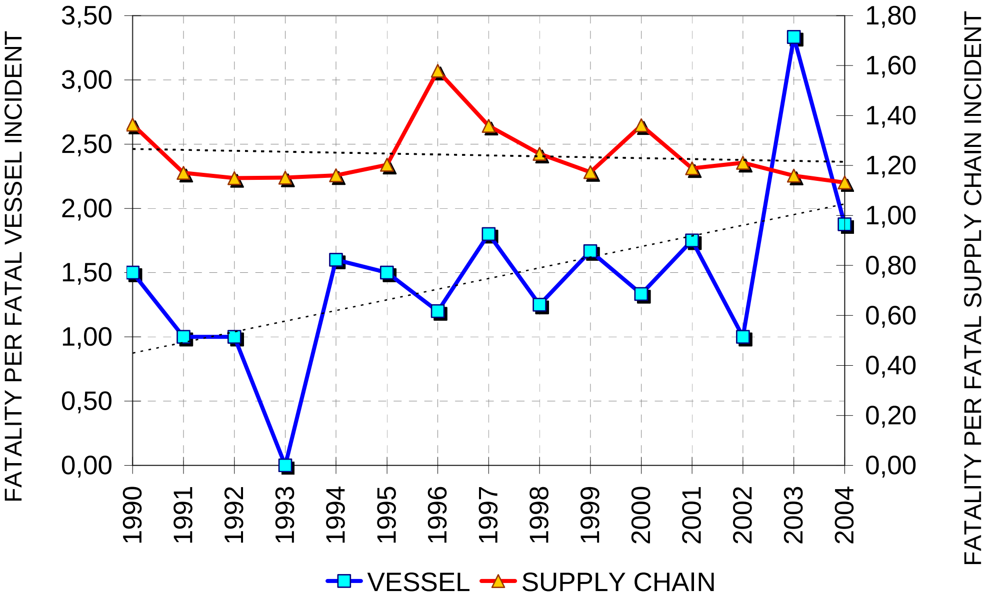

Figure 6.19: Vessel and supply chain fatality risks measured as the ratios between fatalities and fatal incidents (U.S. 1990-2004)

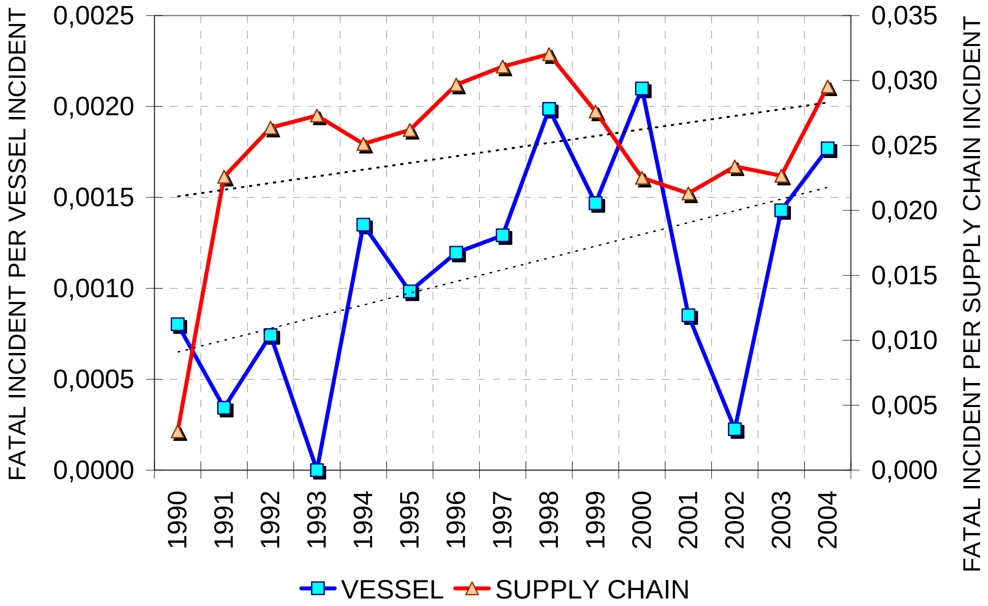

Figure 6.20: Vessel and supply chain fatality risks measured as the ratios between fatal incidents and incidents (U.S. 1990-2004)

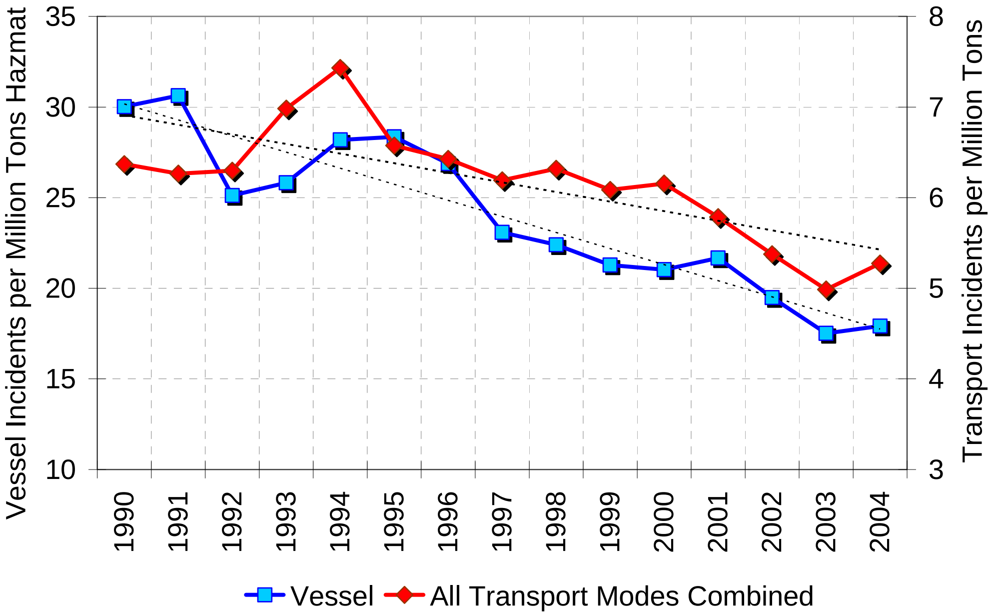

Figure 6.21: Vessel and all transport modes combined incident risks measured as the ratios between incidents and amounts of hazmat shipments (per million tons) (U.S. 1990-2004)

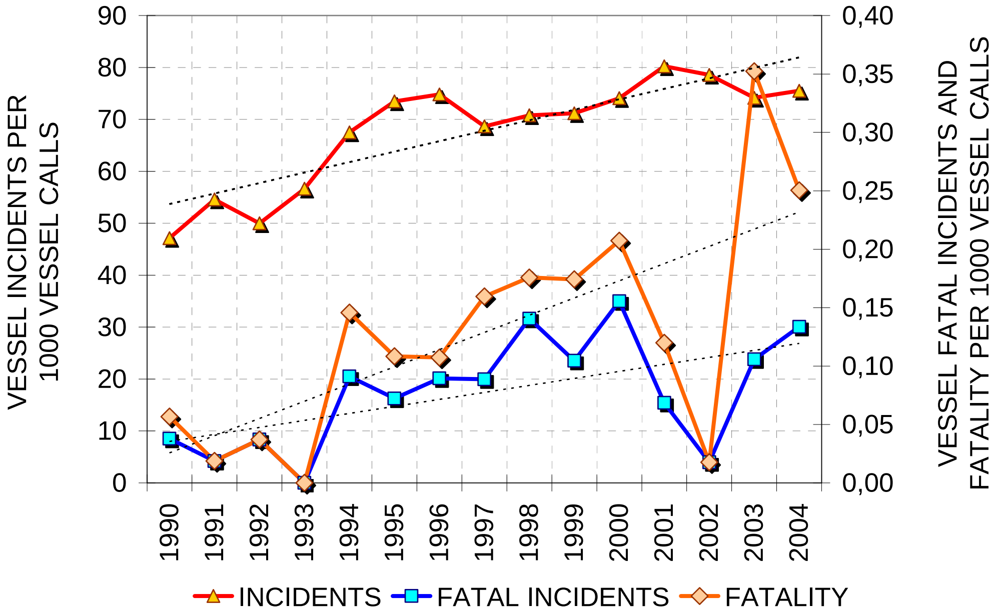

Figure 6.22: Vessel incidents, fatal incidents and fatality risks measured as the ratios between incidents and fatalities and vessel calls (U.S. 1990-2004)

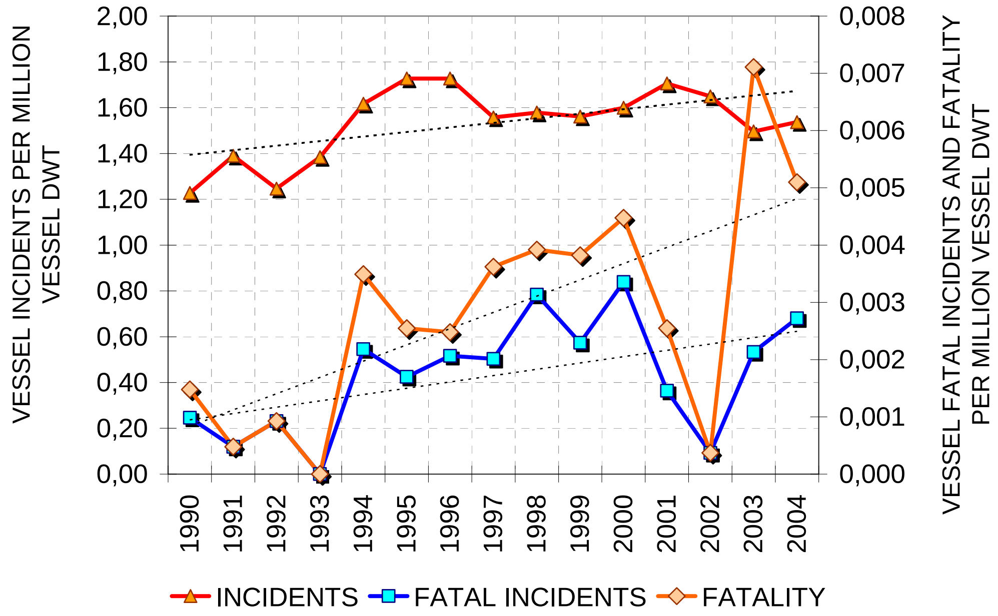

Figure 6.23: Vessel incidents, fatal incidents and fatality risks measured as the ratios between incidents and fatalities and vessel dwt (per million dwt) (U.S. 1990-2004)

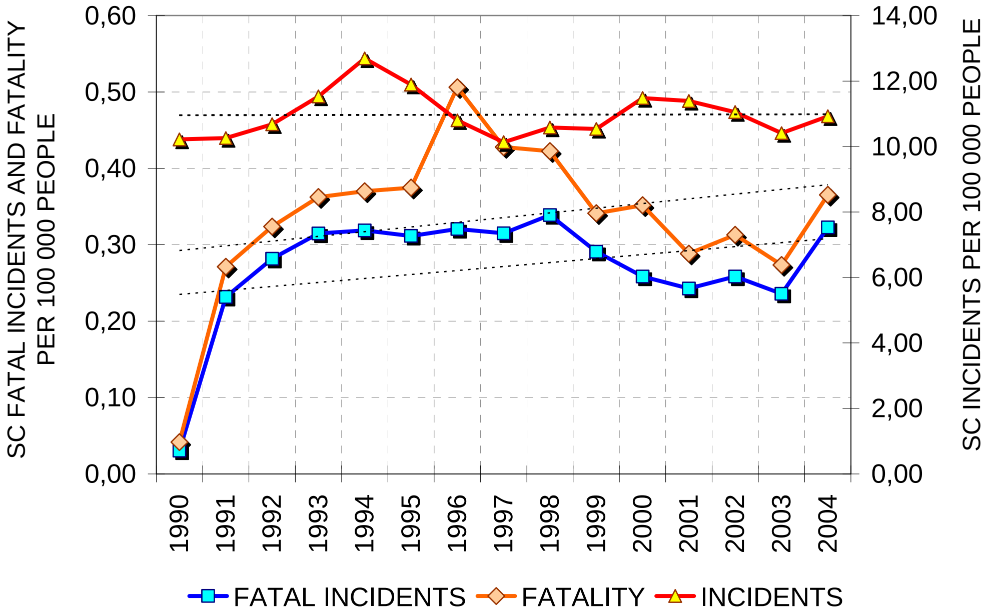

Figure 6.24: Supply chain incidents, fatal incidents and fatality risks measured as the ratios between incidents and fatalities and the population (U.S. 1990-2004)

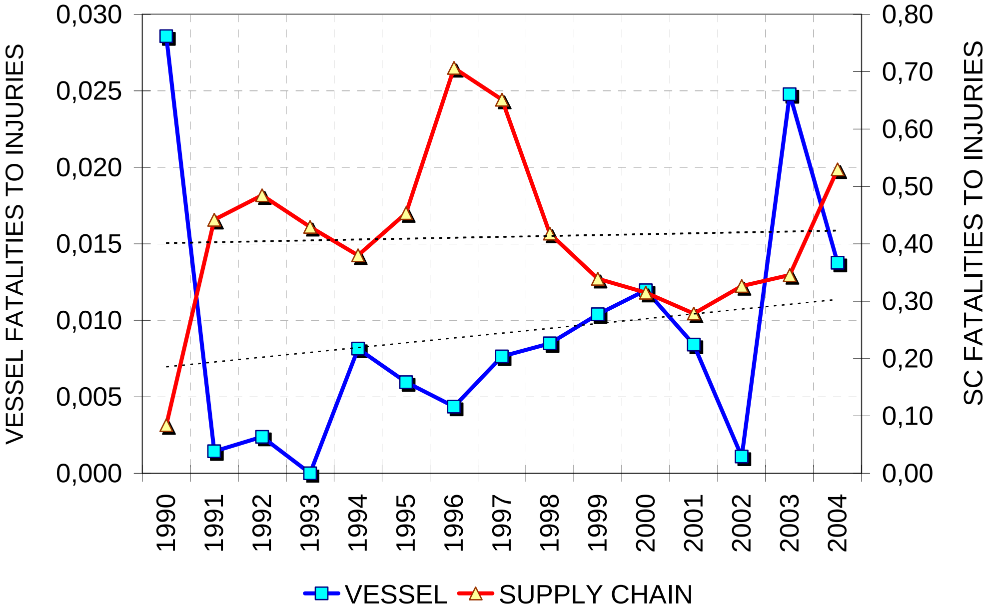

Figure 6.25: Supply chain and vessel fatality risks measured as the ratios between fatalities and injuries (U.S. 1990-2004)

PART III: STAGE 3 - CONCLUSIONS AND RECOMMENDATIONS

7. Stage 3 – Conclusions and Recommendations

In this validating demonstration of the risk analysis framework presented in Chapter 5, Vol. I, efforts have been made to achieve both research objectives and to provide answers to the questions set in Chapters 1, Vol. I and Vol. II. This study provides answers to many questions concerning the risks, which will hopefully contribute to better understanding of the risks of the maritime transport system of packaged dangerous goods as well as other systems and activities of the dangerous goods supply chain. The demonstration showed that the framework satisfies both validity and reliability conditions. The framework is also applicable to other systems and phenomena (i.e. risks) of interest. The results of the study replicated the constituent elements of the framework. Given the representativeness, the large amounts (i.e. the sample size) and the diversity of the datasets used in this study, and the universal properties of the systems and phenomena, the results and recommendations of this study are also valid for other systems (i.e. other systems than the maritime transport system) in other locations, countries or regions (i.e. other countries than the U.S.), including the countries of the Baltic Sea Region. Furthermore, given the large amounts of the data, the results of this study have a higher degree of validity and reliability than the results of many risk studies cited in both volumes. Based on the results and understanding gained in this study, recommendations provided in this chapter (Chapter 7, Section 7.2) and Appendix 3, Vol. II, will contribute to improving of human safety and health and the protection of the marine environment and property.

In the following section, the conclusions and recommendations of the study are discussed in detail.

The conclusions and recommendations (see the **highlighted area** in Figure 7.1) provided in the following section are valid for the m/v SCI accident case and the sub-population of marine accidents represented by the case. Given the representativeness of the case and the large amount and diversity of data used in this study, as well as the universal properties of systems and phenomena (i.e. risks) under the study, many conclusions and recommendations are valid for the general population and sub-populations of marine accidents/incidents involving bulk dangerous cargoes, marine accidents/incidents in general (i.e. those that may not necessarily involve dangerous goods), and accidents/incidents occurring in other systems, activities, countries or regions. On the other hand, given the specific or unique properties of the systems and risks related to the local conditions (i.e. the U.S.), some results and recommendations should be treated with cautions. Thus, the risks of maritime transport system in other countries, regions or at open seas may differ from (higher or lower than) the risks U.S. maritime transport system.

The demonstration of the framework is based on a large amount of different types of datasets, including quantitative and qualitative datasets, mainly collected from U.S. data sources. The U.S. is the world's largest economy and one of the largest sources of goods producers and consumers, including large amounts of many different types of dangerous goods or hazmat. According to the HCB (1986-2003) database records, approximately 17% of the world's marine accidents have been reported in U.S. waters. The m/v SCI accident case is a representative case. The analysis of the m/v SCI accident case was also supported by the quantitative data analysis, including the analysis of two of the U.S.'s largest hazmat incident datasets. Thus, evaluation of the frequency of the m/v SCI accident is largely supported by statistical data. Without this support, evaluation of the frequency would have been an impossible task. In the absence of this evaluation, risks of the m/v SCI accident could not have been evaluated. The risk analysis process and, subsequently, the demonstration of the framework would have been incomplete.

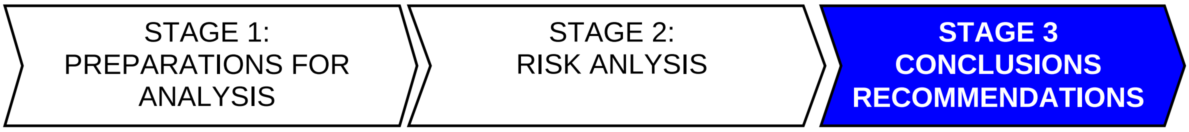

Figure 7.1: Stage 3 – Conclusions and recommendations (continued from Figure 1.1)

7.1. Conclusions

The following section provides concluding remarks concerning the process and results of the validating demonstration:

7.1.1. Preparing for the analysis

In this risk analysis, efforts have been made to provide answers to the fundamental and other questions concerning the risk elements, including transport hazards, causes and contributing factors, exposures, consequences and frequency. The key objectives of the risk analysis were to enhance understanding of dangerous goods risks and provide recommendations for improving safety and health and marine environment and property protection. For the reasons mentioned in Chapter 1, Vol. II, the validating demonstration of the framework was extended to risk analysis in other systems of the dangerous goods supply chain. In order to provide answers to the questions and achieve the objectives, various datasets were selected and prepared for analysis, including the m/v SCI accident case history and other cases, and two of the largest hazmat incident databases in the U.S.

7.1.2. System definition

Prior to the analysis, the main elements of the system under study have been defined. The definitions, concepts and background information presented in this section provided essential support for the analysis of empirical data. The m/v SCI accident involved, to various degrees, a number of states, namely New Jersey, Pennsylvania, Maryland, Delaware and South Carolina. The area, which includes all the mentioned states, is characterised by a high level of industrial and commercial activities, including maritime transport of increasingly large amounts of different types of dangerous goods. The m/v SCI accident was not quite unexpected. It is one of hundreds and thousands of vessel incidents reported each year respectively in the area and in other U.S. waters. However, because of the magnitude of the severity of consequences, the m/v SCI accident became an unusual case, sparking very intense debates in the U.S. The loss of arsenic containers occurred in a sensitive ecological zone of great importance for the local community and beyond. However, the ecosystem of the area has been and still is exposed to a wide range of contaminants, including arsenic compounds, released from various sources. The amount of arsenic carried onboard the m/v SCI was added to the amount of arsenic that has entered and is still entering into the ecosystem, including the marine environment. A large portion of the state of New Jersey population has been and still is exposed to arsenic compounds.

7.1.3. Hazard identification

The risk analysis process began with hazard identification, which provided answers to several questions, such as: “Why and how did the m/v SCI accident happen?” “What were the causes and contributing factors?” The questions (why, how, what, who, where) were systematically asked at the lowest level of resolution for which data were available. Prior to the analysis, due to the large number of complex events associated with the m/v SCI accident, a set of events (top events), from which the analysis process began, was initially identified. Hazard identification followed these key steps:

Top event: The breach of packages leading to the release of dangerous goods was identified as the top event. In the case of the m/v SCI accident, the breach of packagings, which occurred at various levels of packagings, was the necessary and sufficient condition for arsenic trioxide and magnesium phosphide releases. The breach of drums preceded the release events. Transport incidents involving PDG have frequently been associated with the breach of packagings and dangerous goods releases. However, in many cases, the breach events may be neither necessary nor sufficient conditions for the releases and involvements of dangerous goods. The statistical data show that approximately 77% of the top 13 package types involved in transport incidents were box, drum, and bottle/jug. Plastic/fibre package types accounted for 60% of the top 13 package types involved in transport incidents. The m/v SCI accident case showed that, under similar conditions, the plastic container failed disastrously compared to steel containers. The most frequently damaged or failed locations and components of packages are a) areas: top (36.5%) and bottom (24.4%); b) components: packaging materials (41.3%), closure (22.3%) and fitting or valve (7.9%).

Transport hazards: Packages carried onboard the m/v SCI were, to varying degrees, exposed to mechanical hazards, such as shock loads, impacts, compressions and racking. Arsenic trioxide containers and drums lost at sea were (and are expected to be) in addition exposed to corrosion. These hazards caused and/or contributed to the breach of drums. However, not all of the exposed drums breached. Furthermore, many drums were deformed, but still with their integrity intact. The extent of the breach was a function of the combination of different factors including: a) the type, extent/intensity and duration of hazards; and b) packaging design and construction conditions. Some of the mechanical hazards may have exceeded the systems (i.e. the ship, cargo securing and packaging systems) design and construction conditions. The statistical data show that packaging failures are attributed to a wide range of hazards, but the most frequent hazards are reported: a) mechanical hazards, such as those due to puncturing, crushing, cracking, rupturing and pressure; and b) in contact with water, ground and floor. The first category (*a*) of transport hazards is consistent with the m/v SCI accident case. However, transport incidents involving PDG may not necessarily be the result of or associated with any breach or failure of packages due to transport hazards. In many cases, dangerous goods releases have occurred due to technical and operational failures and human errors in connection with the systems and related activities.

Marine accidents/incidents: The m/v SCI containers damage and losses, which by definition fall in the “other” category of marine accidents/incidents, as defined by the relevant maritime organisations or authorities, led to the exposure of drums to excessive transport hazards. The statistical data show that many transport and marine incidents involving PDG (e.g. cargo losses at sea, spills, contamination, toxic releases and fires/explosions) are attributed to transport hazards exerted in marine accidents/ incidents, as defined, including collision, grounding, foundering, listing/ capsizing and fire/explosion (i.e. fire/ explosion other than that due to dangerous goods). Dangerous goods releases or involvements may also be the result of other categories of events, such as deliberate acts.

Causes and contributing factors: The m/v SCI cargo damage and losses were directly attributed to the failures in the cargo securing system. The system failed disastrously as the result of the combination of a large menu of causes and contributing factors, including inherent deficiencies/failures in the packaging and cargo securing systems, inadequate cargo packing, stowing and securing practices and procedures, navigational errors, and severe weather conditions. The cargo securing system was mismanaged and poorly maintained. The crew lacked specific training and expertise in cargo stowing and securing. Lacking a cargo-securing manual and other relevant instructions onboard the ship, the ship personnel poorly improvised cargo stowage and securing. Effects of weather conditions were exacerbated by the combination of unsuitable ship stability conditions (excessive GM) and poor navigational skills of the master as well as other deck officers

The accident and its consequences would have been avoided altogether if the master had taken the reasonable decision of waiting in Port Elizabeth until weather conditions had improved. However, the master’s decision to get the ship to sea regardless of anticipated bad weather conditions may have been affected by the combination of the master's poor decision-making capacity, individual and industry prejudices and business (costs and time) constraints.

The data available suggested that the casualty conditions, such as the rolling angle (35^o), GM (1.86 m), and forces exerted in synchronised heavy rollings and green waters on the ship's deck might have exceeded design and construction specifications. The design and construction of the systems are inferred with assumptions and guesswork.

Even after damage of packages and releases of dangerous substances, there were still many opportunities to respond appropriately in interrupting the chain of events and preventing the human exposures and consequences. Unlike the investigation report and other sources of the m/v SCI accident case cited in this chapter, which primarily put the blame on the ship (master, officers, bosun and crewmembers) and the shipowner for the accident, this risk analysis showed that both ship and shore personnel alike failed, to various extents, deliberately or unconsciously. Neither ship nor shore personnel identified and reported incidents and hazardous conditions. The lack of knowledge and/or negligence of the parties involved, including the responsible authorities, were some of the major factors that contributed to the chain of failures, putting other people, the ship, the marine environment, ports and local communities at risk. Because of the lack of dangerous goods-related training and failure to exercise common sense, good practices and seamanship and due diligence in handling of dangerous goods, some of the ship and shore personnel showed gross negligence and the lack of a safety culture.

The m/v SCI accident and consequences associated with it were the result of a complex cause-effect chain. The main categories of causes and contributing factors consisted of human, technical, operational, managerial, environmental (weather conditions) and other factors. These categories are largely consistent with the categories explored through the statistical data analysis.

7.1.4. Exposures and consequences

The list of dangerous goods: The list of dangerous goods carried onboard the m/v SCI and involved in the accident included arsenic trioxide (class 6.1) (459.3 tons) and magnesium phosphide (class 4.3) (1.8 tons). The ship was also carrying other dangerous goods, but the case history provided no information about the classes and amounts. The dangerous goods involved in the case of the m/v SCI accident were only a very small fraction of the long list of hazmat involved each year in the U.S. In addition, the m/v SCI accident, which involved the loss of arsenic trioxide containers/drums at sea, in an environmentally and economically sensitive and important sea area for the local community, is one of 24 arsenic release incidents occurring on average each year in the U.S. (1990-2004).

The statistical data analysis showed that the top three most frequent classes of hazmat reported involved in transport incidents in the U.S. (HMIS, 1993-2004) have been classes 3, 8 and 6, which combined accounted for approximately 88% of all classes involved in transport incidents. The top two hazmat shipping names involved in all transport modes combined and maritime transport of PDG incidents are reported, respectively, a) corrosive and flammable liquids N.O.S., and b) phosphoric acid and ammonia anhydrous.

Dangerous goods/hazmat hazards: The hazardous properties of arsenic trioxide and magnesium phosphide played an essential role in the course of events and the extent of exposures, consequences and threats. Arsenic is extremely poisonous and carcinogenic. Many credible data sources confirm that arsenic is bioaccumulative and harmful to aquatic organisms. Magnesium phosphide reacted with water and/or moisture inside the hold and emitted phosphine gas, which is highly poisonous and flammable. The gas might have led to spontaneous combustion or explosion if the concentration inside the hold had reached a critical level. Because of the lack of dangerous goods-related training and negligence, neither the ship nor the shore personnel were aware of these hazards. The statistical data show that the vast majority (ca. 75-85%) of all transport modes combined and maritime transport of PDG incidents have involved hazmat posing fire/explosion and corrosion hazards.

The high frequency of involvement of the classes and shipping names mentioned above could be explained by inherent hazardous properties of dangerous goods and the large number of shipments. In cases of transport including maritime transport of PDG incidents, the search, rescue and response teams should be in particular well prepared to deal with the aforementioned dangerous goods classes and hazards.

Routes of exposure – modes of contact: Coming into contact with both chemicals was a necessary condition for chemicals to cause harm to risk receptors. Arsenic trioxide and phosphine gas present hazards by inhalation, ingestion and contact. In the case of the m/v SCI accident, all people affected by arsenic trioxide and phosphine gas were most likely exposed to chemicals through *inhalation*. Other routes of exposure to chemicals are not excluded.

Consequences: Based on empirical data and criteria and definitions available, the order of magnitude of the severity of consequences and threats associated with the m/v SCI accident is judged *serious*:

- *Human*: 40 people were health affected by arsenic and phosphine gas. Of these, 37 stevedores were sent to hospital due to exposure to very high doses of phosphine gas, twice the level of “immediately dangerous to life and health.”
- *Environment*: The analysis of samples taken within and around the area after the accident showed that the level of contamination was insignificant. However, the large amount of unrecovered arsenic trioxide (94 drums or *16 tons*) may pose real serious threats to the marine environment and the local community. The total amount of arsenic lost from the m/v SCI was one of the largest amounts of arsenic releases reported to the NRC database (1990-2004).
- *Properties*: The m/v SCI and her cargo were severely contaminated. It took more than one month to clean up and decontaminate the ship.

- *Activities*: Due to contamination and fire/explosion threats, cargo operations onboard the ship were suspended. The ship was evacuated and sent to the anchorage area for cleanup and decontamination. Due to threats posed by arsenic lost at sea, fishing was banned. The ban stayed in effect for approximately four months (January-April, 1992).
- *Others*: For two months, the m/v SCI accident remained at the centre of U.S. public, legal, media and congressional debates.
- *Costs*: The search and recovery operation related to the m/v SCI accident was one of the largest in U.S. history. Search and recovery operations alone amounted to $ 2.2 million. In terms of costs per unit (kg/ton) of dangerous substances "cleanup", the costs of the m/v SCI accident operation exceeded some of the world's major oil spills and many other incidents reported to the NRC and HMIS databases.

7.1.5. Risk evaluation of the m/v SCI accident

Table 7.1 provides a summary evaluation of risks posed by the m/v SCI accident. Based on the risk criteria available, the analysis of the data contained in the case history and other data available and judgments, the aggregated risks posed by the m/v SCI accident are found to be at a *medium to high risk level*. The risks lay in the area between the upper boundary of the *ALARP Region*, which is the *undesirable risk area,* and the lower boundary of the *Intolerable or Unacceptable Risk Region* (Figure 7.2). In particular, the environmental risks are found to be at a relatively high risk level within the Intolerable Risk Region.

Table 7.1: A summary risk evaluation of the m/v SCI accident

Risks	Risk criteria	Risk level	Tolerability/ acceptability – Risk management strategies and measures
Aggregated (human and property) risks	IMO Risk Matrix	Medium	Acceptable Risks, if made As Low As Reasonably Practical (ALARP)
Aggregated environmental risks	Wright criteria	High	Intolerable/ Not Acceptable Risks - Incorporate risk reducing strategies and measures
Aggregated (human, environmental, property and reputation) risks	ISO Risk Matrix	Medium – High	Intolerable Risks - Incorporate risk reducing strategies and measures
Summary		**Medium – High**	Intolerable Risks - Incorporate risk reducing strategies and measures

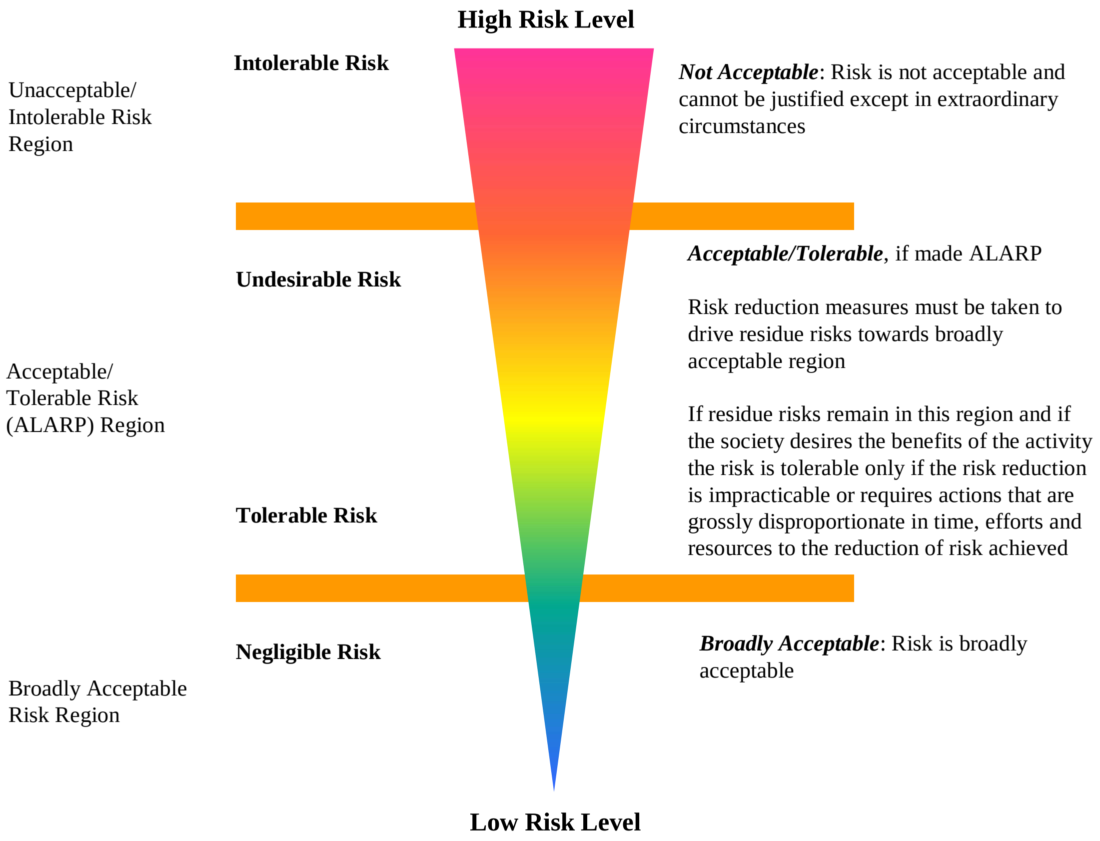

Figure 7.2: Risk regions/levels and principal risk management strategies (adapted after IMO, 2004a; HSE, 1999 and ISO, 1998)

The risk analysis of the m/v SCI accident, based on rigorous scientific analysis procedures, largely considered technical aspects of the risks involved. However, based on the data available, the analysis also dealt, to some extent, with some other non-technical matters, such as public perception, image, reputation and legal aspects. The results of the risks analysis, as well as the case itself, may further undergo thorough analysis and evaluation processes. With all information and tools at their disposal, the relevant decision makers or authorities may decide to further evaluate the significance of the risks, taking into consideration and weighing various aspects of the risks, including technical, socio-economical, political and other aspects. They may judge whether the current risks are socially, ethically and politically acceptable.

Given the large amounts of incidents and other risk-related data available, the risks of dangerous goods are statistically verifiable risks. Therefore, the qualitative risk analysis of the m/v SCI accident case, as well as other individual cases, cannot serve as a substitute for the risk analysis of the maritime transport of dangerous goods in U.S. territorial waters. This is also valid for many other countries. The m/v SCI accident was only one of many vessel incidents occurring each year in U.S territorial waters. However, the results of the risk analysis of this representative case, or other cases, provide valuable lessons and insights for a better understanding and management of risks in the maritime transport of packaged dangerous goods and beyond. The qualitative risk analysis of individual cases can also be valuable when combined with quantitative analysis of the statistical data. The information generated in the qualitative analysis may serve to extend and fill gaps in the statistical data, and provide supports and explanations for the quantitative data analysis.

7.2. Some recommendations

One of the key purposes of the risk analysis is to suggest to decision makers and relevant authorities strategies and measures for improving human safety and health and protection of the environment and property. For more information on principles of risk management strategies and measures, see Chapter 3, Vol. I, and Mullai 2006b. Based on the results of the risk analysis, the following section provides some recommendations.

In the case of the m/v SCI accident, for that part of the aggregated risks, such as human and property risks, which is found to be undesirable and lies within the ALARP Region, strategies and measures should be taken to reduce the risks of the m/v SCI accident category to a tolerable or negligible/broadly acceptable risk level. At present and perhaps in the near future, a complete elimination of all types of dangerous goods risks in all systems and activities of the dangerous goods supply chain by all costs is neither practicable nor economically feasible. At present, modern society relies very heavily on the usage of a wide range of dangerous goods and, subsequently, it desires the benefits of activities related to the dangerous goods supply chain, including the maritime transport of packaged dangerous goods. Therefore, according to the principles of risk management (Figure 7.2), those risks of the m/v SCI accident category that lay within the ALARP Region should be reduced to a level as low as is reasonably practicable and economically feasible. This means that strategies and measures should be technically practicable, and the costs associated with them should not be disproportionate to the benefits gained. The latter is a matter of a detailed costs-benefits analysis.

For that part of the aggregated risks, in particular the environmental risks posed by arsenic trioxide, which is found to be intolerable and lies within the “Unacceptable/ Intolerable Region”, measures should be taken to minimise or even eliminate these types of risks in the future. Some risk management measures may include:

- In the light of new and large amounts of data, including data presented in this volume, review the properties of arsenic trioxide and other arsenic compounds.
- Review regulations and practices governing maritime transport of arsenic trioxide and other arsenic compounds.
- Reduce or limit the amount/number of packages in arsenic shipments carried by water.
- Ensure that arsenic shipments are stowed below the ship’s deck.
- Avoid the carriage of arsenic trioxide and other arsenic compounds through environmentally sensitive areas, in particular in the areas with a high rate of marine accidents.

- Find other alternative modes of transport, such as road and rail transport, when applicable, for the carriage of arsenic compounds and other severe and very severe marine pollutants.
- In order to preserve the entire ecosystem and protect present and future generations, one preventive measure is to ban or phase out pesticides and other highly toxic substances, including arsenic trioxide and other arsenic compounds, and to replace them with "green" products. This solution, which may be part of the integrated risk management concept of the ecosystem, is in the best interests of human beings and the environment alike, and it will satisfy all parties concerned.

A detailed list of recommendations for improving human safety and health and protecting the marine environment and property is provided in Appendix 3, Vol. II.

7.3. Concluding remarks – validity and reliability

The validating demonstration showed that the constituent constructs of the risk analysis framework presented in Chapter 5, Vol. I, and results generated by it application are valid and reliable. The following section provides a detailed discussion.

Construct validity concerns the degree to which a study accurately reflects or assesses the specific concepts that the researcher is attempting to measure (Yin, 1994). The constituent constructs of the framework represent the essential concepts of the maritime transport system and risks associated with it. The risk analysis demonstrated that the framework could facilitate measurement and assessment of the relevant and specific concepts of risks in maritime transport of packaged dangerous goods. The entire risk analysis process focused on providing answers to the fundamental and other questions (concepts) concerning risks.

Internal validity is a concern for explanatory or causal studies only, in which an investigator is trying to determine causal relationships, whether an event *x* led to another event *y* (Yin, 1994) (Sue, 1999). The constituent constructs of the risk analysis framework are essentially interlinked. These relationships reflect the combination of the logic of the analysis processes, relationships among the constituent elements of the system and risks associated with it, and the courses of events of marine accidents/ incidents involving dangerous goods. In addition, the risk analysis demonstrated that the framework has the capacity to facilitate exploration of casual relationships. Based on the combination of qualitative and quantitative data and data analysis methods in this risk analysis, causal relationships among relevant variables have been explored.

External validity is the extent to which the results of the research are generalizable or transferable to the populations and settings of interest (Sue, 1999). The framework has a high degree of application and generalization. The framework facilitated the risk analysis in maritime transport of packaged dangerous goods as well as other systems of the dangerous goods/hazmat supply chain, including other modes of transport. In addition, the framework has the capacity to facilitate risk analyses ranging from qualitative analysis based on a single or a few case histories to large and complicated quantitative risk studies. The m/v SCI accident case history alone could not provide a full demonstration. The case, which is one of the most detailed marine accident case histories reviewed, was, to some extent, “too small to properly fit” into the wide scope of the application of the framework. However, with the support of a combination of other case histories, statistical data and personal work and research experiences, every reasonable effort has been made to provide a complete demonstration. In addition, the results of risk analysis are valid and relevant for understanding and managing risks of maritime transport of packaged dangerous goods and other systems of the supply chain in the U.S. and other countries.

Reliability is defined as the quality of a measure that possesses reproducibility (Batterham and George, 2003). Neither the m/v SCI accident case history nor statistical data had the capacity to induce any significant changes to the framework.[40] The development of the framework is largely grounded on large amounts of diverse empirical data; including thousands of marine accident case histories (see Chapters 2 and 4, Vol. I). On the contrary, the other way around, the principles, guidelines and experiences laid down in the framework facilitated the risk analysis of the m/v SCI accident case and statistical data. The m/v SCI case history contained several data gaps. Every reasonable effort has been made to extend and fill gaps in data and generate valid and reliable results. The procedures and results of the risk analysis replicate the framework. Furthermore, this demonstration showed that the framework could assist risk analysts to generate valid and reliable results. However, it does not provide a full guaranty. The systems and their outcomes consist of many different elements that are in very dynamic and complex relationships. The framework consists of principal representative constructs/ variables, guidelines and principles. The risk analysis relies heavily on the analyst’s abilities and predispositions. The knowledge also derives from reasoning and rationalistic methods of inquiry. Not least, exploration, explanation, evaluation, judgement or reasoning are often based on more than the empirical data and data analysis methods at hand. The analyst’s abilities and predispositions, which may vary among risk analysts, are dependent on a wide range of different important factors, including formal education, qualifications and training, practical and research work experience, socio-economical, political and ethical factors. Risk management is a discipline in its own right. Like many other scientific disciplines, risk management requires specific competences and skills. For example, Australia’s Dangerous Goods Safety Management (DGSM, 2001) Regulation defines suitable competences and skills required to perform risk analysis in chemicals-related systems and activities.

In summary, the risk analysis framework developed in this research consists of valid and reliable constructs representing the maritime transport system and risks associated with it. The framework will facilitate the risk analysis processes. It will assist, but not guarantee, risk analysts to generate detailed, valid and reliable results.

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[40] Compare the original and the current versions of the framework. The original version, which is the version prior to model validation, can be found in Mullai A. 2004, A Risk Analysis Framework For Maritime Transport of Packaged Dangerous Goods, in Brindley C., 2004, Supply Chain Risk, Ashgate Publishing Company, UK, Chapter 9, pp 130-159.

APPENDIXES

Appendixes contain essential information related to the contents of this volume:

1. **Appendix 1: Properties of arsenic trioxide and magnesium phosphide**
2. **Appendix 2: Arsenic concentrations, transformations and effects**
3. **Appendix 3: A detailed list of recommendations**

1. Appendix 1: Properties of arsenic trioxide and magnesium phosphide

The following tables provide detailed information about arsenic trioxide and magnesium phosphide from the U.S. Chemical Hazardous Response Information System (CHRIS) (Table A1.1) and the IMDG Code. The consolidated dangerous goods list of the IMDG Code (2002) provides more detailed information than the 1990 edition. However, *arsenic trioxide has not been designated as a marine pollutant in the 2002 edition of the IMDG Code (2002)* (compare column 7 in Table A1.2 with column 4 in Table A1.3). The data for some toxicological hazards of arsenic trioxide were not available. The U.S. Office of Science and Technology (OST) has performed a data review for arsenic because additional scientific information has been developed regarding its bioaccumulation since the publication of the 304(a) criteria for arsenic in 1985. According to numerous data sources, such as (IPCS and EC, 1994; IPCS, 2001), arsenic bioaccumulates and it is harmful to aquatic organisms. For more information about the effects of arsenic, see Appendix 2.

1.1. Chemical Hazardous Response Information System (CHRIS)

Table A1.1: Arsenic trioxide information sheet based on U.S. sources (from Whipple et al., 1993)

	HAZARDOUS SUBSTANCE INFORMATION SHEET: Arsenic Trioxide
	Sources: Chemical Hazardous Response Information System (CHRIS) and Material Safety Data Sheet
	Common Name: Arsenic Trioxide Chemical Name: Arsenic Trioxide
I	**PHYSICAL/CHEMICAL PROPERTIES**
	Natural physical state: solid – at ambient temp. 20-25^{O}C
	Molecular weight: 197.8 g/g-mole
	Density: 3.7 g/ml
	Specific gravity: 3.7 at 20^{O} C
	Solubility: water 1.82g/100g
	Boiling point: 457^{O} C (855 F)
	Melting point: 315^{O}C (599 F)
	Flash point: N/A
	Other: White metal, solid
II	**HAZARDOUS CHARACTERISTICS**
A	**Toxicological hazards**
	Inhalation: Yes, concentration: 2mg/m^{3}
	Ingestion: Yes, concentration: L 050 – 45mg/Kg
	Skin/eye absorption: Yes, concentration: no data available
	Skin/eye contact: Yes, concentration: no data available
	Carcinogenic: Yes, concentration: no data available
	Teratogenic (causes malformations in a fetus): No
	Mutagenic: No
	Others: if inhaled, ingested or in contact, can cause damage to liver, kidney, lung and lymphatic system
B	**Combustible hazards**
	Combustibility: no data available
	Toxic byproduct: no data available
	Flammability: not flammable
	Explosivity: not applicable
C	**Reactivity hazard**
	Reacts: Yes, reacts with chlorine triflouride, fluorine, hydrogen fluoride, oxygen diflouride, sodium chlorite, strong oxidizers. It will form lethal arsenic gases when in contact hydrogen, water in the presence of active metals such as zinc, aluminum, magnesium, manganese, sodium, iron etc.
D	**Corrosive hazards**
	Corrosive: No
	Neutralizing agent: N/A
E	**Radioactive hazards**
	Radioactive: No

1.2. IMDG Code (1990) List

Table A1.2: Arsenic trioxide and magnesium phosphide information according to IMDG Code List (1990)

Nr.	Categories of information	Arsenic trioxide	Magnesium phosphide
1	Substance or article name	Arsenic trioxide	Magnesium phosphide
2	UN number	1561	2011
3	Class	Class 6.1: Poisonous (toxic) substances: These are substances liable either to cause death or serious injury or to harm human health if swallowed or inhaled, or by skin contact.	Class 4.3: Substances which, in contact with water, emit flammable gases. The substances in this class are either solid or liquids possessing the common property, when in contact with water, evolving flammable gases. In some cases these gases are liable to spontaneous ignition.
4	Packaging group	II	I
5	Subsidiary risk label	-	6.1: see nr. 3 – arsenic trioxide
6	EmS	6.1-04	4.3-02
7	Marine pollutant	P	-

1.3. IMDG Code (2002) List

Table A1.3: Arsenic trioxide and magnesium phosphide information according to IMDG Code List (2002)

Nr.	Categories of information		Arsenic trioxide	Magnesium phosphide
1		UN number	1561	2011
2		PSN	Arsenic trioxide	Magnesium phosphide
3		Class or division	Class 6.1: These are substances liable either to cause death or serious injuries or to harm human health if swallowed or inhaled, or by skin contact. *LD50 for acute oral toxicity*: is that dose most likely to cause death within 14 days in 50% of rats; *LD50 for acute dermal toxicity*: is that dose (mg/kg body mass) of substance which, administered by continue contact for 24 hrs with the bare skin of rabbits, is likely to cause death within 14 days in 50% of animals tested; *LC50 for acute toxicity on inhalation*: is that concentration of vapour, mist or dust which, administered by continuous inhalation to rats for one hour, is most likely to cause death within 14 days in 50% of animals tested.	Class 4.3: Substances in this class are either liquids or solids which, by interaction with water, are liable to become spontaneously flammable or give off flammable gases in dangerous quantities. Certain substances in contact with water may emit flammable gases that can form explosive mixture with air. Such mixtures are easily ignited by all ordinary sources of ignition, for example naked lights, sparking hand tools or unprotected light bulbs. The resulting blast wave and flames may danger people and the environment.
4		Subsidiary risk – marine pollutant	- -	6.1: See nr. 3 – arsenic trioxide -
5		Packing group	II	I
6		Special provisions	-	-
7		Limited	500 g	None

Nr.	Categories of information		Arsenic trioxide	Magnesium phosphide
		quantity		
8	Packing	Instructions	P002	P403
9		Provisions	-	PP31
10	IBC	Instructions	IBC08	-
11		Provisions	B2, B3	-
12	Tank instructions	IMO	-	-
13		UN	-	-
14		Provisions	-	-
15		Ems	6.1-04	4.3-02
16		Stowage and Segregation	Category A. On deck or under deck	Category E. Under the deck in a mechanically ventilated space. Clear of living quarters.
17		Properties and observations	White powder. Slightly soluble in water. Toxic if swallowed, by skin contact or by dust inhalation.	Solid. Reacts with acids or decomposes slowly in contact with water or moist air, developing phosphine, a spontaneously flammable and highly toxic gas. It reacts violently with oxidizing substances. Toxic if swallowed, by skin contact or by inhalation.

2. Appendix 2: Arsenic concentration, transformation and effects

A realistic assessment of the arsenic consequences can only be performed on an on-site basis taking into account background arsenic concentrations in the seawater column, sediments and biota in the specific area (i.e. the m/v SCI accident site: the entrance of Delaware Bay and southern coast of the state of New Jersey, U.S.), local population (biota) tolerance and other local influencing and/or mitigating factors (e.g. salinity, temperature, seawater and sediment organic matter contents, phosphate concentration). The case history contains no such data.

In the absence of exposure and consequences data for this case history, the forthcoming section provides a summary review of the state of the knowledge concerning arsenic. The purpose is to illustrate arsenic concentrations in the environment (air, water, sediments, fauna and flora) and human, processes and transformations and effects. Inferences can be drawn for this particular case history and the area of concern, i.e. the state of New Jersey and Delaware Bay. This summary also contributes the enhancing the understanding of arsenic related issues. The information contained in this summary is collected from various sources, including:

- The International Programme on Chemical Safety (IPCS) report on "Arsenic and arsenic compounds: Environmental health criteria" (IPCS, 2001). This is one of the most compressive reports concerning arsenic issues found. It is based on some 1300 scientific references, some of which are cited in this summary.
- The New Jersey Department of Environment Protection (NJDEP), Delaware River Basin Commission (DRBC) report on the Comparative Risk Project covers ecological (NJDEP, 2000) and human health (NJDEP, 2001) issues of arsenic. These two reports are very relevant because they deal with issues of arsenic in the state of New Jersey. The m/v SCI accident occurred 30 miles off the coast of Cape May, which lies in the southern coastline of the state of New Jersey (Figure 2.15).

The aforementioned reports are largely based on the results of earlier laboratory studies, experiments, field studies and real life studies, such as case histories of accidental and intentional arsenic exposure and poisoning. For many years, arsenic has been the most significant single cause of accidental deaths associated with pesticides in the U.S. (NJDEP, 2001). Unless otherwise stated, the information contained in this summary is obtained from the aforementioned sources including their references.

2.1. Arsenic transformations

Arsenic compounds continually undergo transformations and cycle through all elements of the environment and its habitats. Arsenic can be elevated to high levels in the marine environment because of natural (geology or geothermal) and human activities. The following describes processes and transformations of arsenic compounds:

Concentration in water column: Dissolved arsenic concentrates into the seawater column. Dissolved forms of arsenic in the water column include arsenate, arsenite, methylarsonic acid (MMA) and dimethylarsinic acid (DMA) (IPCS, 2001). The rate of dilution will be affected by different factors, including temperature, dissolved oxygen, pH, and salinity.

Accumulation in sediments: A large portion (as much as 80%) of arsenic that enters into the water is deposed and retained by the sediment (Langston, 1983). Inorganic arsenic can be adsorbed[41] one molecule thick on to charged particles of iron oxyhydroxides and manganese oxides and deposited or accumulated as flocculated[42] particles to sediment. Adsorption process increased as pH increased for sediments (Mok and Wai, 1990).

Biotransformation: Significant biotransformations occur in biological activity zones in the oceans. There are three major modes of arsenic biotransformations (Oscarson et al., 1980) (Scudlark and Johnson, 1982; Cullen et al., 1994):

- Redox is the process of oxidation-reduction, in which transformation between arsenic compounds take place, for example, from arsenite to arsenate;
- Reduction and methylation of inorganic arsenic, that is the process in which inorganic arsenic is converted to an organic form; and
- Biosynthesis[43] of more complex organic arsenic compounds.

There is biogeochemical cycling of compounds formed from these processes (Andreae, 1983).

Bioaccumulation: There is no general consent on whether arsenic bioaccumulates in aquatic organisms and, if it does, to what extent. Some of the data sources of the m/v SCI accident case history state that arsenic bioaccumulation in the marine environment is insignificant. The IMDG Code (2002) has not designated arsenic trioxide as an environmentally harmful substance. Arsenic trioxide has not been given the letter P, which indicates that the substance is a marine pollutant, in the IMDG Code (2002) dangerous goods list. According to the New Jersey Department of Environment Protection report (NJDEP, 2001), arsenic and arsenic-containing organic compounds have not been shown to bioaccumulate to any great extent in aquatic organisms. However, according to numerous sources, including IPCS (2001), Mason et al. (2000), Chen and Folt, (2000) and Maeda et al. (1990), arsenic and its metabolites bioaccumulate in the tissues of aquatic organisms. According to IPCS and EC (1994), arsenic trioxide is harmful to aquatic organisms. This substance may be hazardous to the environment, and, therefore, special attention should be given to birds, fish and mammals (IPCS and EC, 1994; CIS, 2005). Bioaccumulation may take place through all routes of exposure. However, food may be the primary source (Hunter, et al., 1998). For example, the analysis of three *mollusc species* that were collected at the point source of the heavy metal pollutants in the state of *New Jersey* (U.S.) has shown that the level of As accumulated in the tissues of two species was much higher than the permissible level for human consumption (Lau, et al., 1998). The degree of bioaccumulation varies across various species, modes of exposure and arsenic compounds. Organic arsenic compounds that biogenesis[44] from inorganic forms bioaccumulate in aquatic organisms, particularly in algae and lower invertebrates. As they pass through the food chain, arsenic-containing compounds are

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[41] Adsorption is the process in which a substance accumulates on the surface of a solid forming a thin film, often only one molecule thick (CED, 1992).

[42] Flocculate: to form or be formed into an aggregated woolly cloudlike mass (CED, 1992).

[43] Biosynthesis is complex biological reactions of the formation of complex compounds from simple substances by living organisms (CED, 1992).

[44] Biogenesis is the process in which a living organism originates from a parent organism similar to itself (CED, 1992).

catabolized[45] yielding arsenobetaine (i.e. organic arsenic) as a stable end-product (Phillips and Depledge, 1985).

Biomagnification: Chemical concentrations in some organisms may rise (several fold) above the environmental (water, sediments or plants) concentrations. According to Callahan et al., (1979), biomagnification of arsenic in the aquatic food chain is insignificant. Chen and Folt, (2000), Mason et al., (2000), Maeda et al. (1990) and others have concluded that arsenic does not biomagnify into aquatic organisms.

Degradation: All arsenic compounds abiodegrade or biodegrade at various degrees in water and soil. The degradation time (DT) varies across arsenic compounds and environments. For example, DT_{50} means the degradation time for 50% of a compound (half-life). In the environment, arsenic toxicity is affected by a wide range of factors, including temperature, pH and salinity of the seawater, the organic matter contents of the seawater and sediments, phosphate concentration, and the presence of other substances. In seawater, because of the seawater composition and sunlight deficiency, the rates of photochemical decomposition or degradation of arsenic are slower as compared to freshwater (Brockbank et al., 1988). Aquatic microorganisms may influence arsenic properties. Arsine gas may be released through the action of microorganisms (NJDEP, 2000). Under aerobic[46] conditions the mixed microbial cultures of sediments may be able to reduce arsenate to arsenite. Arsenic degradation increases with the increase of organic matter contents of the environment (Dickens and Hiltbold, 1967). Compounds where As is in the 3+ oxidation state are generally more toxic than compounds where As is in the 5+ oxidation state (NJDEP, 2000). Complete degradation of arsenic may range from several hours in water to several months or even years in soil. But, according to NJDEP (2001), inorganic arsenic does not break down and, therefore, will persist in the environment indefinitely.

Recycling: Arsenic recycling by phytoplankton (i.e. a plant consisting of plankton, mainly unicellular algae) is a dominant process of arsenic biotransformation (Millward et al., 1997). Inorganic arsenic is taken up and removed from the water column by planktonic organisms, and is then transported and recycled during degradation and consumption of phytoplankton. Arsenic uptake and transport are species-specific (NJDEP, 2000). Larger aquatic organisms (e.g. mussels and crabs) have the capacity to eliminate arsenic after ingestion of arsenic-contaminated food. The elimination of arsenic from organisms may range from a few days to several weeks. The rate of arsenic elimination depends on the type of organism, arsenic compound, and influencing and mitigating factors.

Summary

Arsenic is recycled and degraded from one form to another, but can remain at harmful concentration levels in the environment and organisms. For example, in seawater, DMA is converted to MMA, or aquatic microorganisms may reduce the arsenate to arsenite and a variety of methylated arsenicals, which are also harmful. Given the aforementioned facts, once released from the unrecovered drums, arsenic trioxide lost from the m/v SCI will be spread on the seafloor. It may persist in the sediments for a long time (in the worst-case scenario: for many years) at a harmful concentration level. The marine organisms, particularly

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[45] Catabolism is the metabolic process in which complex molecules are broken down into simple molecules with the release of energy (CED, 1992).

[46] Aerobic: of an organism or process depending on free oxygen or air (CED, 1992)

shellfish, inhabiting the sediments area will also be contaminated. Despite discrepancies and inconsistencies of study results and opinions, the relevant authorities should adopt a conservative view in evaluating arsenic bioaccumulation in the marine environment. Arsenic should be considered a bioaccumulative substance.

2.2. Arsenic concentrations in air, freshwater and soil

The following summarizes concentrations and exposures to arsenic in air, freshwater and soil, including the area of concern, i.e. New Jersey/Delaware Bay.

Air: Arsenic concentrations associated with particulate matter vary worldwide as follows: 0.007–1.9 ng/m^3 in remote areas; 1–28 ng/m^3 in rural locations, and 2–2320 ng/m^3 in urban environments (Schroeder et al., 1987). Significantly higher concentrations (> 1000 ng/m^3) have been measured in the vicinity of industrial sources. In the state of *New Jersey* (U.S.) alone, a total of 7.1 tons of arsenic per year has been discharged (prior to 1996) into air by various industry groups (NJDEP, 2001). A large portion of the *New Jersey* population is exposed to slightly elevated levels of arsenic in the air (NJDEP, 2001).

Freshwaters: Arsenic is widely distributed in surface freshwaters. Background concentrations in rivers and lakes are generally < 2 µg/litre, except in areas with volcanic rock and sulphide mineral deposits. In the state of *New Jersey* (U.S.), arsenic concentrations in stream water typically are *<2 µg/l* (NJDEP, 2000; Vowinkel et al., 2001). The concentrations of arsenic in unpolluted groundwater are typically in the range of 1–10 µg/litre. Mean arsenic concentrations 500 µg/litre and a maximum of 25 mg/litre have been reported for geothermal waters. Enhanced arsenic levels of <10 mg/litre have been reported near anthropogenic sources such as mining and agrochemical manufacture. Approximately 5 million residents in *New Jersey* are potentially exposed to arsenic in groundwater sources of drinking water, and there have been 4 cases of cancers per year related to drinking water only (NJDEP, 2001). Arsenic in ground and surface freshwaters enters into the sea. Arsenic water quality criterion for the state of *New Jersey* (U.S.) is: freshwater chronic criterion = 190 µg/l (NJDEP, 2000).

Terrestrial soil: Background concentrations in soil tend to range from 1 to 40 mg/kg, with a mean value of 5 mg/kg. Naturally elevated levels of arsenic in soils may be associated with geological substrata such as sulphide ores. Anthropogenically contaminated soils can have concentrations of arsenic up to several percent. The highest concentrations of arsenic in soil tend to be associated with mining waste. Up to 5% of the land acreage in the state of *New Jersey* may be contaminated by past use of arsenical pesticides (NJDEP, 2001). Average soil background for the state of *New Jersey* as a whole is <10 mg/kg; however, some samples with naturally occurring arsenic have reportedly reached as high as 370 mg/kg (NJDEP, 2000). Through ground and surface waters arsenic in soil enters into the sea. The U.S. Federal and the state of *New Jersey* (U.S.) soil cleanup criterion is *20 mg As/kg* (Vowinkel et al., 2001) (NJDEP, 2000).

Freshwater and terrestrial biota (plant and animal life): Background arsenic concentrations in freshwater and terrestrial biota are usually less than 1 mg/kg (fresh weight). Arsenic levels are higher in biota collected near anthropogenic sources or in areas with geothermal activity. Some species accumulate substantial levels, with mean concentrations of up to 3,000 mg/kg at arsenical mine sites. The data sources available do not contain information concerning arsenic concentrations in freshwater and terrestrial biota for the area of concern. However, the aforementioned facts suggest that arsenic concentrations in certain species and locations in the area may exceed the state criteria. The population in the area is exposed to arsenic in biota, which also enters into the sea.

Summary

Arsenic from the aforementioned sources enters into the marine environment of the state of *New Jersey*, particularly in estuaries and coastlines, affecting background concentrations of the seawater, sediments and marine biota. A large portion of New Jersey's population is already exposed to arsenic in land, water and air-based arsenic sources.

2.3. Arsenic concentrations and effects in the marine environment

The following summarizes arsenic concentrations and effects in the marine environment (abiosis and biota), including the area of concern, i.e. New Jersey/Delaware Bay.

2.3.1. Arsenic concentrations in the seawater and sediments (abiosis)

Seawater: Concentrations of arsenic in open ocean seawater are typically *1–2 µg/litre* (Figure A2.1). Arsenic concentrations increase with increasing salinity (Tremblay and Gobeil, 1990). The major inputs to the marine environment are river runoff and atmospheric deposition (Sanders, 1980). Arsenic concentrations are elevated in some estuaries and in waters near heavy industrial or mining and mineral-processing areas. Concentrations of arsenic compounds in *continental shelf waters of the south-eastern U.S.* (samples taken at depths of 30 m and 500 m) ranged between *1.1-1.5 µg/litre* (Waslenchuk, 1978). They were mainly affected by shelf waters and Gulf Stream disturbances (Waslenchuk, 1978). Riverine and atmospheric arsenic inputs to the shelf waters were relatively insignificant, and uptake of arsenic by biota had only a minor effect on arsenic distribution (Waslenchuk, 1978). The data sources available provide no information about arsenic concentrations for the southern coast of the state of New Jersey. The latter probably share similar values with concentrations (*1.1-1.5 µg/l*) in continental shelf waters of the south-eastern U.S. The seawater quality criterion (arsenic) for the state of *New Jersey* (U.S.) is: *saltwater chronic criterion = 36 µg/l* (NJDEP, 2000). This figure (36 µg/l) is very high compared to background concentrations of ocean seawater (1–2 µg/l) and continental shelf waters of the south-eastern U.S. (1.1-1.5 µg/l).

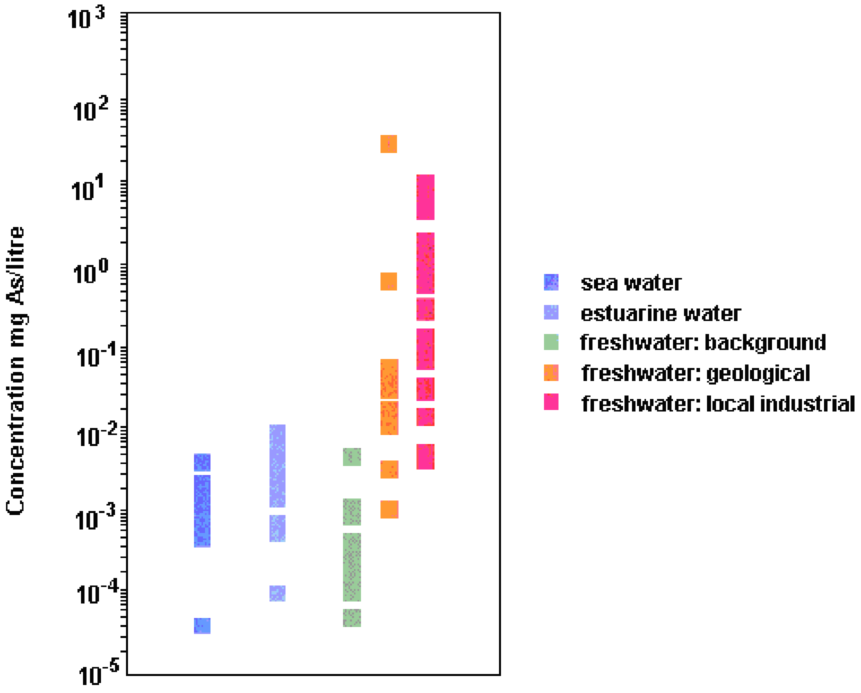

Figure A2.1: Reported concentrations of arsenic in seawater, estuary water and freshwater (IPCS, 2001)

Sediments: Mean sediment arsenic concentrations range from *5 to over 3000 mg/kg*, with the higher levels occurring in areas of contamination. Sediments in aquatic systems often have higher arsenic concentrations than those of the water (Welch et al., 1988). This is explained by the very low solubility of arsenic in water – 1.82g/100g. Most sediment arsenic concentrations reported for rivers, lakes and streams in the *U.S.* range from 0.1 to 4,000 mg/kg, with higher levels occurring in areas of contamination (Welch et al., 1988). Arsenic concentrations in *Maurice River* sediments, (*Delaware River Basin*, *New Jersey*, U.S.) ranged between 25.3-515 (maximum range 291-809) mg As/kg dry weight (Faust et al., 1987a). Sediment samples from the Raritan River (north of *New Jersey coast*, *U.S.*) have showed arsenic concentrations up to 2,200 mg/kg, and sediment from a downstream marsh location had arsenic concentrations as high as 4,030 mg/kg (NJDEP, 2000). Background arsenic concentrations in aquatic sediment for the state of *New Jersey* (U.S.) range from *<1 to 12 mg/kg* (NJDEP, 2000). The sediment arsenic concentration criteria for marine/estuarine of the state of *New Jersey* are: Effects Range-Low (ER-L) = *8.2 mg/kg*; and Effects Range-Median (ER-M) = *70 mg/kg* (NJDEP, 2000).

Summary

Given the low solubility of arsenic in water, the massive body of the ocean water, and water circulations and disturbances in the area (e.g. due to the Gulf Stream), the contamination of the seawater column by the m/v SCI’s arsenic trioxide may be very limited or insignificant. However, given the large amount of arsenic (approx. 16 tons), concentration of arsenic in the seawater over the contaminated sediments areas may easily reach and even exceed the background concentrations (*1–2 µg/l*). Arsenic may as well reach lethal concentrations for the marine organisms in this seawater. Based on assumptions and facts, including some of the above facts, the sizes of the sediments areas that may be potentially contaminated by the m/v SCI arsenic trioxide are estimated in paragraph x-x.

2.3.2. Arsenic concentrations and effects in plants and living organisms

Arsenic has the potential to impact biological integrity, to adversely affect biodiversity and thus to negatively impact ecosystem health and function (NJDEP, 2000). The following summarizes arsenic concentrations and effects on the marine biota, including plats and living organisms.

Aquatic plants: The arsenic toxicity (phytotoxicity) may be characterized by *chlorosis*, a *significant reduction* (fresh weight and height) or *cessation of growth*, *gradual wilting* and *browning*, *dehydration*, and *death* (NAS, 1977). The highest arsenic concentration caused *a significant reduction in growth* when plants were exposed to arsenic. Based on *growth inhibition* of an aquatic plant (duckweed *lemna minor*), Jenner and Janssen-Mommen (1993) have reported 14-day EC_{50} values of 0.63 mg As(III)/litre and 22.2 mg As(V)/litre, and NOECs of < 0.75 mg As(III)/litre and < 4 mg As(V)/litre. Some plants are more sensitive to arsenic than others. Some plants have shown no significant effects at arsenate concentrations of 1 mg As (V)/litre. Arsenic toxicity depends very much on the type of soil. Arsenic is 5-fold more toxic to plants in sands (toxicity threshold 40 mg/kg) than in clay soils (toxicity threshold 200 mg/kg) (Sheppard, 1992).

Marine organisms: Marine organisms normally contain arsenic residues ranging from *< 1 to more than 100 mg/kg*, for the most part as organoarsenical species such as arsenosugars (macroalgae) and arsenobetaine (invertebrates and fish). Inorganic arsenic levels in fish and shellfish are low (< 1% of the total arsenic). Because of a very low phosphate concentration in seawaters, which may lead to a high arsenate/phosphate ratio in oceans, marine organisms can normally contain much higher arsenic concentrations (< 100 mg/kg fresh weight) than living organisms in freshwater and terrestrial biota (background arsenic concentrations are usually < 1 mg/kg, fresh weight). Figure A2.2 summarises acute and chronic toxic effects of arsenic.

- **Micro and macroorganisms**: Aquatic microorganisms (microalgae) have shown a wide range of sensitivities (growth and survival) to arsenic compounds. Some microorganisms have shown resistance to arsenic. The sensitivity ranges from the most *sensitive* alga with a LOEC of 5 µg As(V)/litre to the most tolerant alga with a no-observed-effect concentration (NOEC) of 500 µg As(V)/litre (Hörnström, 1990). Adverse effects on marine periphyton communities were observed at arsenate concentrations of 15–60 µg/litre. *Growth of macroalgae may be significantly reduced* at 212 µg As(III)/litre, and at 300 µg/litre all plants may died. The toxicity of arsenate increase as the phosphate concentration decrease (Thursby and Steele, 1984).
- **Invertebrates**: Acute toxicity (48/96-h LC/EC_{50} values) of inorganic arsenic to marine invertebrates ranges from 0.011 mg As/litre (Forget et al., 1998) to >30 mg As/litre (for shrimps) (Mayer, 1987), and for *mussels* > 3 mg As/litre (Martin et al., 1981). Mean values of arsenic concentrations ranging from 1.1 to 2.7 mg/kg were reported in *clams* and oysters collected from *U.S. coastal waters* in use for shellfish production during 1985-1986 (Capar and Yess, 1996). There has been no significant effect on the number of eggs laid by crayfish, but arsenic *significantly reduced the number of eggs that hatched* (Naqvi and Flagge, 1990). Arsenite caused significant *mortality* in copepods at 4 and 10 mg As (III)/litre (Borgmann et al., 1980). Up until 2001, in the state of *New Jersey* there had been no monitoring programme for the total inorganic arsenic in fish or shellfish tissues (NJDEP, 2001).
- **Vertebrates**: Arsenic residues in *marine fish* vary considerably. In marine fish 96-h LC_{50}s range from 12.7 to 28.5 mg As (III)/litre and from 21.4 to 157 mg As(V)/litre (Hamilton and Buhl, 1990; USEPA, 1985; Taylor et al., 1985). For example, mean arsenic residues of 3.2

mg/kg (dry weight) (1.6–4.2 mg/kg) have been found in *Atlantic* tuna (Hellou et al., 1992). Arsenic residues in marine *fish muscle* have been found in the range from 0.59 to 17 mg/kg (fresh weight) with a mean value of 4.5 mg/kg (Engman and Jorhem, 1998). The mean value was 60 times greater than that found for freshwater fish in the same study. Arsenate toxicity in some fishes increases with an increase in temperature. Studies have shown non-acute lethal effects such as *survival and growth*, *avoidance behaviour* and *fertilization* or *hatching reductions*. *Migration* of trout released after arsenic exposure was *significantly reduced* at the highest concentration. *Growth was significantly reduced* at concentrations of 4300 and 4120 µg As (III)/litre for the two species fathead minnow and flagfish respectively (Lima et al., 1984). *A significant impairment of avoidance behaviour* at 100 µg As (V)/litre has been found on goldfish (Weir and Hine, 1970). The avoidance threshold for golden shiner was 28 µg As (III)/litre (as arsenite) in flow-through tests (Hartwell et al., 1989).

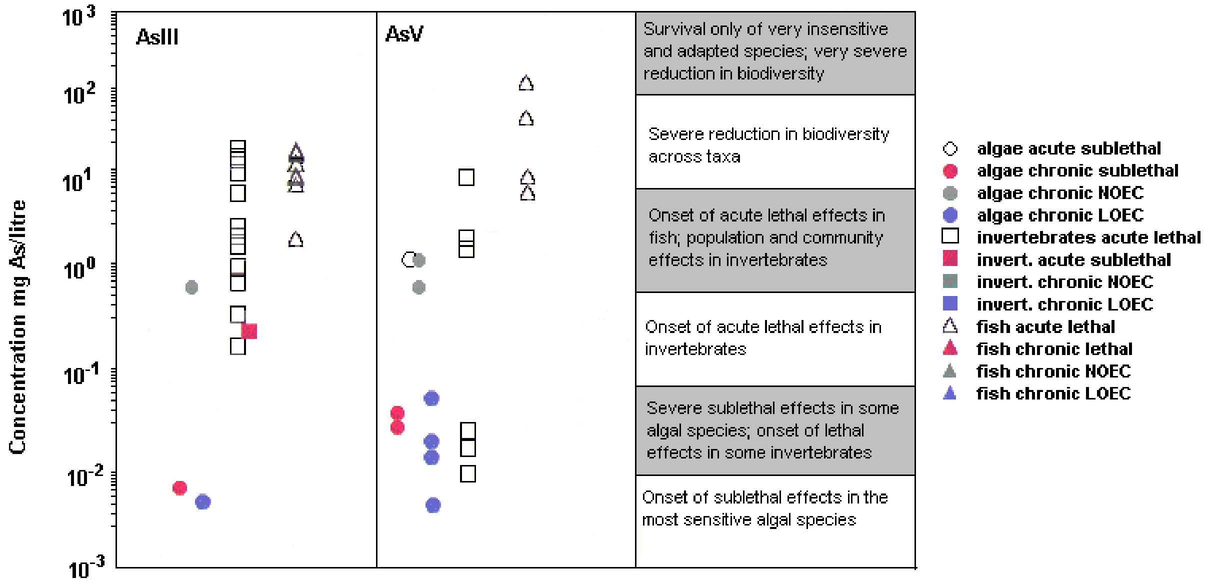

Figure A2.2: Acute and chronic toxic effects of arsenic (arsenite – AsIII and arsenate – AsV) in seawater. Likely effects are given for each order of magnitude concentrations. Effects assume no mitigation of toxicity in the environment (IPCS, 2001).

Terrestrial/coastal plants and vertebrates: Levels of soil arsenic reported to be toxic to terrestrial plants span a wide range, with toxicity thresholds ranging from around 30 mg/kg to 300 mg/kg with toxicity tending to be greater in sandy than in clay soils (IPCS, 2001). The lowest critical plant tissue concentration is approximately 1 mg/kg (PCS, 2001). Exposure to arsenic compounds can significantly affect birds and other vertebrates including those inhabiting coastlines. Signs of acute arsenite poisoning in birds include: *ataxia*[47], *asthenia*[48], *slowness, jerkiness, falling, hypo-reactivity, fluffed feathers, ptosis*[49], *huddled position*, *loss of righting reflex*, *immobility* and *tetanic* (muscle) *seizures* (Hudson et al., 1984). Arsenic exposure can cause *reductions in eggshell thickness*. Arsenic accumulated significantly in brain and liver of ducklings fed 100 or 300 mg As/kg (Camardese et al., 1990) High exposure concentrations can cause a *significant increase in resting time* and a significant *decrease in time spent in alert behaviours* (Whitworth et al., 1991). Exposure to a dose of 200 mg

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[47] Ataxia: lack of muscular coordination (CED, 1992)

[48] Asthenia: an abnormal loss of strength; debility (CED, 1992)

[49] Ptosis: prolapse or drooping of a part, e.g. the eyelid (CED, 1992)

As(V)/kg for 4 weeks has showed *significant reductions in survival* and *growth*, and an increased incidence of histopathological *lesions* (injuries or wounds) (Hoffman et al., 1992). Based on oral toxicity tests, inorganic arsenic is *very toxic to mammals* and has been assigned to toxicity class 1 (Farm Chemicals Handbook, 1989). Experimental animal trials have indicated that arsenic may be *immunotoxic* to mammals (NJDEP, 2000).

Summary

According to the data sources of the m/v SCI accident case history, arsenic does not have any bio-effects on other marine life or birds (U.S. DOT, 1992), whereas the results of the studies cited above have shown that exposure to arsenic can significantly affect marine and terrestrial lives. Marine biota has shown a wide range of concentrations and sensitivities to the arsenic compounds. The sensitivity of organisms to arsenic, which can be modified by biological and abiotic factors, also varies widely. Toxicity of inorganic arsenic in seawater is summarized in Figure A2.2. For marine microorganisms, invertebrates and vertebrates the lowest acute lethal concentrations of arsenic compounds are reported respectively 5 µg As(V)/litre, 11 µg As/litre, and 12.7mg As (III)/litre. For plants, the lowest damaging concentration is around 1mg/kg.

2.4. Arsenic concentrations and effects in human

The m/v SCI accident case history contains very limited data for human exposures and consequences. Based on the following relevant information, extrapolations and inferences can be made in connection with the m/v SCI accident case.

The human health effects of arsenic have been illustrated by various national and international organizations, such as the International Labour Organisation, the U.S. Occupation and Safety Health Administration, the International Agency for Research on Cancer (IARC), the U.S. Environmental Protection Agency (USEPA), and the International Programme on Chemical Safety (IPCS).

The concentration of metabolites of inorganic arsenic in urine reflects the absorbed dose of inorganic arsenic on an individual level. After a single dose, arsenic is eliminated from the human body (blood and tissues) through urinary excretion. The arsenic concentrations in urine vary widely. They may range from < 10 µg/litre in European countries (Trepka et al. 1996, Buchet et al., 1996; Kristiansen et al., 1997; Kavanagh et al., 1998), similar or slightly higher than 10 µg/litre in some parts of the *U.S.* (Gottlieb et al., 1993; Bates et al., 1995; Lewis et al., 1999), approximately 50 µg As/litre in Japan (Yamauchi et al., 1992), and higher than 1000 µg/litre in West Bengal and Bangladesh (Chatterjee et al., 1995; Das et al., 1995).

Arsenic enters into human bodies through various routes of exposure (ingestion, inhalation and contact) and from different sources. In workplaces, arsenic exposure is generally <10 µg/m^3 (8-h time-weighted average [TWA]). However, in some workplaces atmospheric arsenic concentrations may be very high, as high as several mg/m^3. Arsenic exposure through inhalation may contribute up to about 10 µg/day in smokers and about 1 µg/day in non-smokers, and higher in polluted areas.

For people who are not occupationally exposed to arsenic, the most significant mode of exposure to arsenic is through the oral intake of food and beverages. The total daily intake of arsenic from food and beverages is generally between 20-300 µg/day (IPCS, 2001). The arsenic concentrations in food vary widely across various countries depending on the type of food, growing conditions and processing techniques. Arsenic is found in a wide range of foodstuffs including *seafood*. By far the highest concentration of total arsenic is found in *seafood* (Gunderson, 1995) (Yost et al., 1998) (U.S. NRC, 1999) (UK MAFF, 1997) (Dabeka et al., 1993) and (ANZFA, 1994). The arsenic concentrations in *fish* and *shellfish* can range from 77 to 4,830 µg As/kg wet weight (Dabeka et al., 1993).

Arsenic is four times as toxic as mercury (IARC, 2004). The lethal dose of inorganic arsenic ranges between 120 and 200 mg (Baldwin and Marshall, 1999; Bartolome B et al., 1999; Hu, 1998; IARC, 2004). Arsenic is carcinogenic at much lower levels.

There are considerable lethal and non-lethal dose variations among individuals exposed to arsenic and arsenic compounds. Arsenic trioxide doses ranging between 5-50 mg can be toxic. A dose of about 1.8 mg/kg has proved fatal to an adult, but recovery has occurred after much larger doses. Estimates of the minimum lethal dose in humans range from 1-3 mg As/kg/day (U.S. DHHS, 1998, 1999).

Ingestion of large doses of arsenic may lead to acute symptoms within 30–60 minutes, but the effects may be delayed when the arsenic is taken with food (IPCS, 2001). Acute gastrointestinal disorders are the most common symptoms of acute arsenic poisoning (IPCS, 2001). Death may result from severe hypotension and collapse (NJDEP, 2001).

Acute fatal arsenic poisonings have been reported after oral exposure to estimated doses (a single intake) ranging from 2 to 21 g (Levin-Scherz et al., 1987) (Benramdane et al., 1999) (Civantos et al., 1995). Cases with non-fatal effects, often accompanied by permanent neurological damage, usually after treatment, have been reported after oral doses ranging from 1–4 g (Fincher & Koerker, 1987; Fesmire et al., 1988; Moore et al., 1994) up to 8–16 g arsenic (Mathieu et al., 1992). Serious non-fatal intoxications in infants have been reported after doses of 0.7 mg of arsenic trioxide (As_2O_3) (0.05 mg/kg) (Cullen et al., 1995), 9–14 mg (Watson et al., 1981) and 2400 mg (4 mg/kg) (Brayer et al., 1997).

Continuous or repeated oral exposures to arsenic over a short period have also been associated with acute fatality and non-fatal effects. The total dose, the daily dose intake and duration of exposure vary. Among people who drank water containing 108 mg As/litre for 1 week, 2 out of 9 exposed persons died, 4 developed encephalopathy and 8 gastrointestinal symptoms (Armstrong et al., 1984). No deaths, but symptoms mainly from the gastrointestinal tract and skin, were observed among 220 patients studied among 447 who had been exposed to arsenic in soy sauce at a level of 100 mg/litre for 2–3 weeks; the estimated daily dose of arsenic was 3 mg (Mizuta et al., 1956). In a mass poisoning in Japan, where 12 000 infants were fed with milk powder inadvertently contaminated with arsenic at a level of 15–24 mg/kg, leading to an estimated daily dose of 1.3–3.6 mg for a period of varying duration, 130 of the infants died (Hamamoto, 1955).

Arsenic exposure via ingestion and other routes of exposure is causally related to *cancers* (USEPA, 2001b; IARC, 2004; IPCS, 2001; NJDEP, 2001), such as *lung, kidney, bladder, skin, lymphatic system, nasal passages, and prostate cancers*. Based on USEPA assumptions and calculations, a person exposed to 20 ppm of arsenic has a 50 in one million chance of getting cancer over a lifetime due to arsenic exposure alone (Fields, 1999). Absorbed inorganic arsenic accumulates in the liver, spleen, kidneys, lungs and gastrointestinal tract. Arsenic intakes of 50 µg/litre have been associated with increased risks of concentrations of bladder and lung cancers, and signs of skin cancer (IPCS, 2001). Occupational exposure to airborne arsenic is causally related to lung cancer. Cumulative 0.75 mg As/m^3/year exposure has been associated with an increased risk of lung cancer (IPCS, 2001). Arsenic is considered to be *genotoxic in humans* on the basis of clastogenicity in exposed individuals and findings *in vitro* (i.e. biological processes or reactions observed in an artificial environment). Non-cancerous effects of arsenic include *cardiovascular, pulmonary, immunological, neurological, and endocrine* effects (USEPA, 2001b).

Arsenic exposure via ingestion also induces several different *peripheral vascular diseases* (PVD), in both large and small vessels. The causality of the relationship between arsenic exposure and other health effects is less conclusive. The evidence is strongest for *hypertension*, suggestive for *diabetes and reproductive* effects, and weak for *cerebrovascular disease*s (CVD), long-term *neurological effects* and *cancers* other than lung, bladder, kidney and skin. Consumption of shrimp with high natural (organic) arsenic level may cause blood levels to rise (NJDEP, 2001). A recent study indicates that arsenic may cause *endocrine disruption* that distorts hormones responsible for the growth and development of certain tissues in the body (IARC, 2004). Arsenic exposure is also associated with *birth defects* (Kamrin, 2005). Ototoxicity of airborne arsenic particles may result in *hearing loss* (Hendrix and Berry, 2004). Arsenic trioxide is *corrosive to the eyes*, *skin* and *mucous membranes* (NOAA, 1992a).

One study has shown that the people exposed to high doses of arsenic via inhalation suffer from *severe chronic nosebleeds*, *extreme fatigue* and *unbearable headaches*, *disorientation* and frequent *seizures* and *hair loss* (Peters, 1984). Depending on duration and extent of exposure, there is a possibility of permanent nerve damage affecting the extremities, particularly the hands and fingers. Although uncertainty exists as to whether it alone is sufficient to cause the disease, arsenic exposure may be associated to an extreme form of *black-foot disease* (BFD), leading to progressive gangrene of the legs.

Summary

The effects caused by or associated with arsenic exposure range from acute lethality to chronic effects. The onset of chronic health problems, illnesses or diseases due to long-term arsenic exposure at low levels may be slow, but dangerous. Exposure to arsenic may affect several different organ systems, including skin, respiratory, cardiovascular, immune, genitourinary, reproductive, and gastrointestinal and nervous systems. In the case of the m/v SCI accident, people that were exposed or likely to be exposed to arsenic may experience one or combinations of health problems. Repeated oral exposure to arsenic trioxide over a long period of time is remotely likely.

3. Appendix 3: A detailed list of recommendations

The following is a detailed list of recommendations for improving human safety and health, and protection of the environmental and property.

A	The accident	
A.1	**Human/man factor**	
	Causes and contributing factors	**Recommendations**
	1. Ship personnel ***1.1 Master*** • Lack of experience with breakbulk cargo ship • Biased unsound predisposition: “We are sailors – we go to sea” • Poor decision-making capacity • Inappropriate navigational decision • Inadequate navigational skills • Inadequate assessment of weather forecasts • Failure to understand ship-sea interactions • Overestimation of navigational ability ***1.2 Master/deck officers*** • Unfamiliar with local weather conditions • Inadequate knowledge of cyclonic storm characteristics • Failure to recognise the cyclonic storm • Inexperienced second mate • Misunderstanding of securing system mechanics ***1.3 Crew: master, officers, bosun, AB seamen*** • Poor seamanship • Lack of experience and specific formal training for cargo securing **2. Industry/professional mariners** • Industry/professional mariners’ biased unsound	Consider and/or reconsider the following: • Improve formal education and training for masters and deck officers, including the principles of weather forecast and assessment, naval engineering and navigation. Perform regular refresher and updating courses for masters and deck officers. • Update regularly formal education and training programmes with information on the most advanced technology and practices. Comply with the relevant international and national standards and the best practices in the industry. • Avoid assigning ship personnel on short notice, in particular masters and chief officers, to a ship type with which they may not be very familiar. • Work on elimination of biased un-sound predispositions and bad common practices in the industry. Educate ship and shore personnel to think and make decisions based on adequate information, experiences, good practices and sound judgments. • Enhance professionalism and competence of seafarers. Encourage good seamanship practices. • Conduct regularly specific training for ship personnel on the cargo securing system, system mechanics and procedures. • Instruct and enforce good practices for preparing and securing of both the ship and cargo prior to departure, regardless of type of voyages – short or deep sea and long voyage. • See also other relevant recommendations.

	predisposition • The common practice not to secure hatch covers in coastal voyages	
A	**The accident**	
A.2	**Man-Made factor**	
	Causes and contributing factors	**Recommendations**
	1. Hardware/technical ***1.1 Ship)*** • Navigational equipment: - Poor quality/useless radar - Inoperative course recorder • Ship's design and operational characteristics: - Ship's GM design characteristics – excessive GM - Ship's length relative to wave length - Ship's natural rolling and pitching frequency relative to wave period ***1.2 Cargo securing systems*** • Inherent faults in the cargo securing system: ship, packaging and lashings ***1.2.1 Ship system*** • Inherent design and construction shortcomings • Unspecialized ship type • Failure of hatch covers: - Corrosion and damage • Failure of pedestals ***1.2.2 Packaging system – containers and machinery*** • Failure of container securing system – inside and outside • Failure of container structure: - Inadequate in-service structural strength - Container damage and corrosion • Inherent design shortcomings in FRP container: - Inherent weakness in packaging material - FRP has no plastic range	Consider and/or reconsider the following: • Ensure that ships are adequately equipped according to the relevant requirements, including SOLAS 1974, (Regulation 19: Carriage requirements for shipborne navigational systems and equipment), as amended, and good practices in the industry. Equip the ship with adequate and necessary navigational equipment and devices. Such equipment must comply with the relevant performance standards. • Require that masters and deck officers learn more about principles of naval engineering including a ship's design, construction and operational characteristics and behaviour. They should become familiar with characteristics and behaviour of every ship they operate. Prior to every voyage, they should make the necessary estimations and predict changes in characteristics and behaviour of the ship at sea. • In accordance with the relevant requirements and good practices, avoid the carriage of unitized/ containerised sensitive cargo on the deck of unspecialized ships, including marine pollutants, valuable and fragile goods. • Inspect regularly and maintain always in good condition the ship's hatch cover system. After the completion of cargo operations and prior to every voyage, make sure that all hatch covers are properly closed and secured. Comply always with hatch covers' design and construction requirements and conditions. • Study and improve the design and construction of packaging and cargo transport unit (CTU) systems, in particular plastic packagings. Target the weakest and most vulnerable parts of the packaging system. Design more advanced, safer and stronger packaging system solutions to improve the performance of packaging systems, and to reduce the risks and costs of dangerous goods transport incidents.

	- FRP less durable than other materials • Inherent design shortcomings with palletized drums • Failure of machinery securing system: - Awkward shape of the machinery ***1.2.3 Lashing equipment system*** • Wire lashings broke: - Damage and corrosion in wire lashings - Weak wire lashings **2. Regulations/standards** • Lack of standards – a minimum GM • Regulatory faults – vulnerable cargo position • Gaps in regulatory controls and oversight programmes • Lack of objective standards for blocking and bracing arrangements • Lack of a standard approach for container securing	• Study and improve the design of internal and external container securing systems. Develop more advanced technological solutions for blocking, bracing and cushioning of dangerous goods. • Ensure that containers' owners comply with the relevant requirements and good practices, including the International Convention for Safe Containers, 1972 (CSC) and the U.S. regulations (49 CFR 453), as amended, concerning the structural safety, testing, inspection, approval and maintenance of containers. • Revise and improve container inspection procedures and rejection/acceptance criteria. • Enhance the status, which is the acceptance and application, of relevant international conventions related to the carriage of packaged dangerous goods by sea, including the CSC Convention (1972) and 1993 amendments. As of February 2006, the CSC 1972 had been ratified or accepted by only 72 IMO member states whose merchant fleets comprise 61.8% of world tonnage. • Check and ensure regularly that containers and CTUs are properly maintained and in good condition. Ensure that aging containers in deteriorating condition are kept out of service. • Revise the design, construction and performance of FRP containers and other plastic containers. • Ensure that large, heavy and awkwardly shaped cargoes are carried on specialised or purpose-built ships, in particular on deep sea and long voyages. • Improve packing of large, heavy and awkwardly shaped cargoes. If they carried on deck of general cargo ship types, check and ensure that they are properly stowed and secured in accordance with the relevant requirements and good practices. • Require that the shipowner/master maintain always onboard the relevant documents and instructions concerning the carriage of awkwardly shaped cargoes. • Review, study, update and amend regularly the current state-of-the-art of the regulatory system governing maritime transport of dangerous goods. Adjust the regulatory system with changes in the system. • Study whether and how much the current state of the regulatory system affects the safety of maritime transport and the marine environment protection.

		• Enhance regulatory control and oversight procedures and programmes. • Enhance the implementation of the class societies and the IMO’s guidelines and recommendations concerning the cargo securing system, methods and procedures. • Develop more comprehensive standards for cargo/ container securing systems, including blocking and bracing of cargo inside containers, CTUs and aboard the ship. • Require that the ship designers, constructors, class societies and shipowners issue standards for GM values for particular ships. If they are issued, instruct and ensure that masters maintain these standards onboard and consult them. • See also other relevant recommendations.
A	**The accident**	
A.3	**Operational factor**	
	Causes and contributing factors	**Recommendations**
	1. Cargo loading/discharging • Unsuitable stability conditions – excessive GM • Poor planning prior to loading • No remedial measures taken after loading **2. Cargo stowage, packing, securing** ***2.1 Cargo stowage on deck*** • Inadequate stowage of containers • Inadequate stowage of the machinery: - Inherent weakness in stowage configuration ***2.2 Container packing*** • Inadequate container packing: - Inadequate blocking and bracing - Weak blocking and bracing scheme - Inadequate stowage - too much void space inside containers - Inadequate dunnaging materials and arrangement - Uninstalled tomming ***2.3. Container securing***	Consider and/or reconsider the following: • Estimate the ship’s GM in every voyage. Prevent unsuitable and dangerous stability ship conditions (very short and long GM) by combining various measures. • Carry out carefully cargo stowage planning prior to cargo operations to ensure appropriate stability conditions of the ship. • While at port and prior to departure, if practically possible and necessary, take remedial measures to improve the stability conditions of the ship and cargo stowage and securing. • Reject any cargo and cargo/ship related operations that may seriously undermine the safety of people and ship. Think and make decisions in the best interests of the safety of the people – including the crew and other people alike. • Enhance the safety and the marine environment protection awareness of people working ashore and aboard ships. Make container/CTU packers, shippers and third party logistics aware of and appreciate maritime transport hazards. • Instruct and ensure regularly that containers/CTU are adequately packed and secured in accordance with the relevant requirements and good practices. • Carry out and ensure that container/ CTU packers are regularly trained in accordance with the relevant requirements and good practices.

	• Failure of container securing on deck:
	- Inadequate cargo securing
	- Mismatches in the cargo securing system
	  - The pair of rigid hook-type turnbuckles with wire lashings
	  - The pair of penguin hooks with wire lashings
	- Improper application of installation methods
	- Improper installation of penguin hooks/wire lashings
	- Incomplete cargo securing
	- Uninstalled additional turnbuckles and lashings
	2.4 Awkward cargo (machinery) packing and securing
	• Failure of machinery securing:
	- Inadequate securing of the machinery
	- Inadequate packing of the machinery
	- Inadequate application of cargo securing methods
	- Weak lashing configuration
	- Insufficient machinery lashing
	- Insufficient number of wire clips installed
	- Uninstalled lashings
	2.5 Hatch cover securing
	• Failure of hatch cover:
	- Failure to secure hatch covers
	3. Navigational faults
	• Failure to avoid the storm prior to departure and while at sea
	• Failure to track the storm while at sea
	• Failure to use all tools available for tracking the storm:
	- Failure to use radars
	• Failure to avoid (navigate out of) the most dangerous
		Improve training programmes on container/CTUs packing.
		• Set up a quality assurance system for container/CTU packing – audit and certify dangerous goods container/ CTU packers.
		• Improve container packing and securing standards including methods and procedures.
		• If it is not already in place, introduce a legal framework for pre-trip inspections and make container/CTUs inspections mandatory. Set up and station at all or main ports dedicated and well-trained dangerous goods teams of surveyors. Carry out regularly random pre-trip inspections of containers/ CTUs carrying dangerous goods as well as stowage of dangerous goods onboard the ship. For the purpose of combination of the safety, the marine environment protection and security reasons carry out targeted inspections in particular for shipments containing substances possessing fire, explosion, toxic, radioactive, pollution and corrosive hazards. Impose fines or other penalties for any infringements if necessary
		• Further develop compatible standards for different packaging levels – primary, secondary, tertiary packagings; inner and outer packagings. Design dangerous goods packaging systems with simple, compatible and standardised configurations and dimensions.
		• Packagings should be better designed, constructed and maintained to withstand normal transport conditions, in particular mechanical forces such as shock loads, pressures, and stresses, moisture fluctuations and dampness, and corrosion. Ensure that the effectiveness of the packaging system is not reduced by normal changes in conditions. Also, design and construct packaging solutions that: meet common national and international standards, provide suitable and effective stacking/ stowing; light but strong packages; packaging materials containing very low moisture contents and free of infestation risk.
		• Improve in particular standards for container dimensions, design, construction, testing, inspection and maintenance.
		• Inner packagings should be adequately secured and cushioned within the outer packaging to prevent or control movements, damage, breakages or leakages under conditions of transport incidents, such as cargo shifting, listing and collision.

	semicircle of the storm • Inadequate navigation in the storm • Steering with autopilot in severe weather conditions • Inadequate navigation tactics: - Placing the ship into an unsafe position relative to navigational hazards - Setting and keeping an inappropriate ship course relative to the wind/wave direction • Failure to minimise the effects of weather conditions • Failure to test options available: - Several options remained untested - Failure to test turning back and taking shelter - Failure to test speed reduction - Failure to test course changes - Unnecessarily taking a wider turn into Delaware Bay	• Improve and develop more advanced technological solutions for the cargo/container securing systems. Design more effective and stronger securing systems. Reduce many different complex elements into a system with a few simpler, but better and stronger elements. • Prior to loading, inspect carefully cargo sitting or coming ashore. Check carefully for any apparent damage, leakage or any other unusual or suspicious condition. Reject loading of cargo and/or make the necessary remarks in shipping documents. • Secure cargo, including containers and awkwardly-shaped cargoes, by means of well trained personnel. If the crew lacks adequate training and familiarity with cargo securing, or is very small for the task or very tired, leave the task to specialised shore personnel. The safety of the crew, ship and cargo are worth the time and money spent on appropriate cargo securing. • Cargo securing procedures should always be led and supervised by the deck officers on duty and bosun, who should be well trained and experienced. • After the completion of the cargo securing, the chief officer and/or master should inspect carefully the system prior to departure, in particular in cases when large numbers of containers/ CTU and heavy awkwardly-shaped cargoes are carried on deck of an unspecialized ship and the ship is heading on a long voyage with expected bad weather conditions. • In no circumstances leave the port with the ship in dangerous stability conditions or unseaworthy, and the ship or her cargo inadequately secured. Do not hurry; take the time needed and fix it. Make sure that the cargo and the ship are completely and adequately secured. • The chief officer and the master should plan carefully and well in advance cargo securing, including planning and reviewing of the following: cargo stowage; securing/lashing methods and procedures; the state, amounts and types of securing equipment and devices available in the ship's inventory. • When securing equipment and devices available in the ship's inventory are found to be insufficient and/or deemed inadequate (e.g. corroded) for the task, contact the shipowner and order additional and/or new ones in the nearest or next port of

		destination. • Revise and improve constantly the safety of navigation and the regulatory system concerning navigation. Ensure that ships comply with the relevant latest navigational safety requirements, including the requirements of the following relevant conventions: SOLAS 1974, MARPOL 1973/78 and STCW 1978, as amended. • Improve navigational skills through better formal education and training and education/training programmes. Carry out regularly refresher courses and instructions. • Design navigation training solutions, such as simulators, for training deck officers in navigational skills including navigation planning and tactics for various stability conditions of the ship, severe weather conditions and confined waters. • Particularly in unusual weather and navigational conditions, strengthen the resources on the bridge, in the machine room and the radio communication with additional personnel and/or equipment. The master must be always present on the bridge in these conditions. Exercise always due diligence and caution. Make maximum use of all equipment and devices available. • Underestimating the power of the sea and overestimating one's own navigational skills and abilities and the strength and capacity of the ship is a bad combination. In bad weather conditions and/or unstable ship conditions, return to the nearest or suitable port or location for shelter if necessary and conditions permitting. • Avoid steering with autopilot in severe weather conditions • See also other relevant recommendations.
A	**The accident**	
A.4	**Managerial factor**	
	Causes and contributing factors	**Recommendations**
	1. Regulatory system management: inadequate compliance and enforcement • Inadequate container inspection and maintenance • Lack of inspection and maintenance records • Failure of the container owner	Consider and/or reconsider the following: • Enhance dangerous goods regulations compliance and enforcement oversight and programmes including container/CTU packing. • Instruct and enforce regularly compliance with the relevant requirements for container inspection and maintenance. Ensure that container owners maintain good conditions and submit regularly

	to comply with relevant regulations • Inadequate regulation compliance and enforcement oversight • Inadequate regulatory oversight for container packing • Absence of a cargo securing manual • SCI's container securing system neither surveyed nor certified • Absence of IMO guidelines for heavy items **2. Mismanagement: poor maintenance and insufficient supply** **2.1. *Cargo securing systems*** • Mismanagement – poor maintenance - Rogue securing equipment in use/inventory - Improper/ poor maintenance of securing equipment in use/inventory - Insufficient supply of correct securing equipment - Insufficient supply of lashing equipment and gear – long bridges unavailable onboard 2.2. Navigational system: inadequate supply and maintenance • Useless radars • Inoperative course recorder	container maintenance records. • Provide more assistance for countries lacking the expertise, experience and resources, in particular for the safe carriage of dangerous goods by sea and the marine environment protection. • Survey regularly and certify the cargo securing system. • Extend the scope of the harmonized system of survey and certification concerning international shipping regulations, which was adopted by the IMO and entered into force on 3rd February 2000, to cover aspects and regulations governing the safety and the marine environment protection of maritime transport of packaged dangerous goods. Make compulsory the survey and certificate of fitness for the carriage of dangerous goods in packaged form, including the ship's cargo securing system. • Instruct and ensure that relevant cargo (containers and heavy and awkwardly-shaped items) securing documents are available onboard the ship and consulted, including the IMO's, class societies' and other relevant organisations' requirements, guidelines, instructions, manuals and other texts. • Manage and maintain in good condition an adequate inventory of the cargo securing system for the routes/ cargo traffic involved. Refurbish and supply the inventory with additional and/or new elements in due time, if necessary. • Maintain always the navigation system, including radars and course recorders, in good operative condition. Inform the shipowner about the conditions of the navigation system and ask him to supply and maintain the system in accordance with the relevant requirements. In the best interests of the safety of people, inform the relevant and responsible authorities or organisations about bad conditions if necessary. • See also other relevant recommendations.
A	**The accident**	
A.5	**Environment factor**	
	Causes and contributing factors	**Recommendations**
	1. Weather conditions • Fairly severe weather conditions contributed to losses and damage: - Wind properties: speed,	Consider and/or reconsider the following: • Enhance masters' and deck officers' navigational skills and knowledge about naval engineering and weather forecast and assessment through better formal education and training and education/

	direction - Waves properties: height, length, period, direction, speed, frequency • Heavy weather conditions made navigation difficult • Heavy rains and poor visibility prevented any observation and measure **2. Forces** • Exposure to forces acting on the system: - Gravity - Acceleration forces - Forces of winds - Forces of green waters - Vibrations - Other additive forces	training programmes, refresher courses, and regular instruction and guidelines. • Revise and improve regularly weather forecast/assessment and navigational procedures. Study, revise and further improve analytical methods, approaches and assumptions used by the classification societies, the IMO, and ship designers for the estimation of forces acting on the systems and for design and construction purposes. • Study more in depth maximum static and dynamic forces exerted during ship operations that act on the systems, including cargo/packaging, cargo securing and ship systems. Take into consideration variations in maximum values under normal and extreme conditions of various variables, such as ship characteristics, loading conditions, weather conditions, ship motions and accelerations. • Develop efficient methods for estimating and predicting with more accuracy ship's motions and accelerations in the conceptual design phase of the ship. Take into account the main dimensions (length, breadth, block coefficient and forward speed) as well as the operational profiles of the ship. • In the light of new and large amounts of data and advanced technologies, review the current theories in naval engineering and oceanography, including the "linear" theory. Make necessary estimations based on "non-linear" theory and improve accordingly the design and construction of the systems, including the ship, packaging and cargo securing systems • See also other relevant recommendations
A	**The accident**	
A.6	**Other factors**	
	Causes and contributing factors	**Recommendations**
	Business constraints • Costs • Time • Rules	Consider and/or reconsider the following: • Ensure that the ship and her cargo are adequately secured prior to departure. Prevent any cargo/ship securing, in particular large securing operations, while the ship is leaving the port and heading at night into open seas and bad weather conditions. These operations put the crew under pressure to complete cargo securing as soon as possible, before the ship starts rolling and pitching in open seas.

		• Find ways to reconcile the differences in interests between; different actors including shore and ship interests; local/national and regional/ international interests; business, economical or costs and safety and marine environment protection interests. • Study and further develop new approaches, methods or technological solutions that can facilitate the achievement of twin or multiple goals, such as the business/ economical and the safety and marine environment protection goals. • Safety and health and marine environment protection should be the priority in particular for those dangerous goods and related activities and systems posing high and intolerable risk levels. • Instruct and insure constantly that the master is aware of and complies with the relevant requirements concerning the safety of navigation, including SOLAS 1974 Regulation 10-1, as amended. This regulation, which entered into force on 1st July 1997, states that the master of the ship shall not be constrained by the shipowner, charterer or any other person from taking any decision necessary for safe navigation, particularly in severe weather conditions and heavy seas.
B	**The Exposure Event**	
B.1	**Human/Man Factor**	
	Causes and contributing factors	**Recommendations**
	1. Ship personnel ***1.1 Master/chief mate*** • Master and chief mate became aware of damage and spills, but “ignored” them ***1.2 Crew: AB, bosun*** • Crew unaware of the danger • Crew ignored warnings of arsenic trioxide hazards • Crew lacked dangerous goods knowledge and training • Crew failed to “observe” labels and the spill • Bosun’s ability to interpret labels was limited • Crew lacked basic knowledge of the professional English language **2. Shore personnel**	Consider and/or reconsider: • Study and discuss the possibility of making explicitly mandatory the provisions of Chapter 1.3 (Training) of the IMDG Code, which is of a recommendatory nature in the latest edition of the IMDG Code adopted by the IMO in May 2002. • Revise regularly requirements concerning notifications (MARPOL 73/78 Annex III) for preventing pollution by harmful substances carried in packaged form. Ensure that the ship personnel are aware of and comply with these requirements. Ensure that ship personnel, stevedores and other parties are also aware of and comply with national requirements, such as the U.S. Code of Federal Regulations (49 CFR 171 and 176), concerning reporting of hazmat incidents and conditions. • Impose stricter liabilities for those who violate or do not comply with the relevant requirements for

	2.1 Stevedores • Stevedores unaware of hazardous conditions • Stevedores failed to “observe” and recognise hazard labels • Stevedores lacked dangerous goods knowledge and training • Stevedores observed and recognised labels, but ignored them • The incident of sparks and other incidents went “unnoticed” ***2.2 Pilots*** • Pilots unaware of the danger • Negligence of pilots ***2.3 Authorities*** • Port authorities unaware of magnesium phosphide and other dangerous goods spills	notification and warning of dangerous goods incidents, including masters or ships/ shipowners, stevedores, supervisors, shippers, consignees and other parties concerned. • Revise regularly international standards on marking, labelling, and documentation of packaged dangerous goods. Ensure that the ship personnel are aware, well trained and comply with these standards. • Ensure constantly that stevedores comply with the relevant national and international requirements concerning dangerous goods handling at port and related activities. Examine regularly records of dangerous goods training. Improve dangerous goods training programmes for the stevedore profession. • Design technological and procedural solutions for facilitating the identification and recording of incidents involving dangerous goods losses or discharges into the sea and their sources. Design devices that can enable remote and automatic identifications. • Make sure that equipment such as forklift trucks, sweepers and other material handling equipment are well equipped and safe when used onboard the ship, in particular in ships carrying dangerous goods and dangerous areas in port. Design and install fire/explosion protection systems in material handling equipment. • Improve dissemination of lessons learned from accident investigations and results of maritime safety/risk studies. • Revise and improve regularly dangerous goods incidents reporting systems and procedures. Find more effective approaches to improve the quality of the reporting system and increase the percentage of reported incidents. • Enhance the accuracy and quality of dangerous goods incidents data and other risk related data. • Enhance crew competency and quality including knowledge of basic English. Revise and improve regularly minimum standards of the STCW Convention concerning competence of seafarers. Improve recruitment requirements and procedures for seafarers. • Ensure that shore and ship personnel are well trained, familiar with and observe emergency plans to deal with incidents involving packaged dangerous goods.

		• Design and install technological solutions, such as sensor/ detector electronic systems and audible and visual indicators or alarms, for detecting and warning the crew and other people concerned about the existence of unreported/ undocumented or illegal dangerous goods and hazardous conditions inside containers/CTUs and aboard the ship, in particular for toxic, fire, explosion and radiation hazards. Develop chemical leak or spill detection and warning technologies. • Revise and improve regulations concerning fire detection, protection and extinction onboard the ship, in particular for ships carrying dangerous goods. Ensure that the ship is adequately equipped and the crew is aware of fire risks and well trained in accordance with relevant regulations, including international standards for fire safety systems such as the International Fire Safety Systems (FSS) Code and SOLAS 1974, as amended. • Improve or design new technological and procedural solutions for fire detection, warning, protection and extinction onboard the ship, in particular for ships carrying dangerous goods.
B	**The Exposure Event**	
B.2	**Operational Factors**	
	Causes and contributing factors	**Recommendations**
	1. Dangerous goods communication – accident/spill reporting ***1.1 Ship personnel*** *1.1.1 Master* • Master failed to provide a complete report of the accident • Master failed to report the accident in due time • Master failed to inform pilots about arsenic trioxide • Master failed to report spills and incidents *1.1.2 Crew* • Crew failed to examine and report the spill • Crew failed to provide a complete report of the situation • Crew failed to report	Consider and/or reconsider: • Enhance dangerous goods awareness and training programmes for all parties concerned in port, including stevedores, supervisors, shippers, consignees, pilots and port authorities. • Extend dangerous goods awareness and training beyond those who may be identified as employees involved in dangerous goods related activities. • Study and further improve the systems and procedures for collecting, recording, analysing, disseminating and sharing of the relevant information that is necessary for all parties concerned with dangerous goods related systems and activities and emergency responses. • Improve dangerous goods communication systems and procedures. Improve the flow of dangerous goods information among all parties concerned in the supply chain/ transport chain. The availability of timely information will assist the parities concerned to avoid dangerous goods incidents and problems and expedite responses rapidly when

	magnesium phosphine spill • Crew failed to report incidents of chemical exposure ***1.2 Shore personnel*** *1.2.1 Consignee* • Consignee or his representatives failed to inform about the chemicals *1.2.2 Port captain* • Port captain failed to inform the USCG *1.2.3 Pilots* • Pilots failed to report the situation *1.2.4 Stevedores* • Stevedores discharged damaged magnesium phosphide drums without notifying the USCG **2. Ship/cargo inspection** • *Crew* failed to inspect the ship/cargo thoroughly **3. Accident response and investigation** • Delays in accident reporting and response made recovery operations difficult • *Port authorities* failed to perform a thorough investigation **4. Dangerous goods documentation** ***4.1 Shipowner*** • Shipowner failed to list magnesium in the shipping documents ***4.2 Cargo interests*** • Cargo interests failed to provide particulars of magnesium phosphide **5. Cargo discharging** • Stevedores failed to discharge cargo completely	incidents do occur. • Reduce errors in dangerous goods documentation by means of automatic data collection and processing. Design and set up systems that would enable automatic scanning and processing of all dangerous goods-related documents that come in for international and domestic dangerous goods movements, pinpoint errors and discrepancies, and inform the parties concerned, such as shippers, carriers, freight forwarders and relevant port authorities. • Develop or further improve the port-wide total quality management program, including the management of dangerous goods related activities. • Audit and ensure constantly that dangerous goods interests, including shippers, consignees, freight forwarders and other third parties' logistics comply with the relevant national and international requirements concerning dangerous goods shipments and related activities. Audits should address problems of varying degrees of compliance with requirements concerning dangerous goods shipments, activities and trainings of employees. Examine dangerous goods training records and improve training programmes. • In the light of new and large amounts of data and more advanced technologies, update regularly the regulatory system governing the maritime transport system of packaged dangerous goods, such as SOLAS 74, MARPOL 73/78 and IMDG Code to accommodate changes in the system and related activities. Supplement or revise the existing provisions, including the revision of provisions concerning arsenic trioxide and other arsenic compounds. • Keep updated; become acquainted and comply with the most recent developments of the relevant regulations. For example, comply with the 24-Hour Advance Vessel Manifest Rule published by the U.S. Customs Service, which requires carriers and NVOCCs to submit a cargo declaration to the U.S. Customs 24 hours before cargo is loaded onto vessels with a port of call in the United States. Rules apply to all vessels calling at U.S. ports and all cargoes destined or carried via U.S. ports. The rules contain specified cargo information required by the U.S. Customs from the parties concerned. • Discourage violations or non-compliances with

		regulations by increasing the risks of violations or non-compliances through more effective, efficient and targeted inspections. Increase penalties and other restrictive legal and economic measures, in particular for repeaters and deliberate violations. If none exists, create a database for reporting and recording violations and non-compliances with dangerous goods regulations. • Identify the most frequent types of violations and violators. Revise baseline assessments for frequently cited violations of the dangerous goods regulations. • Regulating everything all the time by laws is impossible. Therefore, design more effective incentive measure systems for enhancing awareness, encouraging and promoting the best practices and solutions concerning safety and protecting the marine environment. • Relevant and responsible authorities, organisations or agencies could find effective ways and systems to assist all parties involved in the dangerous goods supply chain including maritime transport, in particular small companies, in being updated and complying with the current state of the regulatory system. If none exists, create a database for the registration of all organisations in the dangerous goods supply chain. • Revise and improve marine accident investigation procedures and the regulatory system governing these procedures. Ensure that investigation procedures are in compliance with the relevant national and international regulations, such as SOLAS 74 regulation I/21 and MARPOL 73/78 articles 8 and 12, codes and good practices, as amended. Investigations should be unbiased, fair, independent and scientific. • Enhance industry, national, regional and international co-operation in marine accident statistics and investigations.
B	**The Exposure Event**	
B.3	**Managerial Factors**	
	Causes and contributing factors	**Recommendations**
	1. Instruction – ship/cargo inspection and accident response monitoring • *Master* failed to provide	Consider and/or reconsider: • Revise and improve procedures for investigation and monitoring of dangerous goods incidents or hazardous conditions aboard ship. Port authorities

	instructions for a thorough inspection • *Master* issued incomplete warnings of the danger • *Chief mate* failed to order and lead a thorough inspection **2. Monitoring accident response** • *Port authorities* failed to monitor the situation properly **3. Supervision of cargo operations** ***3.1 Ship personnel*** • *Master* failed to supervise activities and personnel • *Chief mate and deck officer*s failed to supervise cargo discharging properly ***3.2 Shore personnel*** • *Supervisors* failed to supervise cargo discharging properly **4. Compliance with regulation – reporting of accidents/spills** • *Supervisor* failed to investigate the problem and report it properly • No one (*ship/shore personnel*) reported chemical spills and incidents in accordance with regulations	should investigate more thoroughly and monitor properly incidents involving dangerous goods. • Provide clear and concise instructions to ensure that ship personnel are familiar with characteristics of dangerous goods and operational procedures. • Ensure that ship personnel comply with the International Safety Management (ISM) Code concerning the procedures for the safe operation of ships and pollution prevention. • Promote the safety culture, voluntary and self-regulating in shipping and other related industries. • Provide regularly the master with clear instructions concerning dangerous goods activities and incidents aboard the ship. It should be the master's prime responsibility to supervise and command activities of the ship and shore personnel aboard the ship. • The chief mate, deck officers, bosun and AB seamen on duty should supervise and assure that stevedores perform dangerous goods operations in a safe manner and in full compliance with all relevant regulatory requirements. • See also other relevant recommendations.
B	**The Exposure Event**	
B.4	**Environmental Factors**	
	Causes and contributing factors	**Recommendations**
	1. Weather conditions • Poor weather conditions hampered search and recovery operations	Consider and/or reconsider: • Design or further improve mechanisms that can facilitate local, national and international co-operation and assistance in preparing and responding to dangerous goods accidents, including losses of packaged dangerous goods at sea. • Local, national and regional responsible authorities and agencies should work on developing and maintaining adequate and effective dangerous goods response systems that are able to deal with pollution and other

		dangerous goods emergency situations. In particular, this is important in the following cases: major pollutions or accidents; high risk dangerous goods; high risk and/or sensitive systems or activities; and high risk and/or particularly sensitive locations or areas. • Search and rescue teams should be prepared for all possible situations. However, they should be well prepared, plan and assign the right resources (human, money and equipment) for the right operations of: dangerous goods emergency situations, types/amounts of dangerous goods, locations, conditions and times. • Carry out regularly emergency response exercises at local, national and regional levels. • Organize regularly national, regional and international workshops for sharing information and best practices concerning the safety and marine environment protection issues.

REFERENCES

Anonymous (1992) Drums along New Jersey. Journal of Environment, Heldref Publications, vol. 34, Issue 3, pp. 21-21.

Baldwin D.R. and Marshall W.J. (1999) Heavy metal poisoning and its laboratory investigation. Annals of Clinical Biochemistry, 36, pp. 267-300.

Bartolome B., Cordoba S., Nieto S., Fernandez H.J., Garcia D.A. (1999) Acute arsenic poisoning: clinical and histopathologic features. British Journal of Dermatology, 141: pp. 1106-1109.

Batten S.D., Allen R.J.S. and Wotton C.O.M. (1998) The Effects of the Sea Empress Oil Spill on the Plankton of the Southern Irish Sea. Pergamon, Marine Pollution Bulletin, 1998, vol. 36, issue 10, pp. 764-774

Batterham A.M. and George K.P. (2003) Reliability in evidence-based clinical practice: a primer for allied health professionals. Elsevier, Journal of Physical Therapy in Sport, vol. 4, issue 3, pp. 122-128

Biran A. (2002) Ship Hydrostatics and Stability. Bentham Press, London, UK

Bishop R.E.D., Price W.G., and Wu Y. (1986) A General Linear Hydroelasticity Theory of Floating Structures Moving in a Seaway. Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences, Vol. 316, No. 1538, pp. 375-426.

Brigitte R. and Carsten D.G. (1997) Accidents and risk control. System Analysis Department, Risö National Laboratory, DK-4000 Roskilde, Denmark

Brodie P. (1994) Dictionary of Shipping Terms, Second Edition. Lloyd’s of London Press (LLP)

Carol S., Vilchez J.A., and Casal J. (2001) A new approach to the estimation of the probable number of fatalities in accidental explosions. Safety Science, 39, pp. 205–217

Chen, CY and Folt CL (2000) Bioaccumulation and diminution of arsenic and lead in a freshwater food web. Environmental Science Technology, 34:3878-3884.

Chilvers DC and Peterson PJ (1987) Global cycling of arsenic, In: Hutchinson TC and Meema K.M., Lead, mercury, cadmium and arsenic in the environment. Chichester, John Wiley & Sons, pp. 279–303.

CIS (International Occupation Safety and Health Information Center) (2005) Chemical: Arsenic Trioxide. The ILO, the International Social Security Association, the European Coal and Steel Community and the occupational safety and health authorities, http://www.ilo.org, 2005

CED (Collins English Dictionary) (1992) Harper Collins Publisher

COA (Clean Ocean Action) (2005) The COA's review of sediment monitoring programs and recommendations for monitoring in New Jersey, http://www.cleanoceanaction.org 2005

Crokhill M. (1992) “Santa Clara I” Incident. Hazardous Cargo Bulletin, September, 1992

Derrett D.R. (1999) Ship Stability for Masters and Mates, 5th Ed. Witherby Publishing, London, UK

DGSM (Australia’s Dangerous Goods Safety Management) Act 2000-2001

DNREC (Delaware Department of Natural Resources and Environmental Control, U.S.) (2005), http://www.dnrec.state.de.us/dnrec2000

DNV (Den Norske Veritas) Technica (1995) Feasibility Study For Safety Assessment of RoRo Passenger Vessels. Det Norske Veritas (DNV) Limited, London Technical Consultancy, UK

Dickinson E. (2000) Boat/U.S. Magazine Issue: Jan 2000

DRBC (Delaware River Basin Commission) (2005) Delaware River Basin, Basic Facts, http://www.state.nj.us/drbc 2005

EC (European Commission) (2000) Ambient air pollution by As, Cd and Ni compounds. Position paper, final version, October 2000, Brussels, European Commission, Dangerous goods Environment

FAS (Federation of American Science, U.S.) (2005) http://www.fas.org/main/home.jsp

Fields T. (1999) Findings and Recommendations for the Remediation of Historic Pesticide Contamination. Report of the New Jersey Department of Environmental Protection

FOE (Friends of the Earth) (2002) Briefing on the pesticides in our food. Friends of the Earth International, http://www.foei.org/2005

Ertugrul A. (1995) Risk-based transportation planning practice: Overall methodology and a case example. Journal Inform, vol. 33, no 1, pp 4-19

Gade M. and Redondo J.M. (1999) Marine pollution in European coastal waters monitored by the ERS-2 SAR: a comprehensive statistical analysis. IEEE and Marine Technology Soc, Journal of Oceans '99, vol. 3, pp 1239-1243

Gaskell N.J.J., Debattista C., and Swatton R.J. (1992) Chorley & Giles' Shipping Law, 8th Edition. Pittman Publishing

Gilfillan E.S., Harner E.J., O'Reilly J.E., Page D.S., and Burns W.A. (1999) A Comparison of Shoreline Assessment Study Designs Used for the Exxon Valdez Oil Spill. Pergamon, Marine Pollution Bulletin, vol. 38, issue 5, pp. 380-388

Greenpeace (2006) Greenpeace Report on the Chernobyl Catastrophe: Consequences on Human Health. Greenpeace, Amsterdam, the Netherlands, April 2006

Gould M.C., Baxter T.A., and Kruth D.J. (1986) Case History of the m/v “Rio Neuquen”: Containment and Ocean disposal of Reacting Aluminum Phosphide. Hazardous Material Spills Conference Proceedings, 1986

Goulielmos A.M. (2001) Maritime safety: facts and proposals for the European OPA. Emerald (MCB), Disaster Prevention and Management: An International Journal, vol. 10, issue 4, pp. 278-285

GSO (Global Security Organisation) (2005) http://www.globalsecurity.org/index.html

Gefährliche Ladung, Das Gefahrgut Magazin (1998) (German Hazardous Cargo Bulletin) Constrap. K.O. Storck Verlag, Issue 1998

Hair J.F., Anderson R.E., Tatham R.L. and Black W.B. (1998) Multivariate Data Analysis. Fifth Edition. Prentice Hall, Upper Saddle River, New Jersey 07458, 1998

Hammonds JS (1992) Risk Information to Assist in Risk Management Decision Making. Energy Systems, Inc., Oak Ridge, ES/ER/TM-40, TN

HCB (Hazardous Cargo Bulletin) 1986-2003 Incidents Log

Hendrix R.A. and Berry G. (2004) The Effects of Pollution on Hearing and Balance, html://members.aol.com/tiermensch/pollutionhearing.html, 2004

Hu H. (1998) Heavy metal poisoning, Chapter 397, In: Fauci AS, Braunwald E, Isselbacher KJ, Wilson JD, Martin JB, Kasper DL, Hauser SL, and Longo DL (1998). Harrison's principles of Internal medicine, 14th edition, New York: McGraw-Hill, pp. 2564-2569

Hunter D.A., Goessler W and Francesconi KA (1998) Uptake of arsenate, trimethylarsine oxide, and arsenobetaine by the shrimp crangon. Marine Biology, June 1998

HSC (UK Health and Safety Commission/Executive) (1991) Major Hazard Aspects of Transport of Dangerous Substances. Report of Advisory Committee on Dangerous Substances, Health and Safety Commission, HMSO, UK

HSE (Health and Safety Executive, UK) (1999) Reducing Risks, Protecting People. Discussion document, Health and Safety Executive, UK

IACS (International Association of Classification Societies) (2001) FSA of Bulk Carriers Fore-end Watertight Integrity, Annex 1, Basic Definitions and Abbreviations

IARC (International Agency for Research on Cancer) (2004) Arsenic in drinking water - Summaries and Evaluations. Chemical Safety Information from Intergovernmental Organizations http://www.inchem.org/2004

IMO (International Maritime Organisation) (1992) Search and Recovery Operations of Dangerous Goods.

IMO (International Maritime Organisation) (1994) Report on Marine Casualties, Harmonised Reporting Procedures. Draft MSC/MEPC Circular, FSI 4/18

IMO (International Maritime Organisation) (1996a) Focus on IMO: IMO and dangerous goods at sea.

IMO (International Maritime Organisation) (1996b) Code of the investigation of marine casualties and incidents. IMO Document, FSI 5/10/2, DEC 1996

IMO (International Maritime Organisation) (1997a) Interim Guidelines for the Application of Formal Safety Assessment (FSA) to the IMO Rule-Making Process, Marine Safety Committee MCS/Circ.829

IMO (International Maritime Organisation) (1997b) Formal Safety Assessment, Trial Application to High-Speed Passenger Catamaran Vessels. Report submitted by the UK, London, MSC 68/INF.6, 1997

IMO (International Maritime Organisation) (2002) Guidelines for Formal Safety (FSA) for use in the IMO Rule-Making Process, MSC/Circ. 1023, and MEPC/Circ. 392.

IMO (International Maritime Organisation) (2004a) Formal Safety Assessment (FSA): Risk evaluation. Reported submitted by the International Association of Classification Societies (IACS), Maritime Safety Committee (MSC), 78th session Agenda item 19, MSC 78/19/2, 5 February 2004

IMO (International Maritime Organisation) (2004b) Bulk Carrier Safety: Comparative Study of Single and Double Side Skin Bulk Carriers, Submitted by Greece Maritime Safety Committee, MSC 78/5/1, 78th session 20 February 2004, Agenda item 5

IMO (International Maritime Organisation) (2006) Goal-Based New Ship Construction Standards, Safety Level Approach – Safety Level Criteria. Report submitted by Japan, Maritime Safety Committee, 81st session, Agenda item 6, MSC 81/6/10.

IPCS (International Programme on Chemical Safety) (1989) The Environmental Health Criteria (EHC): Phosphine and selected metal phosphides. Health and Safety Guide No. 28, International Programme on Chemical Safety, Division of Environmental Health, World Health Organization, http://www.inchem.org, 2005

IPCS (International Programme on Chemical Safety) (2001) Environmental health criteria: 224: Arsenic and arsenic compounds. WHO Task Group on Environmental Health Criteria for Arsenic and Arsenic Compounds, (NLM Classification: QV 294), World Health Organization Geneva, 2001, http://www.inchem.org, 2005

IPCS (International Programme on Chemical Safety) (2005) Phosphine and selected metal phosphides. Health and Safety Guide No. 28, Chemical Safety Information from Intergovernmental Organizations, http://www.inchem.org, 2005

IPCS and EC (International Programme on Chemical Safety and the European Commission) (1994), International Chemical Safety Cards: Arsenic Trioxide, ICSC: 0378, http://www.inchem.org, 2005

IPCS and EC (International Programme on Chemical Safety and the European Commission) (2001) Arsenic Trioxide. A peer-review report, April 1997, http://www.inchem.org, 2005

IPCS and EC (International Programme on Chemical Safety and the European Commission) (2004), Chemical: Magnesium Phosphide. ICSC Report, 0744, March 1998, http://www.ilo.org/public 2005

ISO (International Standard Organisation) (1998) International Standards on Functional Safety, IEC-61508-5 Functional Safety Systems of electrical/ electronic/ programmable electronic safety-related systems, Part 5 - Examples of methods for the determination of safety integrity levels, July 1998.

ISO (International Standard Organisation) (1999) Petroleum and Natural Gas Industries - Offshore Production Installations - Guidelines on Tools and Techniques for the Identification and Assessment of Hazardous Events, Draft International Standard (ISO) 17776

Jensen J.J., Mansour A.E. and Olsen A.S. (2004) Estimation of ship motions using closed-form expressions. Journal of Ocean Engineering 31 (2004) 61–85.

Jönson G. (1993) Corrugated Board Packaging. Pira International UK

Jönson G. (1998) Packaging Technology for the Logistician. Department of Engineering Logistics, Lund University

Kamrin M. (2005) Arsenic and CCA wood. Institute for Environmental Toxicology, Agency for Toxic Substances and Diseases Registry, Division of Toxicology, http://www.origen.net/arsenic.html

Kaplan S. and Garrick B.J. (1981) On the quantitative definitions of risks. Journal of Risk Analysis, vol.1, no. 1, pp. 11-27

Kirchsteiger C. (1999) Trends in accidents, disasters and risk sources in Europe. Journal of Loss Prevention in the Process Industries, vol. 12, issue 1, pp. 7-17

Klein D. and Nugent T. (2004) The "steering committee", When big ships come into the Delaware Bay, these pilots guide the way. Delaware Beach Life Magazine

Knott J.R. (1994) Lashing and Securing of Deck Cargoes: including packaged timber, vehicles on ro-ro vessels and containers in non-purpose built ships. The Nautical Institution, London, UK.

Konstantinos G. and Ernestini B.G. (2002) Assessing the risk of pollution from ship accidents. Emerald (MCB), Disaster Prevention and Management, An International Journal, vol. 11, issue 2, pp. 109-114

Lee J.O., Yeo I.Ch., and Yang Y.S. (2001) A trial application of FSA methodology to hatchway watertight integrity of bulk carriers, Marine Structure 14 (2001) 651-667

Lois P., Wang J., Wall A., and Ruxton T. (2003), Formal Safety Assessment of Cruise Ships, Tourism Management 25 (2004), pp. 93-109

Loughran C.G., Pillay A., Wang J., Wall A., Ruxton T. (2002) A preliminary study of fishing vessel safety, Journal of Risk Research 5 (1), pp. 3–21 (2002)

LRS (Lloyd’s Register of Shipping) (1996) Casualty Return Series

LMIS (Lloyd’s Maritime Information Services) (1995) Ships Editorial, Casualty System Guide, Maritime Information Publishing Group

Little D. (1991) Varieties of Social Explanation - An Introduction to the Philosophy of Social Science. Westview Press, USA

Looström B. (1991a) The m/v “Rio Neuquen” Case. Abstract: Maritime Chemical Accidents, Swedish Coast Guard HQ

Looström B. (1991b) M/v “Viggo Hinrichsen” - sunken ship with a cargo of chromium compounds, Abstract report, Swedish Coast Guard Head Quarters.

Looström B. (1979) Report on m/v “Viggo Hinrichsen”, Swedish Coast Guard Head Quarters.

Maeda S., Ohki A., Tokuda T. and Ohmine M. (1990) Transformation of arsenic compounds in a freshwater food chain. Applied Organomet, Chemical, 4: 251–254.

Mahfouz A.B. (2004) Identification of the nonlinear ship rolling motion equation using the measured response at sea. Journal of Ocean Engineering, 31, pp. 2139-2156.

MARS (Marine Accident Reporting Scheme) (1999) Report no. 99040: Dangerous goods – Arsine Accident, Nautical Institute, U.K.

Mason R.P., Laporte J.M. and Andres S. (2000) Factors controlling the bioaccumulation of mercury, methylmercury, arsenic, selenium, and cadmium by freshwater invertebrates and fish. Arch. Environment Contaminant Toxicology, 38:283-297.

McGowan J. (1993) M/v “Santa Clara I” – Why the incident is so unique. Proceedings of the U.S. Marine Safety Council

Merrick G. (1993) When disaster makes a port call. Proceedings of the U.S. Marine Safety Council

Miraglia R.A. (2002) The Cultural and Behavioural Impact of the Exxon Valdez Oil Spill on the Native Peoples of Prince William Sound, Alaska. Pergamon, Spill Science and Technology Bulletin, vol. 7, issue 1-2, pp. 75-87

Monnier N.M. and Gheorghe A.V. (1996) Quantitative Risk Assessment of Hazardous Materials Transport System. Kluwer Academic Publishers

Mullai A. and Paulsson U. (2002) Oil Spills in Öresund – Hazardous Events, Causes and Claims. Report on the SUNDRISK Project, Lund University Centre for Risk Analysis and Management (LUCRAM), Department of Industrial Management and Engineering Logistics, Lund University, Lund, Sweden

Mullai A. (2004) A Risk Analysis Framework for Maritime Transport of Packaged Dangerous Goods (PDG). In Brindley, C (2004) Supply Chain Risk. Ashgate Publishing Company, UK, Chapter 9, pp. 130-159

Mullai A. (2006a) Maritime Transport and Risks of Packaged Dangerous Goods, Safe and Reliable Transport Chains of Dangerous Goods in the Baltic Sea Region (DaGoB) Project Publication Series 4:2006, Turku School of Economics, Logistics, Turku, Finland

Mullai A. (2006b) Risk Management System (RMS) – Risk Assessment Frameworks and Techniques, Safe and Reliable Transport Chains of Dangerous Goods in the Baltic Sea Region (DaGoB) Project Publication Series 5:2006, Turku School of Economics, Logistics, Turku, Finland

NJDEP (New Jersey Department of Environment Protection, U.S.) (2000) Delaware River Basin Commission (DRBC) - Issue: Arsenic. New Jersey Comparative Risk Project, Ecological Technical Work Group, Stressor-Specific Risk Assessment, Tucker and Buchanan: Appendix 3 – part 1, pp. 10-28, http://www.state.nj.us/dep/dsr/njcrp/Appendix3

NJDEP (New Jersey Department of Environment Protection, U.S.) (2001) Delaware River Basin Commission (DRBC), Issue: Arsenic. New Jersey Comparative Risk Project, Human Health Technical Work Group, Stressor-Specific Risk Assessment, Salahi BB: Appendix 4, pp. 738-752, http://www.state.nj.us/dep/dsr/njcrp/Appendix4

NOAA (National Oceanic and Atmospheric Administration) (1992a) Injury Assessment: Santa Clara Arsenic Trioxide Spill. The U.S. Department of Commerce, http://www.darp.noaa.gov/northeast/santa_clara

NOAA (National Oceanic and Atmospheric Administration) (1992b), Santa Clara Arsenic Trioxide Spill. The U.S. Department of Commerce http://www.darp.noaa.gov/northeast/santa_clara

NRC (National Response Center, U.S.) (2005) The U.S. National Response Center Database: reports of all oil, chemical, radiological, biological, and etiological discharges into the environment anywhere in the United States and its territories (1982-2004). http://www.nrc.uscg.mil 2005

Paine F. (1990) Packaging Design and Performance. Pira International, UK

P&I Club (Protection and Indemnity Club, UK) (1999) Loss Prevention Bulletin Series/99

Peters HA (1984) Seasonal exposure to arsenic from burning CCA treated wood. Journal of the American Medical Association JAMA, 251: (18) 2393-96

Persson U. and Cedervall M. (1991) The value of risk reduction: results of a Swedish sample survey. The Swedish Institute for Health Economics, Lund, IHE Working Paper 1991:6, Lund, Sweden

PHE (Physics Encyclopedia) 2005, http://www.physicsdaily.com/

Reade Advanced Materials (2005) http://www.reade.com 2005

Romer H., Haastrup P. and Petersen H.J.S. (1995) Accidents during marine transport of dangerous goods: Distribution of fatalities. The European Commission, Joint Research Centre Ispra, t.p. 650, 1-21020. Journal of Loss Prevention in the Process Industries, vol. 8, no 1

SEPA (Environmental Protection Agency) (1998) Environmental Protection Agency's Handbook for Environmental Monitoring (Handbok för Miljöövervakning)

SNV (Statens Naturvårdsverk - Swedish Nature Protection Agency) (1974) Report on m/v "Viggo Hinrichsen" accident - Rapport om m/s Viggo Hinrichsens förlisning, Statens Naturvårdsverk, Länsstyrelsen i Kalmar Län, SNV PM 445.

SIKA (Statens Institut för Kommunikationsanalys) (1999) Översyn av samhällsekonomiska kalkylprinciper och kalkylvärden på transportområdet, ASEK, SIKA Rapport 1999:6, Stockholm, Sweden

Silicon Publisher (2005) www.silicon.com

Sjöstedt L. (1993) Sustainable Mobility: A System Perspective on Policy Issues addressed by the 10th CAETS Convocation in Zurich

Spices J. (1984) On-Scene Coordinators Report: Recovery and Disposal of Aluminum Phosphide Fumigant from m/v "Rio Neuquen". The USCG, New Orleans, Louisiana, USA

Stockholm Convention (2001) on Persistent Organic Pollutants (POPs)

Sue S. (1999) Science, ethnicity, and bias: Where have we gone wrong? American Psychological Association, American psychologist journal, vol. 54, issue 12, pp. 1070-1077

Texas A&M University, U.S. (2005) Department of Oceanography, http://ocean.tamu.edu/

Trawen A., Maraste P. and Persson U. (2002) International comparison of costs of a fatal casualty of road accidents in 1990 and 1999. Accident Analysis and Prevention 34, pp. 323–332

Trbojevic VM and Carr BJ (2000) Risk based methodology for safety improvements in ports, Journal of Hazardous Materials 71 2000. pp. 467–480

TSE (Turku School of Economics, Turku, Finland) (2006) DaGoB (Safe and Reliable Transport Chains of Dangerous Goods in the Baltic Sea Region) Project website: http://www.dagob.info/2006

U.S. HR (U.S. House of Representatives) (2005) Shipping Containers. The Committee on Transportation and Infrastructure, the Subcommittee on Coast Guard and Maritime Transportation Hearing on Port Security, http://www.house.gov/transportation

U.S. Port and Waterways Safety Act Board of Inquiry (1992) M/v "Santa Clara I" loss of hazardous material in the Atlantic Ocean off New Jersey coast on January 4, 1992

University College London, UCL (2005) Tropical Storm Risk (TSR). Benfield Hazard Research Centre, Department of Earth Sciences, University College London (UCL), http://forecast.mssl.ucl.ac.uk 2005

University of Delaware, UD, U.S. (2003) Graduate College of Marine Studies and the Sea Grant College Program http://www.ocean.udel.edu 2005

University of Delaware, UD, U.S. (2004) How many ships travel the Delaware River and Bay, and what cargo do they carry? University of Delaware Sea Grant Program, http://www.ocean.udel.edu/oilspill/shipping.html

UN (United Nations) Chernobyl Forum (2005) Report on the Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russia Federation and Ukraine, Second Version

UNTAD (United Nations Conference on Trade and Development) (1995) Handbook on the Multimodal Transport

UNEP (United Nations Environment Protection) (2004) Press Release: Stockholm Convention on Persistent Organic Pollutants, http://www.un.org/2004

University of Kansas, U.S. (2005) http://www.ku.edu 2005

UK DE (UK Department of Environment) (1991) Interpretation of major accidents to the environment for the purpose of CIMAH regulations

UCB (University of California-Berkeley, U.S.) (2006) Linear Theory of Waves and Instabilities. The Department of Astronomy, http://astron.berkeley.edu, 2006

U.S. BLS (U.S. Bureau of Labor Statistics) (2006) Survey report: Water Transportation Employment. The Department of Labor, Occupational Employment Statistics (OES)

U.S. BLS (U.S. Bureau of Labor Statistics) (1992/1998) Census of Fatal Occupational Injuries, 1992 and 1998. The Department of Labor

U.S. NFWF (U.S. National Fish and Wildlife Foundation) (2004) http://www.nfwf.org

USCG (United States Coast Guard) (2005) When To Use A "Report of Marine Accident, Injury or Death" (CG-2692) Form http://www.uscg.2005

U.S. DHHS (U.S. Department of Health and Human Services) (1998) Report of the Public Health Service, Agency for Toxic Substances and Disease Registry Toxicological Profile for Arsenic (update), pp. 135

U.S. DHHS (U.S. Department of Health and Human Services) (1999) Diseases, Centers for Disease Control and Prevention, National Center for Health Statistics, National Vital Statistics Reports, vol. 47, no. 25.

U.S. DOC (U.S. Department of Commerce) and U.S. Census Bureau (2000) Censuses 2000 and 1990: Resident Population of the 50 States, the District of Columbia and Puerto Rico

U.S. DOC (U.S. Department of Commerce) (2004) Bureau of Economic Analysis, National Income and Products Account (NIPA) – The U.S. Gross Domestic Product

U.S. DOT (U.S. Department of Transportation) (1992) U.S. Coast Guard, M/v "Santa Clara I". The USCG Board of Inquiry Report Concerning the Loss of Hazardous Materials Near the New Jersey Coast, on January 3-4, 1992

U.S. DOT (U.S. Department of Transportation) (1995) Prevention Through People. Report of the U.S. Department of Transportation, U.S. Coast Guard, Office of Marine Safety, Security and Environment Protection, Office of Navigation, Safety and Water Services

U.S. DOT (U.S. Department of Transportation) (1996) Bureau of Transportation Statistics, U.S. Department of Commerce, Economics and Statistics Administration: 1993 Commodity Flow Survey: 1992 Census of Transportation, Communication, and Utilities, Issued October 1996, TC92-CF-52

U.S. DOT (U.S. Department of Transportation) (1998), Office of Hazardous Materials Safety Research and Special Programs Administration: Hazardous Materials Shipments 1998

U.S. DOT (U.S. Department of Transportation) (1999), Bureau of Transportation Statistics, U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau: 1997 Economic Census: Transportation, 1997 Commodity Flow Survey, Issued December 1999, EC97TCF-US

U.S. DOT (U.S. Department of Transportation) (2000), Bureau of Transportation Statistics, U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau: 1997 Economic Census: Transportation, 1997 Commodity Flow Survey: Hazardous Materials, Issued April 2000, EC97TCF-U.S. (HM) RV

U.S. DOT (U.S. Department of Transportation) (2001a), Maritime Administration, Office of Statistical and Economic Analysis, from Lloyd’s Maritime Information Services, London, England: Vessel Movements

U.S. DOT (U.S. Department of Transportation) (2001b), Bureau of Transportation Statistics: National Transportation Statistics, Washington, DC, from various sources as cited in the report.

U.S. DOT (U.S. Department of Transportation) (2001c), Bureau of Transportation Statistics: Fatalities, 1988–1998, National Transportation Statistics 2000, Washington, DC

U.S. DOT (U.S. Department of Transportation) (2001-2004), Maritime Administration, Office of Statistical and Economic Analysis 2001-2004: Vessel statistics: vessel calls and capacity

U.S. DOT (U.S. Department of Transportation) (2002a), Bureau of Transportation Statistics, based on data from U.S. Department of Commerce, Bureau of Economic Analysis: Survey of Current Business

U.S. DOT (U.S. Department of Transportation) (2002b), Bureau of Transportation Statistics: National Transportation Statistics (NTS) 2002, www.bts.gov; and NTS 2003

U.S. DOT (U.S. Department of Transportation) (1975-2001), Research and Special Programs Administration, Office of Hazardous Materials Safety, Hazardous Materials Information System Database (1975-2001)

U.S. DOT (U.S. Department of Transportation) (2004a), Bureau of Transportation Statistics, U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau: 2002 Economic Census: Transportation 2002 Commodity Flow Survey: Hazardous Materials, Issued December 2004, EC02TCF-U.S. (HM)

U.S. DOT (U.S. Department of Transportation) (2004b), Bureau of Transportation Statistics, U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau: 2002 Economic Census: Transportation, 2002 Commodity Flow Survey, Issued December 2004, EC02TCF-U.S.

U.S. DOT (U.S. Department of Transportation) (2005a) Hazardous Material Safety, Hazardous Materials Information System (HMIS): Hazmat Summary Incident for calendar Years 1993-2004

U.S. DOT (U.S. Department of Transportation) (2005b), Research and Innovative Technology Administration, Bureau of Transportation Statistics, National Transportation Statistics 2005, http://www.bts.gov/

USEPA (U.S. Environmental Protection Agency) (1985) Ambient aquatic life water quality criteria for arsenic – 1984. National Technical Information Service, PB85-227445

USEPA (U.S. Environment Protection Agency) (1992) Ship loses arsenic drums in Atlantic: EPA files suit. EPA Journal, vol. 18, Issue 2, pp. 3-3

USEPA (U.S. Environmental Protection Agency) (2001a) Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring. National Primary Drinking Water Regulations, Part VIII, 40 CFR Parts 9, 141, and 142, http://www.epa.gov/safewater/ars/arsenic

USEPA (U.S. Environmental Protection Agency) (2001b) Fact Sheet: Drinking Water Standard for Arsenic. EPA 815-F-00-015, http://www.epa.gov,2005

USEPA (U.S. Environmental Protection Agency) (2003) Technical Summary of Information Available on the Bioaccumulation of Arsenic in Aquatic Organisms. The Office of Science and Technology Office of Water, U.S. EPA, Washington, DC 20460

USNA (U.S. Naval Academy) (2005) Naval Architecture and Ocean Engineering, http://www.usna.edu//NAOE/index.html 2005

U.S. GPOW (U.S. Government Printing Office Washington) (2003) Cargo Containers: the Next Terrorist Target? Hearing before the Committee on Governmental Affairs, U.S. Senate, One Hundred Eighth Congress, First Session, March 20, 2003

UW (University of Winnipeg, Canada) (2005) http://theory.uwinnipeg.ca

Ventikos N.P. and Psaraftis H.N. (2004) Spill accident modeling: a critical survey of the event-decision network in the context of IMO’s formal safety assessment, Journal of Hazardous Materials 107 (2004), pp. 59–66

Wang J. (1999) A subjective modelling tool applied to formal ship safety assessment, Ocean Engineering 27 (2000), pp. 1019–1035

Wang J. (2002) Offshore safety case approach and formal safety assessment of ships, Journal of Safety Research 33 (2002), pp. 81– 115

Wang J. and Foinikis P. (2001) Formal safety assessment of containerships, Marine Policy 25 (2001) pp. 143-157

Weigkricht E. and Fedra K. (1993). Computer Support for Risk Assessment of Dangerous Goods Transportation. The Institute for Risk Research

Wewerka E.M., Bertino J.P.L., Wagner P., Williams J.M., Wanek P.L. and Wangen L.E. (1978) Trace element characterisation of coal wastes. The second annual progress report, DOE LA-7360-PR; EPA-600/7-78-028a, Washington DC.

Wetzel E.A. (2004) International Shipping: A Focus on the Republic of China: An Interview with Steven R. Blust, Chairman, Federal Maritime Commission. Review of Business, Proquest, vol. 25, issue 3 pp. 5-9

Whipple F.L., Laferriere R.R. and Moon S.K. (1993) M/v “Santa Clara I”: Arsenic Trioxide response – An Operational Review. Proceedings of the U.S. Marine Safety Council

White M. (1996) Why the m/v Santa Clara I had a devil of a voyage. The World Trade, 9, 11; ABI/Inform Global, pp. 64

Wright N.H. (1993) Development of Environmental Risk Assessment (ERA) in Norway. Norske Shell Exploration and Production.

Vowinkel E.F., Grosz A.E., Barringer J.L., Szabo Z., Stackelberg P.E., Hopple J.A., Grossman J.N., Murphy E.A., Serfes M. and Spayd S. (2001) Distribution of Arsenic in the Environment in New Jersey. The U.S. Geological Survey, New Jersey Department of Environmental Protection, West Trenton, N.J.

Yamaoka Y., Takimura O. and Fuse H. (1988) Environmental factors relating to arsenic accumulation by Dunaliella sp. Applied Organomet Chemistry, 2: 359–364.

Yin K.R. (1994) Case Study Research: Design and Methods, 2nd Edition. Saga Publication

Zwillich T. (2005), WebMD Medical News, http://webmd.com,2005

References of Appendix 2

References in International Programme on Chemical Safety (IPCS) 2001:

Andreae M.O. (1983) Biotransformation of arsenic in the marine environment, In: Lederer WH & Fensterheim RJ ed. Arsenic: industrial, biochemical, environmental perspectives. New York, Van Nostrand Reinhold, pp 378–392.

ANZFA (Australia New Zealand Food Authority) (1994) The 1994 Australian Market Basket Survey. A total diet survey of pesticides and contaminants. Canberra, Australia New Zealand Food Authority.

Armstrong C.W., Stroube R.B., Rubio T., Siudyla E.A. and Miller G.B. Jr (1984) Outbreak of fatal arsenic poisoning caused by contaminated drinking water. Arch Environment and Health, 39: 276- 279.

Bates M.N., Smith A.H. and Cantor K.P. (1995) Case-control study of bladder cancer and arsenic in drinking water. American Journal of Epidemiology, 141: 523–530.

Benramdane L., Accominotti M., Fanton L., Malicier D. and Vallon J-J. (1999) Arsenic speciation in human organs following fatal arsenic trioxide poisoning: A case report. Clinic Chemicals, 45: 301–306.

Brockbank C.I. and Batley G.E. and Low G.C. (1988) Photochemical decomposition of arsenic species in natural waters. Environment Technology Letter, 9(12): 1361–1366.

Brayer A.F., Callahan C.M., and Wax P.M. (1997) Acute arsenic poisoning from ingestion of 'snakes'. Pediatric Emergency Care, 13(6): 394–396.

Buchet J.P., Lison D., Ruggeri M., Foa V. and Elia G. (1996) Assessment of exposure to inorganic arsenic, a human carcinogen, due to the consumption of seafood. Arch Toxicology, 70: 773–778.

Callahan M.A., Slimak M.W., Gabel N.W., May I.P., Fowler C.F., Freed J.R., Jennings P., Durfee R.L., Whitmore F.C., Maestri B., Mabey W.R., Holt B.R. and Gould C. (1979) Water-related environmental fate of 129 priority pollutants. Introduction and technical background, metals and inorganics, pesticides and PCBs, Vol. I., EPA-440/4-79-029a, Washington, DC, U.S. Environmental Protection Agency (EPA), Office of Water Planning and Standards

Camardese M.B., Hoffman D.J., LeCaptain L.J. and Pendleton G.W. (1990) Effects of arsenate on growth and physiology in mallard ducklings. Environmental Toxicology Chemicals, 9(6): 785–795.

Capar S.G. and Yess N.J. (1996) U.S. Food and Drug administration survey of cadmium, lead and other elements in clams and oysters. Food Add Contaminants, 13(5): 553–560.

Chatterjee A., Das D., Mandal B.K., Chowdhury T.R., Samanta G. and Chakraborti D. (1995) Arsenic in ground water in six districts of West Bengal, India: the biggest arsenic calamity in the world, Part 1. Arsenic species in drinking water and urine of the affected people. Analyst, 120: 643–650.

Civantos D.P., Lopez R.A., Aguado-Borruey J.M. and Julia Narvaez J.A. (1995) Fulminant malignant arrhythmia and multiorgan failure in acute arsenic poisoning. Chest, 108(6): 1774–1775.

Cullen N.M., Wolf L.R. and St Clair D. (1995) Pediatric arsenic ingestion. American Journal of Emergency Med., 13: 432–435.

Cullen W.R., Li H., Pergantis S.A., Eigendorf G.K. and Harrison L.G. (1994) The methylation of arsenate by a marine alga Polyphysa peniculus in the presence of l-methionine-methyl-d-3. Chemosphere, 28(5): 1009–1019.

Dabeka R.W., McKenzie A.D., Lacroix G.M.A., Cleroux C., Bowe S., Graham R.A. and Conacher H.B.S. (1993) Survey of arsenic in total diet food composites and estimation of the dietary intake of arsenic by Canadian adults and children. Journal of AOAC International, 76: 14–25.

Das D., Chatterjee A., Mandal B.K., Samanta G. and Chakraborti D. (1995) Arsenic in ground water in six districts of West Bengal, India: the biggest arsenic calamity in the world. Part 2. Arsenic concentration in drinking water, hair, nails, urine, skin-scale and liver tissue (biopsy) of the affected people. Analyst, 120: 917–924.

Dickens R. and Hiltbold A.E. (1967) Movement and persistence of methanearsonates in soil. Weeds, 15: 299–304.

Engman J. and Jorhem L. (1998) Toxic and essential elements in fish from Nordic waters with the results seen from the perspective of analytical quality assurance. Food Add Contaminant, 15: 884–892.

Faust S.D., Winka A.J. and Belton T. (1987) An assessment of chemical and biological significance of arsenical species in the Maurice River drainage basin (N.J.). Part I. Distribution in water and river and lake sediments. Journal of Environment Science and Health, 22A (3): 209–237.

Fesmire F.M., Schauben J.L. and Roberge R.J. (1988) Survival following massive arsenic ingestion. American Journal of Emergency Med., 6: 602–606.

Fincher R.M.E and Koerker R.M. (1987) Long term survival in acute arsenic encephalopathy follow-up using newer measures of electrophysioloogic parameters. American Journal of Emergency Med., 82: 549- 552.

Forget J., Pavillon J.F., Menasria M.R. and Bocquené G. (1998) Mortality and LC_{50} values for several stages of the marine copepod Tigriopus brevicornis (Müller) exposed to the metals arsenic and cadmium and the pesticides atrazine, carbofuran, dichlorvos, and malathion. Environment and Safety, 40: 239–244.

Gottlieb K., Koehler J.R. and Tessari J. (1993) Non-analytic problems in detecting arsenic and cadmium in children living near a cadmium refinery in Denver, Colorado. Journal of Exposure Anal Environment Epidemiology, 3: 139–153.

Gunderson E.L. (1995) FDA total diet study-1986–1991-dietary intakes of pesticides, selected elements, and other chemicals. Journal of AOAC International, 78: 1353–1363.

Hamamoto E. (1955) Infant arsenic poisoning by powdered milk in Japanese. Nihon Iji Shimpo, 1649: 3–12.

Hamilton S.J. and Buhl K.J. (1990) Safety assessment of selected inorganic elements to fry of chinook salmon (Oncorhynchus tshawytscha). Ecotoxicology Environment Safety, 20(3): 307–324.

Hartwell S.I., Jin J.H., Cherry D.S. and Cairns J. (1989) Toxicity versus avoidance response of golden shiner (Notemigonus crysoleucas) to five metals. Journal of Fish Biology, 35(3): 447–456.

Hellou J., Fancey L.L. and Payne J.F. (1992) Concentrations of twenty-four elements in bluefin tuna, Thunnus thynnus from the Northwest Atlantic. Chemosphere, 24(2): 211–218.

Hoffman D.J., Sanderson C.J., LeCaptain L.J., Cromartie E. and Pendleton G.W. (1992) Interactive effects of arsenate, selenium, and dietary protein on survival, growth, and physiology in mallard ducklings. Arch Environmental Contaminant Toxicology, 22(1): 55–62.

Hu Y., Su L. and Snow E. (1998) Arsenic toxicity is enzyme specific and its affects on ligation are not caused by the direct inhibition of DNA repair enzymes. Mutat Res, 401: 203–218.

Hudson R.H., Tucker R.K. and Haegele M.A. (1984) Handbook of toxicity of pesticides to wildlife. Resource Publication 153, Washington, DC, U.S. Department of the Interior Fish and Wildlife Service.

Hörnström E. (1990) Toxicity tests with algae – a discussion on the batch method. Ecotoxicology Environment Safety, 20(3): 343–353.

Jenner H.A. and Janssen-Mommen J.P.M. (1993) Duckweed Lemna minor as a tool for testing toxicity of coal residues and polluted sediments. Arch Environmental Contaminant Toxicology, 25(1): 3- 11.

Kavanagh P., Farago M.E., Thornton I., Goessler W., Kuehnelt D., Schlagenhaufen C. and Irgolic K.J. (1998) Urinary arsenic species in Devon and Cornwall residents, UK: A pilot study. Analyst, 123(1): 27–29.

Kristiansen J., Christensen J.M., Iversen B.S. and Sabbioni E. (1997) Toxic trace element reference levels in blood and urine: influence of gender and lifestyle factors. Science Total Environment, 204(2): 147–60.

Langston W.J., (1983) The behaviour of arsenic in selected United Kingdom estuaries. Fish Aquatic Science, 40 (Supplement 2), pp. 143–150.

Levin-Scherz J.K., Patrick J.D., Weber F.H. and Garabedian C.J. (1987) Acute arsenic ingestion. Ann Emergency Med., 16: 702–704.

Lewis D.R., Southwick J.W., Ouellet-Hellstrom R., Rench J. and Calderon R.L. (1999) Drinking water arsenic in Utah: a cohort mortality study. Environment Health Perspective, 107: 359–365.

Lima A.R., Curtis C., Hammermeister D.E., Markee T.P., Northcott C.E. and Brooke L.T. (1984) Acute and chronic toxicities of arsenic(III) to fathead minnows, flagfish, daphnids, and an amphipod. Arch Environmental Contaminant Toxicology, 13: 595–601.

Maeda S., Inoue R., Kozono T., Tokuda T., Ohki A. and Takeshita T. (1990) Arsenic metabolism in a freshwater food chain. Chemosphere, 20(1/2): 101–108.

MAFF (Ministry of Agriculture, Fisheries and Food, UK) (1997) Survey of arsenic in food. The eighth report of the steering group on food surveillance, the working party on the monitoring of foodstuffs for heavy metals. Food surveillance paper No. 8. MAFF, UK.

Martin M., Osborn K.E., Billig P. and Glickstein N. (1981) Toxicities of ten metals to Crassostrea gigas and Mytilus edulis embryos and Cancer magister larvae. Marine Pollutant Bulletin, 12(9): 305–308.

Mathieu D., Mathieu-Nolf M., Germain-Alonso M., Neviere R., Furon D. and Wattel F. (1992) Massive arsenic poisoning – effect of hemodialysis and dimercaprol on arsenic kinetics. Intensive Care Med., 18: 47–50.

Mayer F.L. (1987) Acute toxicity handbook of chemicals to estuarine organisms. Environmental Research Laboratory, U.S. EPA.

Millward G.E., Kitts H.J., Ebdon L., Allen J.I. and Morris A.W. (1997) Arsenic in the Thames plume, UK. Marine Environment, 44(1): 51–67.

Mizuta N., Mizuta M., Ito F., Ito T., Uchida H., Watanabe Y., Akama H., Murakami T., Hayashi F., Nakamura K., Yamaguchi T., Mizuia W., Oishi S. and Matsumura H. (1956) An outbreak of acute arsenic poisoning caused by arsenic contaminated soy sauce (shoyu): A clinical report of 220 cases. Bull Yamaguchi Med Sch, 4: 131–150.

Mok W.M. and Wai C.M. (1990) Distribution and mobilization of arsenic and antimony species in the Coeur d'Alene River, Idaho. Environmental Science Technology, 24(1): 102–108.

Moore D.F., O'Callaghan C.A., Berlyne G., Ogg C.S., Davies H.A., House I.M. and Henry J.A. (1994) Acute arsenic poisoning: Absence of polyneuropathy after treatment with 2,3-dimercaptopropanesulphonate (DMPS). Journal of Neurology, Neurosurgery Psychiatry, 57: 1133–1135.

Naqvi S.M. and Flagge C.T. (1990) Chronic effects of arsenic on American red crayfish, Procambarus clarkii, exposed to monosodium methanearsonate (MSMA) herbicide. Bulletin of Environmental Contaminant Toxicology, 45(1): 101–106.

NAS (National Academy of Sciences) (1977) Medical and biological effects of environmental pollutants: arsenic. The National Academy of Sciences, Washington, DC.

NRC (National Research Council) (1999) Arsenic in drinking water. Subcommittee on Arsenic in Drinking Water, Committee on Toxicology, Board on Environmental Studies and Toxicology Commission on Life Science, National Academy Press, Washington, DC.

Oscarson D.W., Huang P.M. and Liaw W.K. (1980) The oxidation of arsenite by aquatic sediments. Journal of Environment Quality, 9(4): 700–703.

Phillips D.J.H. and Depledge M.H. (1986) Chemical forms of arsenic in marine organisms, with emphasis on Hemifusus species. Water Science Technology, 18: 213–222.

Sanders J.G. (1980) Arsenic cycling in marine systems. Marine Environment Res, 3: 257–266.

Schroeder W.H., Dobson M., Kane D.M. and Johnson N.D. (1987) Toxic trace elements associated with airborne particulate matter: a review. Journal of Air Pollution Control Assoc 37(11) 1267–1285.

Scudlark J.R. and Johnson D.L. (1982) Biological oxidation of arsenite in seawater. Estuary Coast Marine Science, 14: 693–706.

Sheppard S.C. (1992) Summary of phytotoxic levels of soil arsenic. Water Air Soil Pollution, 64(3/4): 539–550.

Taylor D., Maddock B.G. and Mance G. (1985) The acute toxicity of nine 'grey list' metals (arsenic, boron, chromium, copper, lead, nickel, tin, vanadium and zinc) to two marine fish species: dab (Limanda limanda) and grey mullet (Chelon labrosus). Aquatic Toxicology, 7: 135–144.

Thursby G.B. and Steele R.L. (1984) Toxicity of arsenite and arsenate to the marine macroalga Champia parvula (Rhodophyta). Environ Toxicology Chemical, 3: 391–397.

Tremblay G.H. and Gobeil C. (1990) Dissolved arsenic in the St Lawrence Estuary and the Saguenay Fjord, Canada. Marine Pollution Bulletin 21(10) 465–469.

Trepka M.J., Heinrich J., Schulz C., Krause C., Popescu M., Wjst M. and Wichmann H-E. (1996) Arsenic burden among children in industrial areas of eastern Germany. Science Total Environment, 180: 95–105.

Waslenchuk D.G. (1978) The budget and geochemistry of arsenic in a continental shelf environment. Marine Chemical, 7: 39–52.

Watson W.A., Veltri J.C. and Metcalf T.J. (1981) Acute arsenic exposure treated with oral d-penicillamine. Human Toxicology, 23: 164–166.

Weir P.A. and Hine C.H. (1970) Effects of various metals on behaviour of conditioned goldfish. Arch Environment Health, 20: 45–51.

Welch A.H., Lico M.S. and Hughes J.L. (1988) Arsenic in groundwater of the western United States. Ground Water, 26(3): 333–347.

Whitworth M.R., Pendleton G.W., Hoffman D.J. and Camardese M.B. (1991) Effects of dietary boron and arsenic on the behaviour of mallard ducklings. Environment Toxicology Chem., 10(7): 911–916.

Yamauchi H., Takahashi K., Mashiko M., Saitoh J. and Yamamura Y. (1992) Intake of different chemical species of dietary arsenic by Japanese, and their blood and urinary arsenic levels. Applied Organomet Chem., 6: 383–388.

Yost L.J., Schoof R.A. and Aucoin R. (1998) Intake of inorganic arsenic in the North American diet. Human Ecology Risk Assessment, 4: 137–152.