Hazardous Material Incidents – Some Key Results of a Risk Analysis

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Abstract

Human safety and health, environmental and property protection and security concerning hazardous materials supply chain are important issues for many countries, industries and organisations around the world. This paper presents some key results of a comprehensive risk study on hazardous materials supply chain incidents. Based on a risk analysis framework adapted for maritime transport of packaged dangerous goods, this study combines qualitative and quantitative analysis of large and diverse datasets collected from some of the U.S.'s best and largest data sources. The study may be one of the largest of its kind, and some of the results might not be found elsewhere. Incidents have occurred in every system of the hazardous materials supply chain, including platforms, all modes of transport, chemical plants, terminals and storages. The results show that more than half (52.1%) of incidents are attributed to the transport system. The study largely considers incidents happening during maritime transport, which account for 18% of transport incidents. In absolute terms, the FN curves of maritime transport human risks are generally found to be well below the corresponding FN curves of aggregated supply chain human risks.

Keywords

Dangerous goods; hazardous materials (hazmat); accidents and incidents; risks; supply chain; transport; vessel, water or maritime transport.

1. Introduction

Human safety and health, environmental and property protection and security concerning hazardous materials supply chain have become increasingly important issues for many organisations, industries, governmental authorities and the general public (IMO, 1997, 2004a, 2006; EC, 1997, 2006). Such concerns stem mainly from production, transport and use of large and still steadily increasing amounts of different types of hazmat, severe consequences that could result from unintentional accidents and deliberate acts, and the general belief that risks should be better managed. Therefore, it is relevant, important and necessary to analyse hazardous materials risks, further enhance understanding and thereby improve risk management in the field.

Many risk studies have largely been confined to the risks of individual systems of the hazmat supply chain and a few bulk dangerous cargoes carried by water, in particular large oil spills (e.g. EEA, 1995; Batten et al., 1998; Gilfillan et al., 1999; Kirchsteiger, 1999; Goulielmos, 2001; Konstantinos and Ernestini, 2002; Miraglia, 2002). Many risk studies are based on qualitative analysis of a single or a few case histories. This study, which takes a holistic approach including risks of large and increasing amounts of different types of hazardous material carried in packaged form, combines both qualitative and quantitative datasets and data analysis methods.

Risk analysis is, in principal, a rigorous and systematic process facilitated by specific analysis frameworks and techniques. 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 immediate application in all circumstances (IMO, 2002). In recent years, efforts have been made to adapt, further develop, or simply to apply or test the FSA in the maritime related systems or issues concerning 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 vessels (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), but not with risks of the maritime transport of packaged dangerous goods (PDG). The FSA is not readily applicable for risk analysis in the maritime transport of PDG. The framework lacks some essential concepts concerning the system and risks of dangerous goods in general and PDG in particular, including top events, types of failures in the packaging system, transport hazards, a list of dangerous goods and the hazards involved, exposures and routes of exposure. Based on an extensive literature study and the analysis of the large amount of empirical data, a risk analysis framework is adapted for application in the risk analysis of the maritime transport of PDG. In this paper, the analysis process is facilitated by the risk analysis framework presented in Fig. 1. A detailed description of the framework is provided in Mullai, 2004.

2. Methodology

Stage 1 (see Fig. 1) – preparations for risk analysis – encompasses a wide range of activities. Identification, selection, compilation and preparation of datasets for analysis are some very important activities. This study combines qualitative and quantitative datasets and analysis methods for the following interrelated reasons:

- Facilitate data and method triangulations;
- Extend and fill gaps in data;
- Validate and provide a complete demonstration of the risk analysis framework, including testing of external validity that, by definition, concerns the application of the framework to other systems and phenomena of interest. Therefore, the application of the framework is extended to other systems of the hazmat supply chain, including maritime transport of bulk dangerous cargoes and other transport modes;
- Compare and explore relationships among the system and risk elements; place risks of the maritime transport into perspective;
- Employ a holistic or systems approach and provide lessons from various systems and activities of the hazmat supply chain.

The framework validation is based on other datasets than those used in model development. Because of the data quality, quantity, accessibility, format and costs, U.S.'s sources were chosen as data sources for collection of the relevant data. In terms of the amount, quality, diversity, accuracy, public accessibility and availability of the data, U.S. data sources are some of the world's best and largest public (in English) data sources in the field. In compliance with the U.S. Freedom of Information Act (1974), all federal and national organisations and agencies are required to make data publicly available in electronic format. The review of many databases shows that the data quality, availability and accessibility are concerning issues in many countries, including countries in Europe and the Baltic Sea Region. The main datasets used in the risk analysis included:

- The merged dataset from the U.S. Hazardous Material Information System (HMIS) database (U.S. DOT, 2005): 185,612 incident cases (U.S. 1993-2004). The number of maritime transport or vessel incidents (114) is significantly smaller compared to other transport mode incidents reported to this database. However, the database provides valuable lessons for maritime transport and many other hazmat-related systems and organisations.
- The merged dataset from the U.S. National Response Center (NRC) database (NRC, 2005): 453,564 incident cases (U.S. 1990-2004).
- Economic censuses: U.S. Commodity Flow Surveys (CFS) - Hazmat Transportation Reports (U.S. DOT, 1996, 1999, 2000, 2004).
- Marine accident case histories: The m/v "Santa Clara I" (SCI) accident and other cases. The m/v SCI accident is a representative case of cargo damage and loss overboard, human health consequences due to exposure to toxic substances, and the marine environment pollution. The main data sources of the m/v SCI case consisted of the accident investigation report prepared by the USCG's Board of Inquiry (U.S. DOT, 1992), the USEPA (1992) and several papers written by experts in the field (Whipple et al., 1993; McGowan, 1993; Merrick, 1993; and Crokhill, 1992).

In both incident databases, the datasets are organised by year and variable. Databases contain a large number of variables (over 180 variables) representing system and risk elements. For the purpose of demonstration, some important variables are selected, including year, types of incidents, systems, failures, transport hazards, causes and contributing factors, and consequences.

3. Risk Analysis

The risk analysis process attempts to provide answers to three fundamental questions, namely: "What has gone and could go wrong?" "What are the consequences?" and "How likely is that to happen?" - known as "the triplet definition" of risks (Kaplan and Garrick, 1981). The concept of the triplet definition is applied as an element of standardisation (IEC, 1995). The aforementioned questions as well as the methodological requirements and the complexity and the dynamics of relationships in the systems and risks, lead to other important questions that require additional answers, efforts and resources. A key objective of every risk study is to facilitate the decision-making process by providing the decision makers with sufficient, reliable and valid information.

The risk analysis process is facilitated by the risk analysis framework presented in Fig. 1. The exploration and quantification processes are performed simultaneously.

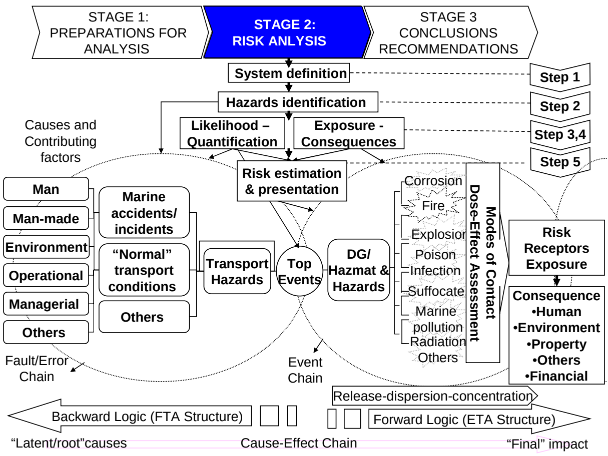

Fig. 1: Risk Analysis Framework (Mullai, 2004)

The following sections present in a stepwise manner (see Fig.1) the risk analysis process.

3.1 System Definition

In the following section, some important elements of the systems and risks are briefly defined and described.

3.1.1 Supply Chain – Maritime Transport System

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

The transport system consists of many elements that are 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 are all related and linked together by the information system and transport related activities, such as cargo and passenger handling operations, documentation, transport. The human element is a very important component of the system that 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.

3.1.2 Dangerous Goods or Hazmat

Dangerous goods, or hazardous materials (hereinafter hazmat) as commonly known in the U.S., are substances, articles, and materials defined and classified under the relevant regulations, such as for the maritime transport the SOLAS 74 Convention and MARPOL, 73/78 Convention. Based on the relevant international regulations, the IMDG Code defines and classifies dangerous goods into 9 classes according to hazards they pose, some of which 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, toxic or poison, infection, suffixation, corrosion, radiation, marine pollution, and other hazards (e.g. carcinogens). Many dangerous goods pose more than one hazard. Detailed definitions and descriptions of dangerous goods are provided in each respective class in the IMDG Code. The terms “dangerous goods” and “hazmat” are often used interchangeably. However, for the purpose of simplicity and consistency with the U.S. data sources, the term “hazmat” is frequently used in this paper.

3.1.3 Packaging System

With regard 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. The packaging is a system in its own right consisting of many different elements that are necessary for the packaging system to perform its designed functions. Hazmat are carried in different packaging levels (e.g. primary, secondary and tertiary) and types. Packagings vary in size, shape, strength and material. For maritime transport, according to the IMDG Code, they include cargo transport units (CTUs) (e.g. freight vehicles, rail freight wagons, freight containers, road and rail tank vehicles/wagons and portable tanks), unit loads (e.g. pallets), intermediate bulk containers (IBCs), and small and medium size conventional packagings (e.g. drums, bags, fibreboard boxes). For packing purposes, dangerous goods of all classes, 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. The IMDG Code provides detailed descriptions and general and specific provisions for construction, testing, handling and transport operations of different types of packagings.

3.1.4 Regulatory System

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

- International Convention for the Safety of Life at Sea (SOLAS, 1974), as amended;
- International Convention for the Prevention of Pollution from Ships 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 1973/1978), as amended;
- International Maritime Dangerous Goods (IMDG) Code, as amended (the latest edition is 2006). The Code provides detailed regulations concerning maritime transport of packaged dangerous goods;
- International Convention of Safe Containers (CSC) 1972 concerning standards for design, construction testing, inspection, and maintenance of containers;
- IMO Resolution A.714 (17) for Cargo Securing Manual;
- IMO Guidelines (MSC Circular 530) for lashing and securing heavy items.

The U.S. Code of Federal Regulations (CFR) concerns a wide range of hazmat-related systems, activities and aspects, including:

- Technical and operational aspects of hazmat transportation;
- Standards for design, construction testing, inspection, and maintenance of containers;
- Reporting of hazardous incidents and conditions;
- Training of people involved in recovery operations of hazmat;
- Planning of search and recovery operations of hazmat.

3.1.5 Concept of Risks

The hazmat supply chain, including transport, is a risk source entailing possibilities of undesirable outcomes. In essence, the concept of risk is defined as the likelihood of consequences of undesirable events (see e.g.

Kaplan and Garrick, 1981; HSE, 2001; IEC, 1995; Mullai, 2006). The main risk elements include undesirable events (accidents and incidents), causes and contributing factors, exposure, consequences (risk receptors – humans, the environment and property) and their likelihood.

The term “undesirable events”, which is often used as a more neutral and generic term, denotes all types of events, from unsafe situations and 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 incident" and "marine casualty" denote undesirable events in connection with ship operations (IMO, 1996), (LRS, 1996). Although there is a distinction between “accident” and “incident” in terms of the magnitude of consequences, for the purpose of simplicity and consistency with the U.S. data sources, the term “hazmat incident” is most frequently used in this paper to denote all categories of undesirable events involving hazmat.

Based on the categories and the magnitude of consequences, risks are classified into human safety and health risks (fatality and injury risks, individual and societal risks), environmental risks, property risks and other risks (ISO, 1999; IMO, 2004a).

Risk elements are defined and classified in a wide range of classification or coding systems, such as the Lloyds Maritime Information Service, the IMO, the USCG and the U.S. DOT, and the SMA (Swedish Maritime Administration). The systems are diverse and, to some extent, incompatible.

3.1.6 Hazmat Incidents

Incidents are the negative outcomes of the systems, which are largely inseparable from their positive outcomes or benefits. The following section presents: a) a brief summary of the m/v SCI incident; and b) some results of the statistical incident data from the HMIS and NRC databases.

The m/v SCI incident

On January 4th, 1992, during a storm, the m/v “Santa Clara I” (SCI) (9593 grt breakbulk ship, Panamanian flag) lost 21 of 25 on-deck-stowed containers and a heavy piece of machinery in the vicinity of Baltimore Bay (USA), which is a sensitive area for the local community. The remaining containers were severely damaged. Six of 21 containers lost overboard contained arsenic trioxide (Class 6.1: Toxic) drums. Because of serious threats posed by the chemical to the fishing industry, fishing in the area was banned for several months. In addition, some 363 kg of magnesium phosphide (Class 4.3) spilled in 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 reacts violently with water, emitting phosphine gas, which is highly poisonous and flammable. Two crewmembers became dizzy and vomited, which is a typical reaction to phosphine gas exposure, after entering into the hold to re-secure cargo. In Port Charleston, 37 longshoremen were sent to the hospital for observation after being exposed to magnesium phosphide while working inside the hold.

The search and recovery operation of arsenic trioxide drums was one of the largest offshore operations in U.S. history. It involved many personnel and sophisticated equipment from different agencies. The operation lasted for 5 and half months. It was estimated that over $ 2.2 million were spent in search, location and recovery of arsenic trioxide drums only. The m/v SCI accident remained at the centre of the U.S. media, congressional and legal debates for two months.

Statistical incident data

The following presents some results of the NRC and HMIS databases. The U.S. National Response Center (NRC) records all types of hazmat, including oil, oil products, chemical, radiological, biological, and etiological or disease causing discharges anywhere in the U.S. and its territories. Based on the system, activity or source of releases, hazmat incidents reported to the NRC are categorised into fixed, vessel, mobile or road, railroad, pipeline, platform, storage tank, continuous, and aircraft. Incidents reported in railroad transport consist of two categories, “railroad” and “railroad non-release (NR)” incidents. A thorough random review of the entire NRC database showed that “railroad NR” incidents were, in many cases, the results of reckless and deliberate acts, and that hazmat releases or involvements might have occurred or remained potential. Many incidents have caused suspensions or disruptions in the system and beyond. The categories of “fixed” and “continuous” consist of incidents reported at shore-based hazmat-related systems, such as chemical plants, power plants, and waste treatment facilities. Prior to 2000, the category of “storage tank” (or storage) incidents was reported as “fixed” incidents.

The HMIS database (1993-2004) is a specialised, recording hazmat incidents in all transport modes (air, road, rail and water or maritime), excluding pipeline. The hazmat includes bulk (e.g. road and rail tanks and bulk freight containers) and non-bulk (e.g. ISO freight containers) hazmat. From the maritime transport point of view, by definition, both aforementioned categories fall under the term packaged dangerous goods (PDG) or hazmat transport.

The databases are diverse, but they also share overlapping areas. With some adjustments, incident records from both databases are merged. In order to avoid any overestimation, only the largest reported number of incidents, i.e. the worst-case scenario, from one database is taken into consideration for respective activities or systems. Thus, the number of vessel incidents recorded in the NRC database is considered because vessel incidents reported to this database are larger (57274 incidents) than those reported to the HMIS database (114 incidents). The following summarizes some key results from the merged datasets (Fig. 2~3):

- During the period 1990-2004, a total number of 607071 incidents, or on average 40471 incidents per year, is reported from a wide range of systems of the U.S. hazmat supply chain. The sources of a large number of hazmat releases are unknown (10.4%).
- Hazmat supply chain incidents per year have steadily

increased from 31795 (1990) to 43254 (2004), which is an increase of 36%. A similar increasing trend is also observed in the transport system. Since 2001, however, the number of incidents has slightly declined.

- More than half (52.1%) of hazmat incidents are reported in the transport system, in which water or maritime transport is the second largest contributor (18%).

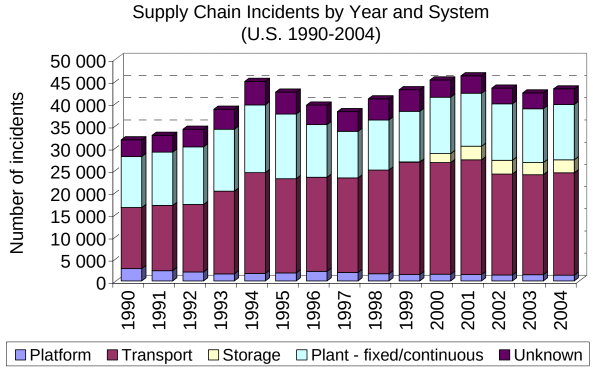

Fig. 2: Hazmat Supply Chain Incidents (%) by Year and System (U.S. 1990-2004)

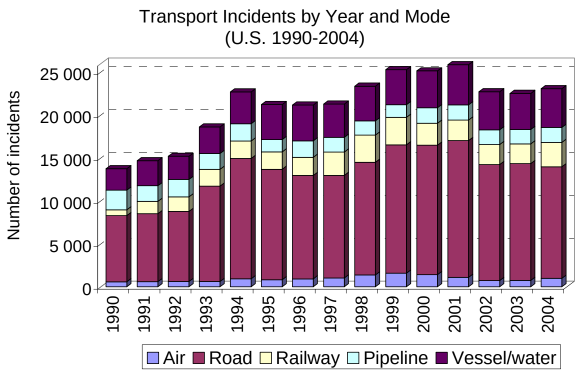

Fig. 3: Hazmat Transport Incidents (%) by Year and Mode (U.S. 1990-2004)

Some plausible explanations for the high numbers of transport incidents include the following:

- The transport system, including the maritime transport system, is characterised by a large number of diverse elements that are in very interdependent, complex and dynamic relationships. Large amounts of many different types of hazmat are transport in the U.S. and other parts of the world.
- Because of its mobility, the transport system is more vulnerable to many hazards than several other systems. The transport system is exposed to a wider range of hazards than many other systems. Certain hazards, such as those associated with transport incidents (e.g. collision), static and dynamic forces (e.g. acceleration/ deceleration), and environmental hazards (e.g. sea hazards), are very specific for the transport system.
- The transport system, including hazmat, packages and means of transport, is exposed to excessive transport hazards for a longer duration than some other systems. 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. Thus, 64% of vessel incidents are reported during the voyage or en route phase. The ship is a larger and a more complex system than other means of transport.
- Failures or deficiencies are generated and propagated throughout the transport system. 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. Thus, Fig. 9 surprisingly shows that the majority (59.2%) of hazmat transport incidents are reported during the unloading phase, which is overrepresented compared to loading (16.8%) and enroute (17%) phases.

Case histories have shown that hazmat incidents are generated and propagated in a chain of events. The chain is characterised by the cause-effect relationships, known as causality or causal mechanisms linking causes and effects. Across this chain, there is a wide range of possibilities to employed strategies and measures for preventing incidents and/or mitigating their consequences. Therefore, understanding of the chain of events involving hazmat and their behavious is very important.

In this paper, the common terminology employed in the field is frequently used to denote elements of the cause-effect chain, including top events, damage or failures, transport hazards, causes and contributing factors, hazmat hazards, and consequences. In the following sections, the chain of events is explored in some detail.

3.2 Hazard Identification

Hazard identification attempts to provide answers to the questions: "What has gone and could go wrong" in the system and "How likely is it?" In this process, based on the principles of backward logic analysis, top events, distribution/transport hazards, and causes and contributing factors are explored and quantified to the extent for which data were available.

3.2.1 Top Events

Hazmat releases are prerequisite conditions for the large numbers and amounts of hazmat to cause harm to the risk receptors. Top or initial events may be considered as the set of events that can lead to hazmat releases, such as damage, failures or deviations from the intended functions of packaging, containment or other parts of the system. The risk analysis could begin at this set of events. Top events are often the necessary, but not always sufficient and immediate, conditions for hazmat releases. The likelihood of packaging failures may be remote for some types of incidents, e.g. minor or near-miss incidents. The latter events provide valuable lessons for preventing and mitigating major accidents.

The main categories of top events related to PDG/ hazmat transport are identified (HMIS, 1993-2004): a) breach (damage or failures) of packaging components mainly due to transport hazards such as bursting, breaking, smashing, cracking, splitting, collapsing etc; b) failures due to improper or wrong operations, defects, weaknesses in the design and construction of packaging systems; c) others, such as contamination or odour, frozen hazmat, contact with water, other liquids or moisture, radiation, moulding etc. Certain types of incidents, such as contamination, radiation and contact with water, may not necessarily involve any hazmat release. The majority of hazmat releases are attributed to the first two categories.

The HMIS database (1993-2004) showed that hazmat transport incidents have often been followed by a string of subsequent events. In many cases, more than one package, hazmat, and means of transport have been involved in a single incident. Further, more than one damage or failure, transport hazard and cause and contributing factor are often reported in a single incident. In the following section, damage or failures in packaging types, materials, components and areas are presented.

Fig. 4~5 show the main packaging types and materials involved in hazmat transport incidents reported to the HMIS database (1993-2004). Three packaging types, namely box, drum and bottle/jug, accounted for 77% of the main types presented in Fig. 4. Whilst, the top 13 packaging types accounted for 75% of all packaging types involved in transport incident sequences (279922), such as fibre boxes, metal and plastic drums, plastic and glass bottles and jugs, metal cans, plastic containers, mounted tank truck and others. Fibre boxes rank as the most frequent packaging type involved - respectively 22% and 29% of all and top 13 packaging types.

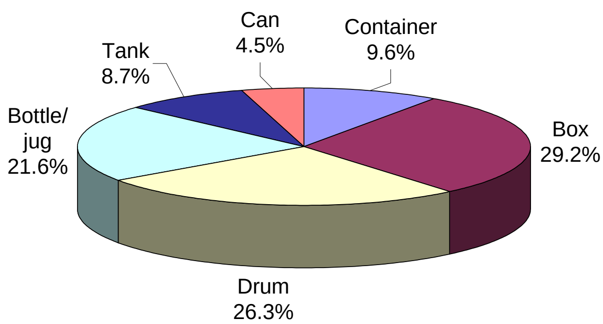

Fig. 4: Packaging types involved in hazmat transport incidents (U.S. 1993-2004)

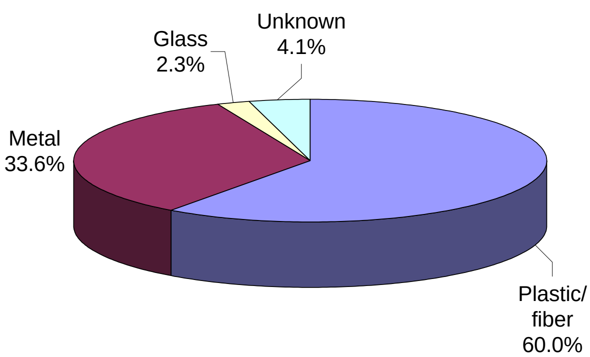

Fig. 5: The main packaging materials involved in hazmat transport incidents (U.S. 1993-2004)

The weakest and/or the most vulnerable packaging components reported are packaging material (41.3%), closure (22.3%), and fitting or valve (7.9%), which combined accounted for approx. 71% of all failures (286661). The "other" category includes a wide range of other packaging components, such as caps, vents, manifolds, nozzles, gaskets, gauges, connections and seals. The weakest and/or the most vulnerable packaging areas reported are top (36.5%), bottom (24.4%) and sides (left and right) (10.5%). Failures of the top and bottom areas combined represented ca. 60% of all failures (296863). The high frequency of damage or failures in the mentioned packaging types, materials, components and areas could be explained by:

- Inherent weaknesses or deficiencies in the design, construction and maintenance of the packaging system.
- Inherent properties of packaging materials and components: Some plastic or fibre packagings may not be able to withstand normal transport hazards. In the case of the m/v SCI incident, the FRP (fibreglass reenforced plastic) container stowed on deck failed disastrously compared to other metallic containers. The FRP material is less durable than other materials. It has no plastic range - it goes from an elastic range, where it springs back to its original shape, to its breakpoint.
- Inherent properties of hazmat, such as liquid, gas and corrosive substances: Liquid and gas substances are much more difficult to contain compared to solid substances. Corrosive substances (Class 8) in combination with other contributing factors are liable to cause damage or weaken packaging performance as well as the cargo securing system and means of transport. Incident data show that Class 8 is excessively represented – Class 8 was the second top class accounting for 37.8% of all classes involved in transport incidents (Fig. 10).
- Bulk liquids and gases are often handled (loaded/ discharged) under pressure.
- Gravity combined with vertical acceleration forces and the stowing or packing patterns and procedures considerably affects top and bottom packaging areas.
- Large numbers of hazmat are carried in various packaging levels. Thus, large CTUs, such as freight containers, vehicles and wagons are often loaded with pallets packed with smaller packages, such as boxes, drums, bottles, jugs and cans. Because of the large number, the latter are more exposed to transport hazards than the CTUs. However, the probability of large hazmat releases or involvements in a single incident is lower in non-bulk or packaged hazmat shipments than in bulk hazmat shipments. Various packaging levels serve as good protecting barriers.

Top events are often attributed to more than one (OR gate, where at least one of the events is present) category of transport hazards, and causes and contributing factors (see Fig. 6~7 and Table 1).

3.2.2 Transport Hazards, Causes and Contributing Factors

Fig. 6~8 and Table 1 present transport hazards, causes and contributing factors of hazmat release incidents as they are recorded in separate variables in the HMIS and NRC databases. In accordance with relevant classification systems and data available, some arrangements and adjustments have been made in categorisation and labelling, in particular in the upper levels of resolutions.

The transport system of PDG/hazmat is exposed to a wide range of hazards (see Fig. 7), which have often preceded failures of packages. The statistical data show that the most frequent failures reported are due to: a) mechanical hazards that are produced by static and dynamic forces, such as those causing puncturing, crushing, cracking, rupturing and pressuring; and b) climate or environmental hazards, such as in contact with water, other liquids, and moisture from the floor of storage terminals or means of transport (Fig. 7).

The transport system, including means of transport, and cargo securing and packaging systems, is designed and constructed to withstand "normal" transport hazards. However, because of many issues, including those related to data and estimation methodology, approximations and "best guesses" are inherent in the design and construction of the system. In many cases, the system is exposed to conditions exceeding the "normal" design conditions. In addition, transport hazards exerted in transport incidents, for example in collision, listing or capsizing, may far exceed the design and construction conditions (see Table 1 and Fig. 8). In the case of the m/v SCI incident, the values of traversal acceleration forces in heavy synchronized rollings (up to 35^{o}) and green water forces might have reached, if not exceeded, design and construction limits of the packaging and the cargo securing systems. The green waters play a very significant role in losses and destruction of on-deck-stowed cargo.

Hazmat transport incidents are attributed to a large menu of causes and contributing factors (see Table 1 and Fig. 8). Classification systems of causes vary widely. However, causes and contributing factors could generally be classified into the following main categories: human, including managerial and operational factors, man-made or technical, environmental and other factors.

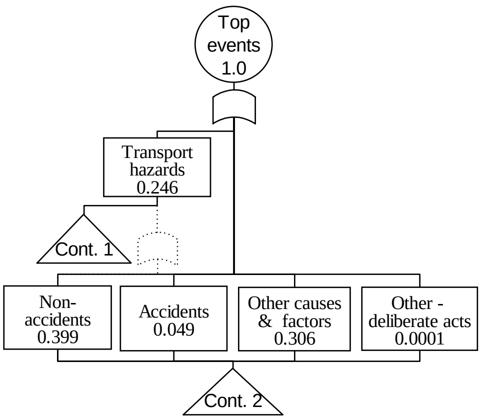

Fig. 6: Transport hazards, causes and contributing factors (U.S. 1993-2004)

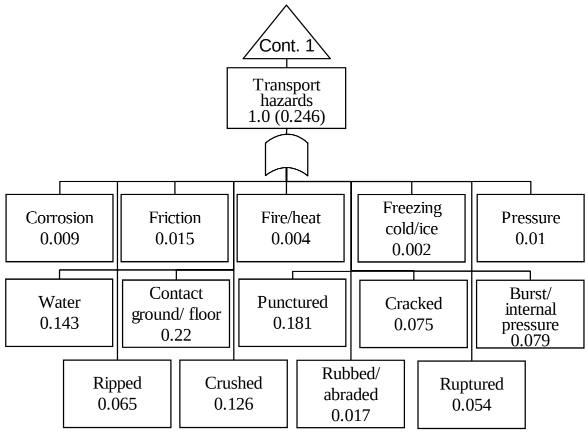

Fig. 7: Transport hazards (U.S. 1993-2004) (from continue 1 in Fig. 6)

Table 1: Transport hazards, causes and contributing factors (U.S. 1993-2004) (from continue 2 in Fig. 7)

Nr.	Transport Hazards, Causes and Contributing factors	Frequency		
		Main category	Sub-category	Sub-category
	Transport hazards (cont. 1)	**0.246**		
1.	**Non-accidents – "normal" transport conditions**	**0.399**		
1.1	***Man-made/ technical***		***0.282***	
1.1.1	Other objects caused failure			0.765
1.1.2	Defective fittings			0.127
1.1.3	Nail or protrusion			0.062
1.1.4	Package overused, defective manufacturing			0.038
1.1.5	Incompatible materials			0.009
	Total – Sub-category			*1.000*
1.2	***Operational***		***0.592***	
1.2.1	Loose fitting or closure			0.268
1.2.2	Package dropped			0.209
1.2.3	Improper loading			0.197
1.2.4	Package struck			0.153
1.2.5	Improper forklift operation			0.089
1.2.6	Improper blocking			0.058
1.2.7	Container overfilled			0.027
	Total – Sub-category			*1.000*
1.3	***Managerial***		***0.126***	
1.3.1	Hazmat not listed			0.786
1.3.2	Requirements not met			0.214
	Total – Sub-category		***1.000***	*1.000*
2.	**Accidental**	**0.049**		
2.1	Other freight responsible			0.831
2.2	Vehicle overturned			0.085
2.3	Collision			0.039
2.4	Another vehicle			0.028
2.5	Obstacle			0.017
	Total – Sub-category			*1.000*
3.	**Other causes and factors**	**0.306**		
4.	**Other - deliberate acts**	**0.001**		
4.1	Vandalism			1.000
	Total – Transport hazards and main category of causes	**1.000**		

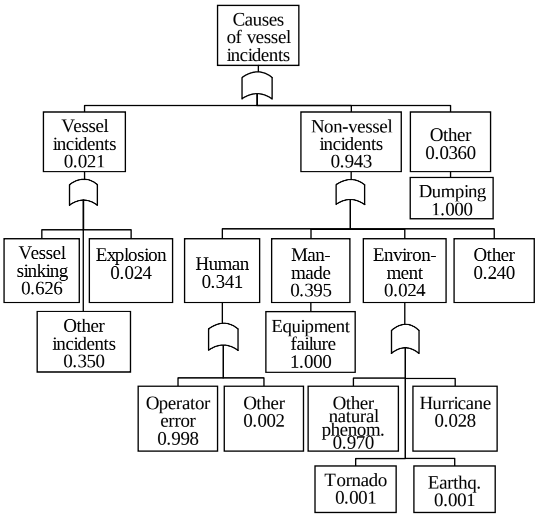

Fig. 8: Causes and contributing factors of vessel incidents (U.S. 1990-2004)

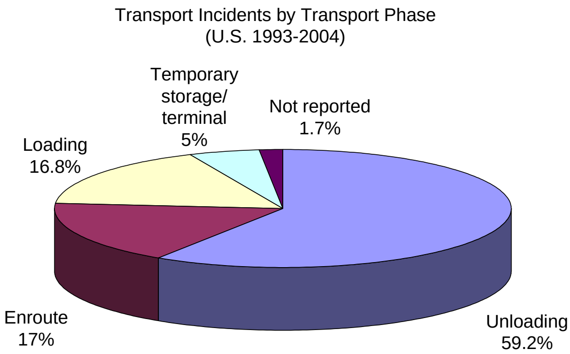

Fig. 9: Hazmat transport incidents by transport phase (U.S. 1993-2004)

In the case of the m/v SCI incident, the entire chain of events was affected by a large menu of causes and contributing factors. Some of them are not found in the HMIS and NRC databases and many other databases. The largest deficiencies were related to the cargo and ship navigation systems, operations and management. Some root causes and contributing factors, which can also provide explanations and serve as illustrative examples for many categories of causes presented above (see Fig. 6~8 and Table 1), included:

Individual and industry predispositions: The master's predisposition was "We are sailors – we go to the sea". A generally prevailing expectation in the industry is that a commercial ship will get underway (U.S. DOT, 1992). These predispositions were also shared by other respected professional mariners (U.S. DOT, 1992). Certainly, perils of sea are parts of shipping. However, it does not mean exposing the ship deliberately at any time and by all means to perils. Seasoned mariners with sound judgments have the capacity to understand and anticipate limitations of the ship and cargo systems to withstand adverse weather conditions.

Business constraints including cost, time and regulation constrains: Under pressure to meet the schedule in the next port, the master was anxious to hastily get the ship loaded and underway. He declined the usage of the shoreside lashing-gang in port, opting for cargo securing with the ship's crew after leaving the dock. The rules of the labour union in port prohibited cargo securing alongside the pier when the shore-side lashing-gang was not used. Cargo securing was generally inadequate and in some parts incomplete. The crew was probably tired after a long day's work and under time pressure while leaving the port in darkness and deteriorating weather conditions.

Poor seamanship: Numerous navigational faults are identified, including those related to preparation and navigation in heavy weather conditions. The master had many years' experience with large tankers, but no experience with small general cargo ships. He underestimated the effects of weather conditions and overestimated his navigational judgments and skills by proceeding according to the schedule and pre-planned courses despite heavy weather. The master's navigational skills and decision-making capacity were inadequate. Not only did he fail to understand and avoid the situation and respond appropriately by offsetting the effects of weather conditions, but, on the contrary, his poor shiphandling at sea amplified these effects.

Many deficiencies were observed in the system and system operations due to poor supervision or mismanagement, in particular in the cargo securing system, including mismatches, insufficient supply of lashing equipment and gears, rogue securing equipment in use and inventory, improper application of installation methods, and misunderstanding of cargo securing system mechanics.

Failures to comply with relevant regulations including inadequate container inspection and maintenance, the lack of inspection and maintenance records, failure of the container owner to comply with relevant regulations, inadequate oversight of compliance and enforcement of regulations, and gaps in regulatory control and oversight programs.

Failures of cargo securing inside containers were mainly due to inadequate container packing, blocking and bracing, weak blocking and bracing schemes, inadequate stowage, inherent design problems in palletized drums, inadequate dunnaging materials and arrangements, and uninstalled tomming.

The lack of knowledge and training was identified, in particular in cargo handling, caring and securing procedures, hazmat identification and handling, and incident reporting.

The master of the m/v SCI was largely blamed for the incident, but the facts suggested that he was not the only culprit. Other people from both sides – ship and shore – also contributed, in different ways and to various degrees, to the incident and its consequences.

It is no surprise that the human element is the largest contributor to hazmat incidents. Paradoxically, the human element is responsible for everything – but not always. Human is responsible for almost everything as it is involved in every activity, including design, construction, operation, maintenance and management of the systems. However, given many constraints and limitations surrounding the human element, in particular individuals, human is not always responsible.

3.3 Exposure and Consequence Analysis

The “gap” between the initial hazmat release events and the actual and “final” consequences is often characterised by a very complex chain of events. Based on forward logic analysis, in the following section attempts have been made to explore some important events in the chain – “What are the consequences?”, “How many?” or “How likely is it?” Prior to the mentioned questions, it is important to provide answers to questions concerning types and amounts of hazmat, release, dispersions, concentration, routes of exposure, dose-effect relationship and exposure to hazmat.

Neither the HMIS and NRC databases nor many other incident databases provide data for some essential events. In order to fill gaps and extend data, the events are explored based on 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 for understanding and preventing consequences of hazmat incidents.

3.3.1 List of Hazmat and Hazards

The amounts, types of hazards and other properties of hazmat have played a determining role in the course of hazmat incidents, including release, dispersion and concentration, routes of exposures, consequences, and response operations. The list of hazmat carried onboard the m/v SCI included:

- Arsenic trioxide (Class 6.1) (459.3 tons in 2700 drums packed in 25 containers), which is liable either to cause death or serious injuries or to harm human health if swallowed or inhaled, or by skin contact.
- Magnesium phosphide (Class 4.3) (1.8 tons in 10 drums packed in 5 pallets), which reacts violently in contact with water emitting flammable and poisonous gases. Magnesium phosphide drums were clearly labelled, but not listed in the shipping documents in accordance with the IMDG Code.
- Other types of hazmat were carried and probably spilt onboard the m/v SCI, but the data sources provide no information about classes and amounts.

Both arsenic trioxide and magnesium phosphide are regulated under the IMDG Code and the relevant U.S. Code of Federal Regulations (49 CFR).

The statistical incident data (HMIS, 1993-2004) showed that all hazmat classes are represented (Fig. 10~11). The top three most frequent hazmat classes involved in packaged hazmat transport incidents reported are Class 3 (flammable liquids), Class 8 (corrosive materials) and Class 6 (toxic and infectious substances), which combined accounted for approx. 88% of all classes (Fig. 10). The most frequent classes or divisions within respective main classes reported 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%). The top two hazmat shipping names involved in all transport modes combined and vessel incidents are respectively a) corrosive and flammable liquids N.O.S., (Table 2) and b) phosphoric acid and ammonia anhydrous. The top 20 hazmat shipping names accounted for more than half (51.1%) of all hazmat (Table 2). Phosphoric acid, ammonia anhydrous, environmentally hazardous liquids, and flammable liquids N.O.S. are reported the top hazmat shipping names involved in vessel incidents. During the period 1990-2004, a total number of 353 arsenic release incidents (24 incidents per year) were reported from different sources to the NRC database. Arsenic trioxide releases are reported in 5.6% of the cases.

The dominant bulk hazmat carried by water are oil and oil products, LNG and LPG, which pose fire, explosion, toxic or environmental pollution hazards. The vast majority of all transport modes combined (93.6%) and vessel (79.6%) incidents have involved hazmat posing fire, explosion, corrosion and toxic as the primary hazards (see Fig 12~13). In many cases, mixtures of hazmat posing more than one hazard have been involved, making the situation more difficult to deal with. In the m/v SCI incident, flammable and toxic gases emitted from magnesium phosphide posed serious threats to the ship and her vicinity.

Some of the world’s worst hazmat disasters, such as, for example, 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 hazmat posing fire, explosion, toxic, radiation and environmental pollution hazards. Response teams should be well equipped and prepared to deal with all possible scenarios, in particular with incidents involving aforementioned hazards.

The high frequency of the mentioned classes and shipping names is mainly attributed to inherent properties of hazmat and large numbers of shipments.

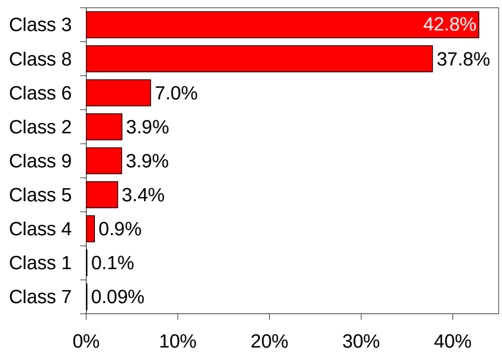

Fig. 10: Ranking of hazmat classes involved in all transport incidents (U.S. 1993-2004)

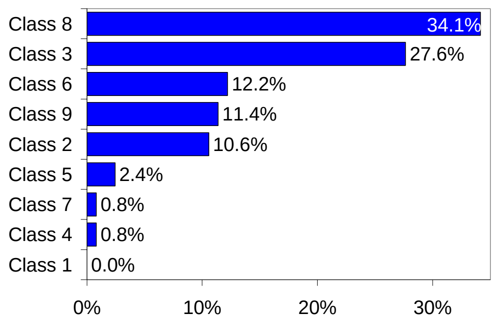

Fig. 11: Ranking of hazmat classes involved in vessel incidents (U.S. 1993-2004)

Table 2: Top hazmat shipping names involved in transport incidents (U.S. 1993-2004)

Rank	Hazmat shipping name	As % of the top 20	As % of the total
1	Corrosive liquids N.O.S.	14.6	7.4
2	Flammable liquids N.O.S.	14.4	7.3
3	Resin solution	7.7	3.9
4	Sodium hydroxide solution	6.2	3.2
5	Adhesives	4.7	2.4
	Total of top 5	47.6	24,2
	Total of top 20	100.0	51.1
	Total		**100.0**

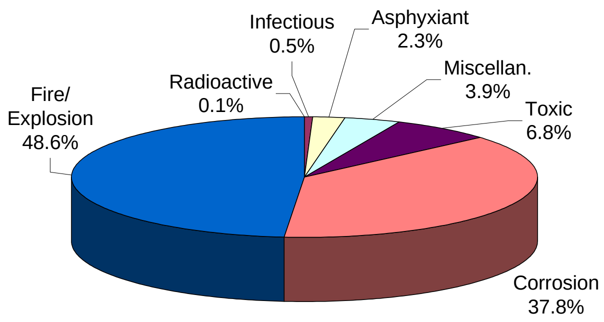

Fig. 12: Hazmat hazards involved in all transport incidents (U.S. 1993-2004)

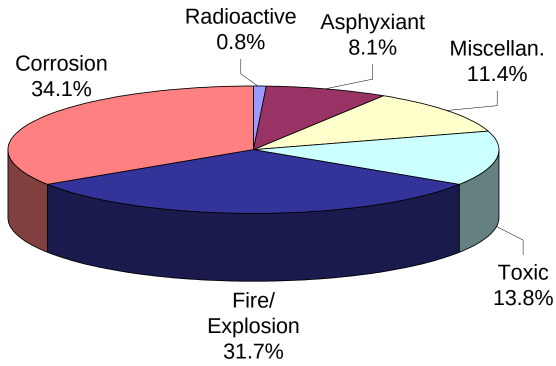

Fig. 13: Hazmat hazards involved in vessel incidents (U.S. 1993-2004)

3.3.2 Hazmat Release, Dispersion and Concentration

In many cases, given physical and chemical properties of hazmat, it is certain that once packages or other forms of containments are breached, hazmat are released or have the potential to be released. A very large portion of hazmat transported are in liquid (i.e. oil and oil products, and many liquid chemicals), liquefied gas and gas forms (i.e. LNG and LPG).

Unlike other transport modes and systems of the hazmat supply chain, in the maritime transport of packaged hazmat, the extent of release, dispersion, concentration and subsequently the consequences of hazmat depend very much on the fate of packages. In the case of the m/v SCI incident, due to heavy weight, damage and negative buoyancy, arsenic trioxide containers and drums sank immediately after falling overboard. Strong winds, waves and sea currents had little effect on drifting and dispersion of drums and containers. They roughly landed on a stretched area along the projected ship's trackline (estimated 12-14 km), coinciding with the most severe ship motions, in particular heavy synchronized rollings. The ROV (Remote-Operated Vehicle) search found cargo largely clustered on the sea floor according to cargo stowage location onboard the ship.

Studies of many marine incidents have shown that the fate of packages lost at sea, including floating and drifting, sinking and dispersion, is affected by a wide range of variables, including:

- *Packaging design, construction and operational properties*: packaging material, shape, dimensions, mass, buoyancy, immersed fraction and cross-sectional area;
- *Weather/sea conditions*: wind direction and velocity, wave properties, integrated water current direction and velocity, vertical and horizontal profiles of water currents, water temperature, viscosity and density, atmospheric and sea level pressure, tides;
- *Environment topography*: water depth, sea, river or other inlandwaters bottom and coastline topography.

Exploring and understanding these events and their influencing factors are very important for the relevant authorities and organisations in many respects, including: a) estimate and predict more accurately drifting, floating and dispersion of packages and other objects lost at sea; b) provide early and accurate warnings to shipping and other maritime-related activities about the danger; c) enhance effectiveness and efficiency in search and recovery operations.

The extent of risk receptors' exposure and actual consequences is significantly affected by the amount, duration, rate and type of hazmat releases. Furthermore, the amount of hazmat released depends on the extent and type of damage and conditions to which packages are exposed. In the case of the m/v SCI incident, the following scenarios at sea and on board are explored:

At sea: The fact that arsenic trioxide was contaminated with seawater suggests that many drums breached and seawater penetrated inside and came in contact with arsenic trioxide. According to the IMDG Code, arsenic is slightly soluble in water (1.82g/100g). Due to the combination of water pressure and temperature differences, water currents, and other environmental conditions, diluted arsenic trioxide spilt and dispersed into the sea. An estimated amount of 200 kg arsenic trioxide was released from 320 drums recovered from the sea floor. Given its chemical properties and the extent of damage to drums, arsenic trioxide released into the sea may have been in dissolved and solid forms.

Onboard the ship: Both arsenic trioxide and magnesium phosphide are solid substances. As the drums rolled on deck and due to the combined effects of gravity, impact, vibration, rain, wind and green waters (for the drums stowed on deck), two tons of arsenic trioxide were spilt from 13 broken drums, and spread on the main deck and several hatches. Blown by strong winds and diluted by rains and green waters, an unknown amount of arsenic trioxide ended up in the sea. In the upper tweendeck of the no.1 hold, as drums rolled over the deck, an amount of over 393 kg toxic powder spilt from 4 broken drums (4 of 10 drums), and subsequently dispersed and piled several inches high in some areas.

In contact with water and/or atmosphere moisture inside the no. 1 hold magnesium phosphide gave off flammable phosphine gases in dangerous quantities. Gases form an explosive mixture with air at concentrations greater than 1.8% by volume (or 18000 ppm) (U.S. DOT, 1992). The high level of phosphine concentration (400 ppm) found in the stevedores' bodies suggests that the level of gas concentration inside the hold was very high, in particular during the voyage and prior to opening of the hatch cover in port. The gas-air mixture might have easily ignited from any ordinary sources of ignition, including defective electrical installations, static electricity and unprotected light bulbs. The situation might have turned into a worst-case scenario. The initial fire/ explosion might have spread to the entire ship that could have caused very serious consequences to the ship and her cargo and beyond.

3.3.3 Routes of Exposure – Modes of Contact

In order to cause harm to risk receptors, hazmat and/or their hazards (e.g. radiation, heat or blast waves) have to come in contact with risk receptors. The main routes of exposure include inhalation, ingestion, skin or eye contact, pressure wave contact, flying object or debris, heat, and radiant flux exposure. Risk receptors may come in contact with hazmat through more than one route. The routes of exposures with hazmat play a very important role in the type and the severity of consequences. For many toxic chemicals, exposures through inhalation and ingestion are more dangerous than other routes. For example, the acute lethal dose of arsenic trioxide to humans through inhalation is significantly lower than the acute lethal dose to humans through ingestion (see below) and skin absorption.

In the case of the m/v SCI incident, arsenic trioxide, magnesium phosphide and phosphine gas presented hazards by inhalation, ingestion and in skin/eye contact. All people affected were exposed to hazmat through inhalation and skin contact. Some 39 stevedores and crew members (39 of 40 or 98%) were exposed to phosphine gas through inhalation. However, other routes of exposure are not excluded. Arsenic trioxide dispersed and concentrated into the seawater column, sediments and flora, comes into contact and accumulates in aquatic organisms. Arsenic accumulation by fish and shellfish takes place through ingestion of arsenic contaminated seawater, sediments and foods. Plants come in contact and accumulate inorganic arsenic by root uptake from sediments or by adsorption of arsenic deposited on leaves or stems. Arsenic can be transferred to humans through consumption of contaminated sea products. Arsenic bioaccumulation may take place through all routes of exposure.

3.3.4 Dose-Effect Assessment

Coming into contact with the risk receptors is a necessary, but still not a sufficient condition for hazmat to cause harm. By virtue of their inherent hazardous properties, hazmat can cause different types of harms to risk receptors at various degrees of the severity – from slightly detectable through severe chronic health effects to death. This depends very much on a particular damage or dose-effect mechanism that is influenced by many factors, such as properties of hazmat, duration and extent of exposure, and features of risk receptors. In many cases, the biological, physical, chemical and other hazmat effects can only occur or be observed after a certain level, also known as the threshold level, of exposure is exceeded. Many risk receptors have, to various degrees, the capacity to withstand certain levels of hazmat hazard exposures. Living organisms contain and are daily exposed to a wide range of chemicals.

In the case of the m/v SCI incident, the fact that no fatality was reported suggests that doses of arsenic trioxide and phosphine gas 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 chemicals over a period of time. Both the ship and shore personnel were, to various extents, exposed to arsenic trioxide for less than 48 hours. Detectable effects (dizziness and vomiting) of arsenic exposure were observed in three crewmembers only. None of them reported incidents and symptoms to the master, the chief mate or the medical officer.

Given the toxic properties of phosphine gas and activities carried out inside the hold, exposure to phosphine gas might have lasted for a range between several minutes and a few hours. The medical analyses showed that the level of phosphine concentration in the stevedores' bodies was 400 ppm, which was twice the level of "immediately dangerous to life and health" (200 ppm) (U.S. DOT, 1992). Due to immediate professional responses and medical treatments, no fatality or serious health effects were reported. Good expertise and understanding of the chain of exposure events and hazardous properties of hazmat may have played a crucial role in saving human lives.

3.3.5 Exposure Analysis

One form of risk estimation is to measure actual consequences relative to (averaged over or divided by) the sub-sets of populations or the universe of risk receptors threatened or exposed to hazmat. This form has become a legal requirement in some countries. The risk receptors consist of humans, the environment and property. A common unit for measuring consequences is the monetary unit ($). The hazmat supply chain, including the maritime transport system, is simultaneously a risk generator and a risk receptor as well. Several properties of the systems can serve as exposure measures. In addition, they can also provide further explanations for hazmat incidents and their consequences. The following are some results of the analysis (see Fig 14~19):

- The U.S. GDP generated from products, assets and services has increased significantly (2.6 fold) (see Fig. 14), which is attributed to good performance of the U.S. economy and the increasing population. Since 1990, the U.S. population has increased by 50 million.
- In recent years, transport performance characteristics (value, tons and ton-miles, and ton-miles per capita) have also shown increasing trends (see Fig. 14~15). Large quantities of different types of hazmat ship-

ments are carried by water in different types and sizes of packages and ships. The size (dwt) and the number of ships calling at U.S. ports increased during the period 2001-2004 (Fig. 18~19). Ocean-going self-propelled vessels (over 10,000 dwt) accounted for 98% of the total vessel capacity calling at U.S. ports. Ships carrying packaged hazmat, such as 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. In 2002, water transport accounted for 10.4% and 26.4% of the total hazmat shipments in tons (of the total 2.191 billion tons) and ton-miles (of the total 326.7 billion ton-miles, excluding pipeline) respectively (Fig. 16~17).

- The patterns of hazmat supply chain incidents, including all transport modes combined and water transport incidents, largely matched the increasing trends in the U.S. GDP and transport performance characteristics (see Fig. 14~15, 18~19). Compared to 1990, the numbers of vessel incidents reported each year will double in the near future if they continue to increase at the same rate (see Fig. 18). This match suggests that the GDP and transport performance have played a significant influencing role in the increase of the number of incidents offsetting the effects of preventive measures. Therefore, in combination with effective risk management strategies and measures, sustainable development is a suitable solution.

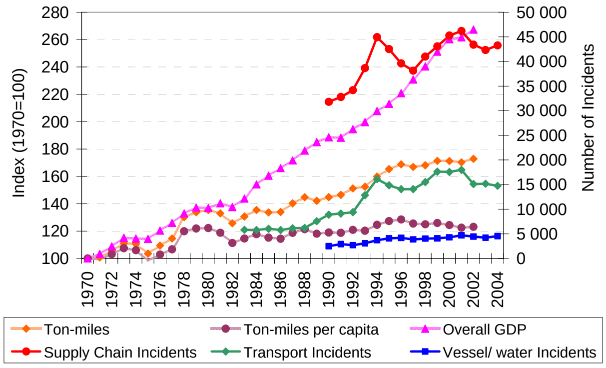

Fig. 14: Comparison between the U.S. economy and transport performance characteristics and hazmat incidents (U.S. 1970-2004) (U.S. DOC, 2004; U.S. DOT, 2004, 2005; NRC, 2005)

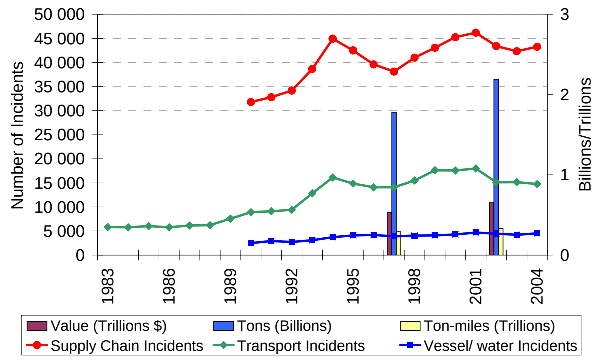

Fig. 15: Comparison between hazmat shipment characteristics and hazmat incidents (U.S. 1983-2004; U.S. DOT, 2000, 2004, 2005; and NRC, 2005)

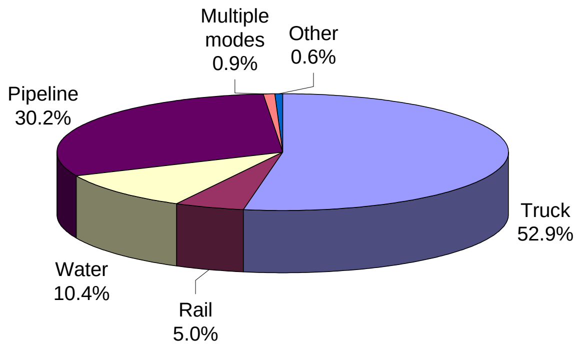

Fig. 16: Hazmat shipment tons by mode (U.S. 2002) (U.S. DOT, 2004)

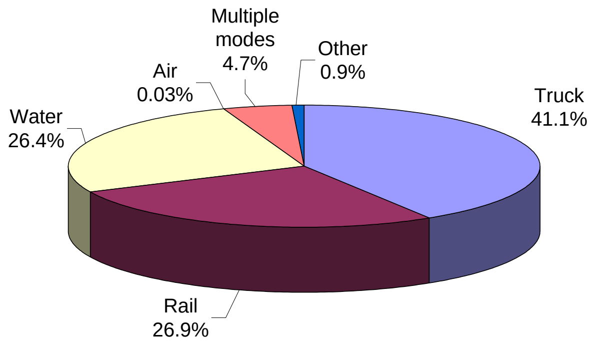

Fig. 17: Hazmat shipment ton-miles by mode, excluding pipeline (U.S. 2002) (U.S. DOT, 2004)

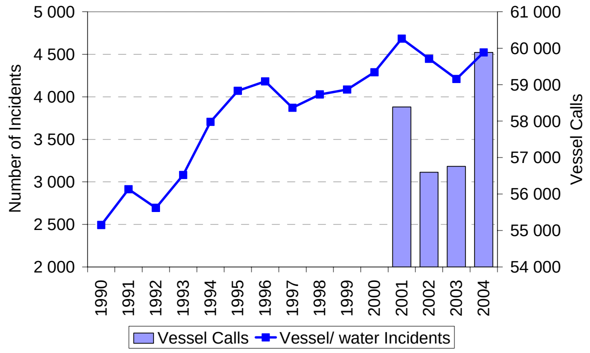

Fig. 18: Comparison between vessel calls and vessel incidents (U.S. 1990-2004) (U.S. DOT, 2001-2004)

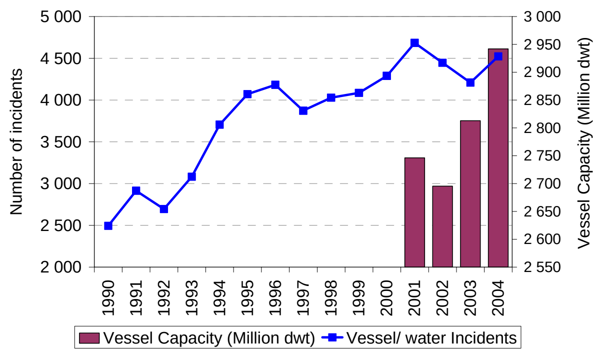

Fig. 19: Comparison between vessel capacity and vessel incidents (U.S. 1990-2004) (U.S. DOT, 2001-2004)

In the case of the m/v SCI incident, the following risk receptors and activities were exposed to hazmat:

- *Humans*, including these categories a) the crews of the m/v SCI (28) and other ships in the vicinity; b) stevedores and supervisors working onboard the m/v SCI and other ships and port areas; c) cleanup workers, and response personnel; d) authorities and representatives, including port, police, and USCG authorities, fire department personnel, representatives of cargo receivers, the shipping company and insurers; e) others including pilots, cargo surveyors, fishermen; and f) local communities.

- *Marine environment*: the marine environment of Delaware Bay and the southern coast of the state of New Jersey, including the seawater, fauna and flora, sediments, coastlines and their amenities;
- *Property*, including these categories a) ships: the m/v SCI and other ships in the vicinity; b) cargoes: cargo of the m/v SCI and other ships; c) properties ashore: properties within the port territory and the local communities.
- *Disruptions of activities* in ships, ports, local communities, maritime-related activities such as fishing, and coastlines.

3.3.6 Consequences Analysis

Hazmat incidents have affected different risk receptors in various magnitudes of severity. In the following section some key results concerning consequences of incidents from both incident databases are presented (see Fig. 20~25):

- The main categories of consequences recorded in NRC and HMIS databases are: human safety and health (fatalities, injuries, evacuation and hospitalizations), environmental, property and other damages (in U.S. $), (see Fig. 20-25) and activity disruptions (in hours). Environmental consequences are also expressed in amounts of hazmat released. Regular recording of hospitalizations started in the year 2000. In many cases, incidents are associated with more than one type of consequence. The type and the magnitude of severity of human and property consequences attributed only to the hazardous properties of hazmat are unclear. Many other incident databases reviewed are confined to fatality and injury records only.
- Road transport accounted for over 50% of the total transport human consequences reported to the HMIS database (1993-2004). Because of the small number of vessel incidents reported to the HMIS database, the human consequences of vessel incidents were zero or insignificant.
- On average, 927 fatalities, 2,289 injuries and 60,540 evacuated people are reported per year to the NRC database (see Fig. 20~22). With some fluctuations, fatalities and injuries per year have increased during the period 1990-2004 (see Fig. 20~21).
- Because of reckless and deliberate acts, the human consequences, in particular fatalities, of railroad NR incidents are overrepresented. In many cases, these incidents have led to or had the potential for hazmat releases. They have often caused disruptions in the system.
- Environmental damages are not confined to oil and oil products spills only. Large amounts of different types of hazmat or chemicals, which can cause severer consequences to human health and environmental damages than oil spills, are released into the ecosystem from a wide range of land-based and offshore sources. Some hazmat can cause long term and irreversible effects. For example, on average, 24 arsenic compound release incidents have been reported per year in the U.S. (1990-2004).
- Based on the IMO's CAF (Costs of Averting a Fatality, i.e. U.S. $ 1.5 million) (IMO, 2004a), human consequences (fatalities and injuries) and damage measured in monetary units ($) are aggregated, as shown in Fig. 24. These costs do not include costs incurred due to evacuations, disruptions of activities, losses to business, fines and legal implications, and the costs of short and long terms and hidden effects.
- The costs of environmental damage accounted for more than a half (53.7%) of the total costs (see Fig. 25). In recent years, the costs of environmental damage have increased significantly. In many cases, fines and business and legal implications constitute a large portion of environmental damage costs. The review of both databases shows that the number and the extent of damage incidents are underreported and underestimated. The costs of hidden, unknown and long-term effects of chemicals, in particular those related to the ecosystem and humans, will be borne by future generations and industries that are directly related to the health services and the ecosystem.

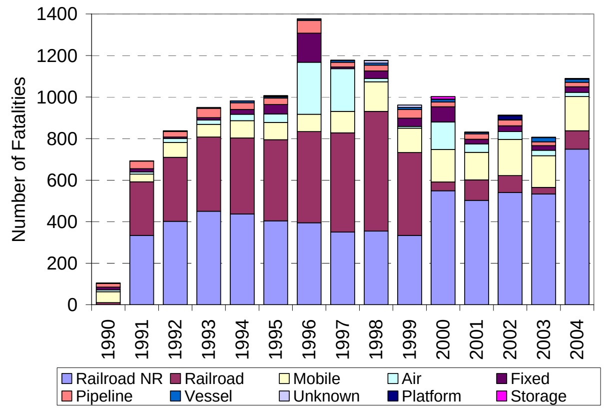

Fig. 20: Supply chain fatalities by year and system (U.S. 1990-2004)

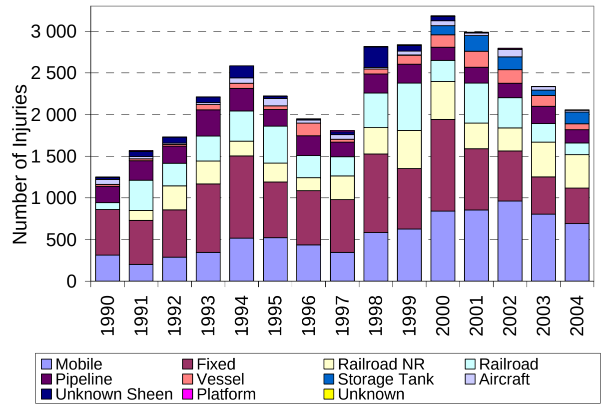

Fig. 21: Supply chain injuries by year and system (U.S. 1990-2004)

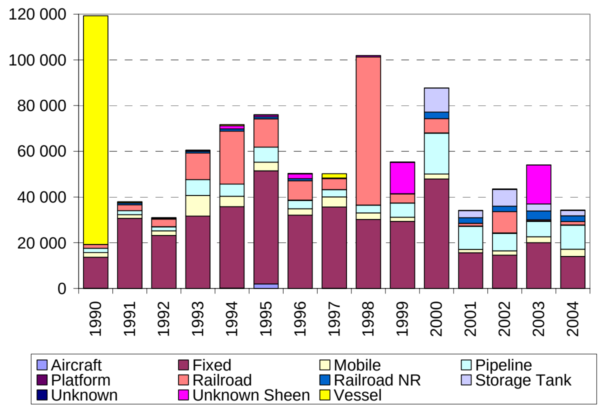

Fig. 22: Supply chain evacuations by year and system (U.S. 1990-2004)

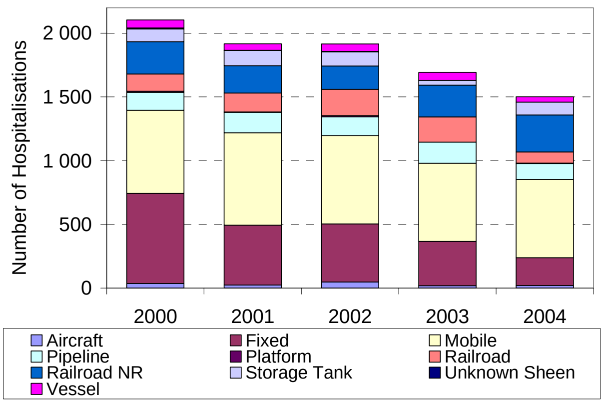

Fig. 23: Supply chain hospitalizations by year and system (U.S. 1990-2004)

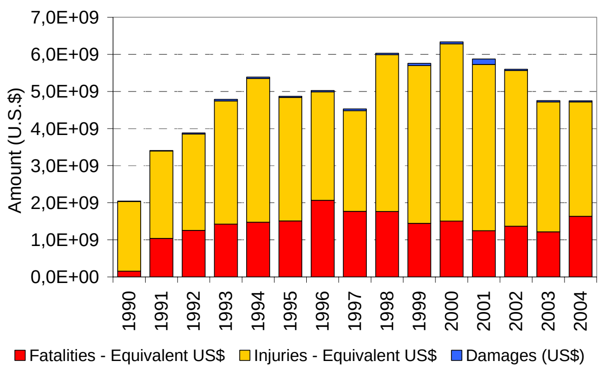

Fig. 24: Aggregated supply chain human (fatalities and injuries) and damage consequences in $ (U.S. 1990-2004)

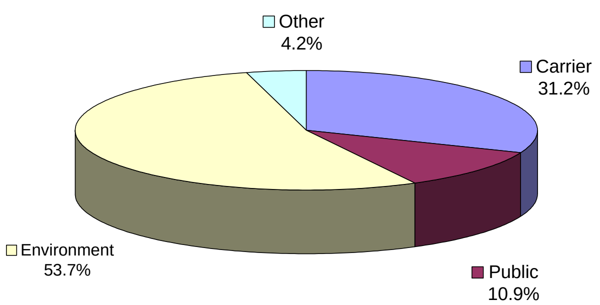

Fig. 25: Economic consequences (U.S. $) of hazmat transport incidents (U.S. 1993-2004)

In the case of the m/v SCI incident, based on the IMO (1996), LMIS (1995) and U.S. DOT (2002) criteria for the severity of incidents and the review of many incidents, given the following facts, the severity of the m/v SCI incident is judged as *a serious marine accident or casualty*. The data also suggest that an incident of the m/v SCI incident magnitude was neither a frequent nor an unlikely or remote incident. During the storm, the m/v SCI sustained serious damage. In the following section the actual consequences and potential threats due only to hazards of arsenic trioxide and magnesium phosphide are explored. Some consequences were the result of concerns, threats and responses to the involvement of hazmat (i.e. domino or knock-on effects).

Humans: The m/v SCI incident did not involve any acute fatality, but the health of many people (40 crew members and stevedores) was affected by hazmat. None of them were either aware or warned about the danger. Three (3 of 28) crew members were reportedly affected. Two crewmembers felt dizziness and one of them vomited, which is a typical reaction to phosphine gas exposure, after entering into the hold to re-secure cargo. Another crewmember took some spilt arsenic in his hands, and he felt sick after smelling the powder. Some 37 stevedores were sent to hospital after exposure to very high doses of phosphine gas (400 ppm). Although no fatality or serious health effects were reported, health implications in the future are not excluded. A single case exposure to some hazmat, including arsenic and phosphine gas, can cause serious chronic health problems or even death after many years. Given the value of Costs of Averting a Fatality (CAF) (U.S.$ 1.5 million) proposed by the IMO (2004a), the amount of U.S.$ 2.2 million spent in search and recovery operations only is equivalent to more than one fatality.

Marine environment: Given the massive body of the ocean water and limited quantity of arsenic trioxide (200 kg+) released from damaged drums recovered from the sea floor (320 drums), there was no or insignificant contamination. In order to assess the environmental impact, numerous samples were taken in and around the debris. The levels of arsenic trioxide concentration in the seawater column, sediments and marine organisms were found within the natural or background levels. According to the investigation report, arsenic bioaccumulation in the marine environment is insignificant (U.S. DOT, 1992). Further, arsenic trioxide has not been given the letter P (pollutant) in the IMDG Code (2002) dangerous goods list. But, according to numerous credible sources, arsenic compounds bioaccumulate in tissues of aquatic organisms (IPCS, 2001). The large amount of unrecovered arsenic trioxide (16 tons) may still pose threats to the marine environment and the local community. Incident records from both U.S. databases showed that the amount of arsenic trioxide involved in the m/v SCI incident was one of the largest amounts of pure arsenic compounds released in the U.S. during the period 1990-2004.

Property: The m/v SCI incident did not involve a ship's total or construction loss, but the ship and her cargo were severely contaminated by hazmat. The main deck and several hatches were covered by arsenic trioxide. The upper tweendeck of the no.1 hold was contaminated by magnesium phosphide. Cargoes in other holds were also contaminated by other hazmat. Cargo, in particular foodstuffs, contaminated with hazmat is discarded.

Activity disruption: Because of contamination and fire/explosion threats, many activities were disrupted. In Port Charleston, cargo operations onboard the ship and ashore were suspended as the USCG ordered evacuation of the ship. With a skeleton crew, the m/v SCI was sent to an isolated anchorage area. The contamination was so severe that it took more than one month to clean up and decontaminate the ship. The lawsuit filed against the m/v SCI and her shipowner for the loss of arsenic trioxide drums also prevented the ship's departure. Because of the possibility of arsenic trioxide drums being caught by fishing nets and the potential contamination of fish, fishing was banned in the area. Several drums were caught in the nets of fishing boats. The fishing ban stayed in effect for approximately four months until drums were found and removed, and environmental consequences were assessed. Many local, national and federal authorities, agencies and organisations and individuals suspended their daily routines and were involved, to various extents, in the m/v SCI incident case.

Bad publicity: Because of the large amount of arsenic trioxide lost in an environmentally and economically important and sensitive sea area, the SCI incident remained at the centre of the U.S. media, congressional and legal debates for two months. The shipowner's attitude and response to the incident further aggravated the situation – from bad to worse. Initially, although well aware of the gravity of the situation, the shipowner neither took any immediate action nor reported the situation to the responsible authorities.

Legal implications: The USCG's Board of Inquiry recommended criminal actions against the shipowner and the crew of the m/v SCI. However, the U.S. Department of Justice declined criminal prosecution of the crew. The crew was granted immunity in return for testifying in a civil action against the shipowner. 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.

Costs of the incident: The costs of the m/v SCI incident are unknown, except for costs of the search and recovery operation. The m/v SCI search and recovery operation was one of the largest operations in U.S. history, amounting to U.S. $ 2.2 millions. The operations required detailed preparations, planning, reviews, meetings, and coordination of several different agencies and organisations across the U.S. Due to the lack of accurate information and delays in incident reporting, search and recovery teams spent nearly two months scouring a huge stretch of the ocean before finding most of the debris. Operations also required large numbers of resources, very specialised and sophisticated equipment, and personnel with specialised training and expertise. In many countries, the expertises and resources may be limited, if not lacking altogether. In terms of costs per ton of hazmat involved, the costs of the m/v SCI incident search and recovery operations only far exceeded (many fold) some of the world's major oil spills (see Mullai and Paulsson, 2002). These costs were only a portion of the total costs of the m/v SCI incident. Cost-benefit analyses based solely on apparent and direct costs may produce invalid and unreliable results. In many cases, the hidden and indirect costs may far exceed the former.

The m/v SCI incident would have been averted altogether and the shipowner would have paid, for example in the form of demurrage for the delay of the ship and other expenses, far less, if the master had made an appropriate decision, either by waiting in port for one or two days until weather conditions improved or by turning the ship to the nearest harbour for shelter.

3.4 Risk estimation and presentation

Risks can be estimated and presented in various forms. For the purpose of demonstration, based on the incident data from the HMIS and NRC databases and some exposure data available, the risks of the U.S.'s hazmat supply chain are estimated and presented as: a) FN curves; and b) annual incident and injury/fatality rates (see Fig. 26~35). The FN curves show the relationships between the orders of frequencies and the severities of consequences (see Fig. 26~31). In order to compare risks of the constituent systems of the hazmat supply chain and in absence of a common denominator available (except people exposed) for all systems (e.g. plants, platforms and transport), the frequencies are estimated in absolute terms based on the empirical data. The severities of consequences are estimated as numbers or amounts of consequences, including fatalities, injuries, hospitalizations, evacuations and damage ($). The FN curves provide a comprehensive view of the risks, permitting graphical presentation and comparison of various dimensions of the individual and aggregated risks. The slope and position of the FN curves of individual risks relative to each other and against the FN curves of the aggregated supply chain risks depict characteristics of the risks. However, the FN curves do not show changes in risks over time.

Fig. 26~31 show that, in absolute terms, risks in the maritime transport system are generally well below the aggregated supply chain risks. They are lower than risks in several systems of the supply chain, but higher than risks in some others. Thus, the fatality risk in the maritime 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 Fig. 26).

In several countries as well as in the shipping industry, the key principles for managing risks and establishing risk evaluation criteria are that the risks should not be unduly concentrated on particular individuals, locations (IMO, 2004a) or systems and all individuals have unconditional rights to certain level of protection (i.e. the equity-based criterion) (HSE, 2001). The FN curves of the risks measured in absolute terms provide valuable information to the decision makers for judging undue concentration of risks.

For the purpose of demonstration, risks are also estimated and presented as consequences relative to the exposed populations (e.g. population, hazmat shipments in tons, vessel calls and sizes), per year (see Fig. 32~35). The risks of vessel and supply chain incidents have generally increased during the period 1990-2004, except the risks of vessel and all modes of transport combined measured as incidents relative to the amounts of hazmat shipments in tons (see Fig. 32). The latter has increased faster than the number of incidents occurring annually. This form of risk estimation and presentation does not show the severities of consequences and the relationship between the orders of frequencies and the severities of consequences.

Case histories have shown that the risks of catastrophic accidents in maritime transport and nuclear power plants have far exceeded the risks of many incidents in all other systems combined. The Exxon Valdes and Chernobyl disasters are two good examples.

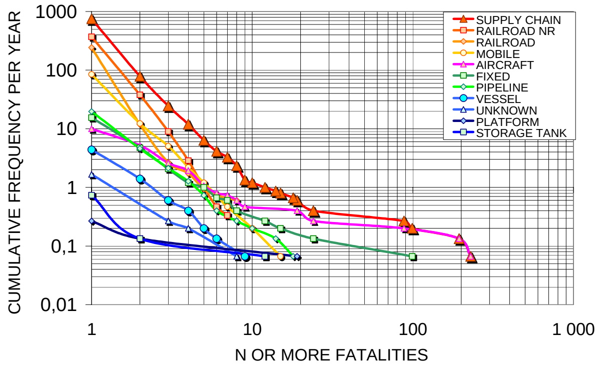

Fig. 26: FN curves of individual and aggregated hazmat supply chain fatality risks (U.S. 1990-2004)

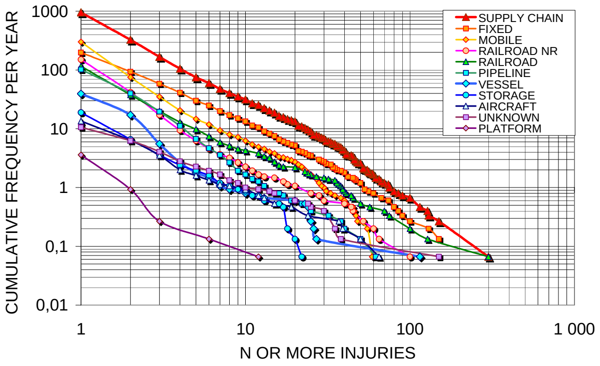

Fig. 27: FN curves of individual and aggregated hazmat supply chain injury risks (U.S. 1990-2004)

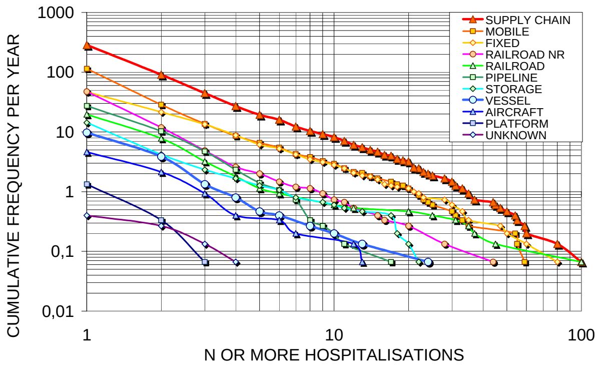

Fig. 28: FN curves of individual and aggregated hazmat supply chain hospitalization risks (U.S. 1990-2004)

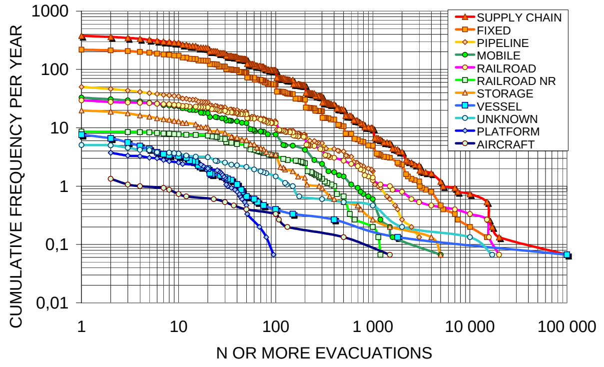

Fig. 29: FN curves of individual and aggregated hazmat supply chain evacuation risks (U.S. 1990-2004)

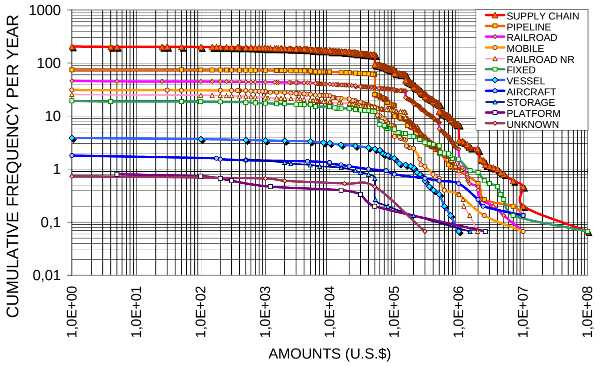

Fig. 30: FN curves of individual and aggregated hazmat supply chain damage (U.S. $) risks (U.S. 1990-2004)

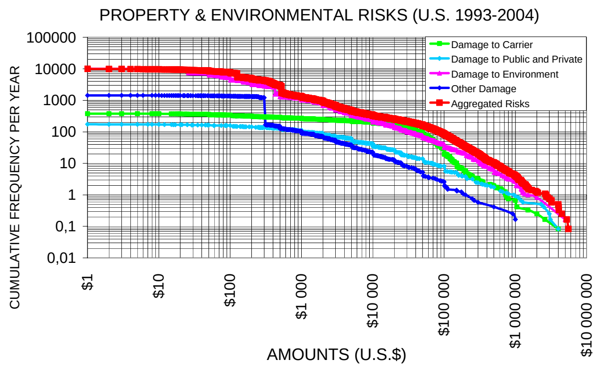

Fig. 31: FN curves of individual and aggregated hazmat transport property and environmental (U.S. $) risks (U.S. 1993-2004)

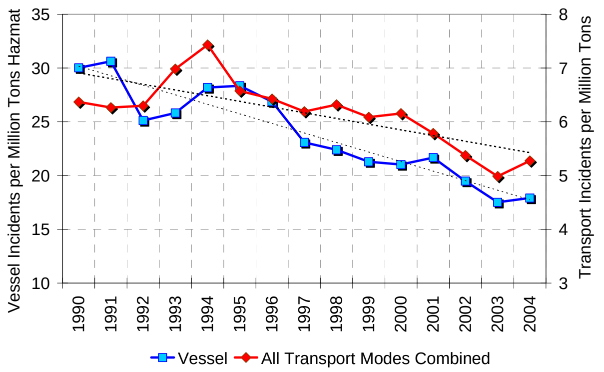

Fig. 32: Vessel and transport incident risks (per million tons hazmat) (U.S. 1990-2004)

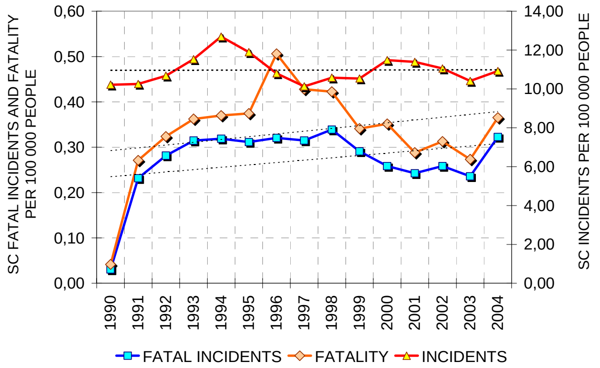

Fig. 33: Hazmat supply chain incidents, fatal incidents, fatality risks (per 100 000 inhabitants) (U.S. 1990-2004)

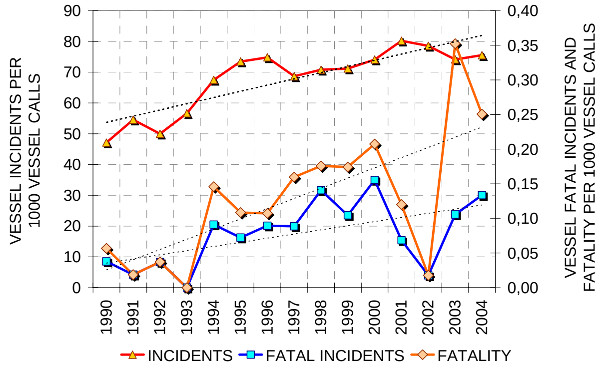

Fig. 34: Hazmat vessel incidents, fatal incidents, fatality risks (per 1 000 vessel calls) (U.S. 1990-2004)

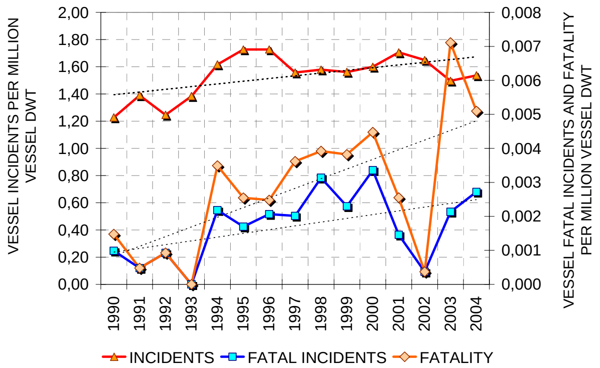

Fig. 35: Hazmat vessel incidents, fatal incidents, fatality risks (per million vessel dwt) (U.S. 1990-2004)

4. Conclusions

The results of the risk analysis presented in this paper contribute to enhancing of understanding of the risks of maritime transport of packaged dangerous goods/ hazmat as well as other systems of the hazmat supply chain. The results demonstrate that the risk analysis framework consists of valid and reliable constructs. The framework will facilitate risk analyses in other systems. It will assist, but not guarantee, risk analysts to generate detailed, valid, reliable and transparent results. Because of many issues related to the data, neither qualitative nor quantitative data alone can adequately facilitate a complete and robust risk analysis in the field. Therefore, every reasonable effort should be made to extend and fill gaps in data, and combine both qualitative and quantitative data analysis methods.

The systems and risks consist of universal and unique properties. Given the universal properties, some results of this study are also valid for systems in other locations. Because of the unique properties, further studies should be conducted in the field based on the data collected for systems in specific local conditions. The process and the results of this study may serve as inspirations or the basis for future researches in the field.

Detailed analysis results, recommendations for improving human safety and health and the protection of the marine environment and property, and future research areas in the field are provided in Mullai, 2007.

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