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Severity, probability and risk of accidents during maritime transport of radioactive material

Final report of a co-ordinated research project 1995–1999

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FOREWORD

In the 1990s, the maritime transport of radioactive material, in particular the shipments from France to Japan of plutonium, of high level vitrified wastes and of fresh mixed oxide (MOX) fuel, attracted much publicity.

In 1992, a Joint International Atomic Energy Agency/International Maritime Organization/ United Nations Environment Programme Working Group on the Safe Carriage of Irradiated Nuclear Fuel and other Radioactive Materials by Sea considered many safety aspects associated with plutonium transports.

The group recommended that the three organizations adopt a draft code of practice for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium, and High Level Radioactive Wastes on Board Ships. The group further considered a number of issues related to accidents at sea, accident statistics, risk studies and emergency response. The group concluded that all the information available in this area demonstrated that there were very low levels of radiological risk and environmental consequences from the transport of radioactive material. The group further recommended that the matter be kept under review by the three organizations involved.

In its ninth meeting, held in Vienna in 1993, the Standing Advisory Group on the Safe Transport of Radioactive Material (SAGSTRAM) recommended that a new co-ordinated research project (CRP) be set up to study the fire environment on board ships. This task was meant to tie in with the recommendations of the Joint Working Group to keep matters related to sea transport of radioactive material under review.

The resulting CRP on the severity of accidents in the maritime transport of radioactive material involved participants from five countries and extended over a period of approximately five years.

This TECDOC represents the final outcome of the work done in the course of many meetings spread over five years. A list of contributors to drafting and review can be found at the end of this report. The IAEA officer responsible for this publication was X. Bernard-Bruls of the Division of Radiation and Waste Safety.

EDITORIAL NOTE

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1. INTRODUCTION

Several events occurred in the early 1990s that drew considerable attention to the transport of radioactive material at sea:

- the publication of a report in 1990, commissioned by Greenpeace, which questioned the adequacy of the International Atomic Energy Agency (IAEA) Regulations for the Safe Transport of Radioactive Material;
- the return of about 1.7 tons of plutonium dioxide from France to Japan by sea-going ship at the end of 1992;
- the announcement by the US Department of Energy in 1993 of plans to review the issue of the import of spent nuclear fuel from foreign research reactors and the consideration of a new policy;
- the adoption, in November 1993, by the General Assembly of the International Maritime Organization (IMO) of a Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium, and High Level Radiated Wastes in Flasks on Board Ships, which had been developed by the Joint International Maritime Organization/International Atomic Energy Agency/United Nations Environment Programme Working Group.

In light of public concern for the safety of maritime transport of radioactive material, and advised by the Standing Advisory Group on the Safe Transport of Radioactive Materials (SAGSTRAM) at its 8th meeting, the IAEA Director General, by letter of 1992-01-21, had suggested to the Secretary-General of the IMO "the formation of a joint IAEA/IMO co-ordinating group in order to consider all activities where transport of nuclear material interfaces with the role of the IMO", for the purposes of ensuring that "the decision process in both organizations be on an informed and scientific basis". This led to the establishment of the IAEA/IMO Joint Working Group which later also included representatives of the United Nations Environment Programme (UNEP).

This Joint Working Group met on two occasions and discussed a broad range of issues, including several addressing the adequacy of the IAEA Regulations. Concern was also expressed by some Member States and non-governmental organizations about whether accidents on board ships would expose packages of radioactive material to more severe thermal and mechanical environments than those accounted for by the IAEA test requirements, and that package failure with subsequent release of radioactive material may occur.

All of the information studied within the Joint Working Group indicated that maritime transport would have a low level of radiological risk and low potential of significant environmental consequence. It was, however, recognized that if information became available which showed that more severe accident environments exist for maritime transport than those encompassed by the IAEA package design requirements and associated regulatory tests, package requirements and tests should be re-evaluated.

The IMO has established international standards for ships carrying certain high activity radioactive material, such as irradiated nuclear fuel, high level waste and plutonium, called the INF Code. The INF Code sets forth requirements in areas of ship design or equipment including damage stability, fire protection, temperature control of cargo spaces, structural considerations, cargo-securing arrangements, and electrical arrangements. Study analysis and results are primarily focused on these high activity materials.

In its 9th meeting, SAGSTRAM recommended that the IAEA establish a Co-ordinated Research Project (CRP) for this topic which would support the activities of the IAEA/IMO/UNEP Joint Working Group. It was also envisaged that the CRP would provide information that the IAEA can use in its ongoing regulatory review and revision process.

In August 1994, the IAEA convened a meeting to establish the terms of reference for the CRP and define the general scope of research required for an assessment of accident environments at sea.

In considering the concerns that had been expressed and the hazards to be evaluated, it was agreed to study not only fires but also to include studies on impact, penetration, and immersion. The CRP would also take into account the design of ships used to transport radioactive material, the environment encountered by the package, and fire propagation on board ships. In studying fires the, CRP would have to consider temperature, duration and location.

The agreed objectives were to:

(a) Perform closer studies to find out whether the existing regulations take adequate account of accidents at sea, taking into account probability and consequence through:

- assessing the severity of accidents on radioactive material packages and their expected frequencies of occurrence during sea transport,
- conducting and examining new studies on fire and impact environment on board ships,
- considering additional research on sea transport, and
- providing input data to the IAEA regulatory review and revision process, through the executive summary report, that allows an evaluation of the adequacy of the design and performance requirements of the IAEA Regulations for Type B packages transported by sea,

(b) Write an executive summary report followed by chapters describing the work done by Member States. The audience for this report was the IAEA Secretariat and the Transport Safety Standard Advisory Committee (in conjunction with the regulatory revision panel).

All research projects, amounting to 11 reports (numbered 1 to 11) were duly completed and submitted to the final Research Co-ordination Meeting (RCM) in December 1998. A further Consultants Services Meeting convened in March 1999 to consolidate the individual reports into this TECDOC. Summaries of the contributed reports from the six contributing Member States are included as annexes to this TECDOC. Full reports are available on request from the originating institutions.

2. SCOPE

While accident statistics on seagoing ships are readily available, data collection on marine casualties has been under way in several countries. Many data, however, are being collected for purposes other than the study of accident scenarios, which means that available data had to be sorted and evaluated carefully for their relevance to the CRP. Wherever possible, Member States were encouraged to initiate new studies under the CRP.

The primary purpose of this CRP was to provide a co-ordinated international effort to assemble and evaluate relevant data using sound technical judgement concerning the effects that fires, explosions or breaches of the hulls of ships might have on the integrity of radioactive material packages. The probability and expected consequences of such events could thereby be assessed. If it were shown that the proportion of maritime accidents with a severity in excess of the IAEA regulatory requirements was expected to be higher than for land transport, then pertinent proposals could be submitted to the forthcoming Revision Panels to amend the IAEA Regulations for Safe Transport of Radioactive Material and their supporting documents.

At the first RCM, held in Vienna in 1995, five research proposals were presented. Subsequently, two more participants joined the CRP. This meeting provided a good opportunity to participants to comment on the proposed studies and make sure that all the objectives were covered. It also provided an opportunity to review the scope and terms of reference for the programme, establish a timetable for further efforts, set priorities, and consider the structure and purpose of the final CRP report.

RCM meetings were held in Cologne in 1996, Albuquerque in 1997 and Vienna in 1998.

Four main areas of research were included in the CRP. These consisted in studying the probability of:

- ship accidents,
- fire,
- collision, and
- radiological consequences.

2.1. Type of materials and packaging

The types of material included in the study were high level waste (HLW), irradiated nuclear fuel and mixed oxide fuel (MOX). These materials are all transported in Type B packages.

The study did not consider Type A packages and small Type B packages.

2.2. Types of ships

While this study encompassed marine transport of packaged radioactive material on four different types of ships: container ships, roll-on/roll-off (Ro-Ro) ships, general cargo (break-bulk) ships, or purpose-built ships, ship accident data covering all types of ships were collected and analysed for the 15-year period between 1979 and 1993. The results of the study are applicable to any ship transporting radioactive material that complies with the applicable cargo ship requirements of the International Convention for Safety of Life at Sea (SOLAS), as well as with the specific requirements of the IMDG Code for the radioactive material considered. In addition, for ships that carry shipments of INF code materials, the study takes into consideration special provisions of the three separate classes of ships, depending on the total maximum radioactive quantity that may be carried on board:

- Class INF 1 Ships: ships that are certified to carry INF cargo with an aggregate activity less than 4000 TBq,
- Class INF 2 Ships: ships that are certified to carry irradiated nuclear fuel or high level wastes with an aggregate activity less than 2×10^6 TBq and those certified to carry plutonium with an aggregate activity less than 2×10^5 TBq,
- Class INF 3 Ships: ships that are certified to carry irradiated nuclear fuel or high level wastes and those certified to carry plutonium with no restriction of the maximum aggregate activity of material.

The requirements established are, of course, more stringent for Class INF 3 ships than for Class INF 1 and 2 ships.

2.3. Accident environment

The accident statistics have been taken mainly from the Lloyd's database and the Marine Accident Investigation Branch (MAIB) of the UK. The Lloyd's database, originally intended for insurance purposes, covers total losses around the world. The MAIB database covers all accidents for the UK ships for which an accident declaration has been submitted to the authorities.

The accident probabilities determined are based on all accidents, while the analyses do not cover military ships, general cargo and fishing ships.

Even though from the beginning the study was meant to focus on fire accident, accidents such as collision, foundering and sinking were also included.

The accidents probabilities have also been divided in accordance with where the accidents occurred. It was shown that the highest probability of certain kinds (collision, wrecked) of accidents are in ports followed by coastal water. The lowest probability of a ship accident is on the open ocean.

2.4. Effects of accidents

The effects of an accident on the package have also been studied. Several reports in the study cover mechanical effects as well as thermal effects on the packages.

As far as the consequences are concerned, the studies include both release to water and to air.

2.5. Summary of the findings

The principal technical conclusions of this CRP are:

- Ship collisions depend on ship traffic density and thus on the region of the ocean in which a ship is sailing. Traffic density does not affect the frequency of ship fires. However, the chance of a fire during a voyage increases directly with voyage distance or sailing time.
- Ship collisions and ship fires are infrequent events; most ship collisions and ship fires will not subject a RAM transport package on the ship to any mechanical or thermal loads; the

chance that a ship collision or a ship fire will subject a RAM transport package to loads that might fail the package is very small.

- If a ship collision subjects a RAM flask to crush forces, the magnitude of these forces will be less than or at most comparable to the inertial forces experienced by the flask during the regulatory certification impact test.
- Ship collisions are unlikely to damage a RAM flask, because collision forces will be relieved by collapse of ship structures, not flask structures.
- Ship fires are not likely to start in the RAM hold. If a fire starts elsewhere on the ship, its spread to the RAM hold is not likely. Even if a fire spreads to the RAM hold, the lack of fuel or air will usually prevent the fire from burning hot enough and long enough in the RAM hold to cause the release of radioactive material from a RAM flask or, given flask failure due to a preceding collision, to significantly increase the release of radioactivity from the failed flask.
- Heat fluxes from small creeping fires which do not engulf the RAM hold are unlikely to exceed the heat fluxes developed by the regulatory test fire for flask certification.
- Most radioactive material released to the interior of a RAM flask as a result of an accident will deposit on interior flask surfaces; therefore, flask retention fractions are large and flask-to-environment release fractions are small.
- Should a ship collision or fire lead to the sinking of a RAM transport ship and thus loss of a RAM flask into the ocean, recovery of the flask is likely if loss occurs on the continental shelf. If this flask is not recovered, the rate of release of radioactive material from the flask into ocean waters will be so slow that the radiation doses received by people who consume marine foods contaminated as a result of the accident will be negligible compared to background doses.
- If a RAM transport ship, while in port or sailing in coastal waters, is involved in a severe collision that initiates a severe fire, the largest amounts of radioactive material that might be released to the atmosphere as a result of the accident would cause individual radiation exposures well below background.

Consequently, since the probabilities of severe ship collisions and severe ship fires are small and since the individual radiation doses that might result in the event of such collisions or fires are smaller than normal background doses, the risks posed by maritime transport of highly radioactive material such as irradiated nuclear fuel, vitrified high level waste and mixed oxide fuel in Type B packages are very small.

3. HOW RADIOACTIVE MATERIAL IS TRANSPORTED AT SEA

Radioactive material plays an important role in our lives. Radioactive material being shipped includes uranium ores, nuclear fuel assemblies, spent nuclear fuel, radioisotopes and radioactive waste. Every year, millions of packages containing radioactive material for use in medicine, agriculture, industry, defence and science are transported across international borders via roads, rails, air and sea. Transport of these materials must be carefully regulated to ensure the safety of transport workers and the public, as well as property and the environment.

3.1. Regulatory framework

Shipment of radioactive material by sea must comply with the standards of the IAEA and IMO. It must also comply with national regulations of the country of origin, the country of destination, the flag country of the ship and countries in which ports of call, if any, are located. The regulations of IAEA Member States are patterned on IAEA standards, and are, therefore, generally consistent with them.

3.1.1. International regulations

3.1.1.1. International Atomic Energy Agency

The Regulations for the Safe Transport of Radioactive Material issued by the IAEA have been an important factor in achieving an excellent worldwide safety record for the transport of radioactive material. The IAEA has issued *Regulations for the Safe Transport of Radioactive Material* since 1961; the latest edition is identified as IAEA *Safety Standards Series No. ST-1* (1996). The Regulations are based on the *Basic Safety Standards for Radiation Protection Against Ionising Radiation and for the Safety of Radiation Sources, Safety Series 115* published by the IAEA and on recommendations made by the International Commission on Radiological Protection (ICRP), an independent organization of physicians, radiologists, and scientists.

3.1.1.2. Shipment preparation

IAEA Transport Regulations establish a regulatory system specifying standards for preparation of packages for shipment. These standards include proper selection of packaging, package marking and labelling, and container or vehicle placarding. Consignors must satisfy requirements for preparation of shipping documents and provide carriers with instructions for exclusive use shipments and emergency arrangements appropriate to the consignment. The regulatory system also includes segregation and stowage guidelines. Packages must be segregated from transport workers and members of the public. Package spacing is determined by the package surface activity or by criticality concerns. Stowage requirements ensure that packages are not placed in holds with other dangerous goods (such as flammable materials) and are secured for transit. Also included in the system are quality assurance programmes for design, manufacturing, testing, documentation, use, maintenance, and inspection of packages.

3.1.1.3. Physical protection and emergency response

The *Convention on the Physical Protection of Nuclear Material* (published as IAEA INFCIRC/274/Rev.1) is a treaty among over 40 nations that are most active in the international commerce of nuclear materials. In addition, most states adhere to IAEA guidelines and recommendations for the physical protection of nuclear material while in transit. These guidelines are published in IAEA’s INFCIRC/225/Rev.2, *The Physical Protection of Nuclear Materials*. In addition, ST-1 requires that, in the event of an accident, emergency provisions established by relevant national and/or international organizations shall be observed. Appropriate guidelines for such provisions are described in Safety Series No. 87, *Emergency Response Planning and Preparedness for Transport Accidents Involving Radioactive Material* (1988).

The IAEA's regulations also serve as the basis for international and modal requirements. More than 50 nations and organizations such as the International Civil Aviation Organization (ICAO) and the IMO have adopted safety requirements based on IAEA standards.

3.1.1.4. International Maritime Organization

The IMO establishes codes and standards for the sea transport of packaged hazardous materials. The principal code issued by IMO in this regard is the International Maritime Dangerous Goods (IMDG) Code for all hazardous materials classes, including radioactive material class 7. The IMDG code for radioactive material primarily establishes standards for shipping papers, marking, labelling, placarding, stowage, segregation, and other handling requirements. For packaging of radioactive material the IMDG Code relies on IAEA standards as established in IAEA Safety Series No. 6 (which will be superseded by the IAEA's 1996 revision, ST-1, when adopted by IMO). The IMDG Code, the IMO's *International Convention for the Safety of Life at Sea (SOLAS),* and IAEA standards do not contain any special design and equipment requirements for the ships that transport class 7 material. Therefore, IMO in co-ordination with IAEA developed the Code for Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes in Flasks on Board Ships (INF), IMO Resolution A.748 (18), to complement the provisions of the IMDG Code, by providing specific requirements for ship design and construction. This Code establishes international standards for ships carrying certain high activity radioactive material, such as irradiated nuclear fuel, high level waste and plutonium, called INF Code materials.

3.1.1.5. Code requirements

The INF Code applies to all new and existing ships (including cargo ships of less than 500 gross tons), regardless of size, engaged in the transportation of INF Code materials.

The specific Code requirements are based on the three separate classes of ships, which are defined by the total maximum radioactive quantity that may be carried on board. The requirements are least stringent for Class INF 1 ships, and most stringent for Class INF 3 ships. Ships that are certified to carry INF cargo with an aggregate activity less than 4000 TBq are classified as a "Class INF 1 Ship". Ships that are certified to carry irradiated nuclear fuel or high level wastes with an aggregate activity less than 2×10^6 TBq and those certified to carry plutonium with an aggregate activity less than 2×10^5 TBq are classified as a "class INF 2 ship". Ships that are certified to carry irradiated nuclear fuel or high level wastes and those certified to carry plutonium with no restriction of the maximum aggregate activity of materials are classified as a "class INF 3 ship".

The INF Code sets forth requirements in the areas of ship design or equipment damage stability, fire protection, temperature control of cargo spaces, structural considerations, cargo-securing arrangements, and electrical arrangements. In each case, the Code relies on international standards, particularly those of the SOLAS Convention, rather than on developing a new set of requirements. The Code also contains requirements for ships to have appropriate radiological protection equipment, a management-training plan, and a shipboard emergency plan. The Code includes survey and certification requirements to strengthen the implementation of the Code by the Administrations. Additionally, the Code requires an initial survey for complete examination of the ship, as well as issuance of a certificate called the International Certificate of Fitness for the Carriage of INF cargo and a subsequent survey scheme under SOLAS Chapter I, to ensure continued compliance with the requirements of the Code.

3.1.1.6. Code compliance

Currently, compliance with the INF Code is voluntary. A number of countries, including the USA, have agreed to comply with it voluntarily. France and Japan have made it mandatory. The European Union has taken steps to make the Code mandatory. The United Kingdom also applies the Code to its ships. IMO will make the INF Code mandatory (through amendment to SOLAS) by 1 January 2002

3.1.2. National regulations

The transport of radioactive material involves a potential radiological hazard. National governments are responsible for ensuring the protection of life, property and the environment. Government authorities regulate the transport of radioactive material in all modes through national regulations, in which relevant international regulations and recommendations are usually taken into account. Considerable harmony exists among regulations of the IAEA and most countries. The domestic regulations are heavily influenced by the international regulations developed and promulgated by the IAEA.

The IAEA Safety Series has become the model that domestic (national) regulators follow in developing modifications to their respective transport regulations. Although the national regulators will generally adopt the requirements in IAEA standards, an individual Member State, depending upon its specific environmental, social, political, or regulatory needs, may impose additional requirements.

3.2. Radioactive material package preparation and shipping process by sea

In general, the consignors and carriers are responsible for ensuring that a consignment of radioactive material is properly prepared and transported according to applicable international and national regulations. The overall regulatory philosophy applied to radioactive material transport is to require that the packaging provide the primary protection with a minimal reliance on operational controls or human intervention. A graded approach has been applied to the required level of performance of radioactive material packages, which is commensurate with the potential hazard presented by the contents of the package.

Radioactive material is specifically packaged in accordance with international and national regulations. The form, quantity, and concentration of the radioactive material determine the type of packaging used. A shipper of radioactive material must first characterize the contents to be packaged and transported. After radioactive material is put in the proper packaging, it is sealed, surveyed with special instruments to ensure radiation is within regulatory limits and checked for external contamination. The package is then marked and labelled to provide information about its contents. Markings on the package list the proper shipping name, the identification number and the shipper’s name and address. Labels applied to the package identify the kind of material, the level of the radioactivity of the package contents and the transport index. A placard on each side of a container or vehicle is used to identify certain types of radioactive shipments.

Four basic types of packages are used: Excepted, Industrial, Type A and Type B. Excepted packages are limited to material with extremely low levels of radioactivity. Industrial packages are used to transport material that, because of their low concentration of radioactive material, present a limited hazard to the public and the environment. Type A packages are designed to protect and retain their contents under normal transport conditions and must maintain sufficient shielding to limit radiation exposure to handling personnel. Type B packages are used to transport material with radioactivity levels higher than those allowed in Type A packages. They are designed to retain their contents under both normal transport and severe accident conditions. Type B packages range from small steel drums (200 litres) to heavily shielded steel flasks that can weigh up to 125 tonnes. Examples of material transported in Type B packages include irradiated nuclear fuel, high level radioactive waste, plutonium, and high concentrations of some radioisotopes, such as caesium and tritium.

Prior to using a Type B package for transporting radioactive material in international commerce, the shipper must have a certificate of competent authority from the appropriate country or countries. Once approval is granted, the shipper must ensure that the packaging and its contents meet the applicable requirements of the approval. Packaged radioactive material must be loaded onto the ship according to regulatory segregation and stowage guidelines. Packages must be segregated from transport workers and members of the public.

Marine transport of packaged radioactive material could occur via a combination of four types of ships: container ships, roll-on/roll-off ships, general cargo (break-bulk) ships, or purpose-built ships. Currently, the preferred method of commercial transport of Type B flasks aboard ships is to mount flasks in metal containers, sometimes called “International Standards Organization (ISO) containers.” The flasks may be containerized, mounted on a wheeled trailer, or free-standing. Free-standing flasks are mounted on a skid, pallet, or cradle to facilitate handling the flask in intermodal transfer and in stowage. Typically, containerized flasks are transported on general cargo ships rather than on large container ships specifically designed for container transport. Individual shipments could be made by scheduled commercial ship, or by charter ship. Purpose-built ships are specifically designed to transport flasks containing large quantities of radioactive material, and they operate as dedicated ships.

A ship transporting radioactive material must comply with the requirements of the *International Convention for Safety of Life at Sea* (SOLAS) to which the ship’s flag state is a party. Radioactive material shipments must also comply with the IMO’s International Maritime Dangerous Goods (IMDG) Code. In addition, ships carrying consignments of INF Code materials should also voluntarily comply with the Resolution A 748 (18), the Code for *the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-level Radioactive Wastes in Flasks On Board Ships*, adopted by IMO in 1993.

Safeguards, such as special security measures, vehicles, sophisticated communications with command centres, and package requiring special facilities to open them, make sabotage of high level radioactive material unlikely. Regulations also require that, in the event of an accident, emergency provisions established by relevant national and/or international organizations shall be observed.

There has been considerable international experience with the shipping of radioactive material by sea. Shipments of high activity radioactive material in Type B package such as irradiated nuclear irradiated nuclear fuel are commonly transported by sea from one country to another. Type B packages, used in transport of material with the highest level of radioactivity, are designed to protect and retain their contents in both normal and severe accident conditions. Real-life accidents involving radioactive material shipments have occurred. To date, none has resulted in serious injuries or fatalities due to radioactive cargo. In fact, data from actual accidents, as well as analytical analyses, show that accidents produce impact and fire conditions far less severe than the hypothetical accident conditions for Type B packages contemplated by the regulations.

4. PROBABILITY OF SHIP ACCIDENTS

4.1. Introduction

The development of ship accident statistics is based on the analysis of the following worldwide or national accident databases.

4.1.1. Lloyd's databases

Two types of databases are available from Lloyd's concerning all propelled sea-going merchant ships in the world of 100 GT[1] and above (or 500 GT and above):

- All incidents or accidents reported to the Lloyd's Maritime Information Services Ltd (LMIS), and
- All total losses reported to the Lloyd's Register of Shipping. The term total losses corresponds to ships which, as a result of being a marine casualty, have ceased to exist either by virtue of the fact that the ships are irrecoverable or have subsequently been broken up.

The definition of the Lloyd's casualty categories is the following, the classification being made on the first event reported:

- Foundering: ships which sank as a result of heavy weather, springing of leaks, breaking in two, etc., but not as a consequence of the other categories listed below,
- Missing: after a reasonable period of time (usually one day to one week), no news having been received of a ship and its fate therefore being undetermined, the ship is posted as 'missing',
- Fire/explosion: when fire/explosion is the first event reported (except where the first event is a hull/machinery failure leading to fire/explosion),
- Collision: striking or being struck by another ship,
- Contact: striking or being struck by an external substance (excluding other ship or sea bottom),
- Wrecked/stranded: touching the sea bottom, a sand bank, the seashore or underwater wrecks,
- Other: war losses, hull/machinery damage or failure which is not attributable to any other category.

[1] GT: Gross tonnage (i.e. ship capacity unit, 1 GT = 100 cubic feet = 2.83 m^3).

4.1.2. The MAIB, UK[2]

The data analysed from the MAIB database deal with UK registered ships of 100 GT or more, corresponding to about a fleet of 1100 merchant ships (in the 1990s). The MAIB database includes the events corresponding to the following criteria:

- Loss of life or major injury
- Ship lost or materially damaged
- Ship stranded or having collided
- Major injury or material damage to the environment.

The classification of the accidents is similar to the one defined by the Lloyd's.

4.1.3. International Maritime Organization

This database (Fire Casualties Records) includes all fires reported to IMO by all member countries. The selection criteria is: any fire which highlights a possible deficiency, inconsistency, etc. in the Safety of Life at Sea Regulations (SOLAS Convention).

4.1.4. Bureau Véritas

Because of the follow-up of the Bureau Véritas on about 10 to 20% of the world fleet, a database was created for severe fire accidents (fire leading to total losses or recovery of the ships after repair). A selection was made from this database of three categories of ships which appeared to be representative of the radioactive material transports (general cargo, container, Ro-Ro/passenger).

4.2. Reference studies and statistical analyses of accidents

The scope and main characteristics of the statistical analyses undertaken by all five counties involved, as part of this CRP, are summarized in Table I.

A description of each of the five studies is provided in Sections 4.2.1 through 4.2.5 below.

4.2.1. CEPN/IPSN (January 1999, France)

The report includes statistical analysis of sea transport accidents reported by Lloyd's register of shipping from 1994 to1997 and the MAIB from 1990 to 1996.

The analysis of the Lloyd's accident reports gives an accident frequency of 2.6×10^{-3} losses/ship-year, and a frequency of fires and explosions of 3.1×10^{-4} fires explosions/ship-year. The analysis of the MAIB accident reports gives the frequencies 4.4×10^{-2} accidents/ship-year and 1.4×10^{-2} fires/ship-year.

Furthermore, the report presents results from a study performed by the Bureau Véritas which deals with fire casualties on general cargo, container, and Ro-Ro/passenger ships 1978–1988. This study gives a fire frequency of 11×10^{-4} fires/ship-year.

[2] It should be noted that in 1989 the annual report of MAIB replaced the publication "Casualties to Ships and Accidents to Men (CVAM)".

TABLE I. STATISTICAL ANALYSIS STUDIES

Study date	Database	Reference period	Category of ship	Subject of interest	Type of results	Unit of the results
CEPN/IPSN Jan. 1999 (F) [1]	Lloyd's	1994–1997	World merchant ships > 100 GT	Accidents with total loss	Frequency: — General — Per ship type — Per category of loss — Location (harbour, close to the coast, open sea)	Per ship-year
	MAIB	1990–1996	UK registered merchant ships >100 GT	Accidents reported to authorities (fires and collision)	Frequency: — General — Per year — Per accident category	Per ship-year
	Bureau Véritas	1978–1988	World (general cargo, containers and Ro-Ro passenger ships)	Fire	Frequency: — Per ship type — Origin areas — Damaged areas — Duration	Per ship-year Per ship km
SRD–AEA Technology/NTL Aug 1991 (UK) [2]	MAIB + CVAM	1981–1990	UK registered merchant ships and Ro-Ros >100 GT	Fire and explosion qualified accidents reported to the authorities	Frequencies of fire, severe fire and explosion per year Location on Ro-Ro	Per ship-year
SRD–AEA Technology/NTL Jan 1992 (UK) [3]	IMO + MAIB	1961–1989	World (fires reported to IMO) UK registered Ro-Ros and car ferries	Fire	Duration for controlling and extinguishing the fire in port and under way	Hours
Study date	Database	Reference period	Category of ship	Subject of interest	Type of results	Unit of the results
SRD–AEA Technology (UK) [4]	Lloyd's	1984–1993	World fleet Ships >500 GT	Fire, explosion, collision Fire with potential effects on the cargo	Frequency of ship fire Frequency of severe fire accident affecting the cargo	Per ship-year

TABLE I. (CONT.)

SeaRAM–SNL May 1998 (USA) [5]	Lloyd's US Coast Guard	1979–1993	World fleet All ships > 500 GT	All reported events for: fire; collision; distance from the shore; port calls; port locations; sailing distances; Specific analysis per route	Frequency of: — fire — collision	Per ship .nautical mile Per port call
JNC (Japan) [6]	Lloyd's	1990–1995	Merchant ships > 500 DWT	All reported events: — per casualty category — per location Specific analysis per route (Europe/ Japan)	Frequency: — general — per casualty category — per location	Per ship-year Per ship. Nautical mile
GRS EC report, Nov. 1998 (Germany) [7]			PNTL ship - INF3	Specific analysis per route (UK to continental northern Europe)	Frequency: — per severe fire — per severe collision	Per voyage

4.2.2. SRD - AEA TECHNOLOGY-NTL (UK)

Five different reports were submitted by the UK.

The first report contains an assessment of the fire frequency on a ship carrying irradiated fuel. The data used in the assessment was obtained from Lloyd’s, covering the worldwide shipping for the period 1984–1993. The determined frequency of 2.9×10^{-4} fires/ship-year was based on a total of 93 incidents identified according to specified criteria.

In the second report the frequency of a severe fire on the freight ferry “Nord Pas-de-Calais” is estimated. The highest frequency of a “severe fire” was found to be one initiating in the machinery space, the frequency of which was estimated as 3.8×10^{-3} per year. The overall frequency for a severe fire developing on the Nord Pas-de-Calais, taking into account all scenarios, was estimated to 7×10^{-3} per year.

The third report studies the duration of a severe ship fire particularly referring to a Ro-Ro ferry. Using data from IMO and MAIB, an average fire duration time of 2 h 20 min was estimated.

The fourth report describes fire modelling on the rail deck and in the engine room of the Nord Pas-de-Calais. The purpose of this study was to investigate the growth of fires in order to establish the likely temperatures to which a flask containing irradiated fuel might be subjected. In none of the seven fire scenarios studied in the report would the flask be exposed to conditions exceeding those specified in the IAEA test requirements for an irradiated nuclear fuel flask.

The last report contains a probabilistic assessment of “Nord Pas-de-Calais” fire scenarios. Event tree analysis has been used to obtain frequencies for various fire scenarios in the separator room, generator room and engine room. The final results showed that the frequency of a fire in the separator room in ventilation limiting conditions was 4.6×10^{-4} per year. A fire occurring with all fire doors and ventilation dampers open in the whole machinery space, leading to a ceiling temperature of 400°C after 2.5 hours, would have a frequency of only 8×10^{-9} per year.

4.2.3. SeaRAM - SNL (May 1998, USA)

The development of ship accident statistics was initiated by obtaining 15 years of ship accident data covering the years 1979 through 1993 from Lloyd’s Maritime Information Services.

Concerning fire events, statistical analysis of the Lloyd’s database showed little variation with ocean location. Therefore, fire frequencies do not need to be developed independently for ocean region or for individual ports. Fire frequencies are proposed per nautical mile sailed (9.6×10^{-8}) and per port call (5.4×10^{-5}).

The number of ship collisions that occurred in congested regions, in coastal waters, in the open oceans, and in individual ports were determined for the period 1979 to 1993. Collision frequencies were derived from the numbers of collisions and from distances sailed in each of the 21 ocean regions during the years 1988 and 1993. Moreover collision frequencies per port call were then calculated for high, medium and low traffic ports from data of port collisions (1979–1993) and port calls in the year 1988. The frequencies are almost the same, possibly because ships are sailed more carefully or sailing is more carefully controlled in busier ports than in less busy ports. A formula is given to determine the probability of a ship collision during a voyage, taking into account collision frequencies per nautical mile sailed and per port call.

4.2.4. JNC (November 1998, Japan)

The JNC study describes and analyses the safety of operations involving the international transport on selected routes of large amounts of plutonium by maritime cargo ships. The analysis focuses on conventional cargo ships, although this amount of plutonium would not be transported on other than purpose-built ships and their accident history in order to provide an estimate of the probability of accident occurrences for such ships.

The probability of severe marine transport accidents was evaluated for three routes. For each route casualty rates per nautical mile were applied. The rates were based on serious casualty data for the period 1990–1995 for general cargo ships of 500 DWT and above, route weighting factors taking into account the geographical conditions along the length of the route (traffic density, proportion of shallow waters or proximity to coastlines or isles and weather conditions) and the casualty rates per port call estimated for the ports of Cherbourg, France and Tokai, Japan. The probabilities of a severe accident range from 5×10^{-3} to 7×10^{-3} per ship movement on each route.

Using the event tree technique, the study evaluated the probability of severe accidents in ports or approach waters to ports which might release radioactive material. The main result of this analysis is that such a probability ranges between 10^{-9} and 10^{-10} per ship movement.

4.2.5. GRS, EC report (November 1998, Germany)

The risk analysis performed in this study dealt with the return by ship of vitrified high level waste arising from the reprocessing of irradiated nuclear fuel at Sellafield, UK to continental Europe.

Internal fire, collisions, collision with subsequent fire and foundering were identified as the most severe scenarios for ships. For this specific route corresponding to a journey of 1000 nautical miles, probabilities of occurrence for these accident scenarios were derived on the basis of a review of statistical studies and taking into account the special safety features of an INF 3 ship which enhance the safety of the shipment.

The estimated probabilities are low. For example, for a severe collision on the open sea (the scenario resulting in the highest probability), the probability is 1.6×10^{-7} per voyage. For a main engine room fire propagating to a cargo hold, the probability was estimated at 5.3×10^{-9} per voyage, and for a collision between a PNTL ship and a tanker leading to a fire engulfing the PNTL ship for a longer period, the probability was 2×10^{-10} per voyage.

Concerning the consequences of the accident scenarios, the conclusion of this study is that the mechanical and thermal loads on flasks do not exceed the IAEA standard test conditions; therefore, the flasks would be expected to retain their integrity and the release of radioactivity to the environment can be excluded.

4.3. Main results

In order to derive probabilities per nautical mile (nmi)[1] specific surveys were performed [JNC, Véritas] from which it was found that the average number of days sailed per year by general cargo ships was 216 and the average number of ports calls was 84. The average annual distance travelled was in the order of 60 000 nmi. About 15% of this distance occurred in coastal waters or near isles at sea, i.e. 9000 nmi. The main part of the distance sailed was on the open sea. The average sailing speed was about 11 to 12 knots.

The following paragraphs summarize the main results for all the categories of accidents and for categories of accidents with fire, collision, collision plus fire, and foundering.

[1] 1 nautical mile = 1.852 km.

4.3.1. All categories of accidents

According to the severity of the accident adopted in the databases, the casualty frequencies reported in the studies ranged from 2.6×10^{-3} to 10^{-1} per ship-year. Table II presents the main figures.

It should be noted that the study on total losses pointed out that:

- among the different types of "cargo carrying ship", slight differences appeared in the annual frequencies of accident, they ranged from 0.94×10^{-3} loss/ship-year for chemical ships up to 3.96×10^{-3} loss/ship-year for general cargo;
- the frequency of losses was broadly dependent on the age of the ship: the category of ships built less than 10 years earlier presented a frequency of about 0.5×10^{-3} loss/ship-year, while the class of vessels 20 years or older presented a frequency of 4.4×10^{-3} loss/ship-year; and
- among the accidents reported with information on the location involved, 16.1% occurred at or close to harbour, 60.3% at a distance less of than 100 miles from the coast, and 23.6% at distance greater than 100 miles from the coast.

TABLE II. ALL CASUALTY FREQUENCIES

Type of accident	Source	Casualty frequency (per ship-year)	Reference period	Number of events	Number of ship-years
All events	MAIB (CEPN-IPSN)	105.1×10^{-3}	1990–1996	888	8447
Serious casualties	Lloyd's (JNC)	22.4×10^{-3}	1990–1995	1988	88 920
Total loss	Lloyd's (CEPN-IPSN)	2.6×10^{-3}	1994–1997	456	17 7418

4.3.2. Fire accidents

4.3.2.1. Fire frequency

According to the severity of the accident adopted in the databases, the fire frequencies reported in the studies range from 0.29×10^{-3} to 16×10^{-3} per ship-year. Table III presents the main figures.

For the specific case of Ro-Ro ships over 100 GT, a UK study for the period 1989–1990 revealed a frequency of initiating fires of 0.07 per ship-year.

The fire frequencies per nmi or per port call were assessed in three studies (Table IV).

TABLE III. FIRE FREQUENCY PER SHIP-YEAR

Type of accident	Source	Fire frequency (per ship-year)	Reference period	Number of events	Number of ship-years
All fires	MAIB (CEPN-IPSN)	13.6×10^{-3}	1990–1996	115	8447
All fires	MAIB+CVAM (SRD)	16×10^{-3}	1981–1990	323	21 225
Serious fires*	Lloyd's (SRD)	2.6×10^{-3}	1984–1993	859	324 220
Qualifying fires**	Lloyd's (SRD)	0.29×10^{-3}	1984–1993	93	324 220
Serious fires	Lloyd's (JNC)	1.71×10^{-3}	1990–1995	152	88 920
Total loss	Véritas (CEPN-IPSN)	1.1×10^{-3}	1978–1988	317	287 675
Total loss	Lloyd's (CEPN-IPSN)	0.31×10^{-3}	1994–1997	55	177 418

* Excluding oil tankers and liquefied gas carriers.
** Engine room fires which spread to the cargo area, or fires of a serious nature arising in the cargo hold.

4.3.2.2. Origin of the fire

For the purpose of analysing safety onboard a ship, the origin of the fire was specified in three studies (Table V).

TABLE IV. FIRE FREQUENCY PER SHIP NMI OR PORT CALL

Type of fire	Source	Fire frequency	Reference period
All fires	Lloyd's (SNL)	Non-port: 9.6×10^{-8} per nmi Port: 5.4×10^{-5} per port call	1979–1993
Serious fires	Lloyd's (JNC)	2.85×10^{-8} per nmi	1990–1995
Total loss	Véritas (CEPN-IPSN)	General cargo: 5×10^{-9} per nmi Container: 3.1×10^{-9} per nmi Ro-Ro: 2.8×10^{-9} per nmi	1978–1988

TABLE V. ORIGIN OF THE FIRE

Origin of the fire*	Véritas (CEPN-IPSN)	Lloyd's (CEPN-IPSN)	MAIB-CVAM (SRD)
Machinery room	64%	61%	40%
Quarters	39%	16%	Not defined
holds	8%	3%	Not defined

* Fires can originate in more than one area (in which case, the total would exceed 100%).

The Véritas data showed that, when both the origin of the fire and the area of the vessel which is affected by the fire were considered, 17% of the fires affected the holds. The data shown in Table V were derived from a UK analysis where it was noted that although the duration of the fire was rarely documented in the databases, some values were available and used to develop these results. They represent 382 fire casualty records over a period of 25 years.

4.3.2.3. Location

The analyses on the location of the ship when the fire occurred showed that in about 40% of the cases, the event occurred when the ships were at port (Table VI).

TABLE VI. LOCATION OF THE SHIP WHEN FIRE ORIGINATED (% OF ALL FIRES)

Location of the ship	Lloyd's (SNL)	Lloyd's (SRD)	Véritas (CEPN-IPSN)
Port fires	38.2%	37.6%	43.4%
Non-port fires	61.8%	62.4%	56.6%

4.3.2.4. Duration

Although the duration of the fires was rarely documented in the databases, some values were available from a UK analysis based on IMO fire data concerning 382 fire casualty records covering a period of 25 years (Table VII).

TABLE VII. TIME REQUIRED TO EXTINGUISH FIRES FOR ALL SHIPS (SDR)

Time to extinguish	At port	Under way
0–30 min	20%	18%
+30 min–2 hr	31%	28%
+ 2 hr–10 hr	29%	28%
+ 10 hr–1 day	9%	15%
more than 1 day	11%	11%

From this analysis, it was determined that the average time to extinguish a fire was about 26 hours when a ship was at port and 19 hours when it was under way.

4.3.2.5. Temperature

It should be kept in mind that no information was provided on the temperatures of the fires. It was also emphasized in the Véritas study that the temperatures of the fires, even in this limited data set, were not available.

4.3.3. Collision accidents

4.3.3.1. Collision frequency

According to the severity of the accident adopted in the databases, the collision frequencies reported in the studies ranged from 0.38×10^{-3} to 44.2×10^{-3} per ship-year. Table VIII presents the main collision frequency figures.

TABLE VIII. COLLISION FREQUENCY PER SHIP-YEAR

Type of accident	Source	Collision frequency (per ship-year)	Reference period	Number of events	Number of ship-years
All collisions	MAIB (CEPN-IPSN)	44.2×10^{-3}	1990-1996	373	8447
Serious collision	Lloyd's (JNC)	2.32×10^{-3}	1990-1995	206	88 920
Total loss	Lloyd's (CEPN-IPSN)	0.38×10^{-3}	1994–1997	68	177 418

The average collision frequencies per nmi and per port call were assessed in two studies (see Table IX).

TABLE IX. COLLISION FREQUENCY PER SHIP NMI OR PORT CALL

Type of collision	Source	Collision frequency	Reference period
All collisions	Lloyd's (SNL)	7.6×10^{-8} per nmi 4.1×10^{-5} per port call	1979–1993
Serious collision	Lloyd's (JNC)	3.86×10^{-8} per nmi	1990–1995

4.3.3.2. Location

The average collision frequency calculated from the Lloyd's database (for the period 1979–1993) has to be considered carefully, as far as a detailed analysis of collision occurrences in 21 ocean regions points up a range of frequencies from 6.8×10^{-9} per nmi in open ocean to 1.9×10^{-6} per nmi for the east coast of Japan (Table X).

In order to examine the influence of port traffic on port collision frequencies, ports were divided into three groups, high traffic ports (13 ports), medium traffic ports (78 ports), and low traffic ports (3499 ports). The division was based on the number of port calls to each port in 1988. Average collision frequencies per port call were calculated for each port category (Table XI).

From these data, a complementary analysis suggested that ship collisions often occurred in port approach waters. Collision frequencies in approach waters for a selection of high traffic and medium traffic ports were calculated, these frequencies ranging from about 3×10^{-7} to 5.6×10^{-6} per nmi (excluding the ports where no collision occurred in approach waters).

TABLE X. SHIP COLLISIONS AND COLLISION FREQUENCY FOR 21 OCEAN REGIONS (SNL)

Region	Collisions 1979–1993	Collision frequency (per nautical mile sailed)
Irish Sea	7	1.7×10^{-7}
English Channel	33	1.0×10^{-7}
North Sea	134	1.9×10^{-7}
Baltic Sea	76	1.8×10^{-7}
Western Mediterranean	29	1.5×10^{-7}
Tyrrhenian Sea	8	1.1×10^{-7}
Adriatic Sea	11	8.1×10^{-8}
Aegean Sea, Bosporus	59	5.4×10^{-7}
Eastern Mediterranean	21	1.3×10^{-7}
Suez Canal, Red Sea, Gulf of Aden	17	3.7×10^{-8}
Persian Gulf, Gulf of Oman	17	1.5×10^{-7}
Approaches to Singapore	41	7.4×10^{-8}
South China Sea, Taiwan Strait	42	1.4×10^{-7}
East China Sea	34	8.0×10^{-8}
Yellow Sea	13	9.6×10^{-8}
Sea of Japan, Korean Strait	35	3.3×10^{-7}
Inland Sea of Japan	193	9.7×10^{-7}
East Coast of Japan	120	1.9×10^{-6}
Western Gulf of Mexico	24	1.2×10^{-7}
Coastal waters	252	1.9×10^{-7}
Open ocean	70	6.8×10^{-9}

TABLE XI. PORT CALLS (1988) AND AVERAGE PORT COLLISION FREQUENCIES (PER PORT CALL) (SNL)

Port	Port collisions (1979–1993)	Port calls (1988)	Collision frequency (per port call)
All high traffic	93	199 609	3.1×10^{-5}
All medium traffic	174	254 121	4.6×10^{-5}
All low traffic	422	656 989	4.3×10^{-5}

4.3.4. *Collision and fire accidents*

Only limited information is available on the combination of collision and fire accidents in the databases. It should be noted that the SNL study based on Lloyd's data mentioned 50 collisions which led to fire among the 1947 collision events (i.e. about 2.6% of the collisions).

4.3.5. *Foundering*

Only two studies consider foundering. The frequencies reported in the studies are presented in Table XII below.

TABLE XII. FOUNDERING FREQUENCY PER SHIP-YEAR

Type of accident	Source	Foundering frequency (per ship-year)	Reference period	No. of events	No. of ship-years
Serious casualty	Lloyd's (JNC)	2.97×10^{-3}	1990–1995	264	88 920
Total loss	Lloyd's (CEPN-IPSN)	1.21×10^{-3}	1994–1997	215	177 418

Foundering represents about half of the total losses reported in the Lloyd's database. Furthermore, an average foundering frequency of 4.95×10^{-8} per nmi was calculated in the JNC study.

4.4. Discussion

It should be kept in mind that all the databases cited in the present section are different as to the number of ships, kind of ships included in the database, definition of accidents, number of recorded incidents and time period. The interpretation of these databases within the different studies therefore gives a wide range of probabilistic information. The different types of information provided in these studies may be combined in order, for example, to derive frequency per nmi from statistics presented on events per ship-year, or to estimate the frequency of fires which occurred in the machinery room. Nevertheless, for performing a safety analysis for a specific ship, it is necessary to specify the category of event considered in the database. Furthermore, no consideration of the safety features of purpose built-ships has been undertaken.

In order to calculate the frequency of different types of events for specific voyages, the following method was adopted.

As for collision, the probability of a ship collision during a voyage can be estimated for any sailing route as follows, taking into account a port call that includes a port entry and a port departure, stops at intermediate ports and sailing in different regions:

$$P_{SC,\,V} = 0.5\,P_{SC,\,Dep\,P} + \sum_i P_{SC,\,R_i} N_i + \sum_j P_{SC,\,P_j} + 0.5\,P_{SC,\,Des\,P}$$

where:

$P_{SC,\,V}$ is the probability that a ship collision occurs during the voyage,

$P_{SC,\,Dep\,P}$ is the probability that a collision occurs during transit in the port of departure,

$P_{SC,\,R_i}$ is the probability that a collision occurs while sailing a nautical mile in Region i,

N_i is the number of nautical miles sailed in Region i,

$P_{SC,\,P_j}$ is the probability that a collision occurs during transit in the intermediate Port j, and

$P_{SC,\,Des\,P}$ is the probability that a collision occurs during transit in the port of destination.

4.5. Use of actual route statistics for theoretical routes

Two studies performed calculations for specific routes of radioactive material: the first considered the transport of radioactive material from Europe to Japan (the JNC study), the second considered the return of radioactive waste from the UK to a northern European port (the GRS study).

The JNC study evaluated the probability of severe marine transport accidents for three routes (between Tokai/Hitachi, Japan and Cherbourg, France) by applying a set of weighting factors to the basic casualty rate information from the Lloyd's database (related to conventional cargo ships). In order to generate a more realistic estimate of the casualty rate per movement on each route, the geographical conditions associated with each Marsden grid cell along length of the route were examined. On the basis of these geographical conditions, the magnitude of each weighting parameter was measured in qualitative bands. Table XIII shows that the total casualty rates for Routes 1, 2, and 3 are essentially the same, ranging between 5×10^{-3} and 7×10^{-3} per ship movement on each route. These casualty rates represent the probability of a casualty along the entire route for each of Routes 1, 2, and 3. The total probability for port accidents on a ship movement basis for each of the routes is in the order of 8×10^{-4} per ship movement in the initial and terminal ports (Table XIV).

TABLE XIII. CASUALTY RATES PER SHIP MOVEMENT ON DESIGNATED ROUTES (JNC)

Route	Distance (nmi)	Collision (CN)	Fire &Explosion (FX)	Foundered (FD)	All casualties*
Route1 (via South Africa)	18 899	7.61×10^{-4}	5.38×10^{-4}	1.04×10^{-3}	7.02×10^{-3}
Route 2 (via South America)	17 785	6.21×10^{-4}	5.07×10^{-4}	1.01×10^{-3}	6.88×10^{-3}
Route 3 (via the Panama Canal)	13 802	6.15×10^{-4}	3.93×10^{-4}	7.00×10^{-4}	5.19×10^{-3}

* Including all other categories of accidents (missing, wrecked/stranded, etc.).

TABLE XIV. CASUALTY RATES FOR ACCIDENTS AT DESIGNATED PORTS

	Collision (CN)	Fire & Explosion (FX)	Foundered (FD)	All casualties*
Cherbourg	9.58×10^{-5}	1.01×10^{-5}	2.45×10^{-5}	3.47×10^{-4}
Tokai/Hitachi	1.02×10^{-4}	1.25×10^{-5}	4.34×10^{-5}	4.13×10^{-4}
Sub-total	1.98×10^{-4}	2.26×10^{-5}		7.60×10^{-4}
Cherbourg/Tokai (collision, wrecked/stranded, fire & explosion)		4.46×10^{-4}		

* Including all other categories of accidents (missing, wrecked/stranded, etc.).

The GRS study considered a voyage from Barrow-in-Furness in the UK to a European port via the Irish Sea, the English Channel and the North Sea. For this study a trip distance of 1000 nmi was assumed. The calculations were performed assuming:

- a collision frequency of 1.5×10^{-7} per nmi (representative for the North Sea, the Channel and the Irish Sea) and the frequencies per port call for the types of port representative of the route based on the Lloyd's data from the SNL study, leading to a frequency of 1.7×10^{-4} for the entire voyage;
- an occurrence probability for a fully developed main engine room fire of 2×10^{-4} per voyage, (based on the Lloyd's data from the SNL study, the MAIB database and Bureau Véritas database (CEPN-IPSN)).

Scenarios with collisions inducing fires and foundering were also considered. Furthermore, considering the special safety features of an INF 3 type ship, probabilities of accident occurrence per voyage were estimated and were considered very low or negligible (in the range of 10^{-7}–10^{-10}).

5. FIRE BEHAVIOUR ON SHIPS

5.1. Fire scenarios, frequency, effect of ship type

5.1.1. Fire scenarios

Fire scenarios of concern to the CRP were those of sufficient severity and duration that might exceed that of the IAEA fire test (800ºC for 30 minutes) or might exceed the total heat input to the package implied by these parameters. The IAEA fire test implies a heat flux of approximately 65 kW/m^2 in the initial stages of the 30 minutes fire test, this value falling as the package heats up at a rate dependent on the package thermal properties, including its heat capacity and surface emissivity. A necessary condition is that the fire meet one of these criteria in the immediate vicinity of the package, for which sufficient combustible material and an adequate air supply are prerequisite. These are referred to in this work as "severe fires", or "qualifying incidents", having the potential to threaten package integrity.

Long duration fires that spread from one part of a ship to another as readily combustible material is consumed need to be carefully considered when defining the duration for which the package is actually closely exposed to fire (Selway [3]). Similarly, those long duration fires known to take place in bulk cargoes (cotton, coal etc.) must be considered from the viewpoint of the (un)likelihood of large Type B(U) or Type B(M) packages being co-located in the same hold, although "creep" of fire from one cargo space to another cannot be excluded, and was considered by Ammerman, et al. [5].

The International Maritime Dangerous Goods Code requires that Radioactive Materials (Class 7) be stowed separated by at least one fireproof and waterproof bulkhead or deck from highly flammable cargoes. Nonetheless, there is no such prohibition, in a mixed cargo situation, of stowing Class 7 packages in the same hold as combustible materials. When, however, radioactive material is carried under "exclusive use" conditions, it will be possible for the consignor to ensure that the packages are not co-mixed in the same hold/compartment with other, potentially combustible, cargo. In this case, propagation of fire to the hold or compartment concerned will be the only potential scenario to consider, since flammable and potential ignition sources will be absent. Important scenarios for study in this CRP have included both real testing of such situations, by Ammerman, et al. [5], and calculation approaches by Selway, et al. [3, 4] and Kay [10].

Engine Room fires, which can spread to cargo areas, are the most common source of severe fires in ships and have been extensively considered during the CRP from the largely qualitative severity information in historical records (Selway [3]), and quantitatively by both calculation (Selway [11]) and by full-scale practical testing (Ammerman, et al. [5]).

Fires may be associated with other precursor (e.g. collision) or subsequent (e.g. sinking) events to which consideration must also been given. Type B(U) and Type B(M) package designs must be capable of withstanding severe impact and puncture environments followed by exposure to a severe thermal environment. However, the scenario of an oil or gas carrier colliding with a ship carrying radioactive packages, followed by severe fire to which the packages are exposed by the precursor impact, is often quoted as a potentially serious thermal threat to such packages. The historical event data, as will be seen in the further analysis below, shows that few serious ships fires are preceded by such impacts and the frequency of such combined events is approximately two orders of magnitude lower than the frequency of serious fires alone (Lange, et al. [7], Kay, et al. [4]). Thus this scenario represents a minor contributor to overall frequency of fire risk and generally permits collision to be considered separately from fire. Nevertheless, the scenario of collision followed by fire and spread of fire from compartment to compartment has been studied by Ammerman, et al. [5] for the case of a four deck, eight hold, break-bulk freighter. This same approach may also be applied for fire from any other initiating event, such as an engine room fire, spreading through cargo spaces.

5.1.2. Frequency

Schneider, et al. [1] carried out statistical analyses of the sea accident frequency records from three databases:

(1) Data on maritime fire accidents leading to severe damage, including total loss, for the period 1994-1997 from the Lloyd's database (world fleet and records of ships casualties);

(2) the ship casualty data recorded by the MAIB for UK ships during the period 1990-1996, from which frequencies of initiating fire events could be determined; and

(3) the fire accident database of the French Bureau Véritas for the period 1978-1988.

Lange, et al. [7] reviewed the sea accident records of Lloyd's, the MAIB, Bureau Véritas, the IMO and the commercial ship casualty database of the U.S. Coast Guard . They used this statistical data as a basis to estimate an upper bound probability of a fire occurring on a purpose-built INF 3 ship being used to transport high level radioactive waste from the UK to continental Europe.

The study by Yamamoto, et al. [6] describes and analyses the safety of the international transport of plutonium by cargo ships for three selected routes between Europe and Japan. The analysis centres on conventional cargo ships and their accident history in order to provide an estimate of the frequency/probability of accident occurrences, including fires/explosions for such ships. This is an ultraconservative approach since the radioactive material described in the study will, in all likelihood, be transported in purpose-built ships that incorporate many safety features not found in regular cargo ships. Follow-up studies can use the information developed in this study in order to estimate the probability of accident occurrences in purpose-built ships. The accident probabilities developed in this study, for conventional cargo ships, provide a conservative bounding estimate of the probabilities for accidents involving purpose-built ships.

Kay, et al. [4] searched the possible sources of information on shipping incidents and, after consideration of the merits of various options, data on fires and explosions covering worldwide shipping, for the period 1984-1993were obtained from Lloyd's,. Further data obtained from Lloyd's, provided information relating to the number of ships in existence, with ship types categorized to be compatible with the fire records. An analysis of the data was carried out to determine how many incidents would have been a potential threat to an irradiated nuclear fuel flask, had one been carried as a cargo item. Oil tankers and liquefied gas carriers were excluded because of their inability to carry flasks. None of the 93 fire incidents identified as relevant to the current study, and which contributed to the main results, arose as a result of a collision. This supported the contention, in 5.1.1 above, that fire incidents consecutive to collision are much less frequent than fire alone and therefore, these two causes of damage could be considered separately.

The data considered by Kay, et al. [4], derived from worldwide sources, may be expected to provide an upper bound estimate of fire frequency of sufficient severity to have the potential to damage a Type B(U) or Type B(M) package, for conventional cargo ships and ships of the INF 1 standard, but may be expected to be progressively pessimistic for ships meeting the higher, INF 2 and INF 3 standards.

Selway, et al. [2] studied the accident statistics of the Marine Accident Investigation Branch (MAIB) of the UK to establish credible frequencies of fires occurring on the rail deck of a particular ferry in regular use to transport irradiated nuclear fuel from Europe to the UK by rail — the "Nord Pas-de-Calais". The resulting event-tree analyses estimated the probability of fire sufficiently severe to be a potential threat to such fuel flasks. Later work by Kay [10] developed Selway's probabilistic analysis further, taking into account revised initiating fire frequencies and new information about the "Nord Pas-de-Calais".

The databases used to estimate fire frequency differ concerning the number of ships, type of ships included in the database, definition of accidents, number of recorded incidents, time period etc. The interpretation of these databases within the different studies therefore gives a wide range of probabilistic information. A summary of the most important data originating from the statistics of the conventional cargo carrying ships is given in Table XVII below.

Analysis of these data permits estimates to be made of fire frequency/probability for the classes of ship which might carry radioactive material packages and for factors to be identified which may influence this frequency. Such factors include the annual distance travelled (which, where known, permit data to be normalized to a per unit distance basis rather than a per unit time basis), date of construction of the ship concerned (ships of more recent construction incorporate better equipment to detect and suppress fire), the age of the ship at the time of the casualty (ships tending to show an increase of casualty rate with age) and other factors, such as flag state, geographic location etc. A significant proportion of maritime fires occur in ports, where better facilities to fight fire may be available, but where the closer proximity to persons may lead to more severe potential consequences. Probability of fire in port can be estimated from the historical data and, when combined with the data for fire probability at sea, provide a basis to estimate risk of particular complete sea transport operations.

The ship type is particularly significant with respect to the effectiveness of the three classes of INF ships used to carry radioactive material in the larger quantities, with consequent larger potential for damage: this issue is addressed separately below.

5.1.3. Effect of ship type

It is the approach of the IAEA transport regulations that safety in the transport of radioactive material should be provided mainly by the design of the package. In 1993 the IMO adopted a "Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High Level Radioactive Wastes in Flasks on Board Ships" (the INF Code). This code requires higher safety standards in design, construction and operation for ships carrying INF materials and is to be seen as an additional safety measure which enhances the safety level of the sea transport of radioactive material. As with the IAEA Transport Regulations, the INF Code adopts a graded approach, defining three standards of ship, INF 1, INF 2 and INF 3, with more stringent requirements applying as the aggregate quantity of radioactive material carried onboard increases.

5.1.3.1. INF 1 ships and conventional cargo ships

The INF 1 class of ship sets a basic level of safety requirements applicable to the transport of irradiated nuclear fuel, plutonium and high level radioactive wastes, which are limited to an aggregate quantity of less than 4000 TBq of activity. For radioactive material other than irradiated nuclear fuel, plutonium and high level radioactive wastes, the INF Code does not apply and such materials may be carried in conventional cargo ships for which the requirements of the International Maritime Dangerous Goods Code (IMDG Code) alone specifies the necessary package safety requirements, based on the IAEA Regulations for the Safe Transport of Radioactive Material.

For an INF 1 class of ship, fire frequency data derived from the historical record of the world cargo carrying fleet, excluding those cargo ships unsuitable for carrying packaged dangerous goods (such as tankers etc.), may be used to estimate an upper bound probability of fire events leading to potential release of radioactive material of a known maximum radioactive quantity, providing it is possible to relate this data to events of sufficient severity and duration to cause a release.

Fire frequency data from historical records may also be used to derive the probability of fire occurring on this class of ship when special circumstances apply. For example "exclusive use" conditions may be applied on such ships, either by chartering the ship for the exclusive use of the consignor of radioactive material, or by arrangement with the shipping company to have exclusive use of one or more holds/compartments of the ship, which may be kept free of readily combustible materials.

5.1.3.2. INF 2 ships

In practice irradiated nuclear fuel, plutonium and high level radioactive wastes in commercial quantity are carried in amounts for which INF 2 (or INF 3) ships are required and much of the focus of this CRP is directed at these types of ships. The Nord Pas-de-Calais, a cross channel Ro-Ro rail/road freight/passenger ferry in service between Dunkirk and Dover, was taken as an example of an INF 2 class of ship and studied in detail during the CRP by Selway, et al. [2, 11], Selway [3] and Kay [10].

For fire protection purposes the Nord Pas-de-Calais is divided into a number of zones. Generally one compartment is one zone, although the cargo decks are divided into several zones. Each zone has several smoke detectors in series, together with manual alarms, and its own remotely operated fire suppression systems. There is also a regular patrol of the cargo and passenger areas which takes about twenty minutes for each circuit.

The remotely-operated fire suppression systems are comprised of a variety of foam, water deluge and halon — which do not operate in all zones. In addition, there are portable water and foam fire extinguishers, and three water cannons aimed at the open section of the upper cargo deck.

The remotely operated systems are controlled from a fire control room situated on the lorry deck, which also contains controls for isolating fuel tanks, shutting off ventilation and closing fire-resisting doors.

The electrical supply to the fire fighting equipment comes from the generators in the generator room. There is also an emergency generator near the bridge which can operate the fire and drainage pumps.

Bulkhead doors are typically secured by six levers. There are a number of fire doors, in escape passageways for example, which are normally held open by electromagnets which release the doors when the alarm sounds, and close automatically. The electromagnets for individual doors can also be switched off locally.

Once per year the ship's halon systems are checked by an outside organization. The deluge systems are tested every six months with fresh water (to minimize rust problems).

The crew has been trained in fire-fighting techniques at accredited training establishments ashore. Fire drills and lifeboat drills are carried out every week and recorded in the ship's log.

5.1.3.3. INF 3 ships

Pacific Nuclear Transport Limited (PNTL) operate a fleet of five special purpose-built ships which meet the INF 3 standard and carry irradiated nuclear fuel from Japan to Europe for reprocessing. A further, smaller, ship of INF 3 standard owned by British Nuclear Fuels Ltd (BNFL) has been in service for a similar period carrying irradiated fuel from Europe to the UK. These six ships have been operated during the last 20 years without any significant accident leading to release of radioactive material. In this period:

- an experience of about 90 ship-years has been accumulated,
- about 150 shipments have been performed,
- about 4.5 million nmi have been travelled,
- about 8000 tonnes of nuclear fuel have been transported, and
- about 4000 flasks (max. 5 tonnes fuel/flask) have been transported.

However, the PNTL/BNFL fleet specific database is not sufficient to estimate realistic probabilities of extreme accident scenarios. It is therefore also necessary to consider generic data for cargo ship accidents and derive corresponding probabilities by such methods as event tree analysis, taking account of the particular characteristics of the PNTL/BNFL ships.

The PNTL/BNFL fleet of ships are provided with comprehensive fire safety protection equipment as outlined below:

(1) The principal fire fighting system incorporated on board ship is based on a halon extinguishing system. Halon supplies are located fore and aft of the ship with outlets in strategic areas. The aft halon store supplies the engine room, while the forward store supplies the cargo holds and forward generator space. The ship's paint store is allocated its own fire extinguishing system, which relies on CO_2.

(2) All the ships gas extinguishing systems are manually actuated to prevent accidental release. In addition to the gas extinguishing system, machinery spaces are equipped with hydrants, fire hoses and portable fire extinguishers. The holds are also equipped with portable fire extinguishers.

(3) Fire fighting arrangements within the accommodation areas rely on fire hose reels and portable extinguishing equipment.

(4) It must be noted that the design of the ships and the nature of the cargoes mean that combustible materials are at minimal levels throughout the ship with the exception of the living accommodation. However, a large water filled tank has been provided between the living accommodation and engine room to segregate the cargo space, its main function being minimization of radiation doses to the crew. This also provides an effective fire wall between the cargo space and engine room.

(5) A full multi-zone fire detection system is installed throughout each ship utilizing smoke, heat and flame detectors as appropriate to the particular space, as well as manual break glass units (push buttons). Alarm status readouts are located on the bridge and in the machinery control room with audible alarms throughout the ship being complemented by visual alarms in high noise areas.

(6) The ship is equipped with a fire main system which uses sea water and is supplied by a total of four pumps, 3 aft, 1 forward, with an additional emergency fire pump forward. The main is of a 'ring main' design with strategically located isolating valves: this

enables sections of the fire main to be isolated in the event of damage, thus allowing the rest of the system to remain operational.

(7) Each ship hold is provided with an independent sprinkler system fed from both sides of the ship by the fire main into the hold lid (hatch cover). As with the gas extinguishing system, this is manually operated to prevent accidental release. The function of this system is twofold, a) to provide a backup fire fighting system and b) to allow the hold to be flooded if required. If necessary, all five holds may be flooded and, under these conditions, the ship would remain afloat.

PNTL ships have been used to transport plutonium oxide from Europe to Japan. It is likely that these, or similar INF 3 ships, will also be used for future transports of high level radioactive waste, mixed oxide fuel (MOX) and other nuclear fuel cycle material back to the countries of origin in Europe and Japan.

When the return of vitrified high level waste arising from the reprocessing of spent nuclear fuel at Sellafield to continental Europe, e.g. Germany, will start, the shipments of the specific flasks will include transportation from port facilities of BNFL (UK) at Barrow-in-Furness to continental Europe via the Irish Sea, the English Channel and the North Sea with ships of the Pacific Nuclear Transport Limited (PNTL and BNFL) classified to the INF 3 standard.

Ships carrying vitrified high level waste (VHLW) from reprocessing plants with an aggregate radioactivity of 2×10^6 TBq or greater are required to be class INF 3 ships by the INF Code.

One of the main issues of the present safety evaluation of these shipments is to compile information and data in order to be able to judge whether accidents involving ships might subject packages with vitrified high level waste to more severe accident conditions than the IAEA regulatory tests and if so at which level of probability.

Lange, et al. [7] note that the accident data based on statistics relating to conventional cargo ships cannot be directly applied to an INF 3 ship and that there are a variety of different approaches to deal with the accident risk associated with an INF 3 ship, bearing in mind that the undesirable event is not the fire accident itself but the potential resulting load on the cargo exceeding the design criteria of the regulations applicable to the flasks. Lange, et al. [7] consider a reference voyage of an INF 3 ship from the BNFL berth at Barrow-in-Furness to a north European port with an assumed voyage length of 1000 nmi and estimate the probabilities and severities of the accidents which could involve the cargo.

Yamamoto, et al. [6] carried out a similar analysis for the purpose-built PNTL ships transporting plutonium from Europe to Japan, using a probabilistic methodology due to Sprung (in Sprung, J.L., et al., Radiological Consequences of Ship Collisions that Might Occur in U.S. Ports During the Shipment of Foreign Research Reactor Spent Nuclear Fuel to the United States in Break-Bulk Freighters, SAND96-0400, Sandia National Laboratories, August 1996), described in Ammerman, et al. [5].

Yamamoto, et al. [9] also performed a study to show that the IAEA Transport Regulations adequately cover the thermal effects of an engine-room fire on plutonium transportation packages stowed aboard a purpose-built ship. The packages are stored in transportation containers located in a cargo hold of the ship. For the study, it was assumed that the packages in the No. 5 hold, adjacent to an engine room, could be subject to heating due to a fire in the engine-room. The No. 5 hold and the engine room are separated by a water filled bulkhead. This study addressed the heat transfer from an engine-room fire that could heat and evaporate water out of the water-filled bulkhead and the resulting temperature conditions around the packages and inside the packages near their elastomeric seals.

5.2. Determination of frequency-probability, severity and duration

5.2.1. Frequency-probability

5.2.1.1. Schneider, et al. analysis of Lloyd's database

In order to determine meaningful frequency-probability information from the historical records, it was first necessary to estimate the size of the world fleet and filter out those data which are not relevant. Schneider*,* et al. [1], based on Lloyd's database, determined that an average of 44 354 "cargo carrying ships" of 100 gross tons or more were on register during the period 1994-1997. During this period, a total of 456 accidents were recorded as "total losses", which Lloyd's defines as ships which "as a result of a marine casualty, have ceased to exist, either by virtue of the fact that the ships are irrecoverable or have subsequently been broken up".

This corresponds to an overall casualty rate of 2.6×10^{-3} loss/ship-year, including all ship types and all causes. Of these casualties, 55 occurred as a result of fire and/or explosions, accounting for a total loss rate of 0.31×10^{-3} loss/ship-year.

Of the average 44 354 cargo carrying ships on register, some 38.9% (~17 254 ships) are classified as "general cargo ships", which are considered to be the most representative of the type of ship which might be used to transport radioactive material. Other ship types, which could also be used for transport of radioactive material and thus relevant to the CRP, are as follows, with the average proportion of the world fleet over the same period shown in brackets: passenger/general cargo (0.8%), container ships (4.2%), Ro-Ro cargo (3.8%), passenger/Ro-Ro cargo (5.2%) and passenger ships (6.0%). Thus a total of 58.9% of all registered ships are considered relevant to the present study.

Since they are not likely to be used for the carriage of packaged radioactive material, the following ship types were not considered relevant to the present study: liquefied gas carriers (2.3%), chemical carriers (4.8%), oil tankers (15.3%), other liquid carriers (0.7%), bulk dry carriers (14.7%) and refrigerated cargo (3.3%); these types of ships aggregate 41.1% of the entire data set.

Removing those categories of ships which are not likely to be used to carry radioactive material reduces the number of relevant casualties arising from fire/explosion from 55 to 34, in a population of ~26125 ships over the four year period corresponding to the following fire/explosion loss rates:

- General cargo = 0.26×10^{-3} loss/ship type/year
- Passenger/general cargo = 0 loss/ship type/year
- Container = 0.40×10^{-3} loss/ship type/year
- Ro-Ro cargo = 0.295×10^{-3} loss/ship type/year
- Passenger/Ro-Ro cargo = 0.54×10^{-3} loss/ship type/year
- Passenger = 0.57×10^{-3} loss/ship type/year

Aggregating these data to cover all relevant ship types gives an overall casualty rate of 0.325×10^{-3} loss/relevant ship type/year. It is noted that this rate is quite similar to the fire/explosion casualty rate for the entire world fleet database mentioned above (0.31×10^{-3} loss/ship·year).

Schneider, et al. [8], also analysed the origins of fires/explosions on ships and found the most common origin (about $^2/_3$ of all events) occurred in the engine room, the second most common (about $^1/_6$ of all events) originated in accommodation areas.

Other noteworthy indications in the database were a marked association between the age of the ships and the accident frequencies with 5.3% of all accidents occurring to ships 0–9 years old, 30.7% to ships 10–19 years old and 64% to ships 20 years old or older. There was also an apparent link between the relative accident frequencies and the flag of registration.

5.2.1.2. Schneider, et al. [1] analysis of MAIB database

A second analysis was performed on the ship casualties recorded by the Marine Accident Investigation Branch (MAIB) for UK ships. This analysis is limited to the frequencies of collision and of fire for UK ships for the 1990–1996 period. It should be noted that this second database is not limited to total loss, but to accidents for which a declaration has been made to the authorities. Thus, the frequencies derived from this second analysis should be useful for determining the occurrence of initiating events with a view to performing a probabilistic safety analysis, but are not necessarily representative of fires sufficiently severe to qualify as having the potential to endanger a Type B(U) or Type B(M) package. The data analysed from the MAIB database deal with UK registered ships of 100 GT or more, corresponding to about 1100 ships each year for the seven–year period. In this database, a large number of incidents is reported as the accident criteria are slightly different from the Lloyd definition. In fact, the MAIB database includes most of the events which lead to compensation from insurance companies. Four categories of accidents are reviewed:

(1) Loss of life or major injury,
(2) Ship lost or materially damaged,
(3) Ship stranded or having collided, and
(4) Major injury or material damage to the environment.

The MAIB data show a reported fire incidence rate averaging 13.6×10^{-3} incidents/ship-year in the period 1990–1996 and averaging 13% of all reported accidents over the entire period. Of most interest is the fact that the rate declined steadily and markedly between 1990 (25.6×10^{-3} incidents/ship-year) and 1996 (1.9×10^{-3} incidents/ship-year), accounting respectively for 20% of all reported accidents in 1990, decreasing to 2% of all accidents in 1996.

5.2.1.3. Schneider, et al. [1] analysis of Bureau Véritas database of fire accidents

This study considered fire casualties on ships supposed to be representative of the radioactive material transporters (general cargo, container, Ro-Ro/passenger). The selection was derived from the world casualties in the period 1978 to 1988 and corresponds to immediate total losses and delayed total losses. Table XV below presents the frequencies associated with different types of ships.

TABLE XV. BUREAU VÉRITAS FREQUENCIES OF FIRE

Type	No. of fires-	Total fleet	Average frequency (fire/ship type/year)
General cargo	284	235 893	From 3.1×10^{-4} to 2.6×10^{-3}= 1.2×10^{-3}
Container	5	9407	From 0 to 2×10^{-3}= 0.53×10^{-3}
Ro-Ro/passenger	28	42 375	From 2.4×10^{-4} to 1.2×10^{-3}= 0.66×10^{-3}
Total	317	287 675	1.1×10^{-3}

These values may be compared with the corresponding frequencies derived from the Lloyd's database: general cargo = 0.26×10^{-3} loss/ship type/year, container ship = 0.4×10^{-3} loss/ship type/year, Ro-Ro/cargo = 0.295×10^{-3} loss/ship type/year, passenger/Ro-Ro cargo = 0.54×10^{-3} loss/ship type/year and passenger ship = 0.57×10^{-3} loss/ship type/year. Whilst the Bureau Véritas figures are generally somewhat higher it should be noted that they relate to an earlier period (1978-1988 compared with the Lloyd's data for 1994-1997) and that the number of fires varies significantly from one year to the next. However, taking account also of the trend seen in the MAIB data, it suggests that the fire casualty rates may be significantly diminishing over time, which may be accounted for by improving standards of equipment and/or operation of ships.

Based on the analysis of ship accidents for which detailed information is available (10 to 20% of the fleet), it appears that nearly half of the accidents occur at dock (out of 113 accidents). Moreover, the record shows that the fires originated mainly in the machinery room (64%), the quarters (39%) and the holds (8%), and they principally affected the machinery room (68%), the quarters (54%) and the holds (17%).

From the periodical survey made by the Bureau Véritas, average annual distances have been evaluated for the different ship types in order to determine the probabilities per km. As presented in Table XVI below, these probabilities reflect only those fires which could potentially harm the freight (i.e, fire events that affected the hold or deck).

TABLE XVI. BUREAU VÉRITAS PROBABILITIES PER KM OF REPRESENTATIVE FIRE

Type	Average annual distance (km)	Probability (fire/ship/km)	Probability (representative fire*/ship/km)
General cargo	115 000	10.5×10^{-9}	2.7×10^{-9}
Container	138 000	3.9×10^{-9}	1.7×10^{-9}
Ro-Ro/ passenger	117 000	5.6×10^{-9}	1.0×10^{-9}

*Holds for general cargo and Ro-Ro/passenger purposes; holds or decks of container ships.

As the duration of the fire is rarely recorded, this data is only available for 20 accidents. Of these, 35% lasted more than 1 day but never more than 7 days. It is important to note that this restricted set of accidents cannot be considered representative as far as it only covers the severe accident with fire class. Furthermore, no information is available on the temperature of the fires. Nevertheless, this analysis clearly points up the existence of accidents associated with severe fires.

5.2.1.4. Ammerman, et al.

Ammerman, et al. [5] noted that ship fires show little variation with ocean location and occur often only in Marsden squares that contain major oil fields (the North Sea and the Persian Gulf). Ship fire frequencies were derived by analysis of 15 years (1979 through 1993) of Lloyd's casualty data and 2 years (1988, 1993) of Lloyd's port call data.

The casualty data contained 2547 fire events, 975 of which occurred in ports; none of the 2547 fire events involved collisions. The casualty data also contained 1947 collisions events, 50 of which led to fires, 39 of these fires resulted from collisions at sea and 11 from collisions in ports. Thus the fire frequency per nautical mile sailed and per port call was calculated to be:

- 9.6×10^{-8} fires per nmi sailed, and
- 5.4×10^{-5} fires per port call.

5.2.1.5. Lange, et al., accident statistics for conventional cargo ships

Lange, et al. [7] considered the accident statistics for conventional cargo transporting ships as a first step to deriving accident probabilities for INF 3 ships.

The databases for these studies were taken from

(a) Lloyd's Register of Shipping, which shows the world fleet and casualty statistics;
(b) the MAIB, which records incidents and accidents to registered ships in the UK;
(c) IMO Fire Casualty Records, based on incidents reports submitted to the IMO by all member countries;
(d) Bureau Véritas; and
(e) the U.S. Coast Guard commercial ship casualty database.

These databases vary in terms of the number of ships, kinds of ships, definition of accidents, numbers of recorded incidents and time periods covered. Therefore, the interpretation of these databases within the different studies gives a wide range of probabilistic information. A summary of the most important data originating from the statistics of the conventional cargo ships is given in Table XVII.

The probabilities shown in Table XVII are to be understood as expectation values. Please note that the derived probabilistic data in the table stem from relatively severe accidents, since only accidents leading to deaths, injuries and/or considerable commercial losses were included in the casualty records. Initiating events or precursors which have resulted in less serious consequences (e.g. successful fire fighting at an early stage) will have higher frequencies than those provided in the table.

TABLE XVII. SUMMARY OF PROBABILISTIC FIRE/EXPLOSION DATA FROM STATISTICS ON CONVENTIONAL SHIPS

Type of event	Frequency Probability	Source[4]	Remarks
Ship fire and explosion, all reported incidents	2.6×10^{-3} /year per ship	[KAY 95], based on Lloyd's worldwide data 1984–93	32 422 ships (excl. oil tankers); 859 incidents in 10 years
Ship fire and explosion, serious fires affecting cargo hold	2.9×10^{-4} /year per ship	[KAY 95], based on Lloyd's worldwide data 1984–93	32 422 ships (excl. oil tankers); 93 incidents in 10 years
Ship fire and explosion, all reported incidents on Ro-Ro ferries	6.7×10^{-2} /year per ship 40% mach. room	[KAY 93], based on MAIB reports for UK Ro-Ro ferries, 1989–92	124 ships; 33 incidents in 4 years
Ship fire and explosion, with total loss	3.1×10^{-4} /year per ship	[CEPN-IPSN], based on Lloyd's worldwide data 1994–97	177 418 ships (cargo); 55 incidents
Ship fire and explosion, with total loss/repair	1.1×10^{-3}/year per ship; 1.8×10^{-8}/nmi 66% mach. room	[CEPN-IPSN], based on Bureau Véritas data 1978–88	317 fires in 287675 ship-years, (cargo, container, Ro-Ro/ passenger), 116 000 km average annual travel distance

TABLE XVII. SUMMARY OF PROBABILISTIC FIRE/EXPLOSION DATA FROM STATISTICS ON CONVENTIONAL SHIPS (CONT.)

Ship fire and explosion, all reported incidents	9.6×10^{-8}/nmi; 5.4×10^{-5}/port call	[SPR 96], based on Lloyd's worldwide data 1979–93	2547 fire events, 975 of which occurred in ports
Ship fire and explosion, all reported incidents	1.7×10^{-2}/year per ship	[MAI 95], based on registered UK merchant ships 1990–94	105 fires in 6300 ship-years
Collision with subsequent fire, all reported incidents	4.2×10^{-9}/nmi for North Sea	[SPR 96], based on Lloyd's worldwide data 1979–93	1947 collision events, 50 of which led to fire
Collision with subsequent fire, total loss	1.9×10^{-10}/nmi	[CEPN-IPSN], based on Lloyd's worldwide data 1994–97	2 incidents in 4 years; 177 418 ships, 110 000 km average annual distance

[4] The references given in Table XVII are those of Lange et al [7] and have been updated for the CEPN-IPSN study.

5.2.2. Severity and duration

Ammerman, et al. [5] found that the casualty data derived from 15 years (1979 through 1993) of Lloyd's casualty data and 2 years (1988, 1993) of Lloyd's port call data contained very little information about accident severity. Their analyses were carried out using all fires in the 15 years of data, without regard to their severity.

Selway [3], after having established estimates for the frequency of a "severe fire" on the INF 2 class freight ferry, Nord Pas-de-Calais, sought to obtain estimates of the fire durations, with particular reference to Ro-Ro ferries.

Only two of a number of organizations dealing with shipping accidents were able to provide specific information on the duration of fires on ships. These were the IMO and the Marine Accident Investigation Branch (MAIB).

The IMO was found to have the largest number of fire reports which gave times to control, and times to extinguish, fires on ships. Over a period of 25 years, IMO has received a total of 382 fire casualty records reporting on ship fires from all over the world. The shortest fire recorded was extinguished in one minute and the longest in seventy-one days. These data produced an estimated average time for a fire of 26 hours while the ship was in port and 19 hours while under way. However, with such a range of duration times, these average figures are only of mathematical interest and could not provide any reliable indication of the time for which cargo in any particular position could have been exposed to fire of any defined severity. Having thoroughly investigated all the available reports of fires, it was concluded that at present, there is insufficient historical data to reach a definitive conclusion on the time period that a fire on a ship would be considered to be intense. Calculation approaches or practical tests must be resorted to, in order to quantify ship fire durations and in turn to relate these to fire severities for particular fire scenarios.

5.2.2.1. Severity and duration of fire on the INF 2 ship Nord Pas-de-Calais

Using fire modelling techniques, Selway, et al. [11] investigated the growth of fires initiating on the rail deck and in the engine room of the Nord Pas-de-Calais in order to establish the likely temperatures to which a flask of irradiated fuel might be subjected.

To determine the type and size of fire on the rail deck, a study was undertaken of the imported cargo inventories which the Nord Pas-de-Calais carried recently. This established that of the eight wagons that could surround the flask, two would likely contain flammable commodities (e.g. timber, chipboard, plastic tubes), four would likely contain non-flammable commodities (e.g. ash slag, steel tubes, mineral water), and the remaining two would likely be empty.

The HAZARD I computer code, developed by the National Institute of Standards and Technology in the USA, was used to model three fire scenarios on the rail deck. From the three fire scenarios considered for the Rail Deck, the restrictions on the ventilation, as a result of the enclosed deck, produced peak temperatures in the upper gas layer of 450°C after twenty minutes. The depth of this upper layer was about 5 m so it would encompass the flask, but heat transfer could not induce a temperature greater than 450°C on the surface of the flask.

The four fire scenarios modelled in the engine room gave a wide range of temperatures, again being dependent on the ventilation, which varied depending on whether the ventilation dampers and/or the fire doors were operated to close off the area. The scenarios involving the fire doors closing, whether the ventilation dampers closed or not, resulted in ceiling temperatures of no more than 160°C. The scenario involving a fire in the engine room with the end fire door staying open achieved a ceiling temperature of 400°C after an average fire duration of $2^1/_2$ hours.

The sensitivity analysis of this final engine room fire scenario extended the fire to a duration of 11 hours and found that the ceiling temperature reached a maximum of 440°C after 8 hours. This temperature is well below that at which the integrity of the engine room ceiling would be considered to be threatened.

In none of these seven fire scenarios would the flask be exposed to conditions more severe than those specified in the IAEA Regulatory Thermal Test for a Type B package.

5.2.2.2. Severity and duration of fire — experimental measurements

Ammerman, et al. [5] conducted eight practical fire tests aboard the US Coast Guard fire test ship Mayo Lykes at Mobile, Alabama. Tests aboard this break-bulk type cargo ship consisted of heptane spray fires simulating engine room and galley fires, wood crib fires simulating cargo hold fires, and pool fires staged for comparison to land-based regulatory fire results. Primary instrumentation for the tests consisted of two pipe calorimeters that simulated a typical package shape for radioactive material packages (though of much smaller thermal capacity than that typical of heavily shielded flasks used to carry spent nuclear fuel or high level radioactive waste). These fire tests were then modelled with the methods of computational fluid mechanics to confirm that analytical models can successfully predict the shipboard fire environment.

Two holds, holds 4 and 5 at the aft end of the ship, were selected for the tests. Level 1 of these holds, immediately below the weather deck, was used for all fires and measurements. In all cases the fires were set in hold 4. Steel pipe calorimeters representing simulated radioactive material packages were placed in both holds 4 and 5. Fires included ignited heptane sprays impinging on the steel bulkhead between holds 4 and 5, and wood crib fires representing combustible cargo fires. The general experimental arrangement is shown in Figure 1.

The sequence of eight fires conducted aboard the Mayo Lykes is shown in Table XVIII. A brief description of each type of fire and major fire characteristics follows. Hold 4 measured 17.6 m wide by 21 m long by 3.8 m high. Hold 5 dimensions were 17.6 m wide by 16 m long by 3.8 m high.

For all tests the calorimeter in hold 5 was located with its centreline 0.4 m above the deck and 2 m aft of the hold 5-4 bulkhead. To avoid potentially explosive conditions with the heptane spray and in-hold pool fires, adequate oxygen was supplied to hold 4 via openings in the hull. Measurements indicate that oxygen levels in the vicinity of the fire were usually near normal atmospheric content.

In sealed ship hold fires at sea, oxygen would be more limited, leading to smouldering fires with even lower heat flux levels than experimentally measured. The experimental fires reported here represent conditions more typical of a fire that could occur during ship loading or unloading in port, where both on ship and off ship fire fighting equipment and personnel would be available.

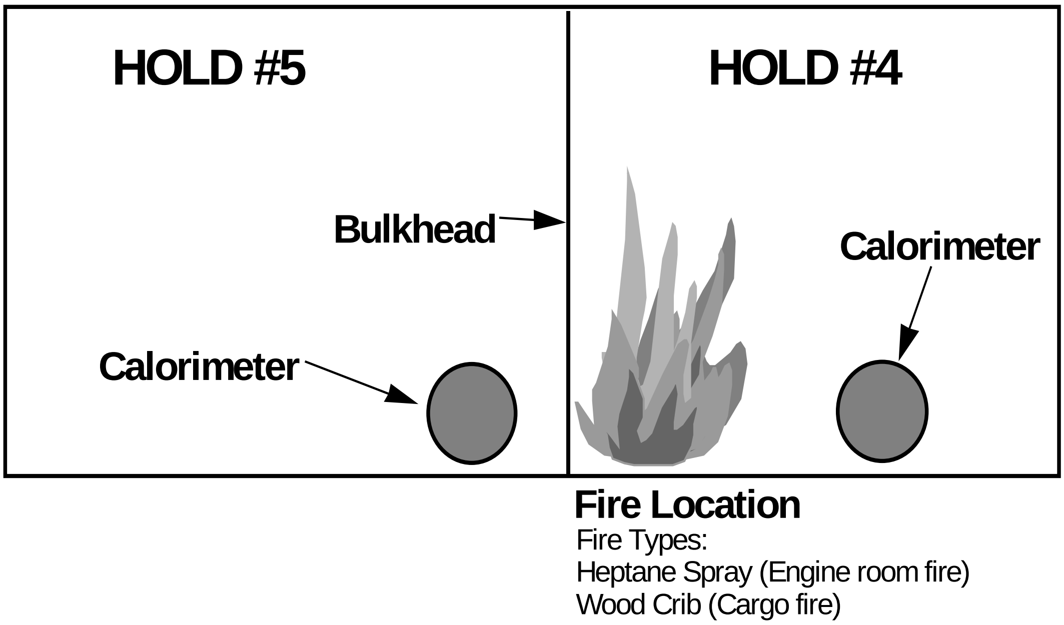

Fig. 1. Fire test arrangement.

For comparison to the in-hold fire test, a 3 m × 3 m pool was built on the weather deck of the *Mayo Lykes* on the port side amidships. The pool was constructed to closely follow the dimensions of the pool built in hold 4. The calorimeter from hold 5 was centred above the pool, 1 m above the fuel surface at the start of the test. A depth of 13 cm of diesel fuel gave a 32 minute burn, typical of a regulatory pool fire. Calculation of the recession rate for this fire led to an estimated average thermal output of 18.8 MW, i.e. somewhat higher than the thermal output of the in-hold pool fire test (15.7 MW).

TABLE XVIII. FIRE TEST SEQUENCE

Test No.	Date, time and duration	Type of test	Peak thermal power, MW
5037	95/9/12, 2:09 PM CDT, 60 min	Two-burner heptane spray test	2.2
5040	95/9/14, 9:13 AM CDT, 20 min	Wood crib fire test with 17 L heptane accelerant	4.1
5041	95/9/14, 12:21 PM CDT, 60 min	Two-burner heptane spray test with diesel fuel in drip pans for smoke	2.2
5043	95/9/15, 8:26 AM CDT, 20 min	Wood crib fire test with 17 L heptane accelerant	4.1
5045	95/11/13, 12:02 PM CDT, 60 min	Four-burner heptane spray test	5.6
5046	95/11/13, 2:46 PM CDT, 60 min	Four-burner heptane spray test with diesel fuel in drip pans for smoke	5.6
5048	95/11/14, 3:09 PM CDT, 27 min	Diesel pool fire in hold 4	15.7
5049	95/11/15, 2:20 PM CDT, 32 min	Diesel pool fire on weather deck	18.8

From this experimental work, heat flux measurements as a function of time were measured and may be compared with the heat flux implied by the IAEA fire test (65 kW/m^2). For heptane and diesel pool fire tests, it is not possible to obtain any direct information on fire duration, since in these tests there was control over fuel supply such that the fire could be terminated at will. However, in the case of the diesel pool fires, information on the pool level recession rate is given by the Ammerman*,* et al. paper, which may be used to estimate fire duration for any particular case in which total fuel availability in the vicinity of a flask is known.

In the case of the wood crib tests, fire duration was limited by the available combustible material in the 20-A size crib design specified in UL Standard 711, to approximately 20 minutes.

In summary, heat fluxes and temperatures measured during the tests were as follows:

Four-burner heptane spray tests:

Calorimeter in hold adjacent to fire:	Max temp. rise above ambient temp.: ~25°C at 70 min
Heat flux	<0.8 kW/m^2

Wood crib tests:

Calorimeter in same hold as fire:	Max temp rise above ambient temp ~215°C at 30 min
Heat flux (max.)	22 kW/m^2. Peak at ~5 min at worst position on calorimeter
Heat flux (min.)	~17 kW/m^2 over period ~20 min at worst position on calorimeter

Pool fire test in hold:

Calorimeter in same hold as fire:	Max temp. rise above ambient ~800°C at 24 minutes
Heat flux (peak)	190 kW/m^2. Peak at ~1.5 minute at worst position on calorimeter
Heat flux (max., discounting peak)	~80–100 kW/m^2 at ~2.5 minutes at various positions on calorimeter, falling quasi inverse exponentially
Heat flux (min.)	~25 kW/m^2 at ~24 minutes at various positions on calorimeter
Flame temperature	~1000°C at 2 minutes, falling to ~900°C at 24 minutes
Flame temperature	~1000°C at 2 minutes, rising to ~1100°C at 24 minutes

Pool fire test in hold:

Calorimeter in hold adjacent to fire:	Heat flux = 0 kW/m^2 at 0 min, rising quasi-linearly to ~1.5 kW/m^2 at worst position on calorimeter at 24 minutes

5.3. Assessment of risk

5.3.1. Lange, et al.

Lange, et al. [7] note that attention must be paid to the fact that the derived probabilistic data in Table XVII originate from relatively severe accidents, since only accidents leading to deaths, injuries and/or considerable commercial losses are consigned in the casualty records. Initiating events or precursors which result in less serious consequences (e.g. in case of successful fire fighting in an early stage) will have higher frequencies than those given in Table XVII.

Regarding the above accident data based on statistics relating to conventional cargo ships, it is evident that these statistics cannot be directly applied to an INF 3 ship. Different approaches are required to deal with the accident risk associated with an INF 3 ship, bearing in mind that the undesirable event is not the fire or collision accident itself but the potential resulting loads on the cargo exceeding the design criteria of the flasks. For a reference voyage from the PNTL berth at Barrow-in-Furness to a north European port with an assumed voyage length of 1000 nautical miles the probabilities and severities of the fire/explosion accidents which could involve the cargo have been estimated. Two types of accidents were investigated.

5.3.1.1. Internal fire

A fire analysis taking into account the particular safety features of the INF 3 ship was performed to quantify the probability of internal fires which could affect the cargo. The procedure of the fire risk analysis for the PNTL ship is adapted from the fire safety analysis for nuclear power plants. From the potential fire scenarios on board a PNTL ship, the locations with the highest frequencies for initiating fires were identified following expert evaluation taking into account their severity with respect to cargo. Based on the fire loads present, the consideration of event frequencies and the possibilities of fire spread to the cargo holds, main engine room fires present the highest fire risk to the cargo. The results of the detailed analysis are summarized in the form of an event tree in Fig. 2.

As mentioned previously, the available accident statistics of the insurance companies include only so-called damage fires, i.e. fires which have developed from an initiating fire to a severity with relevance to the insurers. The event tree therefore starts at the top with such a damage fire inside the main engine room, for which, as a conservative estimate, an occurrence frequency of 2×10^{-7}per nmi has been derived from the accident statistics for conventional cargo ships in general, as summarized in Table XVII. This reveals an frequency of occurrence of 2×10^{-4} per voyage for a fully developed main engine room fire.

This assumption of a fully developed fire — excluding an initial fire without damage — is reflected in the first level of the event tree where only a 20% probability for successful manual fire fighting is assumed. The consecutive level of the event tree refers to the success or failure of the halon system to extinguish the fire in the engine room at this stage. If unsuccessful, the next line of defence with respect to the cargo is a water filled steel bulkhead which separates the main engine room from the cargo area. Concerning all conceivable combustible fire loads in the main engine room, this barrier is sufficient to prevent a fire spread to one of the passageways along the bulkheads of the cargo holds, one on each side of the ship. Only if one of the fire doors leading from the main engine room to a passageway is inadvertently open — contrary to specified procedures and despite the surveillance that would normally be expected from the navigation bridge — is there a possibility for fire to propagate to the passageway. For this conditional probability a conservative value of 10^{-1} was chosen from the literature on fire safety analysis.

All further decision levels and the associated conditional failure probabilities are evident from Fig. 8 of Ref. [7], reproduced below as Fig. 2. Finally, four event sequences of the tree can result in a fire propagation to the interior of a cargo hold and have the end point "potential cargo damage" with associated conditional probabilities lower than 1.5×10^{-5} for each event sequence, equivalent to a probability of 3.0×10^{-9} per voyage taking into account the initial probability of 2×10^{-4} per voyage for a fully developed main engine room fire. This results in a summed probability of all the four branches of the event tree with the potential to affect the cargo of 5.3×10^{-9} per voyage. The fire risk analysis assesses the probabilities and severities of possible fires in a cargo hold. Either way, the available fire loads are small enough that the thermal threat to a large flask is negligible.

5.3.1.2. Fire induced by collision

The evaluation of Lloyd's accident data covering the years 1979 through 1993 shows that only 2.5% of the collision events led to a fire (50 fires in 1947 collision events, see Table I). The most probable of these external events is a collision by an INF 3ship with a tanker whereby flammable liquids could leak into the striking ship or — much more probably — to the surface of the sea.

Penetration of the spilled liquid into the PNTL ship's cargo holds can be excluded as the hatch covers remain closed. If there is also an ignition, this scenario could lead to a fire enveloping the INF 3 ship for a longer period. The probability of a fire of this type with a duration that could lead to a thermal threat to the flasks is estimated to be in the range of 2×10^{-10} per voyage. Additional reduction of the 2.5% collision plus fire probability is given by the chance of setting back the striking ship (failure 0.1), the probability that the struck ship is a tanker (0.2), the probability of a long fire duration, i.e. the failure of cooling and extinguishing actions (0.05). A comparable probability for this scenario can be derived on the basis of a ten year survey on collision and severe fires with tankers.

A fire following a collision could result by damage to the INF 3 ship's fuel tank and subsequent ignition of the diesel fuel. Both events are quite improbable, because the fuel tanks are at the bottom of the ship and the diesel flash point is >60 °C. If this scenario is assumed, a fire of a duration that would threaten the cargo can be excluded, because the content of the damaged fuel tank is limited and the burning layer of fuel on the water surface would spread and rapidly burn off.

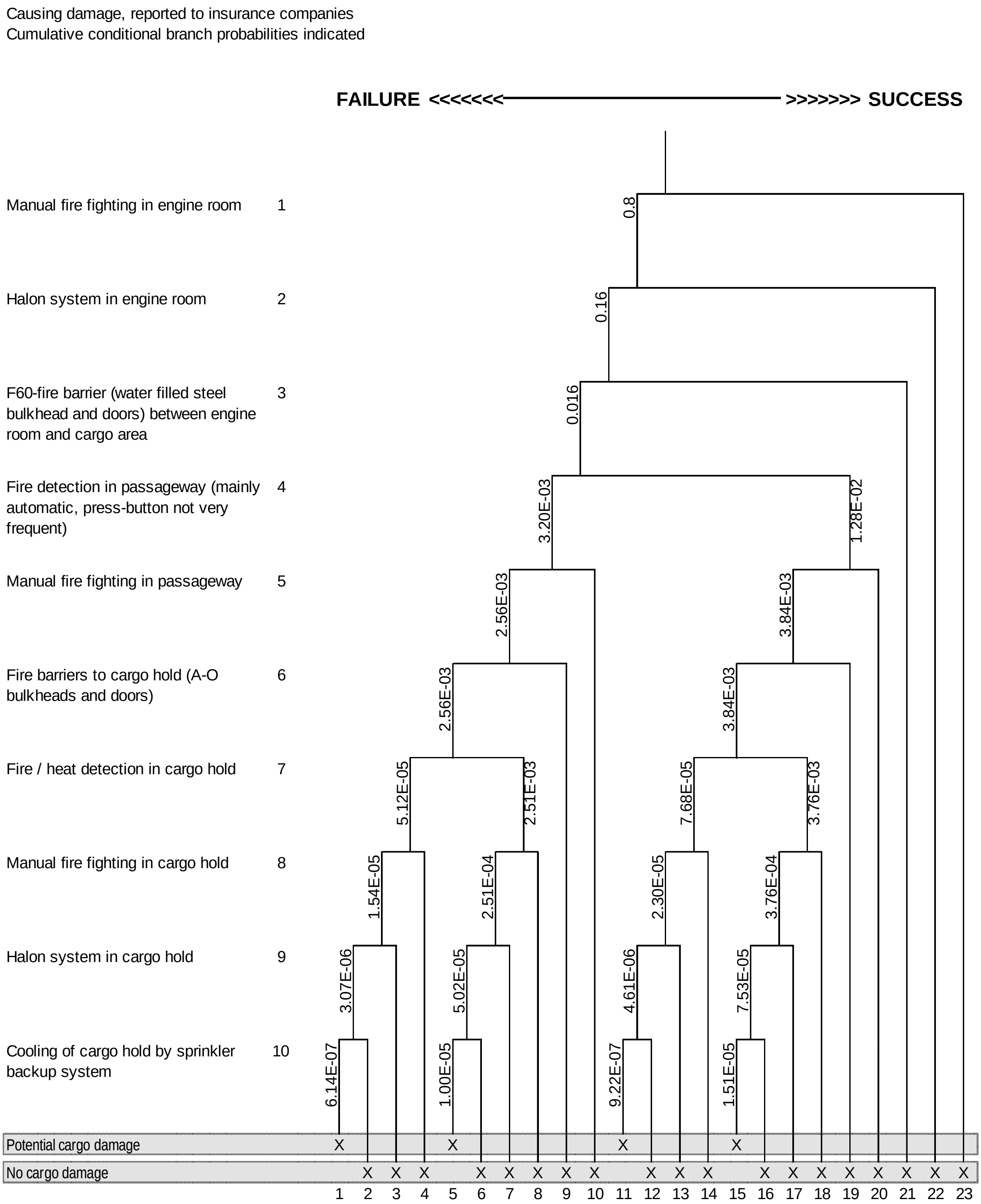

FIG. 2. Event tree for engine room fire.

5.3.2. Yamamoto, et al. study on engine room fire

Yamamoto, et al. [9] carried out a programme to determine whether the IAEA Regulations for the Safe Transport of Radioactive Material adequately cover the thermal effects of an engine-room fire on plutonium transportation packages stowed aboard a purpose-built ship. The packages are stored in transportation containers located in a cargo hold of the ship. For this study, it was assumed that the package in the No. 5 hold adjacent to an engine room could be subject to heating due to a fire in the engine room. The No. 5 hold is separated from the engine room by a water filled bulkhead. The study addressed the heat transfer from an engine-room fire that could heat and evaporate water out of the water-filled bulkhead and the resulting temperature conditions around the packages and inside the packages near their elastomeric seals.

The study indicated that the fire accident condition of 800°C for 30 minutes specified in the IAEA regulations is sufficient and adequate for protecting against a 2 hour engine-room fire. The surface temperature of the ISO-container which affected the environmental temperature of the surrogate package only increased to 95°C after a 2 hour fire, or 142°C when the No. 5 hold remains at 100°C for an extended period of time. Seals of the surrogate plutonium package transported in the No. 5 hold stayed within their design temperature range after a 2 hour engine room fire.

5.3.3. Yamamoto, et al. study on plutonium transport operations

Yamamoto, et al. [6] carried out a programme to analyse the safety of large scale plutonium transport operations by cargo ships for three selected routes between Europe and Japan (1. Via Cape of Good Hope, Indian Ocean and Western Pacific; 2. Via Cape Horn and Pacific; and 3. Via Panama and Pacific). Conventional cargo ship accident history data were used in order to provide an estimate of the probability of accident occurrences for such ships, but it should be recognized that this will yield very conservative results for the purpose-built (INF 3) ships used for such transport that incorporate many safety features not found in regular cargo ships. Follow-on studies can use the information developed in this study in order to estimate the probability of accident occurrences in purpose-built ships.

Casualty rates were determined for each of the three routes from Lloyd's Casualty Database and are summarized in Tables XIX and XX below for "at sea" and "in port" cases, respectively.

Probabilities of potential releases of radioactive material were evaluated, using the methodology due to Sprung (in J.L. Sprung, et al., Radiological Consequences of Ship Collisions that Might Occur in U.S. Ports During the Shipment of Foreign Research Reactor Spent Nuclear Fuel to the United States in Break-Bulk Freighters, Rep. SAND96-0400, Sandia National Laboratories, August 1996), based on six defined severity levels of accident. Severity Levels 1 through 3 are of minor severity and judged not to have the potential to cause a release of radioactive material. Levels 4 to 6 represent the most severe categories of accident, Level 5 being a collision involving impact and crush forces associated with a severe engulfing fire and Level 6, the most severe, additionally assumes convective release from the flask.

TABLE XIX. SUMMARY OF CASUALTY RATES PER SHIP MOVEMENT ON DESIGNATED ROUTES

Route	Route distance (nm)	Collision (CN)	Contact (CT)	Wrecked/ stranded (WS)	Fire & explosion (FX)	Hull/machine failure (HM)	Foundered (FD)	Missing (MG)	Misc. (XX)	Total
Route1 (South Africa)	18 899	7.61×10^{-4}	1.19×10^{-4}	1.07×10^{-3}	5.38×10^{-4}	3.42×10^{-3}	1.04×10^{-3}	3.16×10^{-5}	4.25×10^{-5}	7.02×10^{-3}
Route 2 (South America)	17 785	6.21×10^{-4}	1.27×10^{-4}	1.22×10^{-3}	5.07×10^{-4}	3.32×10^{-3}	1.01×10^{-3}	3.07×10^{-5}	4.00×10^{-5}	6.88×10^{-3}
Route 3 (Panama Canal)	13 802	6.15×10^{-4}	1.10×10^{-4}	1.02×10^{-3}	3.93×10^{-4}	2.30×10^{-3}	7.00×10^{-4}	2.12×10^{-5}	3.10×10^{-5}	5.19×10^{-3}

TABLE XX. SUMMARY OF CASUALTY RATES FOR ACCIDENTS IN DESIGNATED PORTS

Ports	Collision (CN)	Contact (CT)	Wrecked/ stranded (WS)	Fire & explosion (FX)	Hull/machine failure (HM)	Foundered (FD)	Missing (MG)	Misc. (XX)	Total
Cherbourg	9.58×10^{-5}	1.09×10^{-5}	1.24×10^{-4}	1.01×10^{-5}	8.04×10^{-5}	2.45×10^{-5}	7.44×10^{-7}	7.97×10^{-7}	3.47×10^{-4}
Tokai/Hitachi	1.02×10^{-4}	8.97×10^{-6}	1.02×10^{-4}	1.25×10^{-5}	1.42×10^{-4}	4.34×10^{-5}	1.32×10^{-6}	9.87×10^{-7}	4.13×10^{-4}
Sub-total	1.98×10^{-4}		2.26×10^{-4}	2.26×10^{-5}					7.60×10^{-4}

This analysis produced an engineering estimate that characterizes the probability of cargo ship transportation accidents on the three designated routes between Japan and Europe. These route estimates have been further examined to produce an estimate of a severe cargo ship accident. These accident probabilities have been used in conjunction with the phenomenology of flask response for severe irradiated nuclear fuel transportation accidents to estimate the probability of a release of radioactive contents due to a severe accident. The probability of cargo ship transport accidents in ports or approach waters to ports has been estimated. Category 4 accidents were estimated to have a probability in the order of 1.4×10^{-6} per ship movement on the route. A Category 5 accident probability of occurrence was estimated to be in the order of 1.2×10^{-9}per ship movement. A Category 6 accident was estimated to be on the order of 1.3×10^{-10}per ship movement. Thus, the probability of a severe cargo ship transportation accident in a port that might release radioactive material ranged between 10^{-9} to 10^{-10} per ship movement. These probability estimates can be used in risk assessment studies to estimate the health effects of such accident occurrences.

6. COLLISION SEVERITY

6.1. Background

Concern has been expressed by IMO member states and concerned citizens that the regulations for the safe transport of radioactive material (RAM) as listed in IAEA ST-1 do not provide adequate protection for RAM packages during sea transport. To support this position, the extreme amount of kinetic energy available in ship-to-ship collisions is frequently cited. This amount of kinetic energy is orders of magnitude larger than the kinetic energy that is associated with the regulatory impact test that packages are required to withstand in order to be certified. The fallacy of this argument is that, in the regulatory impact accident, all of the kinetic energy of the event is transmitted to the package, while in ship-to-ship collisions only a small fraction of the kinetic energy (or as is often the case, none) is transmitted to the package. However, it must still be demonstrated that the probability of maritime transport accidents exceeding the regulatory hypothetical accident conditions is no higher than the probability of land transport accidents exceeding these conditions. The probability of a release of radioactive material due to a collision at sea is the product of four probabilities:

(1) the probability of having a collision,

(2) the probability of the collision being in the correct configuration to cause damage to the RAM package,

(3) the probability the collision is severe enough to either penetrate to the location of the RAM package or compress cargo around the package, and

(4) the probability that the forces acting on the RAM package are high enough to cause the package to fail.

In this section the last three of these probabilities is discussed, the first having been discussed in Section 5.2.1.

6.2. Mechanics of ship-to-ship collisions

Legal operation of commercial ships does not allow cargo to be stowed in the most forward portion of the ship (ahead of the collision bulkhead). This fact ensures that, if a ship carrying radioactive material package(s) strikes another ship, the package(s) on the striking ship will not be involved in the collision. Also, if a ship carrying the radioactive material package(s) is struck by another ship during a raking collision (a collision with a small angle between the paths of the two ships), the penetration into the struck ship will not be sufficiently deep to involve the RAM package(s) in the collision. Therefore, the only collisions that have a possibility of involving the radioactive material package(s) are nearly right-angle collisions in which the ship carrying the package(s) is struck by another ship. When combined, these factors show that only about one collision in ten will have a configuration that might cause damage to a RAM package. Even if the collision is of a configuration to cause damage to the RAM package, it must still be sufficiently severe to either penetrate the struck ship to the location of the package or compress cargo (or intervening ship structure) around the package. The severity of the collision is a function of the masses of the ships involved and their relative speeds. In this type of accident, the initial kinetic energy of the two ships is dissipated by deformation of ship structure and by hydrodynamic forces acting on the ships. The exact solution of this mixed structural dynamics and fluid dynamics problem is generally not performed. Instead, approximations on the effect of the hydrodynamic forces are made. One frequently used approach is to account for the hydrodynamic resistance by increasing the mass of the struck ship to increase its inertial resistance. This approach allows the collision to be treated in a purely structural mechanics setting.

The amount of damage to a ship struck by another ship is proportional to the kinetic energy of the collision. In the 1950s V.U. Minorsky investigated a large number of severe collisions and developed an empirical linear equation relating the collision energy absorbed by the two ships (calculated by assuming a perfectly plastic collision) to the volume of ship steel damaged [12]. Recently, Reardon and Sprung [13] developed new constants for this linear equation as the result of additional data gained from more recent collisions (beginning in 1959). They also considered the energy absorbed by the crushing of ship cargo. Using this equation it is possible to determine approximately the penetration distance for any collision. Applying this methodology to a wide range of collisions, Reardon and Sprung determined that only about 15 per cent of all collisions occur with a configuration that may result in crush forces being applied to a RAM package for transportation in a small freighter without other cargo, and about 30% for transportation in a larger break-bulk freighter with other cargo stowed in the same hold as the RAM package.

The structure of the Minorsky equation is such that it treats the energy required to penetrate the hull of the struck ship as a constant (the y-intercept of the correlation). For the smaller ships that may be used to transport RAM, and especially small double hull purpose-built ships, treating the energy to penetrate the hull as a constant can lead to substantial errors. The extensive amount of work done to investigate loss of containment for tanker ships has led to a robust method for determining the energy and penetration distance required to cause hull rupture [14]. This method can be used to develop ship specific penetration and energy absorbed at the moment of hull rupture. Further penetration can be treated in a manner similar to that developed by Minorsky. A discussion of this method is included in the technical appendices of this report. No attempt has been made to improve the probabilities for imposing structural loads on RAM packages derived by Reardon and Sprung using this improved technique.

6.3. Magnitude of forces acting on RAM packages

The results of the preceding section only indicate that a RAM package may experience forces as a result of ship-to-ship collision. In this section we will consider the magnitude of those forces. If a collision is severe enough to cause penetration to the location of a RAM package, there are two ways in which the package might be damaged. First, by direct contact of the striking ship bow with the package. However, because the bow velocity and bow rigidity during this impact are much less than those for the regulatory impact, no damage is expected as a result of direct impact of the striking ship bow onto the package. Second, the penetrating bow might subject the package to crush forces either by crushing cargo around the package or by pushing the package up against ship structures, for example, the far hull of the struck hold. In order for a package to be subjected to crush forces, there must be forces acting on both sides of the package. If it is assumed that the bow of the striking ship can supply infinitely large forces on one side of the package (rigid bow assumption), the limit to the magnitude of the crush force is the force restraining the package from moving ahead of the advancing bow once the package has been struck.

When the package is first impacted by the bow of the striking ship it is held in place by the tiedowns that attach it to the deck. These tiedowns are required by regulation to be designed to fail at forces much lower than the force needed to damage the package, and they are also required to fail in a manner that does not decrease the functionality of the package with respect to containment, criticality control, or shielding effectiveness. For this reason, it is impossible for the tiedown system to provide restraining force of a magnitude large enough to cause package damage.

Immediately after the tiedowns fail, the only force restraining the package is friction along the deck. Even if the collision has caused the deck to fold or buckle, the magnitude of this friction force is very small. Therefore, the package will slide/roll across the deck until it strikes other cargo or ship structure. When cargo is present, because most cargo is softer than a RAM package, contact with other cargo will result in crushing of cargo rather than crushing of the RAM package. A paper by Radloff and Ammerman [15] shows finite element calculations of the maximum crush force imparted to a radioactive material package as a function of cargo strength and stiffness. In that paper, it was shown that the presence of intervening cargo has little effect on the magnitude of the maximum load acting on the package. For the case with no other cargo, the RAM package will be pushed across the ship until it strikes some other ship structure (typically the hull on the side of the ship away from the collision). The strength of this structure will limit the magnitude of the crush force that can be applied to the package. Ammerman and Ludwigsen [16] used finite element analyses to investigate the maximum crush force that could be applied to the package as it is pushed through the side shell structure of a single-hull ship. This conservative analysis indicated a maximum force that is very similar to the inertial forces experienced during the regulatory impact accident. Therefore, the probability of the forces acting on the RAM package being high enough to cause the package to fail are very low and the expected result of this scenario is the ejection of the package through the far hull of the struck hold into the ocean.

6.4. Conclusions

The work by Radloff and Ammerman, and Ammerman and Ludwigsen indicates that during the maritime transport of radioactive material, the probability of a RAM package experiencing loads that are greater than the loads experienced during the regulatory certification tests is very low. Therefore, there is no need to require a different set of mechanical certification tests for sea transport than are required for land transport. In actuality, the probability of a package structurally failing as a result of collision during transport at sea is lower than it is for land transport.

7. CONSEQUENCES OF ACCIDENTS TO SHIPS TRANSPORTING RAM PACKAGES

7.1. Hypothetical accidents

Should a ship that is carrying highly radioactive material in a Type B package, for example irradiated nuclear fuel in a flask, be involved in a severe ship accident, a collision and/or a fire, flask failure and/or loss of the flask into the ocean might occur. If flask failure leads to a radioactive release to the atmosphere, gas borne transport of this material from the sea to land could cause population along the overland atmospheric transport path to be exposed to radiation. In addition, deposition of gas borne radioactive material onto the ocean surface or the loss of the flask into the ocean would introduce radioactive material into marine food pathways, whereupon people who would consume the marine foods contaminated as a result of the accident would be exposed to radiation. This section summarizes the results of illustrative consequence calculations that focused on a radioactive release to the atmosphere or to the ocean as a result of ship accidents that might occur (a) in the open ocean during a transoceanic voyage, (b) while sailing a coastal route at a distance from shore of several tens of kilometres, and (c) in a port at a known location.

Sandia National Laboratories (SNL) considered a hypothetical radioactive release to the atmosphere from a TN-12 irradiated nuclear fuel flask following a severe ship accident postulated to occur while the ship was at port or while it was sailing on a coastal route. Port accident consequences were estimated using the MACCS code [17, 18]. Coastal accident consequences were estimated using the RADTRAN code [19, 20].

The incorporation of radioactive material into marine foods following loss of a RAM flask into the ocean was explored by the Institute for Nuclear Safety and Protection and the Nuclear Protection Evaluation Centre (IPSN-CEPN), by SNL, and by the Central Research Institute of the Electric Power Industry (CRIEPI). The IPSN-CEPN calculations used the POSEIDON code [21, 22] to examine the consequences of the loss of 1 kg of plutonium powder into the western English Channel. SNL used the MARINRAD code [23] to estimate the consequences of loss of a TN-12 irradiated nuclear fuel flask into the ocean due to a ship collision while traversing the Grand Banks fishing region. CRIEPI estimated the consequences that might result from the loss into shallow seas and into the deep ocean of anHZ-75T flask carrying irradiated nuclear fuel, a TN-28VT flask carrying high level waste, and an FS-47 package carrying plutonium powder.

7.2. Accident probabilities

Table XXI presents estimates of event probabilities that allow the probability for each of the hypothetical accidents examined by these illustrative consequence calculations to be constructed. Combining the probabilities from Table XXI, it can be shown that for single hull ships (a) the probability of a severe ship collision that leads to failure of the flask seal due to flask crush is about 9×10^{-10} while sailing the urban portion of the New London, CT, to Charleston, SC, coastal route and about 10^{-8} while making a port call at Port Elizabeth, NJ; (b) the probability of a severe ship collision that causes a double failure of the flask (both seal failure and a puncture or shear failure) and also a severe fire is about 4×10^{-15} while sailing the urban portion of the New London, CT, Charleston, SC, coastal route and about 5×10^{-14} while making a port call at Port Elizabeth; and (c) that the probability of loss of a flask into the ocean due to the sinking of a RAM transport ship following a severe ship collision that occurs is about 10^{-7} while sailing through the English Channel, about 10^{-8} while traversing the Grand Banks, about 10^{-6} while sailing up the north-east coast of Japan, and about 2×10^{-7} while sailing across the Pacific from Japan to the Panama Canal. Thus, the chances of hypothetical accidents examined range from about 10^{-6} for a collision that leads to a sinking and thus to the loss of the flask into the ocean to 4×10^{-15} for a collision that leads to a double failure of the flask and a severe fire.

TABLE XXI. SCENARIO EVENT PROBABILITIES

Event	Probability	Value
A collision occurs while the ship is:	$P_{collision}$	
—Sailing the urban portion of the New London to Charleston coastal route (72 nmi)		1.4×10^{-5}
—Making a port call at Port Elizabeth		1.6×10^{-4}
—Sailing through the English Channel (285 nmi)		2.9×10^{-5}
—Sailing through the Grand Banks (400 nmi)		2.7×10^{-6}
—Sailing up the north-east coast of Japan (189 nmi)		3.6×10^{-4}
—Sailing across the Pacific Ocean (8300 nmi)		5.6×10^{-5}
The RAM ship is the struck ship	$P_{RAM\ ship\ struck}$	0.5
The strike location is midship	$P_{strike/midship}$	0.38
The RAM flask location is midship	$P_{flask/midship}$	1.0
The RAM hold is struck	$P_{RAM\ hold\ struck}$	0.33
Crush forces are applied to the flask	$P_{crush\ forces}$	0.1
Flask crush causes the flask seal to fail	P_{crush}	0.01
Flask puncture or shear occurs	$P_{puncture/shear}$	0.1
A severe fire occurs	$P_{severe\ engulfing\ fire}$	4.6×10^{-5}
The ship sinks	P_{sink}	3.6×10^{-3}

7.3. Radioactive release to the atmosphere

For ship accidents that might occur in port or while sailing a coastal route, SNL constructed irradiated nuclear fuel source terms for two hypothetical accidents, a ship collision that fails the seal of a TN-12 irradiated nuclear fuel flask and all of the rods inside of the flask, and a ship collision that fails the flask seal, the flask body and all of the rods in the flask, and initiates a severe fire. For the second accident, differential heating of the flask was assumed to cause a buoyant flow through the flask of combustion gases and air which sweeps all of the radioactivity released to the flask interior out into the atmosphere. Thus, the source term for the second accident constitutes a conservative estimate for an upper bound on atmospheric irradiated nuclear fuel source terms for maritime accidents.

7.3.1. Accidents at port (using MACCS calculations)

Table XXII presents consequence estimates for the two hypothetical port accident scenarios assuming that these accidents occur in the port of New York (Port Elizabeth). Both calculations assumed that the irradiated nuclear fuel flask was being carried in a break-bulk freighter that was also carrying other cargo. Both calculations used the irradiated nuclear fuel inventory from a TN-12 flask calculated using the ORIGEN code [24], accident release fractions based on the studies of Wilmot [25], Sprung [26], and Sandoval [27], one year of variable meteorological data recorded at the New York City National Weather Service Station, and a population distribution constructed from census data for 1990 using POPSEC90 [28]. Although no short term emergency response actions (evacuation, sheltering) were assumed to take place, post-accident relocation of population away from and decontamination and/or condemnation of significantly contaminated property was assumed to take place.

Table XXII shows that the normal background radiation doses and normal rates of cancer deaths among the population predicted to be exposed to radiation as a result of the two hypothetical port accident exceed by factors of about 10^2 to 10^5 the MACCS predictions of mean population dose and cancer fatalities among the same population that might be caused by these two port accident scenarios.

TABLE XXII. MACCS PREDICTIONS OF THE DOSE TO THE POPULATION OVER A PERIOD OF 50 YEARS AND CANCER FATALITIES ARISING FROM A PORT ACCIDENT

Source Term	Probability (per port call)	Population dose (Sv)	Cancer fatalities
Collision only	1.0×10^{-6}	857	37
Collision with fire	4.0×10^{-12}	2.4×10^4	1.0×10^3
50-year background dose		$>1.8 \times 10^6$	
50-year cancer fatalities			$>1 \times 10^5$
Exposed population		$\sim 1 \times 10^6$	

Version 1.5 of the MACCS code [17, 18] was used to develop the Cancer Fatality results presented in Table XXII. MACCS 1.5 calculates latent cancer fatalities using organ-specific linear-quadratic models. These models and their parameter values are documented in NUREG/CR-4214, "Health Effects Models for Nuclear Power Plan Accident Consequence Analysis." which was written by an expert panel selected by the U.S. NRC. The chapter on late somatic effects in that report cites 39 references, including references to BEIR I and BEIR III, ICRP 26, NCRP 64, UNSCEAR.

7.3.2. Accidents while sailing a coastal route (using RADTRAN calculations)

SNL used the RADTRAN code [19, 20] to model the consequences that might arise if either of the two hypothetical transportation accidents occurred while irradiated nuclear fuel was being transported in a TN-12 flask from New London, CT around Long Island and then down the east coast of the United States to Charleston, SC at a distance of approximately 40 km from the coast. These calculations used the same inventory and release fractions that were used for the MACCS port accident calculations and three aggregate route segments (one urban, one suburban, and one rural segment). Table XXIII presents the lengths and average population densities of these three aggregate route segments as calculated using the HIGHWAY code [29] and the coastal highway route from New London to Charleston.

TABLE XXIII. AGGREGATE COASTAL ROUTE SEGMENT LENGTHS AND POPULATION DENSITIES

Segment	Urban	Suburban	Rural
Length (km)	133	415	902
Population density (persons per km^2)	2780	386	13.5

The presence of 40 km of open ocean between the ship and the shore was accounted for by subtracting the results of a 40 km RADTRAN calculation from the results of a standard 121 km RADTRAN calculation [30], thereby obtaining an estimate of the consequences that occurred in the 40-to-121 km distance range, which comprises the first 81 km of land next to the shoreline. Table XXIV presents the results of these RADTRAN calculations.

Table XXIV shows that deposition of radioactive material onto the surface of the 40 km wide region of ocean between the sailing route and the shoreline reduces the estimated population dose by a factor of about three. Thus, correcting for the presence of a near-field region that is devoid of population produces a significant reduction in the estimated dose to the population. Although the 50-year 33 100 Sv dose to the urban population calculated for the collision-followed-by-fire accident scenario seems to be very large, it is in fact about 20 times smaller than the 590 000 Sv background dose that the 3.3 million people in the exposed population would accumulate during the 50 years that follow the hypothetical accident. Thus, even an unusually long epidemiological study of a large portion of that exposed population would not be expected to detect any radiological consequences (e.g. cancer fatalities) attributable to the accident. Finally, not only are the radiological consequences of this extremely severe collision-followed-by-fire accident unlikely to be capable of epidemiological detection, but also, as Table XXV shows, the probability that this accident will occur while sailing near an urbanized shoreline during a voyage from New London to Charleston is so small (4×10^{-15}) that the accident is almost implausible.

TABLE XXIV. FIFTY-YEAR POPULATION DOSES (Sv) CALCULATED USING THE RADTRAN CODE FOR THREE DISTANCE RANGES ON THE NEW LONDON TO CHARLESTON COASTAL SHIPPING ROUTE

Source term	Collision only			Collision followed by fire		
Route segment	Urban	Suburban	Rural	Urban	Suburban	Rural
0 to 121 km	1110	255	8.9	106 000	24 400	855
0 to 40 km	795	183	6.4	72 900	16 700	586
40 to 121 km	315	72	2.5	33 100	7700	269

7.4. Accidents at sea

7.4.1. CRIEPI studies

CRIEPI estimated the consequences of a radioactive release from irradiated nuclear fuel, high level waste, and plutonium due to the loss of the transport package into the deep ocean and into shallow seas off the north-east coast of Japan. In both cases it was assumed that no action was taken to recover the lost package. Submergence of the flask to a depth of 2500 m was assumed after loss into the deep ocean. Loss into shallow coastal waters was assumed to result in flask submergence to a depth of 200 m. Radioactive release into the deep ocean was conservatively modelled assuming that the release rate was controlled solely by leaching of radionuclides from the bulk material matrix with no credit taken for retardation of release by fuel rods, canisters, and/or the radioactive material package. For a radioactive release after a package had been submerged into shallow waters, any retarding effect of fuel cladding or canisters was neglected. Instead, leaching of radionuclides was assumed to cause the water in the package to become saturated by the radionuclides in the radioactive material being shipped; the release of radionuclides-saturated water from the flask was controlled by the buoyancy-driven flow of water that ran through the gap in the failed o-ring seal of the package.

Once released into the ocean, the concentration of radionuclides was estimated using a multi-compartment flow model [31] for deep ocean release and ocean current data [32] for near shore release. The maximum calculated surface concentrations of radionuclides were then used as input to a marine food pathway model [33, 34], which in turn provided doses for individuals whose diet followed a Japanese market basket developed by the Nuclear Safety Committee of Japan and who ate only maximally contaminated marine foods that had become contaminated due to the hypothetical loss of the package into the ocean. Table XXV presents the ‘maximally exposed individual doses’ estimated with the aid of these calculations.

TABLE XXV. CRIEPI ESTIMATES OF 'MAXIMALLY EXPOSED INDIVIDUAL DOSE' RESULTING FROM THE LOSS OF A RAM PACKAGE INTO THE OCEAN

Nuclear material	Quantity	Accident location	Submergence	'Maximally (a) Exposed Individual Dose' (mSv/a)
Spent fuel				
—Normal burnup	1 flask: 7 PWR assemblies	Near shore	200 m	4.1×10^{-4}
—High burnup	1 flask: 12 PWR assemblies	Near shore	200 m	2.3×10^{-3}
High level waste	1 flask: 28 canisters	Near shore	200 m	4.1×10^{-4}
		At sea	2500 m	4.7×10^{-9}
Plutonium powder	1 flask: 14.5 kg	Near shore	200 m	1.4×10^{-5}

(a) "Maximally" means here that all seafood that has been ingested is assumed to be contaminated.

7.4.2. IPSN-CEPN study

IPSN-CEPN used the POSEIDON code [21, 22] to estimate the 'maximally exposed individual doses' that might result if 1 kg of plutonium powder containing about 4×10^{14} Bq of Pu nuclides and Am-241 was released into the western English Channel during a shipping accident. The compartment model implemented in the POSEIDON code models flows between well-mixed compartments and within each compartment adsorption and scavenging of radionuclides by sediments, sediment resuspension, dissolution of adsorbed radionuclides, and entry of radionuclides into marine food chains due to uptake of contaminated water and sediments by marine plants and organisms. Consumption of contaminated marine foods is compared against a market basket for reference population groups that allows doses to be calculated for individuals in the groups who eat seafood caught only from specific ocean regions (ocean compartments). Table XXVI presents the results of these calculations using the POSEIDON code.

TABLE XXVI. CONSEQUENCES OF LOSS OF 1 KG OF PLUTONIUM INTO THE WESTERN ENGLISH CHANNEL

Exposed population		Seafood consumed (kg/a)	POISEDON compartments fished	First year 'maximal(a) individual dose' (mSv/a)
Reference group	Size			
Average European	10^7	13.1	All compartments	5×10^{-5}
Average Frenchman	10^7	17.4	All compartments	2×10^{-4}
French fisherman	10^2	25.0	Western English Channel	9×10^{-4}
IAEA reference man	10	219.5	Western English Channel	8×10^{-3}

(a) Maximal here means that all seafood ingested is assumed to be contaminated. Market basket values reflect critical groups in all areas of the world according to current known dietary habits.

7.4.3. Sandia study

SNL used the MARINRAD code to estimate the ingestion doses that might result from the loss into the ocean of a TN-12 irradiated nuclear fuel flask while traversing the Grand Banks fishing region. The MARINRAD code models transport of radionuclides between ocean compartments by ocean currents, deposition of radionuclides onto compartment sediments, uptake of radionuclides from these sediments and/or ingestion of suspended radionuclides by seaweed, plankton, crustaceans, molluscs, and larval fish, bioaccumulation of radioactivity due to predation in marine food chains, and radiological exposures caused by ingestion of marine foods and desalinized sea water, inhalation of seas pray, swimming in contaminated sea water, and exposure to contaminated sediments.

The calculation assumed that the ship collision caused the TN-12 flask to be lost into the sea and that the entire flask inventory was released into ocean waters over time periods ranging from 3 to 300 years. The results of the calculation indicate that radiological exposures are largely determined by the ingestion pathway and were largest for individuals who consumed seafood taken exclusively from the Top Labrador compartment of the 19-compartment ocean model, the compartment that contains the Grand Banks. Near-term yearly individual doses for individuals who consumed seafood harvested exclusively from this compartment increase as the radionuclide release time decreases. When release takes place over three years, yearly individual doses reach a maximum value of about 18 mSv/a five years after the sinking of the RAM transport ship and then fall to 10 mSv/a 100 years after the sinking. When release takes place over 300 years, average yearly individual doses throughout the first 100 years are about 0.4 mSv/a.

7.5. Discussion

The illustrative consequence calculations described above are quite conservative. The MACCS and RADTRAN calculations are conservative for at least three reasons: first, because the likely result of deep penetration into the RAM hold by the bow of a striking ship is not flask failure but instead is the pushing of the ‘unfailed’ flask through the far shell of the ship into the ocean which would mean that radioactivity would be released into the oceans rather than to the atmosphere as was assumed for these accident analyses; second because, at least for port accidents and probably for coastal accidents near a developed coastlines, fire fighting equipment would be deployed to fight the ship fire and thus the enhanced atmospheric release hypothesized for the fire accident would either not occur or would be substantially decreased; and third because recovery of a flask lost into a harbour channel or into the ocean at a distance of a few tens of kilometres from shore would be routine and would normally be accomplished long before any significant release of radioactivity would take place.

Similarly, for the reasons set forth below, the individual yearly doses estimated for loss of Type B packages into the ocean are also very conservative. They are conservative for irradiated nuclear fuel because CRIEPI studies [35] show that the flask failure does not occur when submergence depths are less than 3000 m after loss of the flask into the ocean. Thus, flask and rod failure will usually have to occur by corrosion. But an ISPN review [36] of steel corrosion rates in sea water suggests that perforation failure of Type B packages is likely to take at least several years if not several decades. Thus, the rapid release of radioactivity assumed in the SNL ocean loss calculations leads to a substantial overestimate of release rate and thus also of the concentrations of radioactivity in marine foods. Moreover, given modern deep ocean salvage capabilities, flask recovery is likely before these flask failure time periods are exceeded. But mainly, the individual yearly doses estimated are conservative because contaminated seafood reaches individuals in the general population through the commercial food distribution system, which means that the individual doses caused by consumption of this contaminated seafood will always be substantially smaller than the 'maximally exposed individual doses' estimated by the ISPN, SNL, and CRIEPI calculations. Thus, the real ingestion doses that might be received by members of the general public following the loss of a Type B package into the ocean will always be very small, much smaller than normal background radiation exposures, and thus of little significance.

In conclusion, even if these conservative assumptions are ignored, the illustrative consequence calculations described in this section have one result in common. They all predict doses that are very small when compared to the average annual dose normally incurred by individuals due to exposure to natural (e.g. cosmic rays, radon, terrestrial radionuclides) or routine man-made sources of radiation (e.g. medical X rays). Thus, these illustrative calculations suggest that the radiological consequences that might result, if a ship transporting a Type B package were involved in a severe maritime accident, are not of great concern.

8. DISCUSSION

8.1. Background

This IAEA Co-ordinated Research Project (CRP) has re-examined the safety of shipping large quantities of packaged radioactive material by sea. First, the frequencies of ship fires, ship collisions, and ship collisions that initiate fires were developed from maritime casualty data. Because these data provided little information about the severity of the collisions and fires, the chance that such events could subject a radioactive material package to conditions that might cause it to fail was examined. Finally, given that flask failure is assumed, the amount of radioactive material that might be released from the flask, its rate of release, and the radiological consequences that might result were estimated for several hypothetical accidents.

Because highly radioactive material, such as spent power reactor fuel and vitrified high level wastes (VHLW), are only transported in very strong, thick walled, heavily shielded flasks called Type B packages, only extremely severe accidents have any chance of subjecting such packages to conditions that might cause the packages to fail and allow radioactive material to escape and enter the environment (the atmosphere or the ocean). The possibility of flask failure during ship fires was examined by performing shipboard fire tests, by modelling those tests and by using the test and modelling results to estimate the likelihood of ship fires severe enough to cause the failure of an irradiated nuclear fuel or VHLW Type B package. The possibility of flask failure during ship collisions was examined by performing finite element calculations which estimated the magnitude of the forces that might be applied to a Type B irradiated nuclear fuel package or a VHLW package during ship collisions. These ship collision forces were then compared to the forces that characterize the regulatory tests that the package must survive in order to be certified for transport.

The radiological consequences were estimated for several hypothetical ship accidents involving radioactive material cargo. The calculations considered accidents that were assumed to lead to the loss into the ocean of Type B packages carrying irradiated nuclear fuel, VHLW, and plutonium as well as accidents that were assumed to cause fission products in spent power reactor fuel to be released into the atmosphere. Release of radioactive material into the ocean and its incorporation into marine food chains was considered for accidents that occur in coastal waters and in the open ocean. Release of fission products from irradiated nuclear fuel to the atmosphere was estimated for two accident locations, in a port and while sailing a coastal route, and for two types of accidents, a severe ship collision that does not initiate a fire and one that does.

8.2. Regulations

The shipment of highly radioactive material (irradiated nuclear fuel, VHLW, plutonium) is very carefully regulated. The IAEA transport regulations provide the bases for consistent international modal and national regulations governing package design, certification, marking, labelling, placarding, and stowage, for contents that can be carried in different types of packages. Other IAEA documents address physical protection and radiation safety measures. The IMO's International Materials Dangerous Goods (IMDG) code establishes standards for the safe stowage, handling and segregation of radioactive material on ships. The IMO's Irradiated Nuclear Fuel (INF) code specifies requirements for three classes of ships (INF Class 1, 2, and 3 ships) that carry irradiated nuclear fuel, high level waste, and plutonium in packages and the amounts of radioactive material that can be carried by each class of ship. The specifications cover ship damage stability, electrical systems, fire protection, cargo stowage, cargo space temperatures, radiological protection equipment, emergency planning, and crew training. INF Class 1 ships can carry radioactive material that contain at most 4×10^3 TBq of radioactivity. Because of their increased requirements for damage stability, fire protection, and electrical supply, INF Class 2 ships can carry material that contain in aggregate as much as 2×10^6 TBq of radioactivity and up to 2×10^5 TBq of plutonium. Larger quantities of radioactive material or plutonium can only be transported on INF Class 3 ships. Existing INF Class 3 ships have double hulls and redundant propulsion, fire protection, and navigation systems, and ship's officers certified for at least one position higher than the position in which they serve.

8.3. Packages

The Type B packages used to transport irradiated nuclear fuel or VHLW typically weigh about 10–20 tonnes if designed for transport by truck or 100 tons if designed for transport by rail. The bodies of these flasks are usually sandwich structures consisting of outer and inner steel shells which encase a thick layer of lead or depleted uranium that functions as a radiation shield. The thick lid of the flask is secured to the flask body by an array of bolts. Lid sealing is provided by elastomer and/or metallic O-ring seals that are set deep within the lid well. Although metal seals are failed by small deformations of the seal region, they retain their sealing function when exposed to the high temperature fires. Conversely, elastomer seals fail if heated to about 400°C but lose sealing function during collisions only if the flask seal region is significantly distorted by very large impact or crush forces.

8.4. Ship accidents

Lloyd's ship casualty data divides ship accidents into the following categories: collision, contact, foundered, wrecked/stranded, fire/explosion, and missing, where contact means striking of the sea bottom or a fixed object, foundered means sunk due to heavy weather, springing of leaks, or breaking apart, and wrecked/stranded means beached on the sea bottom, a sand bank, the seashore, or an underwater wreck. Because ships have double bottoms and a bow compartment in front of the first ship hold, contact accidents cannot damage a RAM flask, although they may cause the ship to founder or to become wrecked or stranded, which might lead to the loss of the flask into the ocean if the ship breaks up or sinks. Thus, only severe ship collisions or ship fires can directly cause the failure of a Type B irradiated nuclear fuel or VHLW flask.

8.5. Ship collision and ship fire frequencies

Per year of sailing, ship collisions frequencies range from about 4×10^{-2} for collisions of any severity to about 4×10^{-4} for collisions that lead to total loss of the ship. Since a typical ship sails about 60 000 nmi/a, this means that the chance of any collision is about 7×10^{-7} per nmi sailed, a result in good agreement with ship collision frequencies per nmi developed for specific ocean regions which range from 7×10^{-9} in the open ocean to 2×10^{-6} in the most heavily sailed regions of the world's oceans, about 2×10^{-7} per nmi sailed in general coastal waters and 4×10^{-5} per port call for collisions in ports, irrespective of port traffic density. Thus, for a 1000 nmi voyage from a departure port across open ocean to a destination port, the chance of a collision is about $4 \times 10^{-5} + 100\ (2 \times 10^{-7}) + 900\ (7 \times 10^{-9}) \sim= 1 \times 10^{-4}$, where the first term represents the chance of a collision while leaving the departure port and entering the destination port, the second term represents the chance of a collision while sailing out to or back from the open ocean through coastal waters, and the third term represents the chance of a collision while traversing the 900 nmi of open ocean that separates the two ports. This simple analysis shows that for a typical voyage, the chance of a collision is about equal while sailing in port, through coastal waters, and in the open ocean.

Per year of sailing, ship fire frequencies range from 10^{-2} for fires of any severity to 2×10^{-3} for fires that start in or spread to cargo holds to 8×10^{-4} for fires that lead to the total loss of the ship. Given that a typical ship sails 60 000 nmi per year, the frequency of fires that lead to the total loss of the ship is about 10^{-8} per nmi, The frequency of fires of any severity is about 2×10^{-7} per nmi which agrees well with the value of 10^{-7} per nmi sailed developed by examination of fire data by sailing region. The examination showed that fire frequencies depend very little on sailing region or traffic density and found that port fire frequencies were about 5×10^{-5} per port call.

Thus, for a 1000 nmi voyage from a departure port across open ocean to a destination port, the chance of a fire of any type is about $2\ (5 \times 10^{-5}) + 1000\ (2 \times 10^{-7}) = 3 \times 10^{-4}$ where the first term represents the chance of a fire while leaving the departure port and entering the destination port, and the second term represents the chance of a fire while sailing out to or back from the open ocean through coastal waters and while traversing the open ocean that separates the two ports.

8.6. Ship collision and ship fire severity

Because of their massive and robust designs, Type B irradiated nuclear fuel and VHLW packages can fail only as a result of unusually severe collisions or fires. Since the casualty data provide little information about accident severity, estimates of the fraction of all collisions or fires that are severe enough to compromise the integrity of a Type B package were developed by modelling ship collisions using Minorsky's correlation and finite element methods and by performing shipboard fire tests, modelling those tests, and developing a simple bulkhead fire spread model and a probabilistic multi-hold fire spread model.

Revalidation and extension of Minorsky's correlation of collision penetration depth with collision energy allowed an estimate to be made of the fraction of all collisions that are severe enough to allow the bow of the striking ship to penetrate a hold to the location where a RAM flask would normally be stowed. For moderately large break-bulk freighters carrying other cargo in addition to the RAM flask, given that the RAM hold has been struck, the chance that the striking ship bow will overrun or compress cargo around the flask thus subjecting the flask to impact or crush forces is about 0.25 to 0.5 per collision, and for smaller freighters chartered to carry only the RAM flask the chance is smaller, about 0.15 per collision, because more of the collision energy is spent pushing a small ship sideways through the water than a large ship.

If the bow of the striking ship overruns or compresses cargo around the flask, impact or crush forces will be applied to the flask. Whether the flask fails depends on how those forces are relieved. Relief of impact or crush forces was examined by finite element calculations that divided the flask and the hull, decks, and bulkheads of the striking and struck ships into many small regions and then modelled the displacement and deformation of these regions due to the applied forces. These calculations showed that the largest crush force that might be applied to a RAM flask during a collision is comparable to the inertial forces experienced by RAM flasks during the regulatory impact test. They also showed that if impact or crush forces are applied to the flask, the forces will be relieved by compression of cargo behind the flask, if other cargo is present in the RAM hold, or by collapse of ship structures after the flask is pushed up against the far hull of the ship or a ship bulkhead. The forces will be relieved by cargo compression and ultimately by collapse of ship structures because the massive and robust nature of flask designs means that RAM flasks are much harder to deform than cargo or ship structures. Because flask structures are so difficult to deform, the probable outcome of severe ship collisions where the RAM hold is struck and deeply penetrated is the pushing of the flask across the struck hold and out through the far hull into the ocean, probably without compromising the integrity of the flask.

For a flask to fail during a ship collision, it must be caught between the bow of the striking ship and some set of structures in the struck ship that are stronger than the flask and thus able to function as a barrier that hinders the flask from being pushed through the far hull of the RAM hold into the sea. The finite element calculations performed for this study never predicted that collapsing ship structures would form a barrier that would prevent the flask from being pushed out of the hold into the ocean and thus allow the flask to be crushed, thereby causing the flask seal to fail. Despite this outcome, the probability of flask crush was qualitatively and conservatively estimated to occur no more frequently than once in every one hundred collisions ($<10^{-2}$) given that crush or impact forces have been applied to the flask. And given that flask crush and seal failure have occurred, the chance that the collision would also lead to a second flask failure by puncture or shearing of the flask body by, for example, a beam torn from some collapsing ship structure, was estimated to be no larger than once in every ten collisions ($<10^{-1}$).

Performance of shipboard fire tests, that did not engulf the test hold and modelling of those tests using a fluid dynamics fire code showed (a) that heat transfer to the flask and to hold bulkheads was dominated by radiation, and (b) that the fire heat fluxes were generally smaller than those developed by the regulatory flask certification fire test. Modelling of fire-spread through a bulkhead by radiative heat transfer to the bulkhead and from the bulkhead to highly combustible cargo in the next hold suggested that small fires located close to a bulkhead can ignite combustible cargo located not far from the other side of the bulkhead. This suggests that some fires on cargo ships (break-bulk freighters and container ships) may creep through holds and from hold to hold. This means that, if ship fires are not extinguished by fire fighting, they may burn for lengthy periods of time even though they are not likely to burn at very high temperatures or for very long periods of time in any one location.

Thus, even if a ship fire reaches the hold where the RAM flask is stowed, it is unlikely to cause the flask to fail and significant quantities of radioactive material to be released from its contents, as only a hot, prolonged fire can heat an object as massive as a Type B irradiated nuclear fuel or VHLW flask to temperatures which not only cause the flask seal to fail but also the irradiated nuclear fuel rods to fail by burst rupture. Furthermore, only a fire fuelled by a large amount of a material that burns with an unusually high flame temperature (considerably greater than 1000°C) can raise the temperature of a VHLW flask and of the glass matrix of the vitrified wastes being carried in the flask to temperatures where the matrix glass might soften or melt, thereby allowing fission products to escape by vaporization from the glass matrix.

Finally, the chance that a ship fire that starts at a random location on the ship while docked in a port with hold covers removed will spread to the RAM hold and there burn at sufficiently high temperatures and long enough to cause the RAM flask to fail and radioactive material to be released was calculated using conservative estimates for the probability that the ship holds contain significant quantities of combustible materials to support fire spread and that the fire is not oxygen starved or extinguished by the operation of shipboard fire suppression systems. Although quite approximate, this analysis suggests that, given that a fire has started, the probability of a fire spreading to the RAM hold and there burning at sufficiently high temperatures and long enough to lead a Type B irradiated nuclear fuel or VHLW flask to fail is of order 10^{-3} for both medium sized break-bulk freighters carrying other cargo and for smaller break-bulk freighters chartered to carry only a RAM flask. Accordingly, for a purpose-built ship which carries no combustible cargo and is equipped with redundant fire suppression systems, given that a fire has started, its chance of spreading to the RAM hold should be even smaller, certainly less than 10^{-4}, an estimate that is consistent with a much more detailed estimate of 10^{-5} for the chance that an engine room fire on a purpose-built ship will spread to a RAM hold.

8.7. Severe accident probabilities

The reviews of casualty data and the modelling of ship collisions and ship fires allows estimates of event probabilities to be made for the events that enter severe ship accident scenarios. Table XXVII lists these events and their probabilities of occurrence for a small break-bulk freighter chartered to carry only the RAM flask.

The data in this table allow estimates to be made for two severe accidents, a collision that leads to the sinking of the struck ship, and a collision that causes a double failure of the RAM flask and also initiates a severe fire that spreads to the RAM hold and there burns at sufficiently high temperatures and long enough to enhance the release of fission products from an irradiated nuclear fuel flask. For a 1000 nmi voyage, the values from Table XXVII can be used to show that the probability of these two accidents are respectively approximately 4×10^{-7} and 4×10^{-14} respectively for a collision followed by a sinking and for a collision with a release of radioactive material. Thus, for a voyage of about two thousand nautical miles, the probability that a collision will lead to a sinking and the loss of a RAM flask into the ocean is of order 10^{-6}; and the probability that a severe collision will lead to a double flask failure, uneven heating of the flask by a severe fire, burst rupture of irradiated nuclear fuel rods, and release to the atmosphere of all fission products released to the flask interior by rod failure due to a buoyant flow of combustion gases through the flask is in the order of 10^{-13}.

TABLE XXVII. SEVERE SHIP ACCIDENT EVENT PROBABILITIES

Event	Probability	Value
A ship collision occurs while making a 1000 nmi voyage	$P_{collision}$	1×10^{-4}
The RAM ship is the struck ship	$P_{RAM\ ship\ struck}$	0.5
The strike location is midship	$P_{strike/midship}$	0.33
The RAM flask location is midship	$P_{flask/midship}$	1.0
Crush forces are applied to the flask	$P_{crush\ forces}$	0.15
Flask crush causes the flask seal to fail	P_{crush}	$<10^{-2}$
Flask puncture or shear occurs	$P_{puncture/shear}$	$<10^{-1}$
The collision initiates a fire	$P_{fire\ start/collision}$	0.016
The fire spreads to the RAM hold	$P_{fire\ spread}$	$\sim 10^{-3}$
The ship sinks	P_{sink}	3.6×10^{-3}

The data in this table allow estimates to be made for two severe accidents, a collision that leads to the sinking of the struck ship, and a collision that causes a double failure of the RAM flask and also initiates a severe fire that spreads to the RAM hold and there burns at sufficiently high temperatures and long enough to enhance the release of fission products from an irradiated nuclear fuel flask. For a 1000 nmi voyage, the values from Table XXVII can be used to show that the probability of these two accidents are respectively approximately 4×10^{-7} and 4×10^{-14} respectively for a collision followed by a sinking and for a collision with a release of radioactive material. Thus, for a voyage of about two thousand nautical miles, the probability that a collision will lead to a sinking and the loss of a RAM flask into the ocean is of order 10^{-6}; and the probability that a severe collision will lead to a double flask failure, uneven heating of the flask by a severe fire, burst rupture of irradiated nuclear fuel rods, and release to the atmosphere of all fission products released to the flask interior by rod failure due to a buoyant flow of combustion gases through the flask is in the order of 10^{-13}.

8.8. Consequences

The doses to a maximally exposed individual that might be caused by the loss of a flask into the ocean in shallow water and into the deep ocean were estimated by CRIEPI to range from 5×10^{-9} mSv/a for loss of a VHLW flask into the deep ocean to 2×10^{-3} mSv/a for loss of a high burn-up irradiated nuclear fuel flask into shallow coastal waters. Release of fission products to the atmosphere due to a severe collision that leads to a double failure of a irradiated nuclear fuel flask and the spreading of a severe fire to the RAM hold was estimated to cause average individual doses among the exposed population of about 0.5 mSv per year for an accident during a call at a major port and about 0.2 mSv/a for people living in urban areas along a coastal sailing route. Since these doses are small compared to normal background radiation doses, which are typically a few mSv/a, even an unusually long epidemiological study of a large portion of the exposed population would not be expected to detect any radiological consequences attributable to these population exposures. Therefore, since these accidental exposures augment background doses negligibly and are also quite improbable, accidents during the maritime transport of RAM in Type B irradiated nuclear fuel or VHLW packages would seem to be of little concern.

8.9. Technical conclusions

Given the preceding, the principal technical conclusions of this CRP are:

Ship collisions depend on ship traffic density and thus on the region of the ocean in which a ship is sailing. Traffic density does not affect the frequency of ship fires. Instead the chance of a fire during a voyage increases directly with voyage distance or sailing time.

Ship collisions and ship fires are infrequent events; most ship collisions and ship fires will not subject a RAM transport package being transported on the ship to any mechanical or thermal loads; the chance that a ship collision or a ship fire will subject a RAM transport package to loads that might cause the package to fail is very small.

If a ship collision subjects a RAM flask to crush forces, the magnitude of these forces will be less than or at most comparable to the inertial forces experienced by the flask during the regulatory certification impact test.

Ship collisions are unlikely to damage a RAM flask, because collision forces will be relieved by collapse of ship structures, not flask structures.

Ship fires are not likely to start in the RAM hold. If a fire starts elsewhere on the ship, its spread to the RAM hold is not likely. Even if a fire spreads to the RAM hold, lack of fuel or air will usually prevent the fire from burning at sufficiently high temperatures and long enough in the RAM hold to cause the release of radioactive material from a RAM flask or, given flask failure due to a preceding collision, to significantly increase the release of radioactive material from the failed flask.

Heat fluxes from small creeping fires that do not engulf the RAM hold are unlikely to exceed the heat fluxes developed by the regulatory flask certification test fire.

Most radioactive material released to the interior of a RAM flask as a result of an accident will deposit on interior flask surfaces; so flask retention fractions are large and flask-to-environment release fractions are small.

Should a ship collision or fire lead to the sinking of a RAM transport ship and thus to the loss of a RAM flask into the ocean, recovery of the flask is likely if loss occurs on the continental shelf. If, however, the flask is not recovered, the rate of release of radioactive material from the flask into ocean waters will be so slow that the radiation doses received by people who consume marine foods contaminated as a result of the accident will be negligible compared to background doses.

If a RAM transport ship, while in port or sailing in coastal waters, is involved in a severe collision that initiates a severe fire, the largest amounts of radioactive material that might be released to the atmosphere as a result of the accident would cause individual radiation exposures well below background.

Consequently, since the probabilities of severe ship collisions and severe ship fires are small and the individual radiation doses that might result should such a collision or fire occur are smaller than normal background doses, the risks of maritime transport in Type B packages of highly radioactive material such as irradiated nuclear fuel, vitrified high level waste and plutonium are very small.

9. CONCLUDING REMARKS

In the autumn of 1994, in response to concerns expressed by some Member States and non-governmental organizations and as advised by SAGSTRAM, the IAEA initiated a Co-ordinated Research Project (CRP) to examine the severity of the ship accidents that might occur during the maritime transport of highly radioactive material (RAM), such as irradiated nuclear fuel and vitrified high level wastes. The CRP was to assess the frequencies of severe maritime accidents, estimate the mechanical and thermal loads that a RAM package might experience as a result of a severe ship accident, and compare those loads to the loads that RAM packages must survive during regulatory certification tests. Where review of the literature showed information to be lacking, it was to be developed by modelling or the conduct of experiments.

As this report, its annexes, and the reports that underlie the annexes show, review of maritime casualty data allowed estimates of the frequencies of severe ship collisions and ship fires and of ship collisions and fires of any severity to be developed per nautical mile sailed and per year of sailing; modelling of ship collisions developed a way to estimate the likelihood of deep hold penetration during severe ship collisions and concluded that should crush forces be applied to a flask due to deep hold penetration, the forces would be relieved by collapse of ship structures rather than flask structures. The conduct of shipboard fire tests, the modelling of these tests, and the use of the modelling results to develop models of fire propagation on ships showed that fire spreading to a RAM hold is not likely and that if a fire should spread to a RAM hold, it is unlikely to burn at a sufficiently temperature or long enough in that hold to cause or enhance the release of radioactive material from a RAM Type-B flask. Finally, illustrative consequence analyses indicated that neither the loss of a flask into the ocean nor the release of radioactive material to the atmosphere as the result of a severe ship collision that initiates a severe fire are likely to subject exposed individuals to radiation doses that are significant by comparison to normal background doses. Thus, the CRP concluded that the risks of transporting RAM, for example irradiated nuclear fuel and VHLW, in Type-B packages, are very small.

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ANNEXES 1–7

Annex 1

STATISTICAL ANALYSIS OF ACCIDENT DATA ASSOCIATED WITH SEA TRANSPORT (DATA FROM 1994–1997)

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Abstract

This analysis is based on Lloyd's database concerning sea transport accidents for the 1994–1997 period and completes the previous analysis based on 1994 data. It gives an accurate description of the world fleet and the most severe ship accidents (total losses), as well as the frequencies of accident (in average on the 1994–1997 period the frequency of accident for cargo carrying ships is $2.57 \cdot 10^{-3}$ loss /ship.year). Furthermore, an analysis has been performed on the ship casualties recorded by the Marine Accident Investigation Branch (MAIB) for UK vessels for the 1990–1996 period, this database including all accidents for which a declaration has been made to authorities (for example, the average frequency of fires derived from this analysis is $1.36 \cdot 10^{-2}$ per ship.year, this occurrence corresponding to the occurrence of initiating events of fire). Concerning fire accidents aboard ships supposed to be representative of the radioactive material transporters, a specific analysis was achieved by the French Bureau Veritas, on a selection of the world casualties (total losses) for the 1978–1988 period. This analysis related to the origin of the fire points out that it originates mainly in the machinery room and quarters. In a few cases the fire duration recorded is more than one day.

1. SCOPE OF THE STUDY AND REFERENCE DATABASES

The aim of this study is to provide a statistical analysis of sea transport accidents for the period 1994–1997. A detailed analysis has been performed for the Lloyd database (world fleet and records of the ship casualties). The accidents considered in this first analysis concern those leading to severe damages to the ship inducing a total loss. Although the severity of the accident maybe discussed as far as it is defined from the insurance point of view, it is interesting to analyse the different characteristics of the accident collected in the Lloyd database as well as the main factors influencing the occurrence of the accident.

A second analysis has been performed on the ship casualties recorded by the Marine Accident Investigation Branch (MAIB) for UK vessels. This analysis is limited to the frequencies of collision and of fire for the 1990–1996 period. It should be noted that this second database is not limited to total loss but to accidents for which a declaration has been made to authorities. Thus, the frequencies derived from this second analysis should be useful for determining the occurrence of initiating events in the perspective of performing a probabilistic safety analysis.

In addition, an analysis using fire accident databases provided by the French Bureau Veritas is presented. This analysis is based on fire accidents aboard ships supposed to be representative of the radioactive material transporters on a selection of the world casualties (total losses) for the 1978–1988 period.

2. ANALYSIS OF THE LLOYD DATABASE

2.1. Structure of the world fleet and activity

The most recent data analysed are related to the 1994–1997 period [1]. This register only considers the sea going merchant ships of 100 gross tonnage (GT)[1] or more. Nevertheless, it should be noted that this selection reflects the general transport and does not take into account the specific requirements for radioactive material which increase the level of safety.

For this analysis, the classification adopted of the merchant ships refers to the Lloyd's register and is presented in annex 1, including the regrouping used in this document. For the 1994–1997 period, an average value of 44354 ships were registered for the category "cargo carrying ships" (which is more representative of ships transporting radioactive material), corresponding to 473.5 million GT and 730 dead weight ton (DWT)[2]. The total number of ships is multiplied about by a factor 2 if ships of miscellaneous activities (fish ships, offshore, towing...) are considered. Table 1 presents the evolution for this period.

Within the category "cargo carrying ships", the sub category "general cargo" appears to be one of the most representative class of ship for the transport of radioactive material. This category is also interesting because it excludes the transport of oil and gas, for example, which are not relevant in itself for the scope of the study, especially when dealing with fire conditions. The distribution, according to the numbers of the main types of ships, is presented in Table 2.

Table 3 presents the age distribution of the general cargo carrying ships, the average age for this category being 18 years.

2.2. Analysis of the Lloyd ship accidents database

The accidents reported in the Lloyd's Register of shipping refer to total losses of propelled sea-going merchant ships of not less than 100 GT [2]. The term "total losses" corresponds to ships which, "as a result of being a marine casualty, have ceased to exist, either by virtue of the fact that the ships are irrecoverable or have subsequently been broken up". Although the objective of these statistics is dealing with insurance, this definition of accident is relevant for the analysis of the risks the most severe associated with the transport of radioactive material. In this perspective, it should be necessary to include the degree of severity of the accident, associated with each category of accident, in order to identify the constraints withstood by the material transported.

For the 1994–1997 period, 456 accidents with total losses were recorded within the category "cargo carrying ship", leading to an annual frequency of accident of 2.6 10^{-3} loss/ship.year. Table 4 provides the variations observed on the period.

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[1] Gross tonnage is a ship capacity unit, 1 GT = 100 cubic feet = 2,83 m^3.

[2] Dead Weight Ton represents the maximum weight expressed in tons a ship is allowed to carry.

Table 1. Evolution of the cargo carrying ships for the period 1994–1997

	1994	1995	1996	1997	1994–1997 Average
Number of ships	42689	43802	45097	45830	44354
Capacity (millions GT)	451	465	482	496,5	473.5
Dead Weight Ton (millions tons)	704	718	740	757,8	730

Table 2. Distribution within the category of cargo carrying ships 1994–1997

	1994		1995		1996		1997		1994–1997	
	Number Ship.a	%	Number Ship.a	%	Number Ship.a	%	Number Ship.a	%	Number Ship.a	%
Liquefied gas	948	2,2	985	2,2	1034	2,3	1045	2,3	4012	2,3
Chemical	2018	4,7	2077	4,7	2187	4,8	2260	4,9	8542	4,8
Oil	6639	15,6	6761	15,4	6878	15,3	6933	15,1	27211	15,3
Other liquids	302	0,7	315	0,7	321	0,7	347	0,8	1285	0,7
Bulk dry *	6164	14,4	6382	14,6	6657	14,8	6811	14,9	26014	14,7
General cargo	16843	39	17180	39,2	17511	38,8	17467	38,1	69001	38,9
Passenger/general cargo	365	0,9	351	0,8	346	0,8	342	0,7	1404	0,8
Container	1603	3,8	1763	4,0	1949	4,3	2187	4,8	7502	4,2
Refrigerated cargo	1537	3,6	1446	3,3	1441	3,2	1443	3,1	5867	3,3
Ro-ro cargo	1655	3,9	1673	3,8	1711	3,8	1742	3,8	6781	3,8
Passenger/ro-ro cargo	2166	5,1	2256	5,2	2342	5,2	2425	5,3	9189	5,2
Passenger	2449	5,7	2613	6,0	2720	6,0	2828	6,2	10610	6,0
Total	**42689**	100	**43802**	100	**45097**	100	**45830**	100,0	**177418**	100

* The type "Bulk dry" includes the bulk dry, the bulk dry/oil, the self-discharging bulk dry, the other bulk dry and the other dry cargo (livestock carrier, barge carrier...).

Table 3. Age distribution for general cargo carrying ships

	1994		1995		1996		1997		1994–1997	
	Number Ship.a	%	Number Ship.a	%	Number Ship.a	%	Number Ship.a	%	Number Ship.a	%
Less than 10 years	3531	21,0	3354	19,5	3458	19,7	3540	20,3	13883	20,1
10–19 years	5896	35,0	5997	34,9	5767	32,9	5189	29,7	22849	33,1
20 years or more	7416	44,0	7830	45,6	8286	47,3	8738	50,0	32270	46,8
Total	16843	100,0	17181	100,0	17511	100,0	17467	100,0	69002	100,0

Table 4. Cargo carrying ships : evolution of total losses (1994–1997)

	1994	1995	1996	1997	1994–1997
Millions GT lost	1,52	0,87	0,85	0,79	4,03
Millions Dwt lost	2,60	1,50	1,36	1,21	6,67
Number of ships lost	116	118	126	96	456
Frequency of accidents (loss per ship.a)	2,72E–03	2,69E-03	2,79E-03	2,09E-03	2,57E-03

2.2.1. Accident frequencies by category of losses

According to the definition of the Lloyd's Register, the following categories of total losses are considered (in the database, the classification is made on the first event reported):

- **Foundered**: includes ships which sank as a result of heavy weather, springing of leaks, breaking in two, etc., but not as a consequence of categories listed below
- **Missing**: after a reasonable period of time (usually 1 day to 1 week), no news having been received of a ship and its fate therefore undetermined, the ship is posted as 'missing'
- **Fire/Explosion**: includes ships lost as a result of fire/explosion, when it is the first event reported
- **Collision**: includes ships lost as a result of striking or being struck by another ship
- **Contact**: includes ships lost as a result of striking an external substance (excluding other ship or sea bottom)
- **Wrecked/Stranded**: includes ships lost as a result of touching the sea bottom, sandbank, seashore or underwater wrecks
- **Other**: includes war losses, hull/machinery damage or failure which is not attributable to any other category

According to these categories, the following figures are observed (Table 5):

Table 5. Accident frequency by category of losses

1994–1997	Number	%	Frequency (10^{-3} loss/ship.year)
Foundered	215	47,1	1.21
Missing	3	0,7	0.02
Fire/explosion	55	12,1	0.31
Collision	68	14,9	0.38
Wrecked/Stranded	90	19,7	0.51
Contact	8	1,8	0.05
Other	17	3,7	0.09
Total	**456**	**100**	**2.57**

This table reveals that the main cause of accidents is foundering, this event being observed in about half of the accidents. Furthermore, the records of the accidents point out that among the accidents for which the information on weather conditions is available, heavy weather is quite frequent (more than 2 thirds of the accidents).

Immediate loss of the ship (called actual total loss: ATL), by opposition to delay loss (ship towed out towards the harbour — called constructive total loss: CTL), is observed in 354 accidents (78%). This information is of interest in the case of the transport of radioactive material because it should have some implications in the recovery of the material. Further to this information, it could be useful to perform a complementary analysis concerning the possibilities and conditions of the recovery of the material. Table 6 presents the distribution on the period.

Table 6. Accidents by type of loss

	1994		**1995**		**1996**		**1997**		**1994–1997**	
	Number	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**
ATL	85	73,3	94	79,7	98	77,8	77	80,2	354	77,6
CTL	31	26,7	24	20,3	28	22,2	19	19,8	102	22,4
Total	116	100	118	100	126	100	96	100	456	100

ATL: actual total loss; CTL: constructive total loss.

2.2.2. Accident frequencies by type of ship

Among the different types of "cargo carrying ship", slight differences appear in the annual frequencies of accident, they range from 0.94 10^{-3} loss/ship.year for chemical ships up to 3.96 10^{-3} loss/ship.year for general cargo. These values are presented in Table 7.

Table 7. Loss frequency for different ship types (1994–1997)

Ship types	**Number**	**%**	**Frequency** (10^{-3} loss/ship type-year)
Liquefied gas transporter	8	1,8	1.99
Chemical	8	1,8	0.94
Oil tanker	36	7,9	1.32
Bulk dry carrier	65	14,3	2.5
General cargo	273	59,9	3.96
Passenger/general cargo	4	0,9	2.85
Container	9	2,0	1.2
Refrigerated cargo	18	3,9	3.07
Ro-ro cargo	12	2,6	1.77
Passenger/ro-ro cargo	11	2,4	1.2
Passenger	12	2,6	1.13
All types	**456**	**100,0**	**2.57**

Table 8. Number of accidents by ship type and loss category (1994–1997)

Type	Foundered/missing	Fire/explosion	Contact-types	Other	**Total**
Liquefied gas transporter	7	0	0	1	**8**
Chemical	3	4	1	0	**8**
Oil tanker	10	12	11	3	**36**
Bulk dry carrier	28	4	28	5	**65**
General cargo	147	18	102	6	**273**
Passenger/general cargo	2	0	2	0	**4**
Container	2	3	2	2	**9**
Refrigerated cargo	9	1	8	0	**18**
Ro-ro cargo	6	2	4	0	**12**
Passenger/ro-ro cargo	2	5	4	0	**11**
Passenger	2	6	4	0	**12**
Total	**218**	**55**	**166**	**17**	**456**

It is interesting to present the cross table between the category of accident and the type of ship involved. These data are summarised in Table 8. In this table, contact category includes collision, wrecked/stranded and contact.

It clearly appears that the fire/explosion category is really significant for oil tankers ($4.4\ 10^{-4}$ loss/ship type.year, i.e. one third of the accidents for this ship type) and chemical ships ($4.7\ 10^{-4}$ loss/ship type.year, i.e. half of the accidents of this ship type), while for the general cargo type, the main category of accidents refers to foundered/missing ($2.1\ 10^{-3}$ loss/ship type.year, i.e. more than half of the accidents of this ship type) as well as contact ($1.5\ 10^{-3}$ loss/ship type.year, i.e. more than one third of the accidents of this ship type). It should be noticed that missing is a marginal cause of total loss (only 3 events are reported for the 1994–1997 period).

2.2.3. Accident frequencies by register flag

With respect to the register flag, it is interesting to notice that the Panamean flag represents about 16% of the world losses on the 1994–1997 period for about 11% of the ships. At the opposite, Japanese flag withstands 6% of the accidents for 12.5% of the total number of ships.

2.2.4. Influence of age on accident frequencies

As the age of a ship could influence its probability of accident, it is interesting to present the distribution of accidents according to the age of the ship (Table 9).

Table 9. Influence of the age on accident number (1994–1997)

Type	0–9 years	10–19 years	20 years and more	**Total**
Liquefied gas	0	3	5	**8**
Chemical	0	4	4	**8**
Oil	2	14	20	**36**
Bulk dry	5	15	45	**65**
General cargo	14	83	176	**273**
Passenger/general cargo	0	0	4	**4**
Container	2	2	5	**9**
Refrigerated cargo	0	6	12	**18**
Ro-ro cargo	0	9	3	**12**
Passenger/ro-ro cargo	0	3	8	**11**
Passenger	1	1	10	**12**
All types	**24**	**140**	**292**	**456**
Accident	***5.3***	***30.7***	***64***	***100%***

It should be mentioned that the first age group (0–9 years) represents only 5.3 of the number of the accidents with 26.5 of the total fleet and the second one (10–19 years) represents 30.7 of the accidents for 34.7 of the total fleet while the third age group (20 years and more) contributes for 64 of the number of accidents with only 38.8 of the fleet. Furthermore, the frequency of accident expressed in 10^{-3} loss/ship.year as a function of the age is presented in Table 10.

Table 10. Influence of the age on accident frequency *(10^{-3} loss/(ship type and age cat.).year) 1994–1997*

Type	**0–9 years**	**10–19 years**	**20 years and more**
Oil	0.25	1.5	1.8
Bulk dry	0.73	1.4	6.1
General cargo	1	3.6	5.5
All types	0.53	2.3	4.4

This table reveals that the frequency of losses is broadly dependent of the ship age. The category of ships ageing less than 10 years presents a frequency of about 0.5 10^{-3} loss/ship.year, while the class 20 years or more presents a frequency of 4.4 10^{-3} loss/ship.year.

2.2.5. Distribution of the accidents according to the localisation

On the basis of the available information in the database concerning the co-ordinates of the accident (longitude and latitude), a classification has been proposed according to the distance from the coast. Nevertheless, the available information just allows to provide a qualitative classification, especially concerning the occurrence of the event in or near the harbour. Thus, the objective of this classification is to evaluate the distribution of the events distinguishing between accident occurring:

- in or close to the harbour
- at a distance lower than 100 miles from the coast
- at a distance greater than 100 miles from the coast

Table 11 presents the results of this analysis.

Table 11. Localisation of the accidents: distance from the coast (1994–1997)

Distance	Number of accidents	%	% excluding the events without information
In or close to the harbour	45	9.9	16.1
<100 miles from the coast	169	37.1	60.3
>100 miles from the coast	66	14.5	23.6
No information	176	38.5	–
TOTAL	456	100	100

(1 nautical mile = 1.852 km).

Such a classification allows to evaluate part of the difficulties associated with the recovery of the ship if an accident occurred, short distances from the coast being a priori more favourable for the recovery operations. At the opposite, the occurrence of a fire in the harbour should be potentially more dangerous for the population (in case of radioactive releases) than the same event occurring far from the coast. From this analysis, it appears that only a few events occur in (or close to) the harbour and the large majority occurs at a distance lower than 100 miles from the coast. A second aspect has to be considered for the recovery: i.e. the depth at which the ship may have foundered. Unfortunately, no information is available on this topic in the Lloyd database.

2.3. Complementary analysis of the fire and explosion of the Lloyd database

A complementary analysis limited to fire and explosion has been performed on the Lloyd database. Among the 456 accidents reported in the database for the 1994–1997 period, 55 events concern fire and/or explosion, explosion alone being limited to about 10 of the events (Table 12).

Table 12. Fire and explosion accidents registered

Year	Number of fire and/or explosion	Fire and explosion	Fire	Explosion
1994	**18**	4	11	3
1995	**14**	2	12	0
1996	**14**	2	11	1
1997	**9**	2	5	2
Total	**55**	10	39	6

Among these 55 events, 31 contain information on the assumed origin of the fire and/or explosion. This information has to be considered as indicative of the origin as far as the classification is still subjective in certain circumstances (i.e. for some events, the sequences of the accident are clearly established while for others it is more assumed origins of the accident which are reported).

On Table 13, it clearly appears that the main origin of these events (fire and/or explosion) is the engine room (assumed origin) with about 2/3 of the total number of accidents, while accommodation is the second origin with about 1/6 of the accidents. It should be kept in mind that these results depend on the available information in the database. Nevertheless, it should be noticed that for more than half of these events, the information is available.

Table 13. Origins of fire and explosion accidents registered (assumed origins)

Year	*Number of events including information*	Engine room	Tank	Accomo-dation	Switchboard	Boiler	Pump room	Hold	Galley
1994	*9*	3	2	2	1	1			
1995	*8*	6					1	1	
1996	*10*	6		3					1
1997	*4*	4							
Total	*31*	19	2	5	1	1	1	1	1

Among the accidents with fire and/or explosion, 3 events have been identified in the database for the 1994–1997 period for which a combination of accident categories appears. These accidents are the following:

1994 — Accident in the Bosphorus with collision followed by fire

This accident occurred in the Bosphorus involving an oil cargo (Nassia registered in Cyprus, built in 1976 and carrying crude oil) and a bulk dry carrier (Shipbroker registered in Cyprus and built in 1980). The sequences of the accident is as followed:

- a collision occurred between the two cargoes due to locked rudder caused by generator blackout for the Shipbroker
- then five explosions occurred on the Nassia followed by a fire on the two cargoes
- the two cargoes stranded.

They were refloated and towed off. The fire on the Nassia oil cargo was extinguished only 4 days later.

1997 — Accident in the China Sea with collision followed by fire

A collision occurred in the South China Sea between the chemical cargo (Ming Hui registered in China and built in 1980) and a merchant vessel (Soon Li Fa). In that case, a caught fire occurred after the collision.

1997 — Accident with grounding followed by fire

A refrigerated cargo (Aster, registered in Mauritius and built in 1978) stranded on rocks. The underside of hull was severely damaged and this event induced controlled explosions. The cargo was carried out to aid break up of the vessel.

3. ANALYSIS OF MAIB DATABASE

An analysis has been performed on the Marine Accident Investigation Branch (MAIB) database for the 1990–1996 period [3]. The data analysed from the MAIB database deal with UK registered ships of 100 GT or more, corresponding to about 1100 vessels each year of the period. In this database, a large number of incidents is reported as the accident criteria are slightly different from the Lloyd definition. In fact, the MAIB database includes most of the events which lead to compensation from insurance companies. Four categories of accidents can be notified:

- Loss of life or major injury
- Ship lost or materially damaged
- Ship strands or in collision
- Major injury or material damage to the environment.

According to this definition, about 100 cases are reported each year, corresponding to about 10% of the registered ships which are involved to an accident each year. Concerning the severity of the accidents, one should notice that only 8 accidents leading to a total loss were reported during the 1990–1996 period. Table 14 presents the analysis of the accident data on the 1990–1996 period for the MAIB database.

Table 14. Evolution of the accidents reported in MAIB database (1990–1996)

	1990	1991	1992	1993	1994	1995	1996	Total
Number of vessels	1446	1398	1212	1141	1103	1081	1066	8447
Number of accidents	183	140	134	124	102	93	112	888
Number of total losses	3	2	1	0	1	0	1	8
Frequency of accidents 10^{-3}/ship.a	126.6	100.1	110.6	108.7	92.5	86.0	105.1	105.1
Number of fires	37	25	21	12	10	8	2	115
Frequency of fires 10^{-3}/ship.a	25.6	17.9	17.3	10.5	9.1	7.4	1.9	13.6
Collisions	61	65	56	41	50	43	57	373
Frequency of collisions 10^{-3}/ship.a	42.2	46.5	46.2	35.9	45.3	39.8	53.5	44.2

It should be noted that the total number of vessels considered decreases regularly on this period (in 1996, the fleet represents only 73 of the existing one in 1990). Concerning the number of accidents, more than 100 events occurred per year on average on this period, the average frequency being 105.1 . 10^{-3} per ship year. Concerning the fire, a significant decrease has been observed on this period, the average frequency being 13.6 . 10^{-3} per ship year while the number of collisions is about 50 events per year, the average frequency being 44.2 . 10^{-3} per ship year.

Table 15 presents the distribution of the accidents reported in MAIB database according to the accident category for the period 1990–1996 as well as the average values estimated for this period.

Table 15. Evolution of the distribution of accidents per category reported in MAIB database (1990–1996)

Accident category	1990	1991	1992	1993	1994	1995	1996	Average
Foundered	3%	4%	4%	2%	5%	3%	3%	3%
Wrecked/stranded	13%	14%	16%	16%	7%	20%	16%	15%
Collision	33%	46%	42%	33%	49%	46%	51%	42%
Fire/explosion	20%	18%	16%	10%	10%	9%	2%	13%
Machinery damage	25%	16%	16%	28%	27%	18%	15%	21%
Bad weather	3%	1%	4%	11%	2%	3%	11%	5%
Remainder	2%	0%	2%	0%	0%	0%	3%	1%

In fact, all these values are not limited to accidents inducing total loss and a large number of accidents are reported each year. Thus, the frequencies derived from the analysis of this database may be of interest when developing a probabilistic safety analysis as the frequencies of fire and of collision can be considered as representative of initiating events of accident, independently of the severity of the accident. Such an approach has been adopted in the probabilistic safety analysis developed in the European study on the return of vitrified fuel from UK to northern Europe [4].

4. ANALYSIS OF FIRE ACCIDENTS FROM THE BUREAU VERITAS DATABASE

At the request of the French Nuclear Safety and Protection Institute (IPSN), the Bureau Veritas has performed a study to characterise the fire accidents. This study deals with fire casualties on ships supposed to be representative of the radioactive material transporters (general cargo, container, RO-RO/passenger) [5]. The selection was derived from the world casualties in the period 1978 to 1988 and corresponds to immediate total losses, delay total losses. Table 16 presents the frequencies associated with different types of ships.

Table 16. Bureau Veritas frequencies of fire [5]

Type	Number of fires (total fleet)	Average frequency (10^{-4} fire/ship type.year)
General cargo	284 (235 893)	12 [1]
Container	5 (9 407)	5.3 [2]
RO-RO/passenger	28 (42 375)	6.6 [3]
Total	317 (287 675)	11

[1] From 3.1 10^{-4} to 2.6 10^{-3} [2] From 0 to 2 10^{-3} [3] From 2.4 10^{-4} to 1.2 10^{-3}

These values are different from the frequencies derived from the Lloyd's database, but it should be noted that the period of time (1978–1988) is more ancient ant that the number of fires varies significantly from one year to the next.

Based on the analysis of ship accidents for which detailed information is available (10 to 20% of the fleet), it appears that nearly half of the accidents occurs on wharf (out of 113 accidents). Moreover, concerning the origin areas of the fire and the areas damaged which can be multiple, the fire mainly originates from the machinery room (64%), from the quarters (39%) and from the holds (8%), while it affects principally the machinery room (68%), the quarters (54%) and the holds (17%).

From the periodical survey made by the Bureau Veritas, average annual distances have been evaluated for the different ship types in order to determine the probabilities per km. As presented in Table 17, these probabilities can be reduced if the fires which can potentially harm the freight are only considered (i.e. hold or deck affected).

Table 17. Bureau Veritas probabilities per km of representative fire [5]

Type	Average annual distance (km)	Probability (fire/ship.km)	Probability (representative fire*/ship.km)
General cargo	115 000	$10.5\ 10^{-9}$	$2.7\ 10^{-9}$
Container	138 000	$3.9\ 10^{-9}$	$1.7\ 10^{-9}$
RO-RO/passenger	117 000	$5.6\ 10^{-9}$	$1.5\ 10^{-9}$

* i.e. holds affected for general cargo and RO-RO/passenger; holds or decks for container.

As the fire duration is rarely recorded, this data is available only for 20 accidents, on this selection, 35 last more than 1 day and never more than 7 days. It is important to note, that this restricted set of accidents cannot be considered as representative as far as it only concerns severe accident with fire. Furthermore, no information is available on the temperature of the fire. Nevertheless, this analysis clearly points out the existence of accidents associated with severe fires.

5. CONCLUSION

This study has been performed on the basis of Lloyd's database related to total losses and for the 1994–1997 period. From this analysis, limited to the category of cargo carrying ships of 100 GT or more, annual frequencies of total loss per ship type and per accident category were derived. For example, the average frequencies of total loss and of fire and/or explosion are: $2.57 . 10^{-3}$ loss/ship.year and $3.1 . 10^{-4}$ fire-explosion/ship.year.

An analysis of the MAIB database for the 1990–1996 period, including most of the events which lead to compensation from insurance companies, shows that the average frequencies of fire and of collision are: $1.36\ 10^{-2}$ fire/ship.year and $4.42\ 10^{-2}$ collision/ship.year. These frequencies can be considered as representative of initiating events of accident, independently of the severity.

The specific analysis achieved by the French Bureau Veritas for fire accidents inducing total loss for the 1978–1988 period points out that the fire mainly originates in the machinery room and in the quarters. In a few cases the fire duration recorded is more than one day.

REFERENCES

[1] Lloyd's Register of Shipping, World fleet statistics 1994, 1995, 1996, 1997.
[2] Lloyd's Register of Shipping, World casualty statistics 1994, 1995, 1996, 1997.
[3] MAIB (Marine Accident Investigation Branch), Annual reports 1994, 1995, 1996, Department of Transport, United Kingdom.
[4] LANGE F., et al., Evaluation of the safety of vitrified high level waste shipments from UK to continental Europe by sea, PATRAM 98, May 10–15, 1998, Vol. 3, 985–995.
[5] BAUDIN M., PARMENTIER G., Constitution d'une banque de données sur les incendies à bord des navires, Bureau Véritas, Mars 1990.

ANNEX. Lloyd's classification of merchant ships

<table>
<tr><th>SHIPTYPES</th><th>BASIC GROUPINGS</th><th></th><th></th><th></th></tr>
<tr><td>Liquefied gas tanker
Liquefied gas/Chemical tanker</td><td>Liquefied gas</td><td rowspan="4">BULK LIQUID CARGO</td><td rowspan="16">CARGO CARRYING SHIPS</td><td rowspan="27">SHIP STRUCTURES</td></tr>
<tr><td>Chemical tanker
Chemical/Oil tanker</td><td>Chemical</td></tr>
<tr><td>Oil tanker</td><td>Oil</td></tr>
<tr><td>Molasses tanker
Fruit juice tanker
Water tanker
etc..</td><td>Other liquids</td></tr>
<tr><td>Bulk carrier
Ore carrier</td><td>Bulk dry</td><td rowspan="4">BULK DRY CARGO</td></tr>
<tr><td>Bulk/Oil carrier
Ore/Oil carrier</td><td>Bulk dry/Oil</td></tr>
<tr><td>Self-discharging bulk carrier</td><td>Self-discharging bulk dry</td></tr>
<tr><td>Cement carrier
Wood chips carrier
Urea carrier
etc..</td><td>Other bulk dry</td></tr>
<tr><td>General cargo ship
Palletised cargo ship
Deck cargo ship</td><td>General cargo</td><td rowspan="8">ALL OTHER DRY CARGO</td></tr>
<tr><td>Passenger/General cargo ship</td><td>Passenger/General cargo</td></tr>
<tr><td>Container ship</td><td>Container</td></tr>
<tr><td>Refrigerated cargo ship</td><td>Refrigerated cargo</td></tr>
<tr><td>RO_RO cargo ship
Container/RO-RO cargo ship
Vehicles carrier
Landing craft</td><td>RO-RO cargo</td></tr>
<tr><td>Passenger RO-RO cargo ship
Passenger/Landing craft</td><td>Passenger/RO-RO cargo</td></tr>
<tr><td>Passenger ship</td><td>Passenger</td></tr>
<tr><td>Livestock carrier
Barge carrier
Heavy cargo carrier
etc.</td><td>Other dry cargo</td></tr>
<tr><td>Trawler
Fishing vessel</td><td>Fish catching</td><td rowspan="2">FISHING</td><td rowspan="8">SHIPS OF MISCELLANEOUS ACTIVITIES</td></tr>
<tr><td>Fish factory ship
Fish carrier
etc.</td><td>Other fishing</td></tr>
<tr><td>Offshore supply ship</td><td>Offshore supply</td><td rowspan="2">OFFSHORE</td></tr>
<tr><td>Offshore support ship
Offshore well production ship
Drilling ship
etc.</td><td>Other offshore</td></tr>
<tr><td>Research ship</td><td>Research</td><td rowspan="4">ALL OTHER ACTIVITIES</td></tr>
<tr><td>Tug
Pusher tug</td><td>Towing/Pushing</td></tr>
<tr><td>Dredger
Hopper dredger</td><td></td></tr>
<tr><td>Motor hopper
Sludge disposal vessel
Crane ship
Cable ship
Ice-breaker
etc.</td><td>Other activities</td></tr>
<tr><td>Barges
Pontoons</td><td rowspan="2" colspan="3">Non-Propelled ships</td></tr>
<tr><td>Moored oil processing ship
Moored cement handling ship
etc.</td></tr>
<tr><td>Yacht
Sail training ship
Naval auxillary ship
etc.</td><td colspan="3">Other ships structures</td></tr>
</table>

Annex 2

EVALUATION OF THE SAFETY OF VITRIFIED HIGH LEVEL WASTE SHIPMENTS FROM THE UK TO CONTINENTAL EUROPE BY SEA

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SUMMARY

The return of vitrified high level waste arising from the reprocessing of spent nuclear fuel at Sellafield to continental Europe, e.g. Germany, will start around the end of the century. The shipment of the specific flasks will include transportation via the Irish Sea, the English Channel and the North Sea with ships of the Pacific Nuclear Transport Limited (PNTL) classified to the INF 3 standard. The assessment approach is to analyse the severity and the frequency of mechanical impacts, fires and explosions with the potential to affect the package.

The results show that there is a high safety margin due to the special safety features of the INF 3 ships compared to conventional ships. The remaining accident probability for a transport of vitrified high level waste from UK to the continent is very low. No realistic severe accident scenarios that could seriously affect the flasks and could lead to a radioactivity release have been identified.

BACKGROUND AND OBJECTIVES

It is the approach of the International Atomic Energy Agency (IAEA) Transport Regulations that the safety in the transport of radioactive materials should be provided principally by the design of the package. In 1993 the International Maritime Organisation (IMO) adopted a code for the safe carriage of irradiated nuclear fuel, plutonium and high level radioactive wastes in flasks on board ships (INF Code). This code requires higher safety standards in design and construction for ships carrying INF materials and is to be seen as an added safety measure, which additionally enhances the safety level in the sea transport of radioactive material. Ships carrying several flasks with vitrified high level waste from reprocessing plants are required to be class INF 3 ships by the code.

Vitrified high level waste arising from the reprocessing of spent nuclear fuel will be returned from the UK to continental Northern Europe towards the end of this decade. The modes of transport for these return shipments to destinations in continental Europe include transportation by sea with ships of the Pacific Nuclear Transport Limited (PNTL) classified to the INF 3 standard.

The intention of the study is to analyse the severity and the frequency of mechanical impacts, fires and explosions with the potential to affect the package. The assessment approach is to apply information on accident severities and frequencies derived from general maritime accident data and to adapt this to the much increased safety features of a specific INF 3 ship. The analysis should help to judge whether and if so at which level of probability accidents involving ships might subject packages to more severe accident conditions than the IAEA regulatory tests. The information is also intended to serve as an objective contribution to the public discussions that are anticipated as a run-up of such transports of vitrified high level waste.

The study was prepared under EC contract and is part of the Co-ordinated Research Programme on Accident Severities at Sea initiated by the IAEA.

SHIP SAFETY FEATURES

One important aspect of the study is to identify and explain the differences between ships carrying hazardous cargoes and those of INF 3 standard which are used for the transportation of high level vitrified waste. Publicly available descriptions of ship design are given in [SPI 88] and [MIL 96]. Figure 1 shows some of the safety features of the ship, especially the fire fighting systems. Nine specific areas of the ships design and operation have been identified as adding overall safety “value” to the transportation of this type of material:

- **Ship structure:** double hull; 400 tonnes additional steel; watertight longitudinal and transverse bulkheads; designed against collision with a vessel of 24 000 tonnes and 15 knots

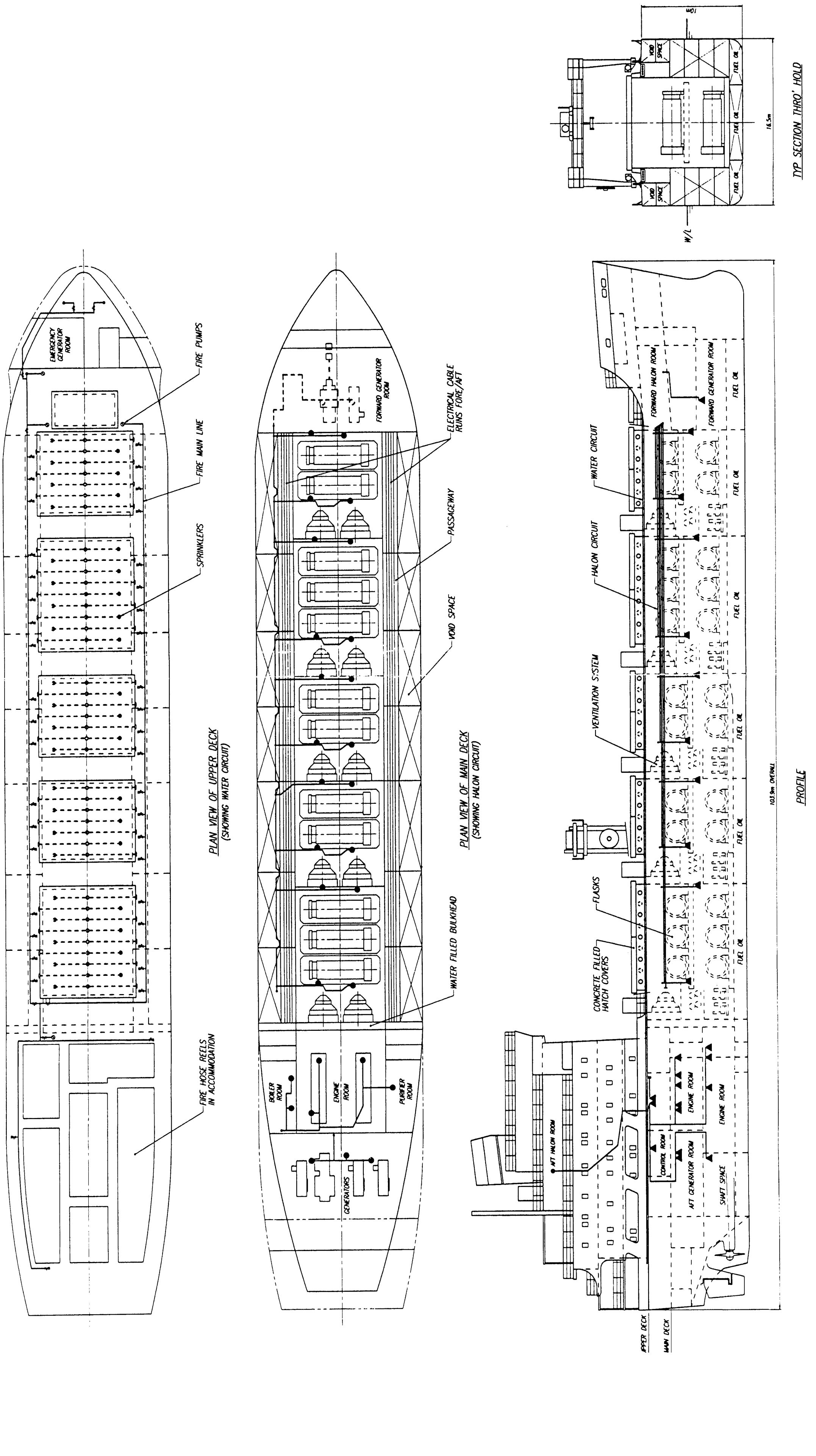
- **Propulsion systems:** duplicate diesel engines, gearboxes, propellers and a bow thruster drive system at the front of the ship

- **Power plant for electrical systems:** two independent generating systems at the front and rear of the ship; additional separate emergency generator and battery system; redundancy of power cabling along both sides of the ship

- **Fire safety:** very low fire load densities within the cargo holds and the passageways; water filled bulkhead between living accommodation/engine room and the cargo holds; watertight and fire resistant bulkhead doors along the passageways; a full multi-zone and multi-sensor fire detection system signalling to bridge and engine room; Halon extinguishing systems with supply for cargo holds, engine room, fore and aft generator rooms; fire hose reels and portable extinguishing systems within accommodation areas and machinery spaces; back up redundant sprinkler systems within each of the holds, fed from both sides of the ship's fire ring main, requires manual connection; 4 main plus 1 emergency fire pump

- **Cargoes:** the cargo of the ship consists exclusively of very heavy (50 to 100 tonne range) flasks of type B standard similar to those used for spent fuel which are mounted rigidly

- **Crew:** 26 men; higher certificates of competence for navigating and engineer officers; multi-skilling; training programmes


PLAN VIEW OF UPPER DECK
(SHOWING WATER CIRCUIT)
EMERGENCY GENERATOR ROOM
FIRE PUMPS
FIRE MAIN LINE
SPRINKLERS
FIRE HOSE REELS IN ACCOMMODATION
PLAN VIEW OF MAIN DECK
(SHOWING HALON CIRCUIT)
FORWARD GENERATOR ROOM
ELECTRICAL CABLE RUNS FORE/AFT
PASSAGEWAY
VOID SPACE
WATER FILLED BULKHEAD
BOILER ROOM
ENGINE ROOM
PURIFIER ROOM
GENERATORS
PROFILE
WATER CIRCUIT
HALON CIRCUIT
VENTILATION SYSTEM
FLASKS
CONCRETE FILLED HATCH COVERS
FORWARD HALON ROOM
FORWARD GENERATOR ROOM
FUEL OIL
AFT HALON ROOM
CONTROL ROOM
ENGINE ROOM
AFT GENERATOR ROOM
SHAFT SPACE
UPPER DECK
MAIN DECK
103.9m OVERALL
TYP SECTION THRO' HOLD
VOID SPACE
16.5m
10m
W/L

- **Communications:** multiple alternate systems such as satellite communication, telex over radio, radio telephone; automatic voyage monitoring system which transmits position, speed and heading reports to the UK control centre every two hours

- **Radar and anti-collision systems:** two independent, type approved radar systems, anti-collision system (ARPA = Auto Radar Plotting Aid)

- **Emergency preparedness:** special home based emergency team; home based tracking system; provision for emergency personnel, procedures and equipment.

OPERATING EXPERIENCE

The six ships of the PNTL fleet have been operated during the last 20 years without any significant accident. In this period

- an experience of about 90 ship years has been accumulated
- about 150 shipments have been performed
- about 4.5 million nautical miles (nm) travelled
- about 8000 tonnes of nuclear fuel transported
- about 4000 flasks (max. 5 tonnes fuel/flask) transported.

ACCIDENT STATISTICS

By employing statistical methods to statistical data without any event, an occurrence frequency (expected value) of an accident of $1.1 \cdot 10^{-7}$/nm can be derived from this experience. However the PNTL fleet specific database is not sufficient to estimate realistic probabilities of extreme accident scenarios.. An alternative method to provide a more realistic estimation of the accident probability of an INF 3 ship is to consider the accident statistics for conventional cargo ships. For this reason there are several attempts in the literature to apply the world wide experience of the large conventional transportation fleet to nuclear cargo transporting ships. The databases for these studies are taken from

- Lloyd's Register of Shipping, keeping the world fleet and casualty statistics
- Marine Accident Investigation Branch (MAIB), recording incidents and accidents to British-registered vessels
- IMO Fire Casualty Records, based on incidents reports submitted to the IMO by all member countries
- Bureau Veritas
- U.S. Coast Guard commercial vessel casualty database.

These databases differ concerning the number of ships, type of ships included in the data base, definition of accidents, number of recorded incidents, time period. The interpretation of these databases within the different studies therefore gives a wide range of probabilistic information. A summary of the most important data originating from the statistics of the conventional cargo carrying ships is given in Table 1.

Table 1: Probabilistic Data from Conventional Ships' Statistics

Type of event	Frequency Probability	Source	Remarks
Ship fire and explosion, all reported incidents	$2.6 \cdot 10^{-3}$/year per ship	[KAY 95], based on Lloyd's world-wide data 1984-93	32422 ships (oil tankers excl.); 859 incidents in 10 years
Ship fire and explosion, serious fires affecting cargo hold	$2.9 \cdot 10^{-4}$/year per ship	[KAY 95], based on Lloyd's world-wide data 1984-93	32422 ships (oil tankers excl.); 93 incidents in 10 years
Ship fire and explosion, all reported incidents on Ro-Ro ferries	$6.7 \cdot 10^{-2}$/year per ship 40% mach. room	[KAY 93], based on MAIB reports for UK Ro-Ro ferries, 1989-92	124 ships; 33 incidents in 4 years
Ship fire and explosion, with total loss	$4.2 \cdot 10^{-4}$/year per ship	[DEL 96], based on Lloyd's world-wide data 1994	42689 ships (cargo); 18 incidents
Ship fire and explosion, with total loss/repair	$2.1 \cdot 10^{-3}$/year per ship; $3.5 \cdot 10^{-8}$/nm 66% mach. room	[DEL 96], based on Bureau Veritas data 1978-88	599 fires in 287675 ship-years, (cargo, container, Ro-Ro/passenger), 108156 km average annual travel distance
Ship fire and explosion, all reported incidents	$1.5 \cdot 10^{-7}$/nm; $5.4 \cdot 10^{-5}$/port call	[SPR 96], based on Lloyd's world-wide data 1979-93	2547 fire events, 975 of which occurred in ports
Ship fire and explosion, all reported incidents	$1.7 \cdot 10^{-2}$/year per ship	[MAI 95], based on registered UK merchant vessels 1990-94	105 fires in 6300 ship-years
Collision, all reported incidents	$7.6 \cdot 10^{-8}$/nm ($1.5 \cdot 10^{-7}$/nm North Sea, Channel, Irish Sea) $4.1 \cdot 10^{-5}$/port call	[SPR 96], based on Lloyd's world-wide data 1979-93	1947 collision events, 702 of which occurred in ports
Collisions and contacts, all reported incidents	$4.3 \cdot 10^{-2}$/year per ship	[MAI 95], based on registered UK merchant vessels 1990-94	273 collision events in 6300 ship-years
Collision, with total loss	$2.8 \cdot 10^{-4}$/year per ship; $4.7 \cdot 10^{-9}$/nm	[DEL 96], based on Lloyd's world-wide data 1994	42689 ships (cargo); 11 collisions (12 ships lost); 110000 km average annual distance
Collision with subsequent fire, all reported incidents	$4.2 \cdot 10^{-9}$/nm for North Sea	[SPR 96], based on Lloyd's world-wide data 1979-93	1947 collision events, 50 of which led to fire
Collision with subsequent fire, total loss	$3.5 \cdot 10^{-10}$/nm	[DEL 96], based on Lloyd's world-wide data 1985-94	9 incidents in 10 years; 42689 ships, 110000 km average annual distance
Foundering	$1.4 \cdot 10^{-3}$/year per ship; $2.4 \cdot 10^{-8}$/nm	[RAF 97], based on Lloyd's world-wide data 1994	59 incidents; 42689 ships, 110000 km average annual distance
Foundering and flooding	$3.8 \cdot 10^{-3}$/year per ship	[MAI 95], based on registered UK merchant vessels 1990-94	24 events in 6300 ship-years

Attention must be paid to the fact that the derived probabilistic data in Table 1 originate from relatively severe accidents, since only accidents leading to deaths, injuries and/or considerable commercial losses are enlisted in the casualty records. Initiating events or precursors which result in less serious consequences (e.g. in case of successful fire fighting in an early stage) will have higher frequencies than given in Table 1.

ACCIDENT RISK ANALYSIS

Regarding the above accident data based on statistics relating to conventional cargo ships, it is evident that these statistics cannot be directly applied to an INF 3 ship. There are different approaches to deal with the accident risk associated with an INF 3 ship, bearing in mind that the undesirable event is not the fire or collision accident itself but the potential resulting loads on the cargo exceeding the design criteria of the flasks. For a reference voyage from the BNFL berth at Barrow-in-Furness to a north European port with an assumed voyage length of 1000 nautical miles the probabilities and severities of the accidents which could involve the cargo have been estimated. The following types of accidents were investigated:

- **Internal Fire**

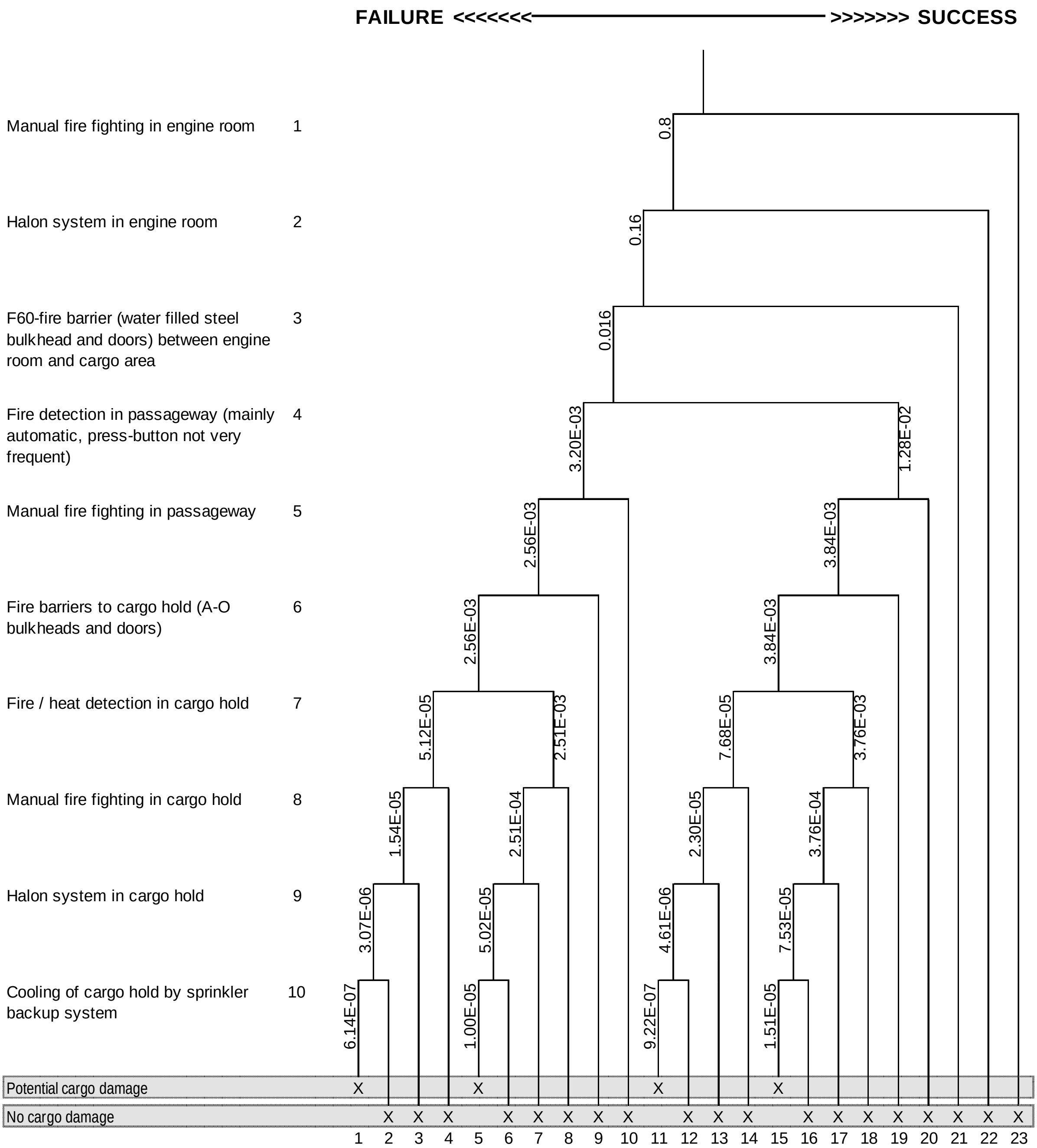
A fire analysis taking into account the particular safety features of the INF 3 ship has been performed to quantify the probability of ship internal fires which could affect the cargo. The procedure of the fire risk analysis for the PNTL ship is adopted from the fire safety analysis for nuclear power plants. From the potential fire scenarios on board a PNTL ship, the locations with the highest frequencies for initiating fires were identified following expert evaluation and take into account their severity with respect to cargo. Based on the fire loads present, considerations of event frequencies and the possibilities of fire spread to the cargo holds, main engine room fires dominate the fire risk to the cargo.

The results of the detailed analysis are summarised in the form of an event tree in Figure 2. As mentioned previously, the available accident statistics of the insurance companies include only so-called damage fires, i.e. fires which have developed from an initiating fire to a severity with relevance to the insurers. The event tree therefore starts at the top with such a damage fire inside the main engine room, for which, as a conservative estimate, an occurrence frequency of $2 \cdot 10^{-7}$/nm has been derived from the accident statistics for cargo ships in general as summarised in Table 1 [SPR 96] [MAI 95] [DEL 96]. This reveals an occurrence frequency for a fully developed main engine room fire of $2 \cdot 10^{-4}$/voyage.

This assumption of a fully developed fire - excluded an initial fire without damage - is reflected in the first level of the event tree where only a 20% probability for successful manual fire fighting is assumed. The consecutive level of the event tree refers to the success or failure of the halon system to extinguish the fire in the engine room at this stage. If unsuccessful, the next line of defence with respect to the cargo is a water filled steel bulkhead which separates the main engine room from the cargo area. Concerning all conceivable combustible fire loads in the main engine room this barrier is sufficient to prevent a fire spread to one of the passageways on both sides of the ship running along the bulkheads of the cargo holds. Only in the case that one of the fire doors leading from the main engine room to a passageway is inadvertently open - contrary to specified procedures and including surveillance from the navigation bridge - there is a possibility for fire propagating to the passageway. For this conditional probability a conservative value of 10^{-1} was chosen from the literature on fire safety analysis [FAK 97].

Figure 2: Event Tree for Engine Room Fire

Causing damage, reported to insurance companies
Cumulative conditional branch probabilities indicated



All further decision levels and the associated conditional failure probabilities are evident from Figure 2. Finally, four event sequences of the tree can result in a fire propagation to the interior of a cargo hold and have the end point "potential cargo damage" with associated conditional probabilities lower than $1.5 \cdot 10^{-5}$ for each event sequence, equivalent to of $3.0 \cdot 10^{-9}$/voyage taking into account the initial probability of $2 \cdot 10^{-4}$/voyage for a fully developed main engine room fire. This results in a summed probability of all the four branches of the event tree with the potential to affect the cargo of $5.3 \cdot 10^{-9}$ per voyage. The fire risk analysis assesses the probabilities and severities of possible fires in a cargo hold. In any case the available fire loads are small enough that the thermal threat to a large flask is negligible.

- **Collision**

In case of collision between two ships, the damage to the struck ship and its cargo is mainly influenced by:

- the speed, displacement and dimensions of the striking ship
- the shape and material properties of the striking bow
- the collision angle
- the point of impact, web frame spacing of the struck ship
- the thickness of deck, bottom and side shell plating.

The double hull of a PNTL ship is designed to withstand at least an impact energy equivalent to a 24 000 tonnes ship striking at a speed of 15 knots. It is conservatively assumed that the penetration of the cargo hold is possible if a striking ship exceeds this kinetic energy and a mechanical loading of the flask might occur. The probability of this event was evaluated to be $1.6 \cdot 10^{-7}$ per trip. The initiating collision frequency ($1.5 \cdot 10^{-4}$ per trip) can be derived from the Table 1 statistics [SPR 96]. Reducing factors for the INF 3 type ships are given by the probabilities that the INF 3 ship is the ship struck (0.5), the anti-collision safety features fail (0.1), the kinetic energy is higher than the design values (0.12), the collision angle is near 90° (0.44), striking a flask (0.35).

This low collision probability does not result in damage to the flasks sufficient to cause release of radioactivity. Finite element calculations of Sandia [POR 96] for a single hulled freighter, covering several collision cases with variation in mass and velocity of the striking ship, led to the conclusion that the impact load from collision will be lower than from a regulatory 9 metre free fall. Sandia calculations also show that crush forces to the package by the bow of the striking ship are limited, because a permanently pushed flask would penetrate the opposite hull. The maximum calculated crush forces during penetration are similar to the dynamic impact force seen in the regulatory impact test [AMM 97].

Higher crush forces could result if there is a collision in a port with the struck ship docked against a quay wall. As the velocities of ships inside ports are strictly limited this event is extremely improbable.

- **Fire Induced by Collision**

The evaluation of Lloyd's accident data covering the years 1979 through 1993 shows that only 2.5 % of the collision events led to a fire (50 fires in 1947 collision events, see Table 1). The most probable of these external events is a collision with a tanker (INF 3 ship strikes tanker) whereby flammable liquids could leak into the striking ship or - much more probable - to the water surface. Penetration of the spilled liquid into the PNTL ship's cargo holds can be excluded as the hatch covers remain closed. If there is also an ignition this scenario could lead to a fire enveloping the INF 3 ship for a longer period. The probability of a fire of this type with a duration that could lead to a thermal threat to the flasks is estimated to be in the range of $2 \cdot 10^{-10}$ per trip. Additional reduction of the 2.5 % collision plus fire probability is given by the chance of setting back the striking ship (failure 0.1), the probability that the struck ship is a tanker (0.2), the probability of long fire duration, i.e. failure of cooling and extinguishing actions (0.05). A comparable probability for this scenario can be derived on the basis of a 10 years survey concerning collision and severe fires with tankers [DEL 96].

Moreover, a fire of the INF 3 ship's fuel content following a collision where the INF 3 ship is struck could result by damage of the INF 3 ship's fuel tank and subsequent ignition of the diesel. Both events are quite improbable, because the fuel tanks are at the bottom of the ship and the diesel flash point is >60 °C. If this scenario is supposed a fire duration threatening the cargo can be excluded, because the content of the damaged fuel tank is limited and the burning layer on the water surface would spread and rapidly burn off.

- **Foundering**

Sinking of a ship of the PNTL fleet is highly improbable because of the stiff double hull construction with watertight subdivisions. The ships are capable of remaining afloat with all cargo holds flooded. Therefore, foundering statistics of conventional ships cannot be applied. For the relevant transports to the European continent the maximum depth is 238 metres, the vast majority of the area covered by these transports is less than 100 metres. In the event of a vessel being lost within the area covered by this study it is BNFL's policy to recover the cargo. Contingency plans are in place to cover this highly improbable situation. For the reference trip of the study it can therefore be excluded that foundering of the ship could lead to a release of radioactivity.

CONCLUSIONS

The probabilities of most severe accidents with the potential of mechanical and thermal impacts to the type B flasks in the range of the IAEA regulatory tests have been evaluated to be in the order of 10^{-7} to 10^{-10} during a 1000 nm sea voyage. The uncertainty of the probabilities is estimated to be one to two orders of magnitude. The results show that there is a high safety margin due to the special safety features of the INF 3 ships compared to conventional ships. There are no realistic severe accident scenarios that could seriously affect the flasks and could lead to a radioactivity release.

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Annex 3

DOSE ASSESSMENT FOR PUBLIC BY PACKAGES SHIPPING RADIOACTIVE MATERIALS HYPOTHETICALLY SUNK ON THE CONTINENTAL SHELF

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Abstract

Radioactive materials such as spent fuel (SF), PuO_2 powder, high level wastes (HLW) and fresh mixed oxide (MOX) fuel have been transported on sea between Europe and Japan. Dose assessments for public have been performed in the past when the packages shipping radioactive materials hypothetically sunk on the continental shelf. These studies employed various conditions and methods in their assessments and the results were not always the same. In this study, the dose assessment for these packages was performed under the same conditions and by the same methods. The effective dose equivalents of radiation exposure to the public for all materials become smaller than the previous evaluations due to more realistic assumption in this study. These evaluated results are far less than the effective dose equivalent limit (1 mSv $year^{-1}$) by the ICRP recommendation.

INTRODUCTION

There is a special safety standard called INF Code at International Maritime Organization (IMO) about structure and systems of transport ship of radioactive materials. On the other hand, for transport of radioactive materials, there is a safety standard stipulated in "Regulations for the Safe Transport of Radioactive Material" issued by International Atomic Energy Agency (IAEA). Transport of radioactive materials has been carried out safely under these standards and regulations. Therefore, there is little possibility for the ship to collide with other ship resulting in abnormal incident such as shipwreck.

However, dose assessment for public by packages shipping various radioactive materials hypothetically sunk into the sea was carried out in the past 20 years for the public acceptance of safe transport of radioactive materials through case studies developing assessment methods by Central Research Institute of Electric Power Industry (CRIEPI) (spent fuel (SF) (1), PuO_2 powder(2), high level wastes (HLW)(3), high burn-up spent fuel(4), fresh mixed oxide (MOX) fuel (5)). These studies employed various conditions and methods in their assessments and the results were not always consistent. It is necessary to make evaluation under the same condition and by the same method.

On the other hand, similar dose assessments have been performed in other countries(6)(7). It is informative to make comparison between our study and their studies.

DOSE ASSESSMENT IN CRIEPI

Scenario of assessment

When a package might be sunk at a 200 m depth which is equivalent to the mean depth of the continental shelf, it would not be collapsed and would keep its integrity. Because the package meets the requirement for the 200 m water submersion test to the package that contains more than $10^5 A_2$ as shown in the IAEA transport regulation (1996Edition). Since it would be possible to salvage the package from a 200 m depth [(8)], a 200 m depth was conservatively assumed for the assessment in case of submergence near shore. The effect of submergence at the depth more than 200 m would become smaller. As a result, the depth of the supposed location of submergence was 200 m near shore.

Figure 1 shows the sequence of the assessment. The barrier effect scenario that the presence of the package reduces the release rate of nuclides to the ocean was employed. The one dimensional flow field was evaluated by using the statistical data for 30 years of Japan Ocean Data Center [(9)]. Nuclide concentration was evaluated calculating three- dimensional diffusion equation in consideration of nuclides decay and scavenging (nuclides removed from seawater by phenomena that nuclides absorb suspended materials in seawater and settle down the seabed) by the finite differences method. The internal effective dose equivalent from ingestion of fish in the area of calculation and the external dose by marine operations were calculated.

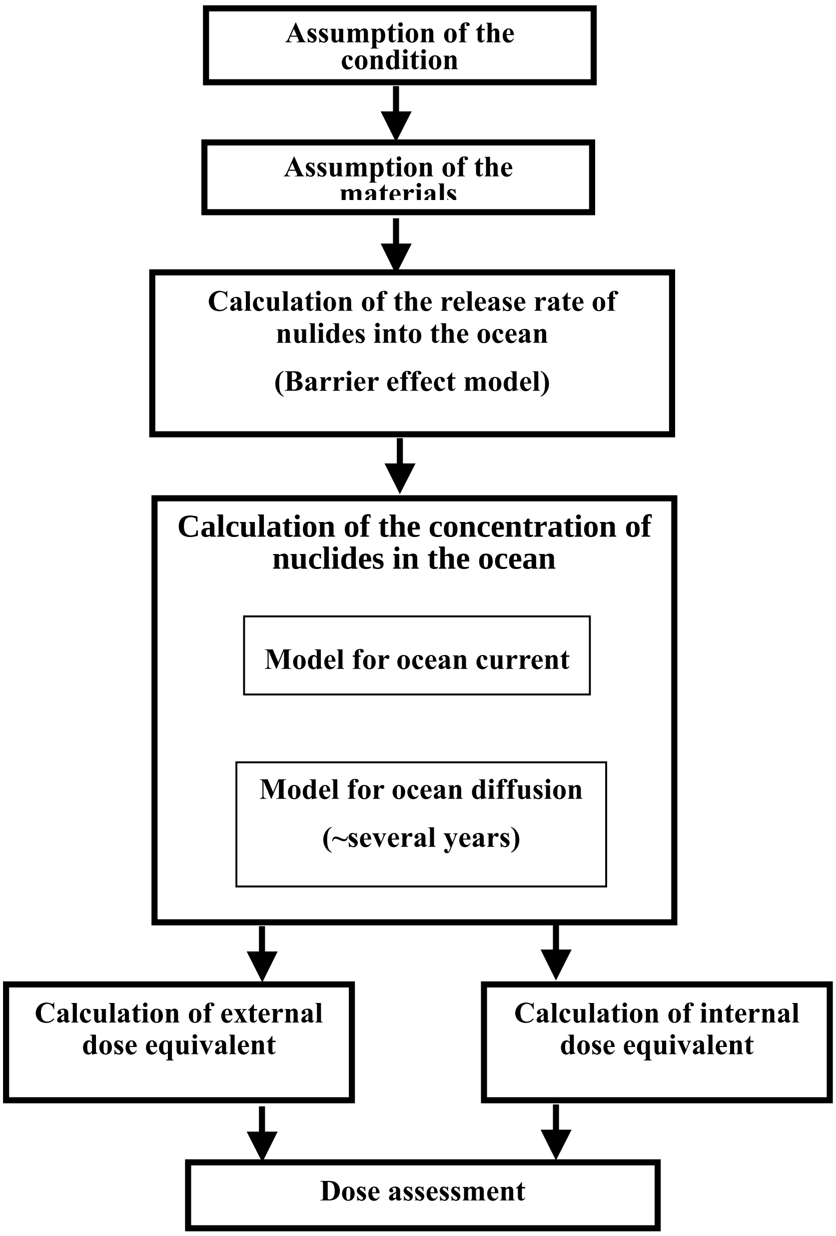


Figure 1. Sequence of dose assessment.

Conditions for evaluations

Location of submergence

The supposed location of submergence was a 200 m depth area 7 km off Shimokita peninsula (Figure 2).

Outlines of the packages

Table 1 shows type, weight and dimension of the packages and form, weight, inner container and activity of the packages for assessment [10]. Here after, the assessment was carried out per package. In this study, the dose assessments for these packages of SF, PuO_2 powder and HLW are performed under the same conditions and by the same methods.

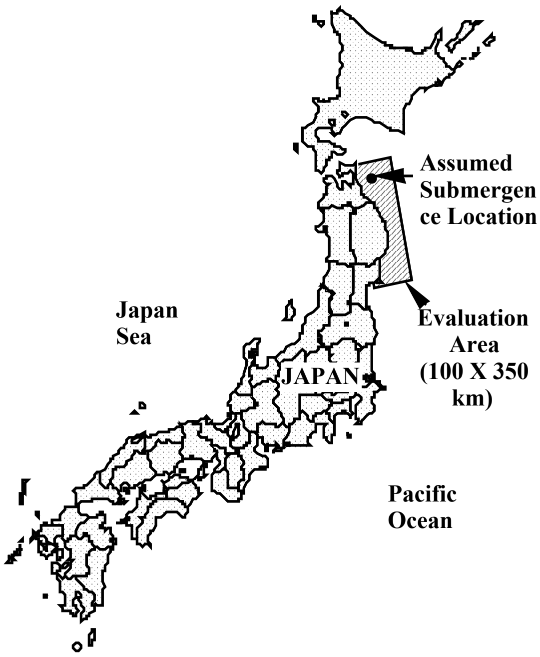


Figure 2. Assessment Area in north-eastern Japan.

TABLE 1. PACKAGES FOR ASSESSMENT [8]

		SF	PuO2	HLW
Packaging	Type	HZ-75T(PWR)	FS-47	TN-28VT
	Weight	70ton	1.5ton	100ton
	Size	ϕ2.3m×5.9m	ϕ0.8m×2m	ϕ2.5m×6.6m
Radioactine Material	Form	Pellet	Powder	Vitrified Residue
	Weight	3.2tU	14.5kg	400kg×28
	Inner Container	Fuel Assembly×7	Can×4	Canister×28
	Activity	81.5PBq×7	5.2PBq	25.5PBq×28

Scenario of nuclides release into the sea

The following conservative scenario was considered.
(1) The package is submerged on the seabed at the depth of 200 m.
(2) After submergence, sealing function is lost by a functional disorder of O-ring immediately.
(3) Seawater enters into the cavity of the package.
(4) All fuel pellets expose to the seawater.
(5) Nuclides leaches into the seawater in the cavity of the package.
(6) The solution of nuclides is released to the ocean through the seal gap.

Outline of the barrier effect model

Release rate of nuclides from the package to the ocean was calculated by the barrier effect model. Outline of the barrier effect model is shown in figure 3. The nuclides would leach into the seawater in the cavity of the package at the leaching rate R_c (Bq year^{-1}) and the solution of nuclides would be released into the sea through the gap at the release rate R_o (Bq year^{-1}). When the leaching rate R_c is larger than release rate R_o, the amount of nuclides into the sea is regulated by the release rate R_o, not by the leaching rate R_c. When the concentration of nuclides in the cavity of package is saturated, nuclides will leach into the seawater that entered the package through the gap with the certain rate. Accordingly, the leach rate would be controlled under this condition. Here after, this effect is called as barrier effect.

Parameters of the barrier effect model

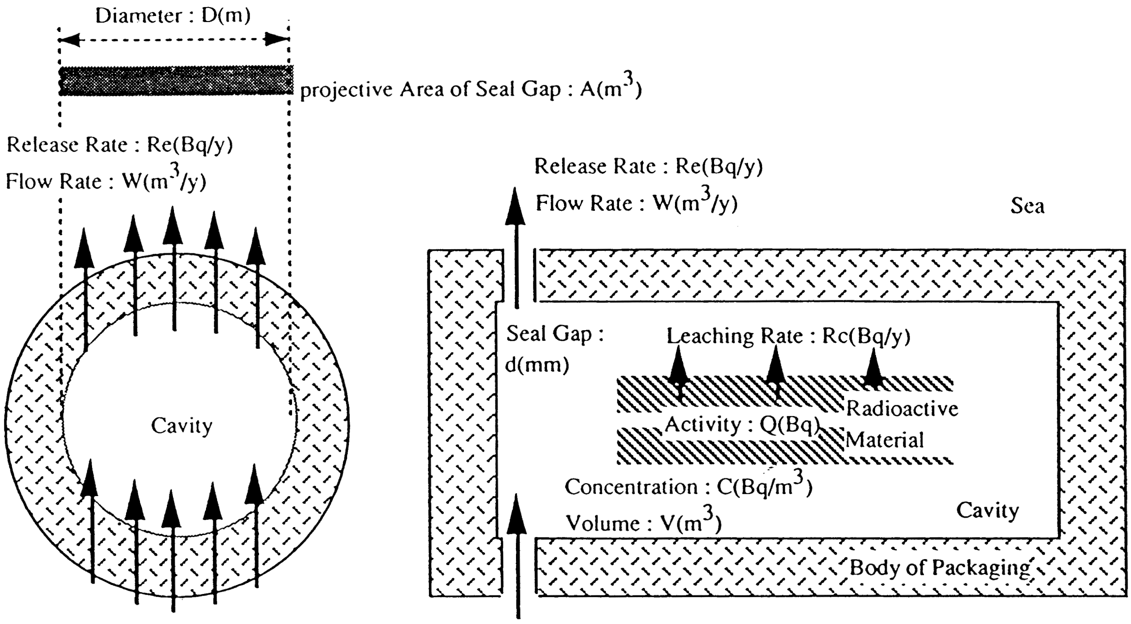
Temperature of seawater in the cavity of package was conservatively assumed to be $200\,°C$ for all materials in this assessment. The value for the HLW package was employed because data of heat value for the entire package were not available. This value is considered conservative for each package.

Table 2 shows the saturated concentration of elements and glass. Insoluble elements such as Np, Pu, Am and Cm are dissolved at a constant rate until the concentration of each element would be saturated. The soluble elements are dissolved into the seawater infinitely. However the soluble elements in the high level wastes were considered to be dissolved into the seawater until the concentration of the vitrified glass to the seawater would be saturated from previous study (3). Taking account of the temperature dependence, the 100 times values of the saturated concentration at the room temperature were employed. From the solubility values for the elements, solubility of isotope (nuclides) were obtained in accordance with the weight ratio.

TABLE 2. SOLUBILITY OF NUCLIDES

Group	Element or Material	Solubility [1] (mole/L)	Adoption to Packages [*1]
Insoluble Nuclides	Np	5.5E-07	Spent Fuel, High Level Wastes, PuO2 Powder
	Pu	5.3E-04	
	Am	3.1E-05	
	Cm	3.1E-05	
Soluble Nuclides	Vitrified Glass (SiO2)	8.5E-01	High Level Wastes
	Pellet	Not given	Spent Fuel

[*1] For insoluble nuclides, these solubility are used for all packages.
Soluble nuclides in High Level Wastes are dissolved in concert with Vitrified Glass.
Soluble nuclides in Spent Fuel are not limited to be dissolved .
In PuO_2 Powder, there is no soluble nuclide .



Scinario of Release

Package is submerged

↓

Seal gap breaks out.

↓

Sea water flows into cavity.

↓

Inner-vessel is broken.

↓

Radioactive Material is exposed to cavity water

↓

Nuclide leaches into cavity water [Eq.①]

↓

Concentration of nuclide in cavity water rises. (limit to solubility) [Eq.④]

↓

Cavity water disolving nuclides flows out into sea [Eq.③]

Equation

①Leaching Rate of Nuclide into Cavity Water

$Rc = Rp \ \mu \ Q$

②Activity of Radioactive Material

$Q' = Q - (Rc + B \ Q)dt$

③Release Rate into Sea

$Re = C \ W$

④Concentration of Nuclide in Cavity Water

$C' = C + (Rc/V - Re/V - B \ C) \ dt$

For Unsoluble Nuclide and Glass $C' \leqq Cs$

Variables

Rc : Release Rate into Cavity Water (Bq/y)
Rp : Laching Rate ($g/cm^2/y$)
μ : Surface/Weight Ratio of Radioactive Material (cm^2/g)
Q : Activity of Radioactive Material(Bq)
Q' : Activity of Radioactive Material (after dt) (Bq)
B : Decay Constant (1/y)
dt : Differential Time (y)
Re : Release Rate into Sea (Bq/y)
C : Concentaration in Cavity Water (Bq/m^3)
C' : Concentaration in Cavity Water (aftre dt) (Bq/m^3)
Cs : Solubility of Unsoluble Nuclides (Bq/m^3)
W : Fow Rate throgh Seal Gap (m^3/y)
V : Volume of Cavity (m^3)

FIG. 3. Release scenario and process of calculating release rate.

The leaching rate of nuclides from pellet (SF) and powder(PuO_2 powder) in seawater was conservatively assumed to be 1×10^{-6} g cm^{-2} d^{-1} by referring to the hot experimental results [(1)(2)]. The leaching rate of nuclides vitrified waste (HLW) in seawater was conservatively assumed to be 1×10^{-4} g cm^{-2} d^{-1} by referring to the hot experimental results [(3)].

Results of release rate

Release rates of radioactive nuclide of spent fuel, PuO_2 powder and high level wastes are shown in Table 3, 4 and 5, respectively. These results varied with time by barrier effect and nuclide decay.

TABLE 3. RELEASE RATE OF NUCLIDES (SPENT FUEL)

Nuclides	Solubility		Release	Release Rate
	For Elements [*1] Cso (mol/L)	For Nuclides [*2] Cs (Bq/m3)	Flow Rate [*3] w (m3/s)	(per Package) (at 20 yr) r (Bq/y)
Sr-90	-	-	9.5E-10	2.8E+13
Y-90	-	-		2.8E+13
Sb-125	-	-		3.4E+10
Te-125m	-	-		1.4E+10
Cs-134	-	-		1.8E+11
Cs-137	-	-		4.0E+13
Ba-137m	-	-		3.7E+13
Pm-147	-	-		3.3E+11
Sm-151	-	-		6.0E+11
Eu-154	-	-		8.4E+11
Eu-155	-	-		2.4E+11
Pu-238	5.3E-04	1.6E+12		4.9E+10
Pu-241		5.9E+13		1.8E+12
Am-241	3.1E-05	8.9E+11		2.7E+10
Cm-244	3.1E-05	1.9E+13		5.8E+11

[*1] Solubolity is at 200℃. For solubule nuclides (Sr, . .,Eu) , solubolity is not given.

[*2] Solubility for an unsoluble element is distributed to each nuclide in accordance with its weig

[*3]Release flow rate is for 200℃ of cavity water and 0.01mm of seal gap.

[*4] This table shows release rate of nuclides at 20 yr after submergence when dose rate becomes

TABLE 4. RELEASE RATE OF NUCLIDES (PuO_2 POWDER)

Nuclides	Solubility		Release	Release Rate
	For Elements	For Nuclides	Flow Rate	(per Package)
	[*1]	[*2]	[*3]	(at 0 yr)
	Cso	Cs	w	r
	(mol/L)	(Bq/m3)	(m3/s)	(Bq/y)
Pu-238	5.3E-04	1.6E+12	9.5E-10	4.7E+10
Pu-239		1.9E+11		5.7E+09
Pu-240		2.7E+11		8.2E+09
Pu-241		5.2E+13		1.6E+12
Pu-242		7.3E+07		2.2E+06
Am-241	3.1E-05	8.9E+11		2.7E+10

[*1] Solubolity is at 200 ℃. For solubule nuclides (Sr, . .,Eu) , solubolity is not given.

[*2] Solubility for an unsoluble element is distributed to each nuclide in accordance with its weight.

[*3]Release flow rate is for 200℃ of cavity water and 0.01mm of seal gap.

[*4] This table shows release rate of nuclides at 0 yr after submergence.

TABLE 5. RELEASE RATE OF NUCLIDES (HIGH LEVEL WASTE)

Nuclides	Solubility		Release	Release Rate
	For Elements	For Nuclides	Flow Rate	(per Package)
	[*1]	[*2]	[*3]	(at 5 yr)
	Cso	Cs	w	r
	(mol/L)	(Bq/m3)	(m3/s)	(Bq/y)
Sr-90	8.5E-01	5.3E+14	9.5E-10	1.6E+13
Y-90	(for Glass)	5.3E+14		1.6E+13
Ru-106		6.2E+13		8.9E+11
Rh-106		6.2E+13		8.9E+11
Cs-134		1.5E+14		4.6E+12
Cs-137		7.6E+14		2.3E+13
Ba-137m		7.2E+14		2.2E+13
Eu-154		4.5E+13		1.4E+12
Pu-238	5.3E-04	1.4E+12		1.6E+10
Am-241	3.1E-05	7.2E+11		2.2E+10
Cm-243	3.1E-05	2.9E+11		8.7E+09
Cm-244		2.2E+13		6.7E+11

[*1] Solubolity is at 200 ℃. For solubule nuclides , solubolity is not given.
For solubule nuclides, solubolity for vitrified glass is given.

[*2] Solubility for an unsoluble element or glass is distributed to each nuclide in accordance with its weig

[*3]Release flow rate is for 200℃ of cavity water and 0.01mm of seal gap.

[*4] This table shows release rate of nuclides at 5 yr after submergence when dose rate becomes maximur

Method of calculation of nuclides concentration in the seawater

Nuclide concentration near shore was evaluated by calculating three dimensional diffusion equation with the finite differences method under the following boundary conditions. The followings show the assessment model, the three-dimensional diffusion equation, the assessment parameters, etc.

Assessment model

The mesh size of the assessment model was a few kilometers in the horizontal (X, Y) direction and tens meters in the depth (Z) direction. The seabed of the offshore of the Tohoku region of Pacific Ocean and its shore have been modeled as steps and straight line, respectively (Figure 4).

The basic equation was the three dimensional diffusion equation (Equation 1) in consideration of advection, ocean diffusion, absorption to suspended particles and sedimentation of nuclides (called scavenging), and nuclides decay.

$$\frac{\partial C}{\partial t} = \underbrace{-U\frac{\partial C}{\partial x} - V\frac{\partial C}{\partial y} - W\frac{\partial C}{\partial z}}_{\text{(Advection)}} \underbrace{+ D_x\frac{\partial^2 C}{\partial x^2} + D_y\frac{\partial^2 C}{\partial y^2} + D_z\frac{\partial^2 C}{\partial z^2}}_{\text{(diffusion)}} \underbrace{- K_d \rho_s w_s \frac{\partial C}{\partial z}}_{\text{(scavenging)}} \underbrace{- \lambda C}_{\text{(decay)}} \quad (1)$$

where, C_I is radionuclide concentration (Bq m^{-3}), t is times (s), x, y and z are geographical coordinatess (m), U, V and W are advective velocities (m s^{-1}), D_x, D_y and D_z are ocean diffusion coefficienta（$m^2 s^{-1}$）, λ is decay constant of nuclides（s^{-1}）, K_d is distribution coefficient of nuclides($m^3 g^{-1}$), ρ_s is concentration of suspension（g m^{-3}）and w_s is the sedimentation velocity of suspension（m s^{-1}）

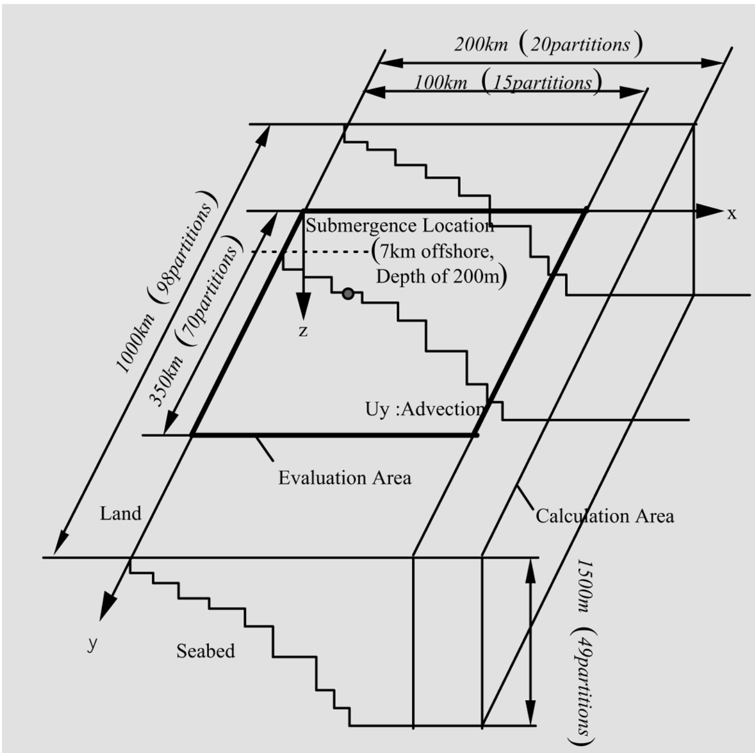


Figure 4. Model of Waters to Calculate Concentration.

Input conditions [3]

The advective velocity for the principal component of each season on the surface of the sea from 1905 to 1989 at 55 locations [9] was used. Within the sea area of calculation the flow was assumed to be uniform. The advective velocity was assumed to be uniform in the depth (Z) direction. The annual means Y directional velocity was 12cm s^{-1}. The diffusion coefficients in the horizontal direction were assumed to be $10^5 cm^2\ s^{-1}$ in the offshore direction (perpendicular to shoreline) and $10^6 cm^2\ s^{-1}$ along the coast (parallel to shoreline), that was based on Richardson's four third-power law on condition that the order of diffusion [11] in the horizontal scale was tens km. For Z (depth) direction it was assumed to be $10 cm^2\ s^{-1}$ [12]. The values of distribution coefficient of element was employed from the safety series No.78 of IAEA [13]. Sedimentation velocity of suspended materials and its concentration in the seawater were determined with reference to published paper [14].

Calculation results of nuclides concentration

The nuclides concentration to be calculated in the ocean were assumed to be the maximum value in the different surfaces and time at the surface layer (0-100 m depth) which is the habitant of fishes ingested. Table 6 shows the concentrations for all nuclides under the condition that the release rate was 1 Bq $year^{-1}$. The difference of distribution coefficient and decay constant were considered in this calculation. The smaller the distribution factor was, the larger the concentration of radionuclide was. And the smaller decay constant was, the smaller the concentration was. The difference of two orders of magnitude was shown in calculated results by the difference of nuclides. The concentration of nuclides in the ocean from the different package was obtained by multiplying these calculated results per 1Bq $year^{-1}$ and the results of release rate into the ocean.

The effective dose equivalent of radiation exposure to the public

Calculation method for the effective dose equivalent of radiation exposure to the public

The internal exposure route was quoted from guideline of the calculation model for evaluating the effective dose equivalent around a nuclear site during the basic planning stage [15]. It was assumed that internal exposure would be caused by seafood ingestion. As to the values for ingested fishes in which the radionuclides are concentrated, the established values for a reference man per day in the guideline for effective dose equivalent evaluation in Japan were employed. The external exposure route was quoted from the case of the evaluation effective dose equivalent of liquid waste [16] for the safety examination of a nuclear power station. The parameters based on the evaluation of effective dose equivalent of liquid waste were employed. Table 7 shows the condition of calculating individual doses.

Result of the effective dose equivalent of radiation exposure to the public

The results of the effective dose equivalent of radiation exposure to the public are shown in Table 8, 9 and 10 in the cases of SF, PuO_2 powder and HLW. The values in table are maximum value in 50 years that is calculated period.

The result of the effective dose equivalent at the case of SF shows the maximum value of 4.1×10^{-4} mSv $year^{-1}$ in 20 years after submergence. This result is 500 times smaller than the previous result in 1976 [1]. The change of the results is mainly caused by the employment of barrier effect model and the consideration of ocean flow to calculate the concentration of nuclides in the ocean. The result at the case of PuO_2 powder shows the maximum value of 1.4×10^{-5} mSv $year^{-1}$ immediately after submergence. This result becomes 2 times smaller than the previous result in 1992 [2]. The difference is not so large because the effect of barrier effect and the change of submerged depth from 500 m to 200 m were canceled out. The result at the case of HLW shows the maximum value of 3.1 × 10^{-4} mSv $year^{-1}$ in 2 years after submergence. This result become a little smaller than the previous result in 1996 (3) due to the consideration of weight ratio of isotope in a element for the calculation of solubility of isotopes (nuclides).

TABLE 6. CONCENTRATION OF NUCLIDES IN SEA WATER (PER 1Bq/Y OF RELEASE)

Distribution Factor [12]	Half-Life Time	Adaptation for Nuclides			Maximum Concentration
Kd	Tr	Spent Fuel	PuO2	High Level	C
	(y)		Powder	Wastes	(Bq/m3)
≦ 1E+4	≦ 0.3	Sr-89, Ru-103, Rh-103m, Te-127m (Te-127)	-		1.9E-15
	0.3 ~ 3	Ru-106 (Rh-106), Sn-123, Cs-134	-	Ru-106 (Rh-106), Cs-134	2.1E-14
	≧ 3	Sr-90 (Y-90), Sb-125 (Te-125m), Cs-137 (Ba-137m)	-	Sr-90 (Y-90), Sb-125 (Te-125m), Cs-137 (Ba-137m), Np-237	2.7E-14
1E+4 ~ 1E+6	≦ 0.3	Zr-95 (Nb-95m), Nb-95	-	Zr-95	1.5E-15
	0.3 ~ 3	-	-	Sn-123	1.7E-14
	≧ 3	Pu-238, Pu-239, Pu-240, Pu-241	Pu-238, Pu-239, Pu-240, Pu-241, Pu-242	Pu-238, Pu-239, Pu-240, Pu-241, Pu-242	2.2E-14
≧ 1E+6	≦ 0.3	Y-91,Ce-141	-	Ce-141	4.2E-16
	0.3 ~ 3	Ce-144 (Pr-144), Pm-147, Cm-242	-	Ce-144 (Pr-144), Pm-147, Cm-242	4.5E-15
	≧ 3	Y-91, Sm-151, Eu-154, Eu-155, Am-241, Cm-244	Am-241	Sm-151, Eu-155, Am-241, Am-243, Cm-243, Cm-244	5.8E-15

TABLE 7. CONDITION AND PARAMETERS FOR ESTIMATION OF INDIVIDUAL DOSE

Item		Condition or Parameters		
Model		ICRP Pub.30		
Dose to Estimate		Effective Dose Equivalent for Individual		
Internal Dose	Ingestion of Seafood	Comsumption (g/d)	Fish	200
			Invertebrade	20
			Seaweed	40
External Dose	Working on Shipboad	Working Period (d/y)		120
	Swimming			4
	Working at Beach			20
	Operation of Fishery Net			80

TABLE 8. INDIVIDUAL DOSE EQUIVALENT (SPENT FUEL)

Nuclides	Internal Dose	Extenal Dose				Total
	Ingestion of Seafood	Working on Boad	Swimming	Working at Seashore	Handling of Fihing-Net	(per Package) (at 1 yr)
	Dw	D1	D2	D3	D4	Dtotal
	(mSv/y)	(mSv/y)	(mSv/y)	(mSv/y)	(mSv/y)	(mSv/y)
Sr-90	1.3E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.3E-05
Y-90	5.7E-05	2.4E-14	2.4E-15	1.3E-12	2.0E-12	5.7E-05
Sb-125	1.3E-08	2.4E-10	1.7E-11	3.8E-08	1.4E-08	6.6E-08
Te-125m	2.3E-07	1.8E-12	1.2E-13	8.1E-11	1.2E-10	2.3E-07
Cs-134	3.3E-07	4.8E-09	3.2E-10	7.4E-07	2.7E-07	1.4E-06
Cs-137	5.6E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.6E-05
Ba-137m	0.0E+00	4.0E-07	2.8E-08	6.4E-05	2.3E-05	8.8E-05
Pm-147	3.4E-08	3.8E-15	2.5E-16	4.4E-13	1.9E-13	3.4E-08
Sm-151	2.6E-08	2.6E-15	2.0E-16	1.1E-13	2.0E-13	2.6E-08
Eu-154	9.8E-07	4.0E-09	2.7E-10	6.4E-07	2.4E-07	1.9E-06
Eu-155	4.1E-08	4.4E-11	3.1E-12	4.3E-09	2.4E-09	4.8E-08
Pu-238	1.5E-05	4.2E-14	3.8E-15	2.6E-12	3.2E-12	1.5E-05
Pu-241	1.1E-05	7.5E-23	4.9E-24	1.2E-20	4.4E-21	1.1E-05
Am-241	1.2E-05	2.0E-12	1.4E-13	1.4E-10	1.1E-10	1.2E-05
Cm-244	1.5E-04	1.5E-13	1.3E-14	1.2E-11	1.1E-11	1.5E-04
TOTAL	3.2E-04	4.1E-07	2.9E-08	6.6E-05	2.4E-05	4.1E-04

Notes : Annual dose eqivalent at 20 yr after submergence is shown, when the value becomes maximum.

TABLE 9. INDIVIDUAL DOSE EQUIVALENT (PUO_2 POWDER)

Nuclides	Internal Dose	Extenal Dose				Total
	Ingestion of Seafood	Working on Boad	Swimming	Working at Seashore	Handling of Fihing-Net	(per Package) (at 1 yr)
	Dw	D1	D2	D3	D4	Dtotal
	(mSv/y)	(mSv/y)	(mSv/y)	(mSv/y)	(mSv/y)	(mSv/y)
Pu-238	4.6E-06	1.4E-14	1.2E-15	8.2E-13	1.0E-12	4.6E-06
Pu-239	6.4E-07	1.9E-15	1.4E-16	2.1E-13	1.2E-13	6.4E-07
Pu-240	9.2E-07	2.7E-15	2.4E-16	1.8E-13	1.9E-13	9.2E-07
Pu-241	3.3E-06	2.2E-23	1.4E-24	3.4E-21	1.3E-21	3.3E-06
Pu-242	2.3E-10	1.3E-18	9.7E-20	1.5E-16	8.2E-17	2.3E-10
Am-241	4.0E-06	6.7E-13	4.5E-14	4.5E-11	3.5E-11	4.0E-06
TOTAL	1.4E-05	6.9E-13	4.6E-14	4.6E-11	3.6E-11	1.4E-05

Notes : Annual dose eqivalent at 1 yr after submergence is shown, when the value becomes maximum.

TABLE 10. INDIVIDUAL DOSE EQUIVALENT (HIGH LEVEL WASTE)

Nuclides	Internal Dose	Extenal Dose				Total
	Ingestion of Seafood	Working on Boad	Swimming	Working at Seashore	Handling of Fihing-Net	(per Package) (at 5 yr)
	Dw	D1	D2	D3	D4	Dtotal
	(mSv/y)	(mSv/y)	(mSv/y)	(mSv/y)	(mSv/y)	(mSv/y)
Sr-90	7.3E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.3E-06
Y-90	3.3E-05	1.4E-14	1.4E-15	7.4E-15	1.2E-12	3.3E-05
Ru-106	4.2E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4.2E-06
Rh-106	0.0E+00	2.6E-09	1.7E-10	4.1E-07	1.5E-07	5.6E-07
Cs-134	8.4E-06	1.2E-07	8.0E-09	1.9E-06	7.0E-06	1.7E-05
Cs-137	3.2E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.2E-05
Ba-137m	0.0E+00	2.4E-07	1.6E-08	3.8E-06	1.4E-05	1.8E-05
Eu-154	1.6E-06	6.6E-09	4.5E-10	1.1E-06	3.9E-07	3.1E-06
Am-241	1.0E-05	1.7E-12	1.1E-13	1.1E-10	8.6E-11	1.0E-05
Am-243	1.3E-07	4.9E-14	3.3E-15	4.1E-12	2.5E-12	1.3E-07
Cm-243	2.8E-06	4.4E-12	3.0E-13	5.9E-10	2.3E-10	2.8E-06
Cm-244	1.7E-04	1.7E-13	1.5E-14	1.4E-11	1.3E-11	1.7E-04
Total	2.8E-04	3.7E-07	2.5E-08	7.6E-06	2.1E-05	3.1E-04

Notes : Annual dose eqivalent at 5 yr after submergence is shown, when the value becomes maximum.

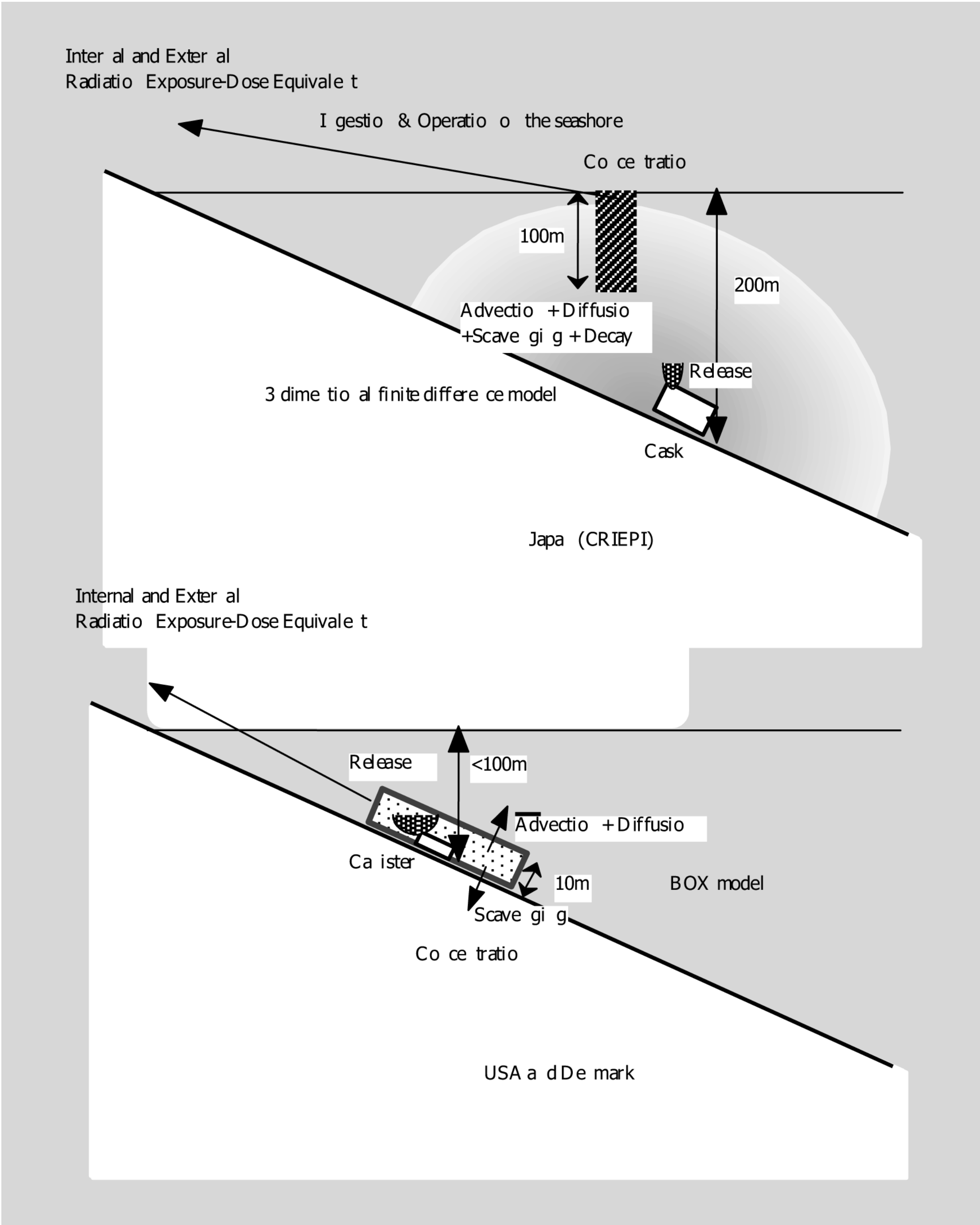


Figure 5. Schematic Drawing of the Sequence of the Assessment.

TABLE 11. THE OUTLINES OF DOSE ASSESSMENTS FOR PUBLIC AT THE SEA TRANSPORT ACCIDENTS NEAR SHORE BY CRIEPI

Country (Organisation)	Nuclear fuel material	Amount	Published year	Submerged area	Scenario of nuclides release into the sea	Flow field	Model to calculate the concentration of nuclides in the sea	Individual dose equivalent
USA (Klett, SNL)[5]	High level wastes	1 canister	1988	Middle Atlantic Bight (< 100 m)	Leaching	Box model (3 boxes) for coastal zone		0.01 mSv/year
Denmark (Neilsen) [6]	Spent fuel	1Tbq	1996	Europian sea (<100 m)	Immediate release	Box model for Europian sea		0.04 mSv/1Tbq release
Japan (CRIEPI)[1]	High level wastes [1]	1 cask (28 canisters)	1995	Off Shimokita 200 m depth	Barrier effect model	One dimensional advection supposed from observed data	Three dimentional finite differences method model	5.9×10^{-4} mSv/year
Japan (CRIEPI)[16]	High burn up spent fuel	1 cask (PWR × 12)	1997					2.3×10^{-3} mSv/year
Japan (CRIEPI)	**High level wastes**	**1 cask (28 canisters)**	**1998**		**Modified barrier effect model**			**3.1×10^{-4} mSv/year**
Japan (CRIEPI)	**PuO2 powder**	**1 cask (14.5 kg)**	**1998**					**1.4×10^{-5} mSv/year**
Japan (CRIEPI)	**Spent fuel**	**1 cask (PWR × 7)**	**1998**					**4.1×10^{-4} mSv/year**

COMPARISON OF OTHER RESULTS

The outlines of dose assessments for public at the sea transport accident by Klett [(6)], Nielsen [(7)] and CRIEPI (Japan) are shown in Table 11. In addition, the result of assessment at the case of high burn up spent fuel [(4)] is also shown in Table 11. This result is larger than the result at the case of conventional spent fuel due to the employment of large cask and its high burn up. In addition, as a recent estimated result, the result of assessment at the case of fresh MOX fuel [(5)] is also shown in Table 11.

The scenario and method of assessment by Klett and Nielsen are different from that by CRIEPI. The major difference is supposed depth of submergence. The supposed depth of submergence by Klett and Nielsen is several tens meters. Even for the case of submergence of cask to the several tens meters in depth, release of radionuclides by hypothetical reasons were supposed. On the other hand, in CRIEPI, the package would not be collapsed and would keep its integrity at 200 m depth. Because the package meets the requirement for a 200 m water submersion test applied to the package that contains more than 10^5 A_2 value according to the IAEA transport regulation [(8)]. Since it would be possible to salvage the package from 200 m depth. The submergence of the package at less than 200 m depth is not necessary for assessment. Schematic drawing of the difference of these assessments is shown in Figure 5. In CRIEPI's study, the concentration of nuclides at the surface (0-100 m depth) where almost of the marine product would be taken is used for dose calculation. On the other hand, in the studies of Klett and Nielsen, the concentration of nuclides near the submerged package is used for dose assessment so that the concentration near package contributes to exposure dose. The release of nuclides from package would not be properly assumed because it would be possible to salvage the package from several tens meters in depth. Although, they described in their papers that the possibility of the release of nuclides into ocean would be extremely small.

CONCLUSIONS

The evaluations for spent fuel, PuO_2 powder and high level wastes under the same conditions and by the same methods were carried out. The result of the effective dose equivalent at the case of spent fuel shows the maximum value of 4.1×10^{-4} mSv year^{-1} in 20 years after submergence. The result at the case of PuO_2 powder shows the maximum value of 1.4×10^{-5} mS year^{-1} immediately after submergence. The result at the case of high level wastes shows the maximum value of 3.1×10^{-4} mSv year^{-1} in 2 years after submergence. All results are smaller than previous results. The effective dose equivalents of radiation exposure to the public for all the materials per package are far less than the effective dose equivalent limit (1 mSv year^{-1}) by the ICRP recommendation.

The comparison among the studies in Klett (USA), Nielsen (Europe) and CRIEPI (Japan) was made. The major differences are the supposed depth of submergence, scenario of release of nuclides from package and numerical model for the evaluation of concentration of nuclide. The assumptions for assessment by CRIEPI (Japan) are considered to be more realistic than the other studies in Klett (USA) and Nielsen (Europe).

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Annex 4

STUDY OF ACCIDENT ENVIRONMENT DURING SEA TRANSPORT OF NUCLEAR MATERIAL: PROBABILISTIC SAFETY ANALYSIS OF PLUTONIUM TRANSPORT FROM EUROPE TO JAPAN

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OBJECT

This study describes and analyzes the safety of a large amount of plutonium transportation operations for the international transportation of plutonium by maritime cargo vessels for selected routes. The analysis centers on conventional cargo vessels and their accident history in order to provide an estimate of the probability of accident occurrences for such vessels. This is an ultra-conservative study since the radioactive materials described in this study will, in all likelihood, be transported in purpose-built ships that incorporate many safety features not found in regular cargo vessels. Follow-on studies can use the information developed in this study in order to estimate the probability of accident occurrences in purpose-built ships. The accident probabilities developed in this study, for conventional cargo vessels, provide a conservative bounding estimate of the probabilities for accidents involving purpose-built ships. This study estimates the safety of transporting plutonium from Europe to Japan. This includes estimating the probability of a severe transportation accident during marine transport over three separate routes.

This study in not meant to be an all inclusive safety analysis, therefore the road or rail transportation between the origin and the origin port and the destination port and the final destination are not analyzed. Those segments may be evaluated using readily available and state-of-the-art environmental analysis techniques. This study concentrates on the development of data structures and analysis techniques that can be used to determine the casualty rates for the marine transport of plutonium. This study relies the examination of sources of transportation information, principally the Lloyd’s Casualty Register that contains marine casualty information dating from 1979 through 1995. The marine transport accidents are partitioned into the categories of port accidents, accidents in coastal waters leading to or from ports, and accidents in the open ocean.

ACTIVITY

The first step was the determination of the probability of occurrence of transportation accidents in the nine accident categories included in the Lloyd’s Casualty database. The history of actual marine transportation as recorded in the Lloyd’s Casualty File was examined. The physics of actual marine transport accidents was examined to develop the severity of the categories of accidents that have actually occurred as recorded in the Lloyd’s Casualty Files.

The probability of an accident during marine transportation can be evaluated for three zones. The first zone is the coastal waters near a large land mass. The second zone is the approach waters to the origin port or the destination port. Accident occurrences in both of these zones are more likely because of the relative congestion of vessel traffic in coastal and port waters. The third zone is the open ocean (termed global commons) which is removed from the relative congestion of coastal and port waters and is not near populated regions of land masses.

Sailing speeds in ports are much less than sailing speeds at open sea for at least two reasons. First, harbor operational rules limit ship speeds in port channels, typically to speeds less than 15 knots. Second, when sailing near docks, to prevent collisions, ships normally sail at minimum speeds (3 to 5 knots). Since collision damage decreases with decreasing collision speeds, accidents in ports, even if congested with vessel traffic, are not likely to lead to large releases of radioactive materials.

Because keel structures are massive and very sturdy, groundings rarely lead to significant damage to cargo, although monetary losses due to the sinking of cargo or the vessel can be substantial. Therefore, since immersion to depths of harbor channels is unlikely to damage a transportation package or pose a significant retrieval problem, groundings were not analyzed in.

The basic analysis of marine transportation of radioactive materials described in this report deals with conventional cargo vessels and uses the accident phenomenology in Ref. 1 for all classes of radioactive materials. Purpose-built cargo ships have been constructed for such transport. Special features such as separate watertight compartments, double hulls, and sophisticated fire control systems have been incorporated into the purpose built ships but credit for such features has not been taken in this analysis.

For the purpose of this study, three routes are analyzed. These routes have the same origin and destinations but different global pathways. Route 1 traverses the Atlantic around the southern tip of Africa through the Indian Ocean to Japan. Route 2 traverses the Atlantic Ocean around the southern tip of South America, through the Pacific Ocean to Tokai port in Japan. Route 3 traverses the Atlantic Ocean, passes through the Panama Canal, and then traverses the Pacific Ocean to Tokai port.

The Marsden grid is a rectilinear division of global positions. Each “cell” in the Marsden is a rectangular section of the globe that is 10 degree latitude by 10 degree longitude. For purposes of identification, the Marsden grid cells are numbered. Global locations of ship casualties listed in the Lloyds database are referenced to the Marsden grid.

The Lloyds Casualty Register was used to construct the marine transport accident characteristics of designated routes for this analysis. The following route descriptions describe the Marsden Grid cells along the routes. The accident occurrences within these cells are tabulated in each of the cells. Further, each cell is designated as being a “port cell”, a “coastal cell” or a “global commons” cell. The designation of a port cell is determined by a port being within the boundary of a designated Marsden cell. A coastal cell is one located adjacent to the coast of a continental land mass. A global commons cell is a Marsden cell that is in the open ocean and is not adjacent to a continental land mass. In the route descriptions that follow, the port cells are for the ports of Cherbourg and Tokai/Hitachi. Coastal cells are the intermediate cells in the route description although coastal cells may contain also contain ports. Global Commons cells are the open ocean portion of the routes.

Route 1: Cherbourg to Tokai Port (near Hitachi)

Route 1 Description: South from France, through the Atlantic around the southern tip of Africa, through the Indian Ocean, through the Western Pacific to Japan.

Route 1 is described by 40 Marsden grid cells commencing from cell number 145, which contains the location of port Cherbourg, France of and leading to Marsden grid cell number 130 which contains the location of the port of Tokai, Japan. The complete description of Route 1 is as follows:

Cell 145, (the Origin Cell, Port of Cherbourg, France), Cells 146, 110, 111, 75, 39, 3, 302, 337, 338, 373, 372, 408, 443, 442, 441, 440, 439, 438, 437, 436, 435, 470, 469, 468, 467, 466, 465, 464, 427, 428, 391, 355, 319, 20, 56, 57, 93, 94, (Intermediate Route cells), and Cell 130 (the Destination Cell, Port of Tokai, Japan).

Route 2: Cherbourg to Tokai Port (near Hitachi)

Route 2 Description: South from France, through the Atlantic, around the southern tip of South America, through the Pacific ocean to Tokai.

Route 2 is described by 39 Marsden grid cells commencing from cell number 145, which contains the location of port of Cherbourg, France and leading to Marsden grid cell number 130 which contains the location of the port of Tokai, Japan. The complete description of Route 2 is as follows:

Cell 145, (The Origin Cell, Port of Cherbourg, France), 146, 110, 111, 75, 39, 3, 302, 339, 375, 411, 412, 448, 484, 485, 486, 487, 488, 489, 454, 455, 419, 420, 384, 385, 386, 350, 351, 315, 316, 17, 18, 19, 55, 56, 57, 93, 94 (Intermediate Route cells), and Cell 130 (the Destination Cell, Tokai Port, Japan).

Route 3: Cherbourg to Tokai Port (near Hitachi)

Route 3 Description: From Cherbourg, France through the Atlantic ocean, through the Panama Canal, through the Pacific to Tokai Port.

Route 3 is described by 26 Marsden grid cells commencing from cell number 145, which contains the location of port of Cherbourg, France and leading to Marsden grid cell number 130 which contains the location of the port of Tokai. The complete description of Route 3 is as follows:

Cell 145 (the Origin Cell, Cherbourg, France), cells 146, 147, 111, 112, 113, 77, 78, 43, 44, 8, 9, 10, 11, 12, 13, 14, 50, 51, 52, 53, 54, 55, 92, 93 (Intermediate route cells), and Cell 130, (the Destination Cell, Tokai Port, Japan).

To evaluate the shipment route casualty rate, it was necessary to estimate the casualty rate on a per ship-mile (nautical mile) basis. This required an estimate of the average annual mileage of a general cargo ship.

Lloyd’s Register’s SeaData database was used for this purpose, which maintains a record of the movements of every registered ship. The movements of five ships (of approximately 4000 Dwt each) over a recent 12 month period were examined. It was found that the average number of days sailed by these vessels was 216 and the average number of ports called was 84.

Independent estimates were also obtained from master mariners both within Lloyd's Register and shipping companies outside of Lloyd's Register. Based on the information gathered, it was concluded that the average annual distance traveled by a general cargo vessel is on the order of 60000 nm. About 15 % of this distance occur in coastal waters or near isles at sea, i.e. 9000 nm. The remainder of the distance sailed is in the open sea. The average sailing speed is about 11 to 12 knots.

The casualty frequency was estimated by dividing the number of casualties over a specified period of time (the six-year period from 1990 through 1995) by the corresponding number of ship-years. Since the size of a typical cargo vessel that could transport radioactive materials is on the order of 4000 dead wt. tons (Dwt). It was decided that it was appropriate to use the casualty data for general cargo ships of 500 Dwt and above. Hence, data for worldwide serious casualties of these vessels was used. The corresponding worldwide fleet for these vessels was found to be 14 820 vessels.

The average casualty rate per ship mile was estimated by dividing the number of casualties by the cumulative nautical miles of the corresponding ships, both evaluated over the period of 1990 through 1995. The coastal mileage was used in the calculation of the grounding accident rate, while the total mileage was used for all other types of casualties.

Port calling statistics (number of vessel visits) during 1997 were obtained from Lloyd's Maritime Information Services (LMIS) for the Cherbourg and Tokai ports. Because Tokai is a small private port, the nearby port, Hitachi, was used as a reference port. Cherbourg had 62 calls, Tokai had only 3 and Hitachi had 138 calls.

The casualty data for 1990 through 1995 did not reveal any casualties in the vicinity of Cherbourg, Hitachi or Tokai. As a result, the period of search was extended to 1980 for these port areas, i.e. Marsden Grids 145 and 130. The extended data sample recorded three serious casualties (one fire and two Hull/Machinery failures) in the vicinity of the Cherbourg port and none near Hitachi or Tokai. Inquiry to the Hitachi port authority through the Lloyd's Register local offices yielded two minor contact accidents in a recent period of six months. One was where a vessel contacted a buoy and the other was where a vessel struck a berth, both occurred while departing. Neither of these two accidents caused any material damage to the vessels concerned, and hence they would not merit inclusion in the estimation of a serious casualty rate.

Hence, the most that could be said about serious casualties would be the occurrence of three serious casualties involving general cargo vessels in a period of 18 years in the vicinity of these three ports (Cherbourg, Tokai, and Hitachi). From the total port callings, this would suggest a casualty rate of 8.2×10^{-4} per visit, or 4.1×10^{-4} per movement, in the port area.

Collision, fire and explosion casualties

Of particular interest in this study is the occurrence of collisions and fire and explosion casualties since these casualties categories are the ones most likely to provide major threats to the containment boundary of a radioactive material package. The terminology Fire and Explosion is a casualty category in the Lloyd's Casualty File and since explosives cannot be carried in cargo holds with Type B accident resistant packages we use the term Fire and Explosion, in this study, to mean the occurrence of a fire.

This study examines the potential for the occurrence of a serious casualty in the approaches to ports or in the port that is near populated regions. Serious casualties involving collisions may occur in approaches to ports because the vessel velocity may be larger than the vessel velocity when the vessel is steering into a berth.

Route analysis and route weighting factors

If the average casualty rates were applied to the distance of each transportation route it would follow that the longest route would have the highest casualty likelihood. This is not always true. It certainly does not allow the comparison of two different routes of equal distance.

To generate a more realistic estimate of the casualty rate per movement on each route, the geographical conditions associated with each Marsden grid cell along the length of the route were examined. Those being the portion of shallow waters or proximity of the Marsden grid cell to coastlines or isles, the traffic density in the cell and, weather conditions, e.g. periods of storm conditions

The magnitude of each weighting parameter was measured in qualitative bands, e.g. Low, Medium and High. The influence of a parameter of a given band on the casualty rate of a particular type was then assessed by allocating a numerical value, named the weighting factor for the parameter. This factor represented a multiplier to the average casualty rate. A value greater than one indicates a casualty rate higher than the average, and a value smaller than one represents a casualty rate lower than the average. If a given casualty type is influenced by more than one parameter, then the product of all relevant weighting factors would apply.

Where there is no weighting factor assigned, it means that the corresponding parameter does not materially influence the casualty rate, or the influence cannot be quantified with meaningful degrees of confidence.

Weighting factor rationale

The rationale for the assigned weighting factors is as follows:

Collisions

The main influencing parameters are traffic levels and weather conditions. The busiest areas from a traffic viewpoint are known to be the English Channel and the Panama Canal. Previous studies performed by Lloyd's Register found that the collision likelihood in the English Channel is several times that of a typical coastal area. It was therefore judged that weighting factor of 5 would be appropriate for areas of HH traffic density such as the English and the Panama Canal. At the other extreme, i.e. in the open sea areas, the traffic is several orders of magnitude lower. An earlier study by Lloyd's, showed that the traffic density in the English Channel ranges from 100 times to 1000 times or more in the traffic 200 nautical miles off Great Britain in the Atlantic Ocean. It was judged reasonable to assume that the traffic density in the HH band was 500 times that in the LL band, which represents deep seas. Since the collision rate for a vessel is approximately proportional to the number of encounters with other vessels, or traffic density, it is considered that the same ratio of 500:1 could be applied to the collision weight factor, hence 0.01 for the LL band. The intermediate values were based on similar logic of assessment.

Regarding weather influence, it was considered that most collisions occurred in bad weather such as storm and poor visibility conditions. However, the influence of weather was not considered to be as significant as the traffic density. It was judged that the likelihood of collision in areas having prolonged period of bad weather (more than 6 months), is probably three times that of the average, while that in areas having calm waters (sheltered) is about half of the average. It follows that for the low storm region (less than 3 months a year, or 0.125 proportion of a year) the weighting factor is 0.8 ($3 \times 0.125 + 0.875 \times 0.5$), and for medium (3 to 6 months a year) and high (greater than 6 months a year) the weighting factors are 1.4 and 2 respectively.

Grounding/Stranding

The main influencing parameter is the proximity of the vessel to coastlines or isles. The grounding likelihood is sensitive to the distance of the shipping lane to the coastlines of isles. Theoretical modeling (Ref. 2) suggested that most accidents arose from ships that originally sailed on shipping lanes within 20 nautical miles of coastlines or isles, but for various reasons deviated from their intended course and ran aground. For practical reasons, it may be assumed that the contribution from shipping outside 50 nautical miles is negligible. Hence, with reference to the base rate (using coastal mileage), the weighting factor can be simply equated to the proportion of waters in a cell within 50 nautical miles of coastlines or isles. The weighting factors allocated for groundings/strandings, represent the middle value of such proportions within the bands. The maximum value is one.

Contact

Contact accidents could also occur in the open seas, such as striking floating containers, ice floes or other objects. The likelihood was considered to be at least an order of magnitude lower than the average. To be conservative, a factor of 0.1 was used.

Fire and explosion

Although these accidents are influenced by parameters such as sea states, it was not considered practicable to quantify the effects without extensive analysis outside the scope of the present study. Therefore, the average casualty rate was used without any adjustment.

Hull machinery failure, foundered, missing

These accidents are mainly influenced by weather conditions such as sea-states. It was considered for simplicity that the same weather weighting factors used for collisions could be applied to these casualties.

The probability of severe marine transport accidents (Ref. 2)

The probability of severe marine transport accidents for Routes 1, 2 and 3 was evaluated by applying the weighting factors, if applicable, to the basic casualty rate information. A complete listing of the distance traversed in each Marsden grid cell on the route and the applicable weighting factors for each grid cell on each of the route is listed in Ref. 2. This information is compiled for each casualty category and each Marsden grid cell on the entire shipment route. The adjustments provided by the weighting factors represent adjustments of the values of the basic accident rates. The final results were summed for all of the grid cells on the routes to determine the casualty rate for each casualty category for each route. The results of this calculation are summarized.

SUMMARY OF CASUALTY RATES PER SHIP MOVEMENT ON DESIGNATED ROUTES.

	Route Distance (nm)	Collision (CN)	Contact (CT)	Wreck/ Strand (WS)	Fire & Explosion (FX)	Hull/ Machine Failure (HM)	Founder (FD)	Missing (MG)	Misc. (XX)	Total
Route 1 (Via South Africa)	18899	7.61E-04	1.19E-04	1.07E-03	5.38E-04	3.42E-03	1.04E-03	3.16E-05	4.25E-05	7.02E-03
Route 2 (Via South America)	17785	6.21E-04	1.27E-04	1.22E-03	5.07E-04	3.32E-03	1.01E-03	3.07E-05	4.00E-05	6.88E-03
Route 3 (Via Panama Canal)	13802	6.15E-04	1.10E-04	1.02E-03	3.93E-04	2.30E-03	7.00E-04	2.12E-05	3.10E -05	5.19E-03

In the Casualty Rate Summary Table above, one can observe the total casualty rates for Routes 1, 2, and 3. These accident rates range between 5×10^{-3} and 7×10^{-3} per ship movement on each route and are of the same order of magnitude. These casualty rates represent the probability of a casualty along the entire route for each of the routes, 1, 2, and 3. Since this represents accident rates for all cells on the route we can extract the casualty rate for the port cells of Cherbourg and Tokai/Hitachi from the source data in Ref. 2. These data are the casualty rates for the port cells of 130 (Tokai/Hitachi) and 145 (Cherbourg) and are presented in the following table. Further, it has been judged that the most significant casualty input might come from the casualty categories of collision, wrecked/stranded, and fire and explosion, the probability of a severe casualty in each of these categories have been totaled. The total probability for port accidents on a ship movement basis for each of the routes is on the order of 8×10^{-4} per ship movement in the initial and terminal ports. The contributing components of this rate are on the order of 2×10^{-4} for collisions and 2×10^{-4} for wrecked/stranded casualties. For fire casualties, the casualty rate is an order of magnitude smaller for port accidents with a rate of 2×10^{-5} casualties per ship movement on the route. Considering the size of the port cells, these port cell accident rates can also provide an estimate of the probability of an accident as the vessel is in the approaches to a port.

It can be reasoned that the casualty category of wrecked/stranded would not cause significant damage to a radioactive material package in a cargo hold since most of the physical damage would occur on the ship bottom with little or no crushing of the package in the hold. If wrecked/stranded were not included with the collisions and fire/explosion data, the total probability of occurrence for a collision and fire in the port cells would be on the order of 2.2×10^{-4}, not a significant change from the probability of 4.46×10^{-4}. Thus, the inclusion of the wrecked/stranded casualty category does not significantly effect the probability of occurrence of a serious accident in the port area.

SUMMARY OF CASUALTY RATES FOR ACCIDENTS IN DESIGNATED PORTS

	Collision (CN)	Contact (CT)	Wreck/ Strand (WS)	Fire & Explosion (FX)	Hull/ Machinery Failure (HM)	Foundered (FD)	Missing (MG)	Misc. (XX)	Total
Cherbourg	9.58E-05	1.09E-05	1.24E-04	1.01E-05	8.04E-05	2.45E-05	7.44E-07	7.97E-07	3.47E-04
Tokai/Hitachi	1.02E-04	8.97E-06	1.02E-04	1.25E-05	1.42E-04	4.34E-05	1.32E-06	9.87E-07	4.13E-04
Sub-total	1.98E-04		2.26E-04	2.26E-05					7.60E-04
	Cherbourg/Tokai (Collision)(Wrecked/Stranded) (Fire&Explosion)			4.46E-04					

Evaluation of the probability of potential releases of radioactive materials in severe marine transportation accidents

As mentioned earlier, we shall use the phenomenology of Ref. 1 to model the potential for release of radioactive contents from casks that might be exposed to serious (severe) marine transportation accidents. The 6 levels of severity for collision range from 1 through 6 with the sixth level nominally being the most severe. Categories 1 through 3 accidents represent accidents that are of minor severity of those with a severity similar to that of the cask certification tests. Category 1 through 3 accidents have no possibility that a release of radioactive contents will occur during the accident sequence. The objective of this section is to calculate the probability of release of radioactive contents from a cask and we shall call this probability P_{ST}.

The supporting information for the cask accident analysis is as follows:

P_{ST} = Source Term Probability (Probability of release of radioactive contents from a cask in a severe marine transport accident)

$P_{Collision} = 10^{-4}$ collisions per port call

$P_{Hold} = 1/7 = 0.143$

$P_{Impact} = 0.0$

$P_{Crush} = 0.1$

$P_{Severe\ Fire} = 10^{-2}$

$P_{Engulfing\ Fire} = 10^{-1}$

$P_{Convection} = 10^{-1}$

$$P_{ST4} = P_{Collision} \times P_{Hold} \times (P_{Impact} + P_{Crush})$$

$$P_{ST5} = P_{Collision} \times P_{Hold} \times (P_{Impact} + P_{Crush}) \times P_{Severe\ Fire} \times P_{Engulfing\ Fire}$$

$$P_{ST6} = P_{Collision} \times P_{Hold} \times (P_{Impact} + P_{Crush}) \times P_{Severe\ Fire} \times P_{Engulfing\ Fire} \times P_{Convection}$$

Probability of collision in ports ($P_{Collision}$)
Ref. 1, Section 3.4.3.1

Ref. 1 examined ship casualty data for the years 1978 through 1993 and port call data for the years 1992 through 1993 to determine the probability that a severe ship collision, ($P_{Collision}$) would occur in the port or while traversing port waters. In addition, the data search also attempted to determine the probability that the collision would lead to a severe fire ($P_{Severe Fire}$). For collisions in US ports, the number of collisions per port call ranged from 10^{-3}, 10^{-4}, and 10^{-5} collisions per port call for high, medium and low traffic ports. Because it was unlikely that spent fuel would be shipped into high traffic ports, it was judged that 10^{-4} collisions per port call were used in the consequence calculations in Ref. 1. An examination of the collisions per port call for representative ports in Japan was conducted by Sandia National Laboratories (SNL) and Lloyd's Register (under contract to SNL-see Ref. 2). The number of collisions per movement as evaluated on routes 1, 2, and 3 were on the same order of magnitude 10^{-4} per ship movement of the routes.

Probability that a RAM Hold is struck (P_{Hold})
Ref. 1, Section 3.4.3.2

If radioactive material packages are shipped singly as is assumed in this study, then (P_{Hold}), the probability that the hold that contains the spent fuel cask is the hold that is struck, equals, $1/N_{Hold}$, where N_{Hold} is the number of holds in the ship transporting spent fuel casks. A typical break bulk cargo vessel used in Ref. 1 had seven holds. Therefore for a typical cargo vessel, with seven hold, $P_{Hold} = 1/7 = 0.143$.

Probability of internal rod impact inside transport casks (P_{Impact})
Ref. 1, Section 3.4.4.3.

Fuel rods may experience impact forces if, during a strong acceleration event, they are driven against the interior of the transport cask, the internal basket or come into hard rod-to-rod contact. Section 3.4.4.3 of Ref. 1 analyzes this probability of occurrence which is designated as P_{Impac}. The analysis conducted in Ref. 1 disclosed low average accelerations, generally on the order of 1 per cent relative to the accelerations expected in US Nuclear Regulatory Commission regulatory accident conditions. Consequently, the impact of fuel rods internal to transport casks are not expected to do any damage to the fuel as the result of collisions in port or on the high seas. Therefore, it was concluded the P_{Impact}=0.0.

Probability of crush forces being applied to a transport cask (P_{Crush})
Ref. 1, Section 3.4.4.4.

P_{Crush} is discussed in detail in Ref. 1 and represents the conditional probability that crushing of a large spent fuel cask will occur. P_{Crush} consists of two components, P_{Solid} and $P_{Contact}$. P_{Solid} represents the probability that the cargo will go solid in character and apply crush forces to the cask. $P_{Contact}$ represents the probability that the bow of the striking vessel will overrun the location of cask. See section 3.4.4.4 for other details dealing with P_{Crush}. Four cargo cases were examined, no cargo, light cargo, medium cargo and heavy cargo. A conservative value of P_{Crush} of 0.4 was determined in the analysis of Ref. 1. In keeping with the rationale in Ref. 1 for packages being subjected to crush it was estimated that the probability of crush might vary from about 0.1 to 0.4 depending on stiffness of the cask. The final total probability is not extremely sensitive to the exact magnitude of P_{Crush} and a value of 0.1 was used for P_{Crush}.

Probability of severe fire ($P_{Severe\ Fire}$)
Ref. 1, Section 3.4.3.3

The fifteen years of Lloyd's casualty data examined in Ref. 1 contained 1073 ship collisions in ports located anywhere in the world. Eleven of these collisions led to fires, five caused extensive fire damage, and one involved buckling of structures due to thermal loads. Therefore the Lloyd's data suggests that the chance that a ship collision leads to a severe fire is about $5/1073 = 4.5 \times 10^{-3}$. Additional referenced studies in (Ref. 1) indicated an average fire probability on the order of 7.0×10^{-3} which was rounded to the nearest order of magnitude suggesting that $P_{Severe\ Fire} = 10^{-2}$. Similar frequences for the occurrence of fires were found in Ref. 2.

Probability that a severe fire engulfs a RAM cask ($P_{Engulfing\ Fire}$)
Ref. 1, Section 3.4.3.4

$P_{Engulfing\ Fire}$ is the probability that a severe fire starts on or spreads to a deck where a radioactive material cask is stowed, and then completely engulfs the cask. Studies referenced in Ref. 1 indicate that for fires which occur on typical break-bulk frieghters while the ship is in port 3.7 per cent of such fires involve one deck in a single hold and 2.3 per cent of the fires involve all of the decks in single hold and 3.0 per cent of the fires involve the entire vessel. Typical break-bulk freighters examined in Ref. 1 have 21 decks in 7 cargo holds. Each cargo hold may have 2, 3, or 4 decks. In Ref. 1, the probability of occurrence of fire spreading to other decks in holds with two, three or four decks was determined and weighted to determine the probability of occurrence of a engulfing fire to be on the order of 10^{-1}. This value is considered to be reasonable, although a conservative estimate, that a severe fire will occur and spread to the deck of a break-bulk freighter and fully engulf the cask.

Probability of convective flow through the failed cask ($P_{Convection}$)
Ref. 1, Section 3.4.4.6

The source term probability that enough convective airflow occurs through the transport to cause the element Ruthenium to be oxidized to RuO_4. In a review of ship fire data and the temperatures required to oxidize Ru to RuO_4 (See Section 3.4.4.6 of Ref. 1) disclosed an estimated value of 0.1 for $P_{Convection}$.

The probabilities of occurrence of marine transport accidents that could potentially cause a release of radioactive contents were evaluated using the input information given above. The probability of a serious cargo vessel accident on each of the three transport routes, per ship movement on the routes, is presented earlier. The greatest likelihood of a serious transport accident occurrence is when the vessel is in approaches to port waters or in port waters. The probability of occurrence of a serious port accident was extracted from Ref. 2 for the ports of Cherbourg and Tokai/Hitachi. Further, it was judged that collisions, wrecks/strandings, and fires/explosions were the casualty categories that would provide the most serious damage to a transport cask. The probability of occurrence of a serious accident in port waters (per ship movement on a route) is on the order of 4 $\times$ 10^{-4}. This value was used to determine the probability of a serious accident occurrence (an accident occurrence which involves collisions, wrecks/strandings and fires/explosions). The probability of occurrence of such a severe accident is conservatively estimated as being on the order of 1 $\times$ 10^{-4} per ship movement through port waters. Thus, this value is used to calculate the probability of occurrence of a serious ship accident in port waters. The phenomenology of the work in Ref. 1 was incorporated into the probability calculations that extended the work of Ref. 2 to estimate the probability that a severe collision in a port could provide a release of radioactive material, the health effects of which can be determined using state-of-the art risk assessment analysis codes.

Concluding remarks

This analysis has produced an engineering estimates that characterizes probability of cargo vessel transportation accidents on three designated routes between Japan and Europe. These route estimates have been further examined to produce an estimate of a severe cargo vessel accident. These accident probabilities have been used in conjunction with the phenomenology of cask response for severe spent fuel transportation accidents to estimate the probability of a release of radioactive contents due to a severe accident. The probability of cargo vessel transportation accidents in ports or approach waters to ports is displayed. Category 4 accidents were estimated to be on the order of 1.4 $\times$ 10^{-6} per vessel movement on the route. A category 5 accident probability of occurrence was estimated to be on the order of 1.2 $\times$ 10^{-9}. A category 6 accident was estimated to be on the order of 1.3 $\times$ 10^{-10}. The probability of a severe cargo vessel transportation accident in a port that might release radioactive material ranged between 10^{-9} to 10^{-10} per ship movement. These probability estimates can be used in risk assessment studies to estimate the health effects of such accident occurrences.

The probability of a serious cargo vessel accident was developed for cargo vessels similar in size to purpose-built vessels that have been developed for performing the international marine transportation of radioactive materials. None of the features of a purpose-built vessel have been invoked in this study. Therefore, the estimated probability of occurrence of a serious cargo vessel accident, as presented in this analysis, is much larger (more probable) than the probability of occurrence of such an accident with a purpose-built cargo vessel.

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Annex 5

STUDY OF ACCIDENT ENVIRONMENT DURING SEA TRANSPORT OF NUCLEAR MATERIAL: ANALYSIS OF AN ENGINE ROOM FIRE ON A PURPOSE BUILT SHIP

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OBJECT

The program goal was to show the IAEA safe transport regulations adequately cover the thermal effects of an engine-room fire on plutonium transportation packages stowed aboard a purpose built ship. The packages are stored in transportation containers located in a cargo hold of the ship. For this study, it was assumed that the package in No. 5 hold adjacent to an engine room could be subject to heating due to a fire in the engine room. The No. 5 hold is separated from the engine room by a water-filled bulkhead. This study addressed the heat transfer from an engine-room fire that could heat and evaporate water out of the water-filled bulkhead and the resulting temperature conditions around the packages and inside the packages near their elastomeric seals.

This study was performed by joint research between Power Reactor and Nuclear Fuel Development Corporation (PNC) and Sandia National Laboratories (SNL). The study was designed to estimate the thermal response of a plutonium package in the hold of a purpose built ship during a shipboard fire. And furthermore, to confirm the sufficiency and adequacy of the current IAEA transport regulation.

ACTIVITY

Description of purpose built ships

Purpose-built ships for nuclear transport were designed to provide enhanced protection for the ships, crews, and their cargo, thus increasing the safety and reliability of transportation operations. The ships are constructed with a double hull. The inner shell that embraces the cargo space is formed by watertight, transverse bulkheads. The structure and subdivision of the hull are designed so that the vessel will stay afloat after it has sustained damage. Wing tanks formed by this construction are used for normal ballast and trimming requirements except for the tanks abreast of No. 5 hold, that are allocated for holding bilge water. The wing tank space is also structurally stiffened against impact damage that could be sustained by packages within the holds in the event of a collision with another vessel.

Wing space is also used to provide all-weather passageways on both sides of the ship, immediately below deck level for access to the holds and forward plant rooms. Subdivision of the hull is preserved throughout the passageways by the use of watertight doors.

Cargo handling

The transport packages are loaded into the available holds in ISO-containers. These transportation containers are ~2.4 × 6 × 2.6 m, are stacked transverse to the ship axis (their long dimension faces the bulkheads between the holds). The No. 5 hold is large enough to be loaded with three rows of ISO-containers stacked three high. Each ISO-container can hold 10 plutonium packages.

Segregation between the cargo space and the normally occupied space is provided by radiation shielding in the form of a water tank extending the full width and depth of the cargo hold at the aft end of No. 5 hold. The tank is formed by two transverse bulkheads (each 40-mm thick) that are separated by 750-mm of water space. Radiation shielding is extended forward from the bridge by concrete overlaid on the deck and beneath the hatch covers.

Ambient temperature in the cargo holds can be controlled within the limits of -40°C to +38°C. This has been achieved by providing two forced circulation air chillers in each hold, which reject the heat directly to sea. The chilled air is ducted to distributors low down in the hold and extracted at a high level using axial flow fans.

Each air chiller consists of two independent refrigerator units sharing a common air-circulating duct. Actual loading conditions can usually be met by running only one refrigerator. The heat is rejected to sea directly by sea water circulating pumps. All essential components of the systems are duplicated.

Even upon complete failure of the hold air cooling systems, the packages will reach an acceptable thermal equilibrium at all outside ambient air temperatures. In a conservative analysis of a thermal heat transfer due to an engine room fire, the active cooling will be assumed to be inoperable during the fire.

Cargo

Plutonium is transported in packages designed and approved in accordance with regulations of the International Atomic Energy Agency (IAEA). This study was done using a PNC surrogate plutonium package instead of an FS-47 package. The surrogate plutonium package was typical of packages approved for transporting uranium oxide, plutonium oxide and mixed uranium and plutonium oxide powders packed in storage cans.

Ship thermal characteristics

The double hull structure, overhead radiation shielding, and water-filled bulkhead need to be taken into account when developing a model for thermal analysis of heat transfer from a fire aboard ship. In the simulation, heat was allowed to flow from the holds through the double hull structure, the wing tanks, and passageways to an ambient temperature outside of the ship. Heat was also allowed to flow through the deck, the ship fuel storage areas between the deck and hull to an ambient temperature below the ship. The overheads are connected to outside ambient air through their concrete shielding.

Engine room fire scenarios

In this study, fuel was assumed to leak from local storage tanks and cover the entire deck of the engine room. The fuel ignites and the fire reaches up to the overhead covering the full area of the water-filled bulkhead, resulting in maximum heat transfer into the No. 5 hold.

A pool fire with sufficient oxygen will have a fire temperature of approximately 982°C [1]. Such a pool fire will consume fuel with a linear recession rate [2] of 4.7mm/min for large pool fires — those with characteristic sizes of 3 m or greater. Fuel in the engine room is stored locally in service and settling tanks. For this analysis, a fire might be fed from the primary service tanks and settling tank, which contain approximately 50 m^3, or 50 000 liters of fuel. In the event of an engine-room fire, this fuel might be spilled across the deck of the engine room, supplying enough fuel for a two hour fire.

An engine room fire

In the fire scenario, there is a fire in the engine room adjacent to the water-filled bulkhead, and the cooling system in the No. 5 hold is off. Such a fire was assumed to quickly engulf the full surface of the bulkhead, heating it uniformly over its surface. Under these conditions, the water in the bulkhead would be heated from 38°C (the ambient regulatory temperature) to 100°C in ~64 minutes. Over a period of two hours the water level in the water filled bulkhead would be decreased by 1 meter if the water were lost due to heating and evaporation.

The thermal heat transfer process into the No. 5 hold can be evaluated in two stages:

Stage 1: heat transfer through the water-filled bulkhead during heating of water from 38°C to 100°C.

Stage 2: evaporation of the water in the water-filled bulkhead with heat transfer below the water line with the water at 100°C and higher temperatures above the water line.

From these assumptions a set of thermal boundary conditions can be established. The water-filled bulkhead starts at 38°C temperature and is heated to 100°C by the engine-room fire. As the fire continues and the water evaporates, the bulkhead area above the water-line will be heated to a much higher temperature (~508°C) providing a higher temperature heat-transfer process over an increasing bulkhead area in the No. 5 hold.

Fuel for an engine-room fire could come from a rupture in a service tank or settling tank or a fuel line leading to or from a tank. If the leaking fuel forms a pool on the deck of the engine-room, this fuel ignites, and there is sufficient oxygen present, the fire would reach up to the overhead in the engine-room. For this analysis we conservatively assume the fire quickly covered the entire surface of the bulkhead. The fuel would cover the engine-room deck, approximately $10.6 \times 9.1 m^2 = 96.5 m^2$. The resulting fire would rise to a height near that of the overhead, fully engulfing the area of the water-filled bulkhead in the engine-room.

Derivation of bulkhead temperatures

An open pool fire with a readily available oxygen supply was assumed for these simulations. From this heat source, an equilibrium temperature can be determined for the bulkhead on the far side of the water-filled bulkhead. While water is present in the water-filled bulkhead, the bulkheads in contact with the water would be at a maximum temperature of 100°C where the thermal properties of water at standard pressure and temperature are assumed to apply.

When no water is present, an equilibrium temperature for the far-side bulkhead can be derived by assuming steady state conditions. Consider the scenario with a fire in the engine room adjacent to the water-filled bulkhead.

Assume the following: a fire temperature of 982°C with a fire emissivity of 0.9, that the bulkhead between the No. 5 hold and the No. 4 hold (referred to here as bulkhead 3) is at 38°C, that the space between two bulkheads comprising the water-filled bulkhead and the bulkhead between holds No. 5 and No. 4 is a transparent medium, and that the thermal gradients through the bulkheads are small. For two infinitely large, parallel plates with a uniform temperature (a reasonable assumption for this conservative analysis), a steady state radiative heat transfer analysis predicts that the water-filled bulkhead on the No. 5 hold side would be heated to 508°C. Therefore, the No. 5 hold-side of the water-filled bulkhead above the water in Stage 2, will have a temperature of approximately 508°C.

Stage 1: Heating of the water-filled bulkhead

A water-filled bulkhead separate the engine room from No. 5 hold, comprised of two, 40-mm thick steel bulkheads separated by 750 mm. The space between these bulkheads is filled with water. This steel and water barrier provides both radiation shielding between the cargo area and the crew area of the ship and a thermal barrier in the event of a fire. The 40-mm bulkheads extend the full breadth of the ship, and are approximately 15.6 m wide and 8 m high (extending from the lower hull up to the upper deck). The cargo and engine room are, however, approximately 8.5 m wide, due to the double hull.

When water is present in the water-filled bulkhead, the bulkhead temperatures below the water line will be at their initial uniform temperature due to the high thermal conductivity of the water. This bulkhead is conservatively assumed to initially be at 38°C.

The two steel bulkheads comprising the water-filled bulkhead, each 40-mm thick, have a total mass of 40 000 kg. The volume between the two thick bulkheads is 95.4 m^3. The total mass of the water is then 94 900 kg. Since the heat capacity of steel is 452 J/kg-K and that of water is 4175 J/kg-K, the energy required to heat the water-filled bulkhead from 38°C to 100°C is 2.7×10^{10} J. The time required to heat the water-filled bulkhead is then 63.9 minutes.

Stage 2: Evaporation of the water out of the water-filled bulkhead

The latent heat of evaporation of water is 2.255×10^6J/kg. The energy required to evaporate the water is then 2.14×10^{11} J. The time required to do this can be estimated again. The water-filled bulkhead would be at 100°C below the level of the water during this stage. Above that level, the bulkhead was assumed to be at 508°C. The heat flow from the fire into the water is determined by the vertical surface area of the water in contact with the bulkhead. Under the modeling assumptions used here, the evaporation rate will be constant, with the water level decreasing at a constant rate of 2.65×10^{-4} m/s.

Simulation model of an engine-room fire thermal heat transfer process

During an engine-room fire, heating the water-filled bulkhead from 38°C to 100°C would not generate a temperature increase of concern for packages in the No. 5 hold aboard ship. Elastomeric seals used in the construction of the packages are designed not to fail below 230°C [3, 4, 5] and higher under certain conditions [3]. The greatest possible heat transfer to the packages would be expected to occur sometime during Stage 2, in which the water in the water-filled bulkhead is evaporating and the bulkhead above the water level is reaching 508°C. Absorption of radiant energy by water vapor and steam cooling of the water-filled bulkheads are neglected in this conservative analysis.

To model Stage 2 in the engine-room fire scenario, a simulation with a state-of-the-art, time-dependent, 3D, thermal, computational fluid dynamics code is required. The hull, port and starboard bulkheads, and the bulkhead to the No. 4 hold are thermally connected to an ambient temperature sink. The overhead of each hold is covered with concrete, which would act as an insulator in this fire scenario, and the water-filled bulkhead would act as a thermal source. Heat transfer by convection would dominate at low temperatures on all ship, container, and package surfaces. As the upper portion of the water-filled bulkhead is heated to 508°C, radiation from this hot surface would become the dominant heat transfer mode to the first row of ISO-containers, which have a direct view of the hot bulkhead. Convective airflow established in this region would provide an additional heat transfer mode to all the containers and needed to be evaluated in detail.

For this simulation, the CFX code from AEA Technology is the best code currently available that incorporates all of the required heat transfer modes (conduction, convection, and radiation). For this study, the simulation was conducted in two parts. In the first part, the simulation concentrated on the heat transfer from the water-filled bulkheads to the ISO-containers. In the second, detailed heat transfer into a package was determined.

For the first simulation, the ISO-containers were modeled as two rows of containers: the row nearest the water-filled bulkhead was treated as a single unit and the two farthest rows were treated as a second unit. These assumptions allow evaluation of the radiative coupling to the first row of ISO-containers, while accounting for the thermal sink presented by the two farthest rows. A more detailed simulation also was performed to assess heat transfer to the packages in an ISO-container.

In the first model, the bulkheads, overhead, and deck were assumed to be 15-mm thick and made of carbon steel, except for the water-filled bulkhead, which is 40-mm thick. The water-filled bulkhead was treated as a heat source. The overhead, which is covered with concrete, was assumed to be an adiabatic surface. The deck, port and starboard bulkheads, and bulkhead between the No. 5 and No. 4 holds were assumed to be connected to an ambient temperature of 38°C. The ISO-containers and packages were assumed to be at 38°C in the simulation.

The hold is approximately 8.5 × 13 × 9.1 m. ISO-containers are ~2.4 × 6 × 2.6 m in three rows stacked three high and loaded transverse to the ship axis (their long dimension faces the water-filled bulkhead). The ISO-container walls are ~1.5-mm thick steel. Each container can have 10 packages in it. The surrogate plutonium packages have 1.5 mm stainless steel walls around a balsa layer.

The first row of ISO-containers were treated as a single volume and the packages were treated as a single surrogate package in order to understand the principle heat transfer mechanisms from the water-filled bulkhead, through the ISO-container walls, to the packages. The front surface areas of the ISO-container and packages facing the water-filled bulkhead were preserved in order to account for the dominant radiation heat transfer to these surfaces. The second two rows of ISO-containers were also treated as a single volume with a single surrogate package. The thermal mass and conductivity of the surrogate packages and lumped ISO-containers was designed to generate a good estimate of typical individual ISO-container and package temperatures from the simulation.

The simulation accounts for conduction through the bulkhead, deck, overhead, ISO-container walls, and package walls. It uses convective and radiative heat coupling to all surfaces, calculating the heat flow in detail at each node. And it models the airflow within the No. 5 hold, and inside ISO-containers around the surrogate packages.

The simulations were done separately for the two stages described above. In all stages, the water-filled bulkhead was treated as a temperature source. In Stage 1, it was assumed to start at 38°C and rise linearly with time to 100°C over 63.9 minutes.
In Stage 2, the water-filled bulkhead started at a uniform 100°C. As time progressed and the water level decreased in the water-filled bulkhead, the area of the bulkhead above the water level was changed to 508°C. This provided an increasing heat flow into the No. 5 hold and increasing radiative heat transfer to the ISO-containers and packages.

Results from the two stages were then used to establish boundary conditions on an ISO-container for heat transfer to a surrogate plutonium package.

Stage 1 simulation

In the Stage 1 simulation, the same model for the No. 5 hold, ISO-containers, and packages was used. During the time that the water in the water-filled bulkhead rose from 38°C to 100°C, the peak temperature from the simulation of the first row of ISO-containers was 52°C. From the same simulation, the surrogate package reached a peak temperature of 42°C. That temperature would not compromise the integrity of the seals in the packages even when taking into account the internal heat from the plutonium.

Stage 2 simulation

The ambient temperature for this simulation was assumed to be 38°C, since this temperature is described as ambient temperature in the IAEA regulations and provided a conservative simulation for the heat transfer.

The No. 5 hold was modeled with ~40,000 nodes and used millimeter grid spacing near all conducting surfaces. The airflow was treated as buoyant with a k-ε model for turbulent flow.

During the first half-hour of the simulation, the airflow in the No. 5 hold established a single large cell between the water-filled bulkhead and the first row of ISO-containers. The air flowed vertically upward near the water-filled bulkhead with varying velocities and downward near the first ISO-container model. The peak velocity at this time was approximately 0.6 m/s (rising to ~0.8 m/s at 2 hours). Note that there was a significant flow over the top of the ISO-containers.

After approximately 120 minutes as the area of the 508°C bulkhead increased, radiative heat transfer to the front of the ISO-containers established an upper level, hot, airflow cell, and a cooler, counter rotating air cell below that. This division in the airflow results in a larger convective coupling between the hot bulkhead and the upper level of the ISO-containers in contact with the upper cell than the convective coupling with the lower, cooler cell, an effect which would not be accounted for in a simpler analysis.

The temperature of the ISO-containers started at 38°C, the initial boundary conditions in the simulation, and within 5 minutes came up to 40°C, a level consistent with the water-filled bulkhead being at 100°C. Even if the engine-room fire continues for two hours, the surface temperature of the ISO-container which affects the environmental temperature of the surrogate package only increases to 89°C. Because there is no significant environmental temperature rise after extinction of the fire, the accident condition of 800°C for 30 minutes specified in the IAEA regulations is sufficient and adequate for a 2-hour engine-room fire.

Simulation model of a surrogate plutonium package in an ISO-container

The temperature change near the seals of a surrogate plutonium package was simulated in a more detailed model of a package aboard a purpose-built ship. This model included a surrogate plutonium package in an ISO-container. The transient boundary conditions for this model were obtained from the large-scale, No. 5 hold model described above. The model had ~20 000 nodes and used millimeter grid spacing near all conducting surfaces. The airflow was treated as buoyant with a k-ε model for turbulent flow. Details of the surrogate plutonium package, its properties, and initial conditions were obtained from PNC. The initial surface temperature for the surrogate plutonium package was 38°C. The temperature at which the package would be if it were not loaded with plutonium, which fuel acts as an internal heat source. The simulation was run with these initial conditions, and the resulting temperature changes determined during a two-hour engine room fire. The result for packages with fuel was then determined by the principle of superposition [6] adding the temperature changes obtained in the simulation to those determined in the PNC analysis of the surrogate plutonium package for normal conditions of transport.

CFX model description

CFX was used to model the surrogate plutonium package in an ISO-container. The top ISO-container nearest the water-filled bulkhead received the greatest heat flux from an engine room fire and was the one modeled in this conservative simulation. The ISO-container was modeled with a single surrogate plutonium package near a plane of symmetry. The walls of the ISO-container are stainless steel with an emissivity of 0.8. The front, back, and side walls, and the top of the ISO-container each have time-dependent temperatures obtained from the No. 5 hold simulations. The floor of the ISO-container modeled is treated as an adiabatic surface since it is resting on another ISO-container in the No. 5 hold.

The surrogate plutonium package model

The balsa layer of the surrogate plutonium package was modeled in this simulation, as was the air between the package and the ISO-container walls. The inner surface of the balsa layer is conservatively treated as an adiabatic surface boundary. The critical area of the container seals is near the upper lip of the balsa region. The time-dependent temperature history of this area is presented in detail in the full report.

The air surrounding the surrogate plutonium package is modeled as a weakly compressible fluid with buoyancy. Conduction, convection, and radiation are modeled in this region. The simulation accounted for conduction through the ISO-container and package walls. It used convective and radiative heat coupling to all surfaces and it modeled the airflow within the ISO-containers around the package.

The time-dependent temperatures of the ISO-container walls were obtained from the No. 5 hold simulations. The heat from the walls was coupled to the surrogate plutonium package via radiation and convection. It then flowed into the package by conduction, with the temperature dependent conduction obtained from earlier PNC studies.

Simulation results

At five minutes into an engine room fire adjacent to the water-filled bulkhead, the surrogate plutonium package/ISO-container model temperatures and the airflow are minimal. The surface temperatures were fairly uniform at this time. The peak airflow velocity was ~0.07 m/s (rising to ~0.22 m/s 2 hours into the simulation). At 15 minutes into an engine-room fire, gradients in temperature began to appear and the left-hand side of the package appears warmer than the right. At 30 minutes, the temperature gradients are clear. Approximately one hour into an engine-room fire near the water-filled bulkhead, the water in the bulkhead reached 100°C and began to boil off. The bulkhead above the water line then reached temperatures above 100°C, and significant heat transfer from this warmer bulkhead was by way of radiation.
At this point in the simulation, the surface temperatures inside the upper ISO-container are obvious. The ISO-container wall on the left side and the left side of the package are clearly at a higher temperature than the right. Two hours after the start of the engine room fire, there is a 10°C temperature difference from the left to right external surface of the package.

This is the maximum length of fire considered for this simulation of a fire in the engine room near the water-filled bulkhead. It is unlikely that there would be sufficient fuel to burn this long or that a fire would continue unabated for so long a period on a purpose-built ship.

Internal temperatures in a surrogate plutonium package

The external surface temperatures provide a picture of the environment a package might be exposed to in the case of an engine room fire. This detailed simulation also provided information on heat flow into the package. The temperature of the inside of the surrogate package changes little during the two-hour engine-room fire. The temperature information from this heating portion of the simulation can be used to determine the maximum temperature near the seals in the surrogate package over longer time scales.

A 1-D model of the package, using PATRAN/Pthermal from MacNeal-Schwindler Corporation, was developed for determining the temperature increase near the area of the seals over long time scales. This model assumed that the package contained a 100 W internal heat load from the plutonium that resulted in a uniform, internal heat flux. For an ambient temperature of 38°C, the radial temperature distribution through the package near the area of the seals was obtained for normal conditions of transport. A package loaded with plutonium for transport will have an internal temperature near the seals of 90°C in steady state.

Seal area temperatures

To determine the temperature change near the seals, the 1-D model was run with the ISO-container wall increasing in temperature from 38°C to 82°C in accordance with the 3-D simulation results. Heat flowed from this surface to the package through radiation, convection and conduction.

For a two-hour fire in the engine room, the temperature time-history of the inner surface of the surrogate plutonium package balsa near the area of the containment vessel seals was obtained (Fig. 1). The left-hand curve is the temperature history of the warmest region of the external surface of the surrogate plutonium package. The right hand curve is the corresponding temperature response of the internal surface near the seal area. The external surface increases in temperature by 36°C as a result of the fire. While the internal surface responds to this change, increasing by only 4°C.

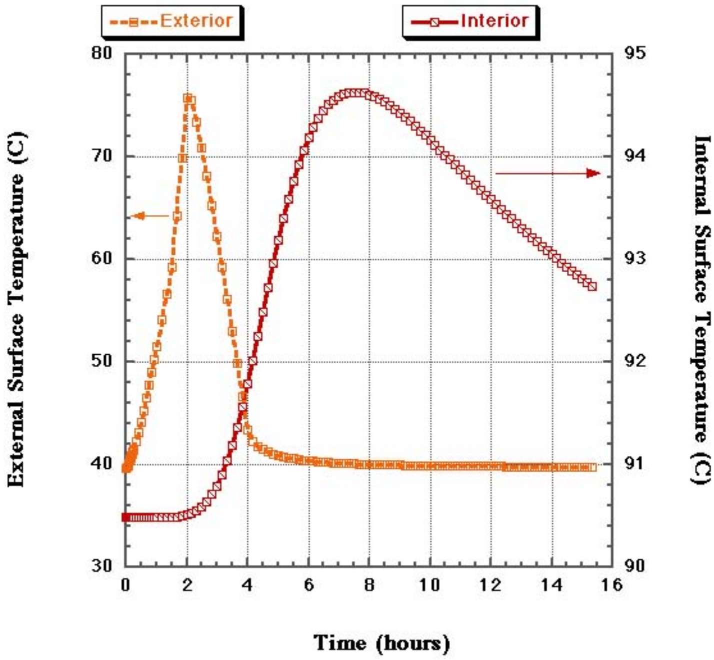

FIG 1. Surrogate plutonium package temperature response for a two-hour engine-room fire.

Thermal analysis of the surrogate plutonium package shows that the peak temperature of the seal region of the surrogate plutonium package occurred approximately 6.5 hours after the start of the fire reaching a maximum temperature of 94.6°C.

It is clear that even in this case, the seal area inside the package stays below the 230°C manufacturer's limit for the operating range for the elastomeric seals for this 2-hour fire duration.

The water in the water-filled bulkhead, however, will cool down slowly. Therefore the ISO-container wall will continue to be heated for a longer period of time. A 1-D model for the package with its internal heat source and an ISO-container wall fixed at 100°C was developed. This model simulated the scenario in which the No. 5 hold was heated by a two-hour engine-room fire, and the hold remained at 100°C for an extended period of time. Analysis of this model showed that the peak temperature near the seal area would only reach ~142°C approximately 50 hours after the start of the two-hour engine-room fire. This simulation provided an upper limit for the temperature of the seal area. The recommended lifetime for elastomeric seals at a constant 142°C is over 1000 hours [3]. Therefore the thermal environment even in this conservative scenario did not threaten the integrity of the seals.

CONCLUSION

The well-planned construction of purpose-built ships provides excellent protection for sea transport of plutonium oxide powder in packages from an engine-room fire thermal event.

This study indicated that the fire accident condition of 800°C for 30 minutes specified in the IAEA regulations is sufficient and adequate for a 2-hour engine-room fire. The surface temperature of the ISO-container which affected the environmental temperature of the surrogate package only increased to 95°C after a 2 hour fire, or 142°C in the case where the No. 5 hold remains at 100°C for an extended period of time. Seals of the surrogate plutonium package transported in the No. 5 hold stayed within their design temperature range after a 2-hour engine-room fire.

The seal integrity was maintained in spite of the following conservative assumptions:

1. Ambient temperature was 38°C for the local air temperature, ship hold temperature, and the initial water-filled bulkhead temperature, and the refrigeration units in the No. 5 hold were off during the engine-room fire.
2. Spilled fuel from a settling tank and two service tanks was available for supporting a two-hour fire.
3. There was sufficient oxygen resulting in a fire temperature of approximately 982°C.
4. The engine-room fire adjacent to the water-filled bulkhead engulfed its full surface and heated it uniformly over its exposed surface.
5. When no water is present, an equilibrium temperature for the far-side bulkhead can be derived by assuming steady state conditions, with the bulkheads treated as infinitely large, parallel plates with a uniform temperature.
6. The space between two bulkheads comprising the water-filled bulkhead and the bulkhead between holds No.5 and No.4 is a transparent medium and absorption of radiant energy by water vapor and steam cooling of the water-filled bulkheads are neglected.
7. Thermal gradients through the bulkheads are small.
8. The overhead, which is covered with concrete, and the inner surface of the balsa layer were adiabatic surfaces.

During the stage of a fire in which water in the water-filled bulkhead is being heated, packages in the No.5 hold will not rise in temperature beyond the seal operating temperature since the water can only be heated to 100°C.

For an ongoing engine-room fire, two convection cells would be established in the No.5 hold in this model, posing changing thermal heat transfer modes to upper and lower ISO-containers; the upper ISO-containers are subject to the highest heat flux. The seal area will remain within its temperature-operating region for the two-hour fire.

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Annex 6

PROBABILITY AND SEVERITY OF FIRES ON BOARD SHIPS CARRYING RADIOACTIVE MATERIALS

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Abstract

This paper summarises the five UK contributions to the International Atomic Energy Agency's Co-ordinated Research Programme (CRP) on Accident Severity at Sea During Transport of Radioactive Material (CRP) on Accident Severity at Sea During Transport of Radioactive Material [1].

INTRODUCTION AND BACKGROUND

At the outset of the Co-ordinated Research Programme (CRP) on Accident Severity at Sea During Transport of Radioactive Material, concerns about the safety of transport of certain radioactive materials in large quantity had been addressed by the adoption by the International Maritime Organization's Assembly of the "Code for the Safe Carriage of Irradiated Nuclear Fuel and High Level Radioactive Wastes in Flasks on Board Ships" (INF Code). Concerns nevertheless remained in some quarters about the ability of flasks to remain safe in certain severe accident scenarios, particular to the marine transport mode. One such concern was the adequacy of the IAEA's fire test specification in the light of fire accident reports which showed average ship fire durations of ~20 hours.

The INF Code requires extensive fire detection and suppression measures on the ships carrying the largest quantities of INF material (INF 3). Nevertheless substantial quantities of INF material can be carried on ships meeting the intermediate (INF 2) standard. Therefore, as the cross channel roll-on roll-off (RO-RO) railroad ferry "Nord Pas-de-Calais" was in service to transport spent fuel from mainland Europe to the UK, it was considered appropriate to study this particular INF 2 ship in some detail with regard to fire accident conditions.

SCOPE OF UK STUDIES

Historical records were investigated to obtain an indication of the frequency, duration and severity of ships fires, particularly those which may have had the potential to pose a threat to the integrity of the Type B(U) or Type B(M) packages used to carry radioactive material in large quantity, such as irradiated nuclear flasks.

Data on ships fires were available at the International Maritime Organization (IMO), in the form of annual reports of incidents to the IMO's Fire Protection Committee and further data was available from other sources such as Lloyds Register of Shipping and from the Department of Transport's Marine Accident Investigation Branch.

There was no record in any of the data studied of a case where a Type B(U) or Type B(M) package was present on a ship where a fire incident has taken place of sufficient severity to have posed any threat to package integrity. Therefore analyses were carried out to produce an estimate of the frequency of fires on ships of capacity greater than 500 grt of all types which would have been suitable to carry Type B(U) or Type B(M) packages. Thus data for tankers and liquefied gas carriers were not included.

However, the usefulness of historical data to the current studies was limited, particularly as a means to estimate fire severity and duration. Such estimates were needed which might be compared against the standard IAEA fire test conditions which apply to Type B(U) and Type B(M) packages. These packages are designed with safety margins in hand relative to the test requirements and may be expected to fail progressively under conditions exceeding those of the regulatory tests.

Thus data for fire frequency was selected on the basis of qualitatively defined "severe fires", or "qualifying incidents" of fires/explosions, having the potential to threaten package integrity, but there was insufficient historical data to determine whether such incidents would in fact have caused any loss of integrity had a package been present during the incident. Thus the frequency data derived in these studies are very much upper-bound estimates of the frequency with which some loss of package integrity *might* occur and should not be read as frequencies with which loss of integrity *would* occur.

In order to establish the likely fire temperatures and durations to which a flask of irradiated fuel might be subjected, which could not readily be established from historical data, further work was carried out, using fire modelling techniques. Studies of the growth of fires initiating on the rail deck and in the engine room of the "Nord Pas-de-Calais" were performed to obtain temperature and duration data for this particular ship which would be representative of an INF 2 roll-on roll-off (RO-RO) rail/road ferry carrying mixed cargo.

ASSESSMENT OF FREQUENCY OF FIRE ON A VESSEL CARRYING IRRADIATED NUCLEAR FUEL [1]

A search was made of possible sources of information on shipping incidents. After consideration of the merits of various options, data on fires and explosions were purchased from Lloyd's, covering world-wide shipping, for the period 1984-93. A further similar purchase of data provided information relating to the number of ships in existence, with ship types categorised to be compatible with the fire records.

An analysis of the data was carried out to determine how many incidents would have been a potential threat to a nuclear flask, had one been carried as a cargo item. Oil tankers and liquefied gas carriers were excluded because of their inability to carry flasks.

The resulting fire frequency of 2.9×10^{-4} per ship·year was based on a total of 93 incidents identified according to specific criteria. If these criteria had not been applied, the fire frequency would have been 2.6×10^{-3} per ship·year. None of the fire incidents contributing to the main result arose as a result of a preceding collision.

The much lower rate of total losses from all causes for the UK compared with a world-wide basis is a good indication that the fire frequency quoted above is pessimistic. It is to be expected that ships meeting the INF 2 or INF 3 requirements should suffer lower, or considerably lower, fire frequency in view of the additional fire safety features required by the INF Code, compared with those of general shipping from which the fire frequency data was derived.

FREQUENCY OF A SEVERE FIRE ON THE FREIGHT FERRY "NORD PAS-DE-CALAIS" [2]

The ferry "Nord Pas-de-Calais" entered service for SNCF in December 1987, and up until 1996 completed three round trips every day between Dover and Dunkirk. It has two through decks, both of which can transport lorries; however the lower one is fitted with rails for the transportation of rail wagons. This lower deck can also be subdivided to separate "hazardous" from "non-hazardous" materials. Irradiated fuel was transported on a rail wagon in the "non-hazardous" area.

Having proposed a number of definitions for a "severe fire", two were selected as being appropriate. For a fire initiated in the non-hazardous area of the rail deck, a severe fire is defined as one which threatens the cargo. For a fire initiated in the compartments adjacent to the non-hazardous area of the rail deck, a severe fire is defined as one which breaches the containment of that compartment.

Shipping statistics from a range of sources were studied to establish credible frequencies for fires on ferries. The fire statistics published by the Marine Accident Investigation Branch of the Department of Transport were finally selected as the basis for calculating the frequency of fires on the rail deck and in adjacent compartments of the ferry. These were the initiating fire frequencies from which event trees were developed.

An event tree consists of an initiating event - in this case the initiating fire - and a series of branches, each denoting a possible outcome of a chain of subsequent events. A series of event trees were drawn to investigate under which circumstances an initiating fire could develop into a "severe fire". The frequency of these "severe fires" was calculated by assigning probabilities to each of the branches of the event trees.

Of the areas investigated, the highest frequency of a "severe fire" was found to be one initiating in the machinery space (i.e. separator/engine/generator area) of the ferry, the frequency of which was estimated as 3.8×10^{-3} per year. The second highest was a fire initiating on the lorry deck while the ferry was at sea, estimated as 1.7×10^{-3} per year. The overall frequency for a "severe fire" developing on the "Nord Pas-de-Calais", taking account of all scenarios, was estimated to be 7×10^{-3} per year. Assuming fifty flask movements annually, the frequency of such a fire developing while a flask is on board would be less than 2×10^{-4} per year.

It should be noted that this frequency is not related to any failure mechanisms of the flask, which are designed to withstand the specific fire criteria laid down by the International Atomic Energy Agency. The severity, in terms of fire temperatures and durations, also needs to be established in order to assess the threat of fire to a package. Further work was put in hand to quantify these.

STUDY OF TYPICAL TIMES FOR THE DURATION OF A SHIP FIRE [3]

Having established estimates for the frequency of a "severe fire" on the freight ferry "Nord Pas-de-Calais", Nuclear Transport Limited commissioned Safety and Reliability Directorate to investigate the duration time of a fire on a ship, with particular reference to Roll on/Roll off Ferries (RO-ROs).

Having consulted a number of organisations, only two of them were able to provide specific information on the duration of fires on ships. These were the International Maritime Organization (IMO) and the Marine Accident Investigation Branch (MAIB).

The IMO was found to have the largest number of fire reports which gave times to control and times to extinguish fires on ships. Over a period of 25 years, IMO has received a total of 382 fire casualty records reporting on ships' fires from all over the world: the shortest fire recorded was extinguished in one minute and the longest in seventy-one days. This produced an average time for a fire of 26 hours while the ship was in Port and 19 hours while underway. With such a range of duration times, these average figures are only of mathematical interest.

From the IMO and the MAIB a total of thirty reports were found for fires on RO-ROs/Car Ferries (Car Ferries and similar vessels have been included because of the difficulty in identifying true RO-ROs from the earlier reports). The most frequent figure reported was the time taken to extinguish the fire, so this was used to calculate the average time to extinguish a fire on a RO-RO/Car Ferry, and it was found to be 2 hr 20 mins.

Some reports also gave a time to control the fire which represented 42% of the extinguishment time, ie approximately 1 hr for a fire on a RO-RO. Further analysis of the reports reveals that over 70% of the fires started in the engine room and 95% of the fires were limited to the area in which they started.

The fire reports which were studied proved to be elusive in indicating how long the fire could be considered to be intense. However, using standard fire manuals, it was estimated that a fire could be considered intense for 50-60% of its life. For the longest fire recorded on a RO-RO/ Car Ferry the fire could be intense for as long as six hours.

Having thoroughly investigated all the available reports of fires, it was concluded that at present, there is insufficient historical data to reach a definitive conclusion on the time period that a fire on a ship would be considered to be intense.

FIRE MODELLING ON THE RAIL DECK AND IN THE ENGINE ROOM OF THE "NORD PAS-DE-CALAIS" [4]

The purpose of this further study was to investigate, using fire modelling techniques, the growth of fires initiating on the rail deck and in the Engine Room of the "Nord Pas-de-Calais", in order to establish the likely temperatures to which a flask of irradiated fuel may be subjected.

To determine the type and size of fire on the rail deck, a study was undertaken of the imported cargo inventories which the "Nord Pas-de-Calais" had carried. This established that of the eight wagons that could surround the flask, two would contain flammable commodities (e.g.

timber, chipboard, plastic tubes), four would contain non-flammable commodities (e.g. ash slag, steel tubes, mineral water) and the remaining two would be empty.

The HAZARD I computer code, developed by the National Institute of Standards and Technology in America, was used to model three fire scenarios on the rail deck. The code estimated that temperatures in the upper gas layer peaked at about 400ºC after 20 minutes and then subsided due to the limited ventilation.

Four fire scenarios were modelled in the Engine Room involving burning fuel, all with varying levels of ventilation. In the event of a fire in the engine room of the "Nord Pas-de-Calais", dampers shut off the ventilation and fire-resisting doors seal off the engine room. With no air input, HAZARD I predicts that the fire burns out within 10 minutes. Even with the dampers staying open, the fire peaks after 20 minutes producing a ceiling temperature of about 130ºC. The final fire scenario assumes a fire-resisting door does not close, and uses the average fire duration, as previously established, of 2½ hours. After this time the ceiling temperature had reached 400ºC.

Because the temperature after 2½ hrs was still rising, this final scenario was run again with an extended time. This predicted that the ceiling temperature levelled off after 8 hours at 440ºC; this temperature is well below that at which the integrity of the engine room ceiling would be considered to be threatened.

In none of these seven fire scenarios would the flask be exposed to conditions more severe than those specified in the IAEA Regulatory Thermal Test for an irradiated fuel flask.

PROBABILISTIC ASSESSMENT OF "NORD PAS-DE-CALAIS" FIRE SCENARIOS [5]

In a previous contract, the frequency of a severe fire on the Nord Pas-de-Calais was determined as 3.8×10^{-3} /year for the machinery space. Further work was done to determine the consequences of several fires covering a wide range of possible scenarios. The current project has focused on the mitigating factors without which most fires would eventually become severe.

A revised initiating frequency for fires has been determined, and new information about the ferry has been taken into account. Event tree analysis has been used to obtain frequencies for various fire scenarios in the separator room, generator room and engine room. These results have then been used to calculate frequencies for the specific scenarios featured in the previous work. The final results showed that, in particular, the frequency of a fire in the separator room in ventilation limited conditions was found to be 4.6×10^{-4}/year. A fire occurring with all fire doors and ventilation dampers open in the whole machinery space, leading to a ceiling temperature of 400°C after 2½ hours, would have a frequency of only 8.0×10^{-9}/year.

This very low figure reflects the initiating frequency of 2.7×10^{-2}/year, the probability that incidents will be safely dealt with, and the extent of mitigation, whereby potentially serious incidents are restricted in their consequences. However, the precise specification of the conditions defining this scenario is also a contributory factor in the attainment of such a low frequency. A more useful figure may be the frequency of 3.0×10^{-4}/year for the most serious machinery space scenarios, in which ventilation contributes to the severity of the fire.

CONCLUSIONS

Analyses have been carried out to produce an estimate of the frequency of fires on ships of capacity greater than 500 grt of all types which would have been suitable to carry Type B(U) or Type B(M) packages.

Data for fire frequency were selected on the basis of qualitatively defined "severe fires", or "qualifying incidents" of fires/explosions, having the potential to threaten package integrity and thus frequency data derived in these studies are very much upper-bound estimates of the frequency with which some loss of package integrity might occur and should not be read as frequencies with which loss of integrity *would* occur.

Fire modelling techniques have been applied to the rail deck and in the engine room of the "Nord Pas-de-Calais" to obtain temperature and duration data for this particular ship which would be representative of an INF 2 roll-on roll-off (RO-RO) rail/road ferry carrying mixed cargo.

Assuming typically fifty flask movements take place annually, using this particular ship, the frequency of a fire developing while a flask is on board, with potential to affect package integrity would be less than 2×10^{-4} per year.

IMO fire report records indicate an average time for a fire of 26 hours for ships in port and 19 hours while underway and only limited anecdotal information is available concerning fire severity. The average time taken to extinguish a fire, on a RO-RO/Car Ferry, was found to be 2 hr 20 min. However these data is of little usefulness in determining the times for which fires may be both sufficiently severe and sufficiently closely located to a flask to cause concern for its integrity.

It is concluded that at present, there is insufficient historical data to reach a definitive conclusion on the time period that a fire on a ship would be considered to be intense.

Fire modelling techniques have been used to estimate the growth of fires (severity and duration) initiating on the rail deck and in the Engine Room of the "Nord Pas-de-Calais".

Fire conditions on the rail deck were estimated to reach a temperature in the upper gas layer of about 400ºC after 20 minutes and then to subside due to the limited ventilation.

In the event of a fire in the engine room of the "Nord Pas-de-Calais", dampers shut off the ventilation and fire-resisting doors seal off the engine room. With no air input, HAZARD I predicts that the fire burns out within 10 minutes.

Should the dampers stay open, the fire peaks after 20 minutes producing a ceiling temperature of about 130ºC.

Assuming a fire-resisting door does not close, the engine room ceiling temperature reaches ~400ºC after 2½ hours, levelling off after 8 hours at 440ºC, a temperature well below that at which the integrity of the engine room ceiling would be considered to be threatened. Such a fire would have a frequency estimated at 8.0×10^{-9}/year.

In none of these seven fire scenarios considered would the flask be exposed to conditions more severe than those specified in the IAEA Regulatory Thermal Test for an irradiated fuel flask.

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Annex 7

SeaRAM: A US DOE STUDY OF MARITIME RISK ASSESSMENT DATA AND METHODS OF ANALYSIS

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Abstract

This annex describes ship collision and fire frequencies, a model of ship penetration depths during ship collisions, finite element calculations that examine the crush forces applied to a RAM cask during ship collisions, shipboard fire tests, modeling of these tests using a computational fluid dynamics code, a simple bulkhead fire spread model that is based on the fire test modeling, a probabilistic ship multi-hold fire spread model, modeling of the release of spent fuel radionuclides to the environment from a Type-B spent fuel transportation cask, and illustrative estimates of the consequences that such a radioactive release might cause.

1. INTRODUCTION

1.1 SUMMARY

In 1994, the US Department of Energy (DOE) 's National Transportation Program (NTP) initiated a study called SeaRAM at Sandia National Laboratories (SNL) as a follow-on to the earlier study titled "Safety of Shipments of Plutonium by Sea," which was performed to satisfy a mandate in the US Energy Policy Act of 1992. In the same year, at the recommendation of the Standing Advisory Group on the Safe Transport of Radioactive Material, the International Atomic Energy Agency (IAEA) established a Coordinated Research Program (CRP) to conduct an assessment of the accident environment at sea. DOE decided to support this CRP because of a major stake in the outcome of this research program due to the Foreign Research Reactor fuel return program and the fissile materials disposition program, both of which have aspects of sea transport of radioactive materials. Therefore, DOE/NTP directed SNL to conduct additional technical studies in the pursuit of the CRP mission.

As a result of this study, the principal researchers have ascertained the following principal conclusions:

- Ship collisions depend on ship traffic density and thus on the region of the ocean in which a ship is sailing.
- Ship collisions are unlikely to damage a spent fuel cask, because collision forces will be relieved by collapse of ship structures, not cask structures.
- Ship fire frequencies appear to depend only on ship trip durations.
- Fires are not likely to start in the RAM hold; if a fire starts elsewhere on the ship, its spread to the RAM hold is not probable; and, even if a fire spreads to the RAM hold, lack of fuel or air will usually prevent the fire from burning hot enough and long enough in that hold to cause a significant release of radioactivity from the RAM cask.

- Most radioactive materials released to the interior of the RAM cask due to collisions and/or fires will deposit on interior cask surfaces; so cask retention fractions are large and cask-to-environment release fractions are small.
- Consequently, the risks of maritime transport of RAM spent nuclear fuel cask are very small.

This report summarizes the principal results of the SeaRam study. Complete descriptions of study results, analysis methods, and input data are presented in the program's final report titled, *SeaRam: A US DOE Study of Maritime Risk Assessment Data and Methods of Analysis* (SAND99-0275) by D.J. Ammerman, J.A. Koski, and J.L. Sprung [1-1].

1.2. BACKGROUND

Substantial quantities, of order one billion curies per year from 1992 through 1996, of radioactive materials are routinely transported in ships on the world's oceans. For example, during the next decade, the United States will receive 700 to 800 shipments of research reactor spent fuel containing some 500 million curies of radioactivity. In addition, the United States may ship radioactive military waste materials and power reactor spent fuel from the US to Europe for reprocessing into vitrified high-level waste and Mixed Oxide Fuel. Although all of these shipments are or will be made in accordance with regulations established by the International Maritime Organization (IMO) and the International Atomic Energy Agency (IAEA), private citizens, Greenpeace, and members of congress have all expressed concerns about their safety.

Several US environmental studies [1-2, 1-3, 1-4, 1-5] have examined the safety of trans-ocean shipments of radioactive materials (RAM). Review of these studies suggests that they may have significantly overestimated the risks associated with the maritime transport of radioactive materials because the analytical methods and assumptions used in these studies

- greatly overestimated the probability that an accident will lead to a release of radioactivity,
- significantly underestimated retention by deposition onto cask surfaces of the radioactive vapors and aerosols released to the cask interior as a result of the accident, and
- sometimes overestimated population exposures because real non-uniform population distributions were replaced by approximate uniform distributions which caused the number of people situated near to the accident site and consequently population doses both to be overestimated.

Because of the number of ocean shipments likely to occur during the near future and the concerns expressed about these shipments, and because previous studies may have overestimated the risks posed by maritime shipments of RAM, in 1994, DOE directed Sandia National Laboratories (SNL) to undertake a general study of ship accident risks. DOE stated that this study, which was given the name SeaRAM, should evaluate the ship accident data base, evaluate the thermal and mechanical loadings that transport casks might experience during ship accidents, and support the IAEA Coordinated Research Programne (CRP) titled Accident Severity at Sea. This annex summarizes the principal results of the SeaRAM Program. Full details are presented elsewhere [1-1].

1.3. SEARAM PROGRAM

The SeaRAM Program had four objectives. First, to define and describe a robust methodology for the assessment of the risks associated with the shipment of radioactive materials (RAM) by sea. Second, to illustrate the use of this methodology by the performance of illustrative calculations. Third, to develop credible technical estimates of the probabilities of ship collisions and ship fires and the chance that collisions and/or fires may damage a RAM transport cask so severely that radioactive materials are released from the cask. And fourth, to model the details of a few severe, ship accidents in order to determine whether these accidents would damage a RAM transport cask were one onboard the ship involved in the hypothetical accident.

Because this was a generic study, DOE stated that the analyses should be substantial but not exhaustive, and that all calculations performed should be illustrative and thus should not examine any specific RAM shipping campaign. The following approach was selected to fulfill this mandate. First, an appropriate risk assessment methodology was identified and described. Then, the methodology was illustratively applied to the transport of spent commercial reactor fuel in a typical transport cask onboard a charter freighter and a break-bulk freighter. Data needed to support these calculations or to develop or validate the models used in these calculations was developed, where necessary by the performance of experiments and detailed collision and/or fire calculations. Finally, illustrative consequence calculations that examined the risks posed by accidents that might occur while these ships were sailing at sea, in coastal waters, and in ports were performed.

1.4. PROGRAM ELEMENTS

This annex is divided into 7 sections. This section introduces the program and lists the program elements. Sections 2 through 6 present the results developed by each SeaRAM Program element. Finally, Section 7, summarizes the picture of maritime RAM transport risks that emerges from the results of the individual program elements. Specifically,

- Section 2 develops ship collision frequencies per nautical mile sailed for 19 ocean regions, for all coastal waters not in one of these 19 regions, and for the open ocean. The section also develops fire frequencies per nautical mile sailed.
- Section 3 revalidates Minorsky's correlation of ship collision damage with ship collision energy, illustratively applies the correlation to collisions of ships in the world fleet with a small two-hold charter freighter and a seven-hold break-bulk freighter, and extends the correlation by coupling it two a mechanistic model of shell damage, thereby producing a model that can treat low-speed collisions and collisions where the struck ship has a double hull.
- Section 4 describes finite element calculations that examine the impacts on a RAM transport cask of severe collisions that penetrate so deeply into the RAM transport hold of the struck ship that the stowage location of the cask is overrun or other cargo in the hold is compressed about the cask subjecting it to crush forces.
- Section 5 (a) describes three shipboard fire tests, a heptane spray fire, a wood crib fire, and an in-hold pool, that were performed to develop data about ship fire heat transport processes and fire propagation; (b) presents the results obtained when the fire tests are modeled using a detailed computational fluid dynamics code; (c) uses the fire test results

and the insights developed by modeling these tests to formulate, validate, and illustratively apply a simple hold-to-hold fire spread model; and (d) develops a probabilistic fire spread model for a multi-hold break-bulk freighter and uses the model to illustratively estimate the chance that a severe fire initiated by a ship collision will spread to a hold where a RAM transport cask is stowed and then burn hot enough and long enough in that hold to cause or substantially increase the loss of radioactivity from the cask.

- Section 6 describes illustrative consequence calculations that model hypothetical ship accidents assumed to occur while sailing at sea, along a coastal route, or in port.

REFERENCES

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[1-3] Environmental Assessment on Shipment of Taiwanese Research Reactor Spent Fuel (Phase II), DOE/EA-0363, US Department of Energy, Washington, DC, June 1988.

[1-4] Environmental Assessment of the Risks of the Taiwan Research Reactor Spent Fuel Project, DOE/EA-0515, US Department of Energy, Washington, DC, June 1991.

[1-5] Environmental Assessment of Urgent-Relief Acceptance of Foreign Research Reactor Spent Nuclear Fuel," DOE/EA-0912, US Department of Energy, Washington, DC, April 1994.

2. ACCIDENT STATISTICS

2.1. ACCIDENT DATA

Ship collision and ship fire frequencies were derived by analysis of 15 years (1979 through 1993) of Lloyd's casualty data and 2 years (1988, 1993) of Lloyd's port call data [2-1]. The casualty data contained 2547 fire events, 975 of which occurred in ports, and 1947 collision events (where a collision is the striking of one ship by another ship and is not the ramming of a fixed structure or a grounding), 702 of which occurred in ports. Only 50 of the 1947 collisions events led to fires, 39 of these fires resulted form collisions at sea and 11 from collisions in ports; none of the 2547 fire events involved collisions. Because the casualty data contained very little information about accident severities, all of the analyses reported here considered all collisions and all fires in the 15 years of data without regard to their severity.

The accident data contained coordinates for 758 of the collision events and for 812 of the fire events that occurred outside of port waters. When histograms of the distance from shore of these 758 collision and 812 fire events were constructed, the histograms showed that most collision events occur near shore (90 per cent within 60 miles of a coast), while fire events seem to occur more or less uniformly at all distances from shore (e.g. the distance within which 90 per cent of the fire events occur is 300 rather than 60 miles and many occur well out to sea). Assignment of these same events to the 478 Marsden squares [2-2] that contain ocean waters also showed that fire events are more widely dispersed than collision events (169 squares contain at least 1 fire event while only 109 squares contain at least 1 collision event;

32 squares contain at least 10 fire events while only 20 squares contain at least 10 collision events). Thus, the histograms and the event counts by Marsden square suggest that the occurrence of fires on ships is not strongly dependent on location, while the occurrence of ship collisions is strongly dependent on location, being much more frequent where ship traffic is high (e.g. in the 20 Marsden squares that each contain at least 10 collision events).

2.2. CONGESTED OCEAN REGIONS

Because ship collision seemed to depend strongly on ship traffic density, ship collision statistics were developed per nautical mile sailed for 19 congested ocean regions (regions thought to be heavily sailed), which encompassed large parts of those Marsden squares that contained 10 or more ship collisions, for all coastal waters not contained in any of the 19 congested regions, and for the open ocean. Table 2-1 identifies the 19 congested ocean regions.

Table 2-1. Congested Ocean Regions

1	Irish Sea	6	Tyrrhenian Sea	11	Persian Gulf, Gulf of Oman	16	Sea of Japan, Korean Strait
2	English Channel	7	Adriatic Sea	12	Approaches to Singapore	17	Inland Sea of Japan
3	North Sea	8	Aegean Sea, Bosporus	13	South China Sea, Taiwan Strait	18	East Coast of Japan
4	Baltic Sea	9	Eastern Mediterranean	14	East China Sea	19	Western Gulf of Mexico
5	Western Mediterranean	10	Suez Canal, Red Sea, Gulf of Aden	15	Yellow Sea		

2.3. ACCIDENT LOCATIONS

The number of ship collisions that occurred in each of the 19 congested regions, in coastal waters, in the open oceans, and in individual ports were determined by manual inspection of the text fields in the Lloyd's accident data that described each accident. Region assignments were straightforward when the text field contained accident coordinates. When coordinates were lacking, some combination of descriptive text that specified the identities of cities, geographic features (e.g. bays, islands), or structures (e.g. lighthouses) located near the accident site, and/or the identity of the Marsden square in which the accident occurred almost always allowed the accident to be assigned to one of the 19 congested regions, to coastal waters, to open ocean, or to the waters of a port (only 8 of the 1947 collisions could not be assigned to a region or a port).

2.4. PORT CALLS AND PORT LOCATIONS

The two years of port call data listed calls at 3590 different ports, trips between 105 000 different pairs of ports (where a trip is a sailing from one port directly to another port without any intervening port calls), and 2,391,118 total trips. Coordinates were specified for many of these ports. When port coordinates were not specified, they were taken from the Fairplay Encyclopaedia [2-3] or from an atlas [2-4]. Next, coordinates were specified for the vertices of irregular convex polygons that just encompassed the ocean waters of each of the 19 congested regions. Ports were then assigned to congested regions by application of the right hand rule for vectors [2-5].

2.5. TRIP SAILING DISTANCES

Although voyage distances can be obtained from the Fairplay Encyclopaedia [2-3] and from Publication 151 of the US Defense Mapping Agency [2-7], neither of these references can be automatically searched. As distances were needed for 105 000 different trips, a way to compute trip distances had to be developed. The method selected was an extension of the distance algorithm used in Publication 151. Publication 151 defines 25 ocean junction points and specifies distances between these junction points and from ports to those junction points that lie nearest to the port. Coordinates were defined for an additional 24 junction points, which all lay on the edges of the 19 congested regions identified in Table 2-1. The great circle distances from these additional junction points to all other nearby junction points, both those taken from Publication 151 and those chosen to define the edges of the 19 congested regions, were then calculated, and all of the distances between pairs of junction points were entered into a lookup table. Trip distances were then calculated as follows. For trips between ports in the same congested region or in coastal waters not separated by one of the 25 junction points defined in Publication 151, distances between the two ports were calculated as great circle distances. For all other trips, distances were calculated as the sum of two great circle distances (the great circle distances from the departure port to the nearest junction point on the route and from the last junction point on the route to the destination port) plus the sum of the distances between the set of successive junction points (taken from the lookup table) that defined the minimum distance route from the departure port to the destination port, where the minimum distance route was identified using the Dijkstra shortest path algorithm [2-6]. Figure 2-1 illustrates this procedure.

Figure 2-2 shows that great circle distances can significantly underestimate real sailing distances if the actual sailing route does not approximate a great circle route. Specifically, the great circle distance from Rotterdam to Antwerp is 45 nautical miles, but the true sailing distance is 121 nautical miles.

The magnitude of the underestimate of sailing distances caused by the use of great circle distances was investigated by comparing the distances calculated using the sum of several great circle distances to the sailing distances specified in the Fairplay Encyclopaedia for the set of most sailed trips that accounted for 10 per cent of the total distance sailed during the year 1988. The comparison showed that use of great circle distances on average underestimated true sailing distances by less than ten per cent although sometimes by factors of as much as two for specific trips.

2.6. APPORTIONMENT OF TRIP DISTANCES TO OCEAN REGIONS

Sailing distances in congested regions were calculated as great circle distances from a port in the region to a junction point at the edge of the region, when a trip began or ended in that region, or as the distance between two junction points located on the edges of the region, when the region was traversed. A sailing distance of 50 nautical miles was assigned to the coastal waters region whenever a departure or destination port was not located in one of the 19 congested regions. Finally, the balance of each trip sailing distance was assigned to the open ocean region.

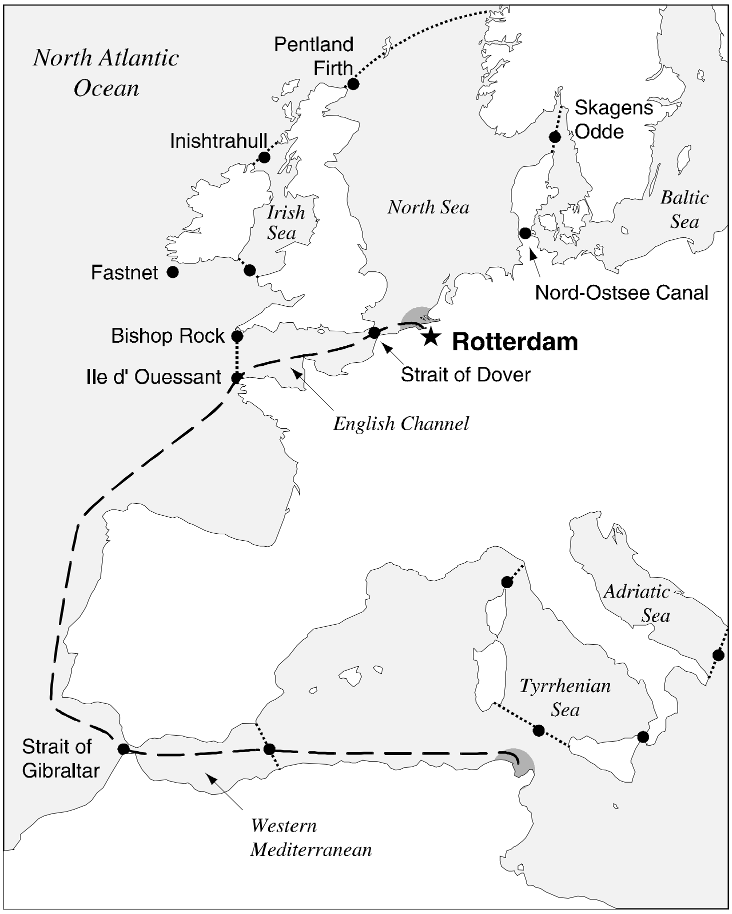

FIGURE 2-1. Sailing route from Rotterdam to Tunis showing the congested ocean regions traversed (North Sea, English Channel, and the western Mediterranean) and the four junction points (•) passed when sailing this route (Strait of Dover, Ile D'ouessant, Strait of Gibraltar, and the eastern edge of the western Mediterranean congested region). Also shown are four congested regions (Baltic Sea, Irish Sea, Tyrrhenian Sea, Adriatic Sea) and eleven junction points (Nord-Ostee Canal, Skagens Odde, Pentland Firth, Inishtrahull, Fastnet, southern edge of the irish sea, bishop rock, three points on the edges of the Tyrrhenian Sea, and the southern edge of the Adriatic Sea) used in other distance calculations.

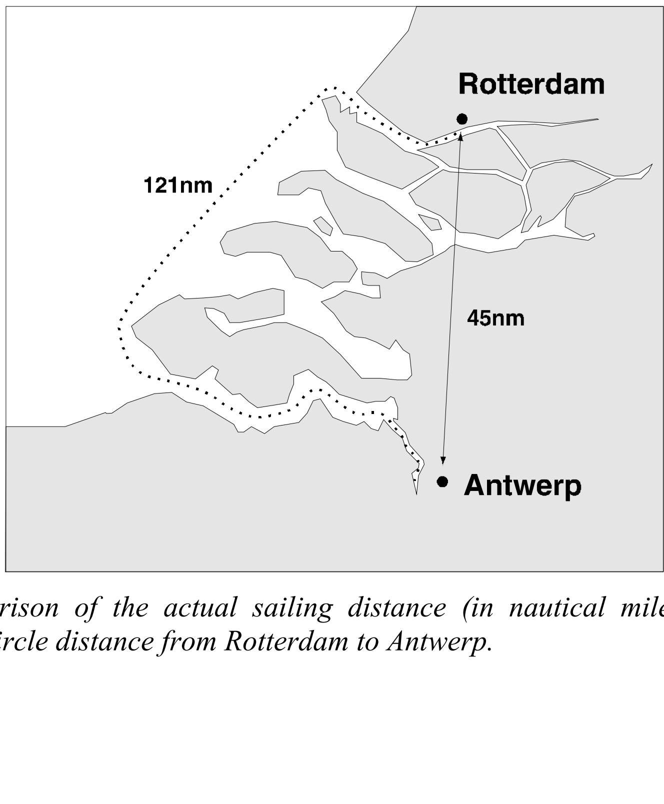

FIGURE 2-2. Comparison of the actual sailing distance (in nautical miles) from Rotterdam to Antwerp to the great circle distance from Rotterdam to Antwerp.

2.7. REGION SAILING DISTANCES AND COLLISION FREQUENCIES

Table 2-2 presents the distances sailed (d_{1988} and d_{1993}) in each of the 21 ocean regions during the years 1988 and 1993, the average of these two distances, the number (N) of ship collisions that occurred in each region during the 15 year period from 1979 to 1993, and the collision frequency per nautical mile sailed (F), calculated ($F = [N/15]/[(d_{1998} + d_{1993})/2]$) from this data for each region under the assumption that the port call data for the years 1988 and 1993 is not unlike the port call data for other years in the 15-year period.

Table 2-2. Distances Sailed, Ship Collisions, and Collision Frequency for 21 Ocean Regions

Region	Distance Sailed (nautical miles)			Collisions 1979-1993	Frequency (per nautical mile sailed)
	1988	1993	Average		
Irish Sea	2 829 048	2 683 242	2 756 145	7	1.7×10^{-7}
English Channel	21 879 012	20 497 594	21 188 303	33	1.0×10^{-7}
North Sea	48 945 873	46 676 760	47 811 317	134	1.9×10^{-7}
Baltic Sea	26 150 331	30 410 544	28 280 438	76	1.8×10^{-7}
Western Mediterranean	12 527 256	12 508 332	12 517 794	29	1.5×10^{-7}
Tyrrhenian Sea	4 713 083	5 163 556	4 938 320	8	1.1×10^{-7}
Adriatic Sea	8 847 482	9 216 251	9 031 867	11	8.1×10^{-8}
Aegean Sea, Bosporus	6 979 278	7 521 944	7 250 611	59	5.4×10^{-7}
Eastern Mediterranean	9 717 480	11 511 423	10 614 452	21	1.3×10^{-7}
Suez Canal, Red Sea, Gulf of Aden	30 562 346	30 397 942	30 480 144	17	3.7×10^{-8}
Persian Gulf, Gulf of Oman	6 123 288	9 272 603	7 697 946	17	1.5×10^{-7}
Approaches to Singapore	30 056 459	43 928 308	36 992 384	41	7.4×10^{-8}
South China Sea, Taiwan Strait	16 959 614	24 003 990	20 481 802	42	1.4×10^{-7}
East China Sea	24 138 006	32 718 462	28 428 234	34	8.0×10^{-8}
Yellow Sea	7 483 030	10 559 045	9 021 038	13	9.6×10^{-8}
Sea of Japan, Korean Strait	6 223 109	7 748 095	6 985 602	35	3.3×10^{-7}
Inland Sea of Japan	12 440 950	14 106 520	13 273 735	193	9.7×10^{-7}
East Coast of Japan	4 169 250	4 497 723	4 333 487	120	1.9×10^{-6}
Western Gulf of Mexico	12 907 874	14 124 048	13 515 961	24	1.2×10^{-7}
Coastal Waters	80 737 497	97 489 242	89 113 370	252	1.9×10^{-7}
Open Ocean	655 875 934	709 598 653	682 737 294	70	6.8×10^{-9}

2.8. PORT COLLISION FREQUENCIES

In order to examine the influence of port traffic on port collision frequencies, ports in the two years of Lloyd's port call data were divided into three groups, high traffic ports (13 ports), medium traffic ports (78 ports), and low traffic ports (3499 ports). Somewhat arbitrarily, high traffic ports were then taken to be any port with more than 8900 port calls during 1988 because 8900 port calls per year is about 1 port call per hour; medium traffic ports, any port with 2 700 to 8 900 port calls during 1988, and low traffic ports, all ports with fewer than 2700 port calls during 1988. Collision frequencies per port call were then calculated individually for all 13 high traffic ports and for 6 medium traffic ports, and calculated collectively for all high, all medium, and all low traffic ports. Table 2-3 presents these port collision frequencies.

Table 2-3. Port Calls (1988) and Port Collision Frequencies (per port call)

Port	Port Collisions[1] (1979-1993)	Port Calls (1988)	COLLISION FREQUENCY (per port call)
High Traffic Ports			
Antwerp	10	16585	4.0×10^{-5}
Europort	2	9772	1.4×10^{-5}
Gibraltar	1	13991	4.8×10^{-6}
Hamburg	8	14645	3.6×10^{-5}
Hong-Kong	7	14216	3.3×10^{-5}
Istanbul	3	24926	8.0×10^{-6}
Kobe	7	9133	5.1×10^{-5}
Panama Canal	2	11058	1.2×10^{-5}
Port Said	13	8936	9.7×10^{-5}
Rotterdam	11	26153	2.8×10^{-5}
Singapore	18	27129	4.4×10^{-5}
Suez	3	9742	2.1×10^{-5}
Yokohama	8	13323	4.0×10^{-5}
All High Traffic	**93**	**199 609**	$\mathbf{3.1 \times 10^{-5}}$
Medium Traffic Ports			
Bangkok	2	3889	3.4×10^{-5}
Barcelona	2	5743	2.3×10^{-5}
Lisbon	2	3984	3.4×10^{-5}
Los Angeles	0	6587	0
Marseilles	2	4238	3.2×10^{-5}
New York	12	5144	1.6×10^{-4}
All Medium Traffic	**174**	**254 121**	$\mathbf{4.6 \times 10^{-5}}$
Low Traffic Ports			
All Low Traffic	**422**	**656 989**	$\mathbf{4.3 \times 10^{-5}}$

1. Thirteen port collisions occurred in ports that did not appear in the two years of port call data.

2.9. FIRE FREQUENCIES

Because ship fires show little variation with ocean location and occur often only in Marsden squares that contain major oil fields (the North Sea and the Persian Gulf), fire frequencies were not developed independently for each ocean region or for individual ports. Therefore, the fire frequency per nautical mile sailed and per port call was calculated as follows:

$$\frac{1572 \text{ non - port fires}/15 \text{ years}}{2{,}174{,}900{,}488 \text{ nautical miles sailed}/2 \text{ years}} = 9.6 \times 10^{-8} \text{ fires per nautical mile sailed}$$

$$\frac{975 \text{ port fires}/15 \text{ years}}{2{,}391{,}118 \text{ port calls}/2 \text{ years}} = 5.4 \times 10^{-5} \text{ fires per port call}$$

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[2-7] Defense Mapping Agency Hydrographic/Topographic Center, *Distances Between Ports, Publication 151, Seventh Edition,* Bethesda, MD, 1993.

3. SHIP COLLISION SEVERITIES

3.1 INTRODUCTION

For a ship collision to damage a Radioactive Material (RAM) cask being carried in a hold of one of the ships involved in the collision, the ship transporting the RAM cask must be the struck ship, the striking ship must strike the hold where the RAM cask is stowed and penetrate deeply enough into that hold to apply crush forces to the cask either by overrunning the stowage location of the cask or compressing other cargo stowed in the hold about the cask, and the forces applied to the cask must not be relieved by collapse of ship structures (e.g. ship bulkheads or the shell of the struck ship on the far side of the struck hold. This section examines collision penetration depths by revalidating and extending a correlation of collision damage volumes with collision energy published in 1959 by V. U. Minorsky [3-1]. Relief of crush forces due to collapse of ship structures is examined in the next section.

3.2 MINORSKY'S CORRELATION

The empirical correlation of ship collision kinetic energy with the volume of the ship structures damaged by the collision published by Minorsky in 1950 [3-1] assumes (1) that only the component of the striking ship speed normal to the course of the struck ship contributes to the kinetic energy available to cause collision damage, (2) that the mass of the water entrained behind the struck ship during the collision is equal to 40 per cent of the displacement of the struck ship [3-2], and (3) that the collision is an inelastic event (i.e. upon colliding, the ships stick together). Under these assumptions, the kinetic energy expended damaging structures during the collision (*ΔKE*) is given by

$$\Delta KE = \left[\frac{M(m+dm)}{2(M+m+dm)}\right][V_M \sin\theta\ ]^2 \quad (1)$$

where M and m are the displacements (loaded masses) of the striking and struck ships, V_M is the speed of the striking ship, dm = 0.4 m is the mass of water entrained behind the struck ship, and θ is the angle between the velocity vectors of the two ships (the collision angle).

Minorsky implicitly assumed that the kinetic energy expended puncturing and tearing the shell of the struck ship would be about the same for most ships. Thus, in developing his empirical correlation, he plotted the sum of the volumes of damaged internal ship structures (decks, flats, and double bottoms in both ships, transverse bulkheads in the struck ship, longitudinal bulkheads in the striking ship, and 70 per cent of the area of the torn shell of the striking ship), but did not include the volume of the damaged shell of the struck ship, which therefore entered his linear correlation as the correlation intercept. Thus, Minorsky's correlation has the following functional form,

$$\Delta KE = mR_T + b \text{ where } R_T = \sum_i d_i w_i t_i \quad (2)$$

d_i, w_i, and t_i are the penetration depth, width, and thickness of the ith damaged structure in the struck or striking ship, ΔKE and b are expressed in MJ, and R_T is expressed in m^3. When m and b were determined by correlating collision kinetic energies and damage volumes for nine high-speed collisions, Minorsky obtained the following correlation,

$$\Delta KE = (47.2 \pm 2.4)R_T + (32.7 \pm 13) \quad (3)$$

In order to use this correlation to estimate collision penetration depths, some relationship between structure damage volumes and the depth of penetration of the bow of the striking ship into the hold of the struck ship must be assumed, as penetration distance determines whether the RAM cask is struck or, if cargo is present, whether cargo compression consumes all of the empty space in the RAM hold, thereby subjecting the RAM cask to crush forces. In addition, because ship designs changed significantly starting in the 1980's (e.g. the bulbous bow was introduced), data for a number of modern high-speed ship collisions were added to the collisions that entered Minorsky's original correlation for which ship identities could be determined.

In this section we present a revalidation of Minorsky's correlation using ship collision data from identified sources, we constrain the intercept of the revalidated correlation using a theoretical model for a wedge cutting a plate [3-3, 3-4], we connect damage volumes to the penetration distance of the striking ship bow into the hull of the struck ship by assuming that the bow of the striking ship is largely undeformed by the collision (non-deformable bow assumption), and then we use the revalidated model with the non-deformable bow assumption to estimate the chance that a RAM cask transported on a typical break-bulk or charter freighter will be damaged, given that the RAM hold of the freighter has been struck by another ship.

3.3 REVALIDATION OF MINORSKY'S CORRELATION

Minorsky's paper does not specify the values of the nine points that entered his correlation and identifies only one of the collisions, the Andrea Doria - Stockholm collision, represented by the points. A literature review showed that the six of the eight unidentified points corresponded to entries in a table of collision data contained in a report prepared by Gibbs and Cox, Inc. [3-5] that surveyed collisions that occurred before 1958. This literature search also identified nine post-1970 high-speed collisions suitable for inclusion in Minorsky's correlation. Because ship designs changed significantly starting in the 1980's (e.g. the bulbous bow was introduced), these collisions were added to the set of collisions used to revalidate Minorsky's correlation. For these nine modern collisions, missing data required by the correlations was from other sources or by estimation techniques [3-6].

As collision data was gathered, new plots of Minorsky's correlation showed that the value of the correlation intercept (the energy expended penetrating the shell of the struck ship) varied greatly with the set of points plotted. Therefore, the value of the intercept was independently estimated using the following theoretical model for a wedge cutting a plate [3-3,3-4],

$$\frac{W}{\sigma_y t^3} = C_1 \left(\frac{l}{t} \right)^{1.4} \text{ where } C_1 = 2.34 \mu^{0.4} \delta^{0.2} \quad (3)$$

where W is the work done by the wedge cutting the plate, t and l are the plate thickness and the length of the tear in the plate, σ_y is the material yield stress of the plate, μ is the friction coefficient, δ is the crack-opening displacement, and C_1 has values [3-3] that range from 0.9 to 3.5. Because values for μ and δ were difficult to estimate, C_1 was taken to equal the midpoint of its range, namely 2.2. This model was used to calculate the energy expended penetrating the shell of the struck ship during seven of the sixteen high-speed ship collisions for which data had been developed. Averaging of the shell penetration energies for these collisions yielded a value of 28.4 MJ which agrees well with the value of the intercept in Minorsky's original correlation.

Minorsky's correlation was now recalculated with the correlation intercept constrained to 28.4 MJ. The recalculation used data for the nine modern collisions combined with data for the seven points from Minorsky's original correlation, whose identities had been determined. The recalculation assumed that none of these sixteen collisions damaged ship bulkheads, that all struck ship decks were penetrated to the same distance (this neglects the effect of the rake angle of the bow of the striking ship), that the thickness of all decks and shells were 0.83 and 0.60 inches respectively (these are the thicknesses given in the example calculation in Minorsky's paper), that damage widths were the same for all decks in the struck ship, and that damage areas were rectangular for all collisions except the Andrea Doria collision where the damage area was assumed to be triangular. Given these assumptions, the following revalidated correlation was obtained:

$$\Delta KE = (47.1 \pm 8.8) R_T + 28.4 \quad (4)$$

Comparison of the revalidated correlation (Equation 4) to Minorsky's original correlation (Equation 3) shows that adding nine modern collisions to the correlation and constraining the correlation intercept to a value of 28.4 MJ still yields a value for the correlation slope (47.1 MJ/m^3) almost identical to the value of the slope of Minorsky's original correlation (47.2 MJ/m^3).

3.4. EXTENSIONS

To apply Minorsky's correlation to collisions that might occur during the transport of radioactive materials on ships, some relation between penetration depth (d) and damage width (w) must be assumed. Here these two quantities are related by assuming that the bow of the striking ship is essentially non-deformable. Therefore, $w = 2d \tan\phi$ where ϕ is half of the bow angle of the striking ship, and consequently, for damaged decks in the struck ship when the collision angle is 90°, $R_T = (1/2) wdt = d^2 t \tan\phi$. For off-normal collisions, relations from analytic geometry lead to the following expression for the area (A) of damaged decks in the struck ship

$$A = \frac{d^2 \tan\phi}{1-\left[\tan^2\phi/\tan^2\theta\right]} \quad (5)$$

Because of the rake angle of the bow of the striking ship, higher decks in the struck ship will be more deeply penetrated than lower decks. Specifically, if the penetration of the highest damaged deck is d_o, then the penetration d_i of the ith damaged deck below this deck is $d_i = d_o - h_i/\mathbf{tan}\ \alpha$, where h_i is the distance between the highest damaged deck and the ith damaged deck and α is the rake angle of the bow of the striking ship.

Following Minorsky, for each deck in the struck ship that slices through the shell of the striking ship, shell damage is $R_T = 2\ (0.7)\ w\ d\ t$, where $w\ d\ t$ is the damage volume in the shell on each side of the bow of the striking ship, 0.7 $w\ d\ t$ is the projection of this volume along the normal to the course of the struck ship, and w, the width of each tear in the shell, is taken to be 5 ft.

Lastly, because the hold in which the RAM cask is stowed may contain other cargo in addition to the RAM cask, cask damage may result from the compression of cargo about the cask and not from the cask being struck by the penetrating bow of the striking ship. To account for damage due to cargo compression, Equation 4 is modified by adding a term for the work done compressing cargo,

$$\Delta KE = 47.1 R_T + 28.4 + W_{\text{cargo}} \text{ where } W_{\text{cargo}} = A_{\text{bow}}\, \sigma_{\text{cargo}} \left(d - \text{f B}\right) \quad (6)$$

where A_{bow} is the area of the surface compressing the cargo in the RAM hold (i.e. the effective surface area of the deformed bow of the striking ship), σ_{cargo} is the crush strength of the cargo, d is the penetration depth, B is the beam of the struck ship, f is the fraction of space along the beam of the struck ship between and within cargo in the RAM hold that is empty, fB is the penetration depth that will use up all of the empty space in the RAM hold along that beam, $A_{bow}\sigma_{cargo}$ is the compressive force applied to the cargo after the cargo closes up around the cask, d - fB is the distance over which that force acts, and following ORI [3-7],

$$A_{\text{bow}} = \left(d/\text{B}\right)\left(1/3\right)\text{H}\left(\text{L}/10\right) 2\tan\phi \quad (7)$$

where H and L are the height and length of the striking ship.

3.5. APPLICATIONS

The revalidated Minorsky correlation, as modified to permit the calculation of collision penetration distances, was used to estimate the probability that a RAM transportation cask would be damaged during a ship collision where the striking ship collides with the RAM hold of the RAM transport ship. Two RAM transport ships with structural features similar to INF class 1 and class 2 ships were considered: a four deck, small charter freighter (CF) with a displacement of 1740 tonnes and a five deck, break-bulk freighter (BBF) with a displacement of 23 500 tonnes (1.0 tonne = 1000 kg). Penetration distances were calculated for collisions where these two ships were struck by tankers and bulkers, general cargo freighters, container ships, and passenger ships that had for each of nine displacement ranges typical rake angles, bow angles, and beam widths. Consistent with RAM cask shipping practice, the calculations assumed that the charter freighter carried no cargo besides the RAM cask and that the break-bulk freighter might be carrying three types of cargo, palletized paper cartons containing light weight products (light cargo), palletized wooden boxes containing medium weight cargo (medium cargo), or heavy machinery (heavy cargo). For each of these three hypothetical types of cargo, reasonable values were chosen for the cargo compression model parameters, f and σ_{cargo}. Finally, the distributions of striking ship displacements, collision speeds, and collision angles needed for these calculations were taken from a prior study of waterborne transport accident severities [3-7].

The revalidated and extended Minorsky correlation (Equations 1, 2, and 6 through 8) expresses an implicit non-linear dependence of collision penetration depth on ship specifications and displacements, collision speeds and angles, the rake and bow angles of the striking ships, and cargo characteristics. These equations were solved iteratively for penetration depth by Newton's method or in some cases by binary search. Eight sets of calculations were performed. One set of calculations was performed for each cargo type with each of the two RAM transport ships, the charter freighter and the break-bulk freighter. Each set of calculations considered each of the four broad classes of ships in the world fleet and all possible combinations of collision speed, collision angle, and striking ship displacement. Thus, each set of calculations consisted of 3 366 trials. After each calculation, the resulting penetration depths were binned into twelve penetration intervals that spanned the beam of the struck ship.

Because the RAM cask was assumed to be stowed on the midline of the hold of the RAM transport ship, for each penetration distance, the following four results were possible: (1) the cask is overrun by the bow of the striking ship, (2) the bow does not overrun the cask, and, if the RAM hold could contain other cargo, then (3) close-up of cargo consumed all of the empty space in the hold, or (4) cargo close-up failed to consume all of the empty space in the hold. If the cask is overrun or cargo close-up occurs, the cask would probably be subjected to asymmetric forces large enough to damage both the cask and its contents [3-8]. Therefore, whenever a calculation predicted that the RAM cask was overrun or complete close-up of cargo occurred, it was conservatively assumed that the cask was subjected to crush forces and failed (lost containment integrity). These assumptions lead to the distributions of cask crush presented in Table 3-1.

Table 3-1 shows that shell penetration is much more likely for the heavier break-bulk freighter than for the lighter charter freighter, presumably because, if struck, the lighter charter freighter is easier to push through the water than the heavier break-bulk freighter, and thus more energy is expended pushing the lighter ship and less penetrating into its hull. Table 3-1 also shows that if the hull of the charter freighter is penetrated, because of its narrower beam, a greater fraction of shell penetration collisions lead to cask crush. Specifically, for the charter freighter, cask crush results for 72 per cent of all shell penetrations, while for the break-bulk freighter, cask crush results about 42 per cent of all shell penetrations for the no, light and heavy cargo case and for 81 per cent of all shell penetrations for the medium cargo case.

Table 3-1. Probability of Shell Penetration and Cask Crush on Representative Charter and Break-bulk Freighters

Collision Result	Charter Freighter	Break-Bulk freighter			
	Cargo Type				
	None	None	Light	Medium	Heavy
Shell Penetration	0.200	0.563	0.563	0.563	0.563
Cask Overrun	0.144	0.238	0.049	0.000	0.000
Cargo Goes Solid	0.000	0.000	0.187	0.458	0.236
Total Crush Probability	0.144	0.238	0.235	0.458	0.236

Finally, it is important to note that these results are probably conservative for two reasons. First, if the RAM cask is overrun by the bow of the striking ship, its tie-downs may fail which could prevent the cask from experiencing crush forces. And second, if the tie downs fail and the cask is pushed across the hold to the far shell of the struck ship or if other cargo in the hold does completely close up about the cask, crush forces should be reduced by bulging or failure of hold bulkheads or the shell of the struck ship at far side of the struck hold, or by pushing cargo up into the empty space above the cargo below the overlying deck.

3.6. MODIFIED SHELL PENETRATION ENERGY

3.6.1. TSAMC method

The constant shell penetration energy used by Minorsky in developing his correlation can be eliminated by substituting results from mechanistic calculations of the energy required to produce hull rupture, for example, the Tanker Structural Analysis for Minor Collisions (TSAMC) method developed by M. Rosenblatt & Son [3-9]. For minor ship collisions, the TSAMC method accurately predicts absorbed energy and hull deformations up to the point of hull rupture. This method works for all types of ship structures, including double hull ships. Deformations beyond the point of hull rupture can then be modeled in a manner similar to the Minorsky method. The external mechanics used to determine the amount of energy that must be absorbed are treated the same as in the Minorsky method.

The TSAMC method uses static analysis based on simplified models of various structural components of the struck ship. The energy absorbed by each component is calculated and summed. The method is based on observations of actual collision damage and laboratory tests of structural models. Most of the energy is absorbed by membrane tension in the side shell and the stiffeners. Seven ships ranging in displacement from 570 to 23 300 MT with various framing types and both single and double hulls were analyzed. These analyses lead to the following observations:

1) The energy absorbed in rupturing the hull varies significantly from ship to ship.
2) The amount of penetration required to cause hull rupture also varies.
3) The penetration required to cause hull rupture is a significant portion of the ships beam.
4) Many collisions do not have sufficient energy to cause hull rupture.

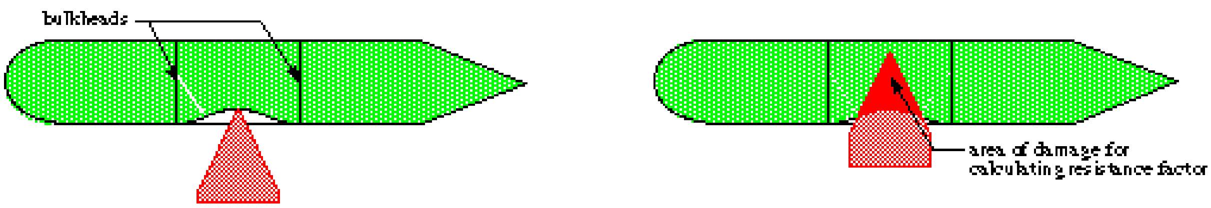
These observations suggest that for small ships, such as those frequently used to transport radioactive material, the penetration distance calculated using the Minorsky method may have a significant error. Actual penetration may be greater or less than that calculated using the simple empirical equation.

3.6.2. CALCULATION OF FURTHER PENETRATION

If the collision energy is greater than the energy required to rupture the hull as estimated using the TSAMC method, additional resistance to penetration will come from deforming structures that are transverse to the penetration, such as the bottom hull, the double bottom, and decks. A Minorsky-type calculation can then determine the energy absorbed by these structures due to additional penetration. To perform this analysis a resistance factor must be calculated that only includes the damage due to this additional penetration. In calculating the resistance factor, the following assumptions are made: only damage that occurs after hull rupture is used, the area of increased damage is triangular in shape, and the depth of penetration can be calculated for any level based on the maximum penetration and rake angle.

Based on this resistance factor, the amount of energy absorbed by deformation of the bottom hull, double bottom, and decks can be determined by multiplying times the Minorsky coefficient. The total energy absorbed is then the sum of the energy required for hull penetration; bottom hull, double bottom, and deck deformation; and crushing of cargo (if present).

Figure 3-1 shows a graphical representation of the area deformed at the point of hull rupture and the additional area deformed due to penetration beyond that required to cause hull rupture. The energy absorbed and penetration distance prior to hull rupture is determined using the TSAMC method and is shown in the top part of the figure. The energy absorbed and penetration distance after hull rupture is determined using a resistance factor calculation. The area used for the calculation of resistance factor is the dark shaded portion in the lower part of the figure. In an example calculation, this method predicted a penetration depth of 9.9 m compared to a depth of 11.8 m calculated using the revalidated Minorsky method discussed earlier.



a: Penetration and damage prior to hull rupture. b: Penetration and damage after hull rupture.

Fig. 3-1. Calculation of damage using the modified Minorsky method.

3.6.3. Advantages of using mechanistic hull rupture with Minorsky's Correlation

The modified Minorsky method developed accurately accounts for the strength of the side structure of the struck ship. The amount of energy absorbed prior to hull rupture is calculated based upon sound engineering principles and the observed behavior of the deformations of ships involved in collisions. Due to the wide variation in ship hull designs, the amount of energy required to rupture the hull is very ship-dependent. Modeling the hull rupture energy as the intercept in a linear correlation of resistance-factor with absorbed energy can lead to substantial errors. For the smaller vessels typically used during the maritime transportation of radioactive material, the amount of energy absorbed prior to rupture of the side shell is much larger than the amount absorbed during additional penetration. Also, the penetration distance prior to rupture of the hull is a significant portion of the beam of the struck ship.

The modified Minorsky method is simple enough to use for the many accident cases needed for risk assessments. The level of information and amount of computational time required by this method is considerably more than is required for the regular Minorsky method, but much less than what is required for a finite element calculation of collision deformations. For purposes of risk analyses, collisions with less energy available than the amount required to rupture the hull can be quickly screened out. Collisions with more than this amount of available energy can then be treated using Minorsky's correlation without its non-mechanistic constant incercept.

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4. STRUCTURAL FINITE ELEMENT ANALYSES

4.1. INTRODUCTION

The simplified methods for predicting penetration distance discussed in the previous chapter are useful for determining if a radioactive material package will be affected by a ship-to-ship collision, but they do not provide any information about the magnitude of the forces acting on the package. In order to determine the way that a stowed radioactive material transportation package interacts with the transport vessel (and a striking vessel) during a ship-to-ship collision a series of finite element analyses of the entire system was performed. The combination of relatively small structural members and very large overall sizes of ships makes it beneficial to perform the analyses in several stages. The entire system is modeled in the initial stage. In this model a relatively coarse finite element mesh is used to represent the radioactive material package, the transport ship, and the striking ship. This analysis is used to determine the global behavior of the system and to define appropriate boundary conditions for subsequent analyses. It is described in section 4.2 below. In the second stage of analysis only the parts of the ship necessary to determine the maximum crush loading experienced by the package are included. The results of these analyses are presented in section 4.3. Changing assumptions about the manner of transporting high level radioactive material by sea leads to the possibility of interactions between the RAM package and other cargo. The effect of other cargo on the crush loading experienced by the package is presented in section 4.4. All of the analyses are performed using the transient dynamic code PRONTO-3D developed by Sandia [4-1].

4.2. SHIP COLLISION ANALYSES

4.2.1. PROBLEM DESCRIPTION

The problem modeled is that of a small freighter with the dimensions shown in Figure 4-1 impacted by ships of the same mass or more. The struck freighter is assumed to have a mass of 1675 metric tons and zero initial velocity. Two series of analyses were performed. In each series, the response of the freighter was evaluated when impacted by a striking ship of various masses travelling at various initial velocities normal to the longitudinal axis of the freighter. The striking bow was assumed to be vertical (zero rake angle), and all impacts were assumed to occur near the midsection of the freighter to maximize the damage incurred by the freighter. The first series of analyses (designated 1S to 4S) incorporated a crude representation of a single RAM package initially located adjacent to the hull of the freighter opposite the striking ship. The package represented is that of a 22.7 tonne truck cask. In the second series (designated 1M to 4M), a representation of a row of similar packages was incorporated. Impact velocities ranged from 10 to 30 knots (5.1 to 15.6 m/s) and the mass of the striking ship ranged from 1675 MT to 16 750 MT.

The packages were modeled with a coarse mesh using elastic rectangular prisms with four elements each, because they were used only to evaluate average forces and not to analyze deformation. The multiple package representation consists of seven packages side-by-side spanning 80% of the breadth of the freighter. In order to get a conservative estimate of the forces on the packages, they were assumed to be rigidly tied together. In all analyses performed, the packages were free to move. No tie-downs were modeled there was no gravity and no friction.

4.2.2. Results

Results of the finite element computations for the first series of analyses indicate penetration distances ranting from 0.8 to 5.2 meters. Figure 4-2 contains plots of the deformation of the struck ship from the top view. One can easily see the increased damage in case 4S. However, even in this case the striking ship only penetrated the struck ship to slightly more than half of its breadth. Therefore, during this series of analyses, the package initially located adjacent to the hull farthest from the striking ship was not directly impacted by the striking ship during the impact event.

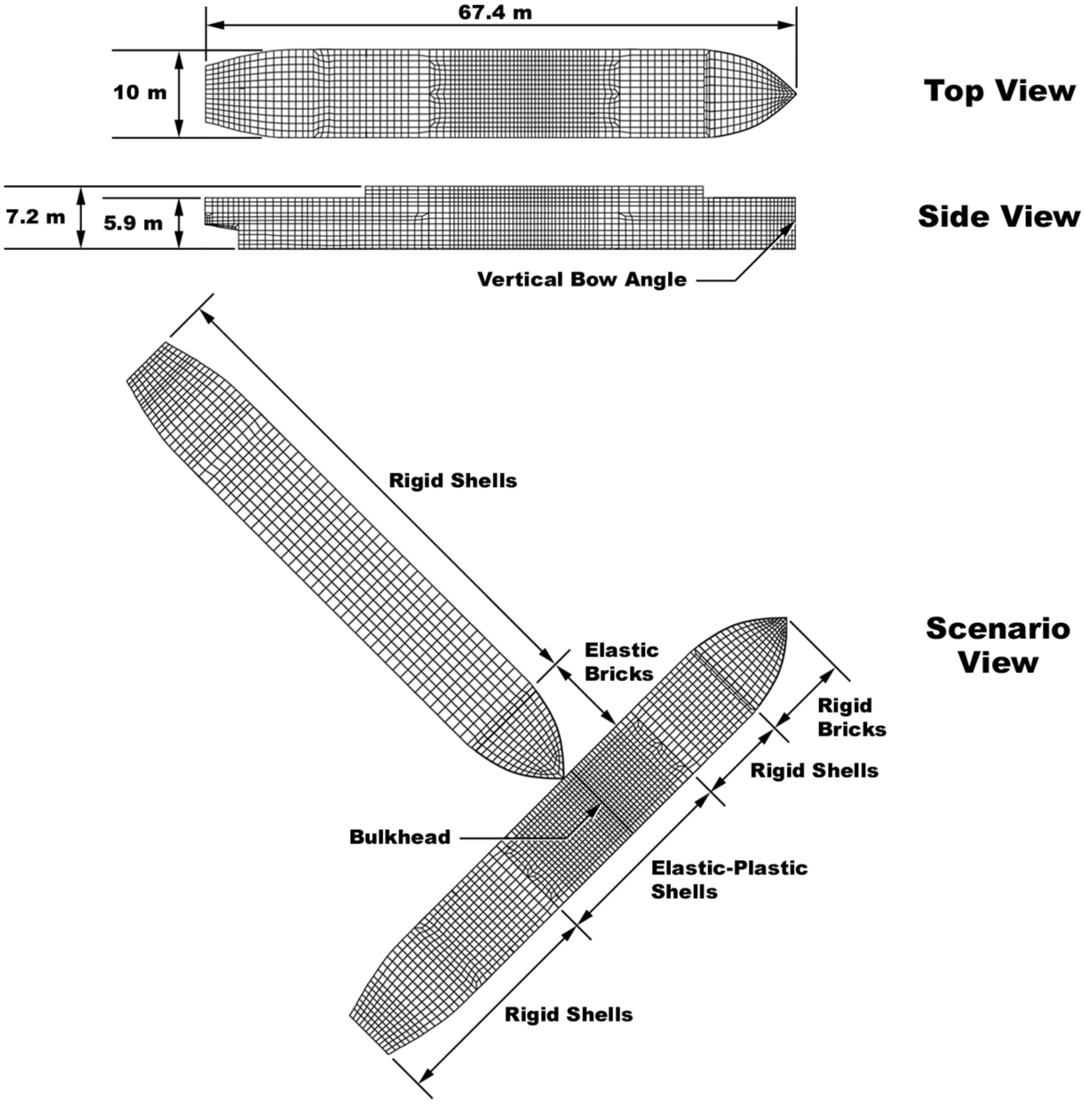


Fig. 4-1. Finite element model used for the ship-to-ship collision analyses.

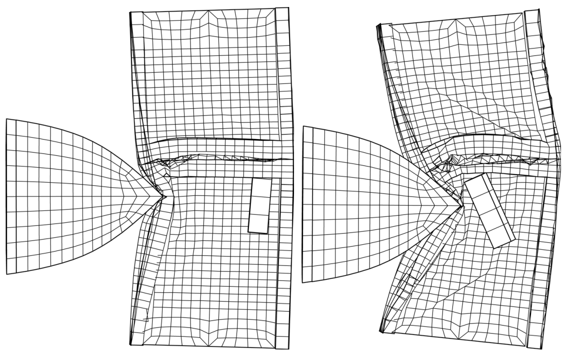


Fig. 4-2. Maximum deformation for case 2S (v = 15 knots, mass = 10 050 tonnes, t = 0.50 sec.) and case 4S (v = 30 knots, mass = 16 750 tonnes, t = 0.68 sec).

A second series of analyses was conducted in order to measure the force that a RAM package might experience during a ship collision. In these analyses, a representation of a row of packages spanning 80% of the breadth of the ship was incorporated to ensure direct impact and crushing of the packages in at least some of the analyses. Deformation of the freighter at maximum penetration for cases 2M and 4M are shown in Figure 4-3. For both cases the maximum crush force is about 130 MN, although case 4M has double the impact velocity.

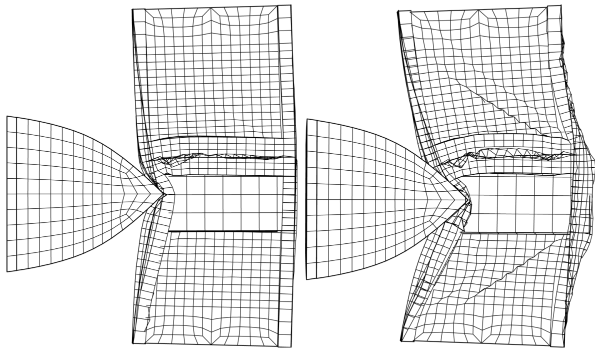


Fig. 4-3. Maximum deformation for case 2M (v = 15 knots, mass = 10 050 tonnes, t = 0.47 seconds) and case 4M (v = 30 knots, mass = 16 750 tonnes, t = 0.50 seconds).

4.2.3. Discussion of ship collision analysis results

The amount of penetration seen in these analyses is less than the amount predicted using simplified calculations, such as the Minorsky method, and the degree of tearing is less than is typically seen in this type of impact. Some of the reasons for these results are the fact the impact point on the struck ship is very near to the transverse bulkhead. This is the stiffest region of the struck ship for side impacts. Also, the artificial stiffening of the shell elements to eliminate the need to model the web frames and stiffeners makes these elements more resistant to tearing. It is likely the stiffening of the ship does not decrease the crush forces seen by the simulated radioactive material packages because the back hull of the struck ship is stiffer as well. So even though the penetration distance and tearing of the struck portion of the ship are underestimated, the forces acting on the package are probably conservative. To obtain a more accurate assessment of the crush forces acting on a radioactive material transportation package, a more detailed analysis of the interaction between the back hull and the package has been performed and is described in the following sections.

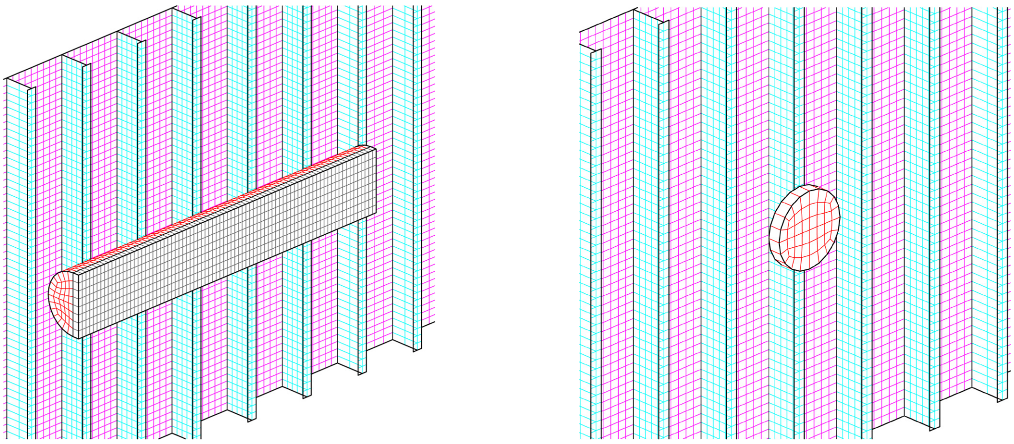
4.3. CRUSH LOADINGS WITHOUT OTHER CARGO

4.3.1. Introduction

In this section, a more detailed finite element model of the region of the ship where the package interacts with the back hull is used to determine the maximum crush force that can be applied to the package. It is assumed that the collision is severe enough to allow the penetrating bow of the striking ship to apply an infinite force on one side of the package. In order for the package to be crushed, a force must be applied to the other side as well. The analyses in this section are aimed at estimating an upper-bound for this force.

4.3.2. Finite Element Model

The finite element meshes used to determine the crush force acting on the package are shown in Figure 4-4. Two cases are considered; the package contacting the hull in a side-on orientation and the package contacting the hull in an end-on orientation. The boundaries of the model are the bulkheads on either end of the hold containing the RAM package and the floor deck of the hold with the package and the floor deck of the hold above the package (this boundary could also be the top deck of the ship). The web frames for the transversely framed ship are included in the model. These frames are spaced at 1 meter. The section of hull modeled is assumed to be rigidly attached to the boundaries (no displacements or rotations at the edges). The plate thickness for the hull is 1.9 cm. The web frames are rigidly attached to the hull plate, but the weld at this location is not included in the model.



a: side-on orientation

b: end-on orientation

Fig. 4-4. Finite element meshes used for determining the crush force exerted on a RAM package from the ship's side structure.

Deformation of the RAM package is not considered in the analysis and no details of the package are included in the model, but the size and shape match that of a typical cask for transporting spent fuel or high level waste by truck. The dimensions are 0.9 meter in diameter by 5.5 meters long. For the side contact case only the front half of the package is modeled and for the end contact case only a short segment of the end of the package is modeled. As the purpose of this work is to determine the crush forces acting on the package, the model is set up for the package to be a force transducer. Therefore, assuming package rigidity is appropriate

4.4.3. Analysis results

For the side-on orientation, the maximum force the hull can supply to the package is about 105 MN. This load is distributed almost uniformly along the length of the package. The level of crush force is less than the maximum crush force from the ship collision model discussed above because some of the conservative assumptions from that model have been removed for this refined analysis. For the end-on orientation the maximum force is about 42 MN. This maximum is nearly identical to the load required to buckle the web frame in this configuration.

4.4.4. Discussion of results without other cargo

The results of these analyses show that the strength of the side structure of the ship transporting the RAM package limits the crush load that can be applied to the package. Due to conservatisms in the finite element model used, the forces determined in these analyses are larger than would be seen in an actual collision. The boundary conditions used in the simulation for the side structure make this structure stronger than it would be in an actual collision, especially for the side contact case. For both cases the global membrane stress in the side structure as a result of the ship's participation in the collision are neglected. These stresses would add to the stresses caused by the penetrating package and reduce the force required for penetration. In addition, for the side contact case the amount the package penetrates the back hull is greater than the package diameter, so it would be impossible for even a rigid bow from a striking ship to not interact with the side structure. This interaction can only decrease the amount of force the side structure is able to impart to the RAM package.

The type of framing typically used for large vessels (transverse) causes the load path from the package to the ship structure to be primarily in the vertical direction. This implies that the magnitude of the force is proportional to the length of side structure participating in the contact. This is clearly illustrated by the much lower maximum force for end contact (0.9 meter of side structure contacted) than for side contact (5.5 meters of side structure contacted). For this reason the amount of force generated for penetration of a larger package, such as a cask for rail shipment of spent fuel,, is not expected to be much larger in the side contact case than it is for the smaller truck cask, as these packages are of about the same length.

Although it is not possible to directly relate these crush forces to the impact forces generated during the regulatory 9-meter drop test, the relative magnitudes can be compared. For a package with a weight of 25 tonnes (typical for truck casks), the side contact force corresponds to an acceleration of about 480 Gs. Similarly, the end contact force corresponds to an acceleration of about 180 Gs. Peak accelerations seen during impact tests are frequently higher than these values.

The results of these analyses indicate that the magnitude of crush force that radioactive material packages transported by sea are likely to be subjected to during even the most severe ship-to-ship collisions is limited by the strength of the side structure of the transporting vessel. The side structure used in these simulations is typical for a large freighter or container ship. Smaller vessels, such as charter freighters that have been used in the past for shipment of spent fuel, have weaker side structure. The amount of crush force that can be imparted by a weaker side structure is therefore less than that predicted by the simulations performed here. If the ship transporting the radioactive material packages has other cargo in the same hold the interactions between the package, the cargo, and the ship hull may increase the length of side structure participating in resisting penetration, thereby increasing the maximum crush force. The effect of other cargo will be discussed in the next section.

5. FIRE SEVERITIES

In this section, test results for a series of eight test fires ranging in size from 2.2 to 18.8 MW conducted aboard the Coast Guard fire test ship *Mayo Lykes* at Mobile, Alabama are presented and discussed. Tests aboard the break-bulk type cargo ship consisted of heptane spray fires simulating engine room and galley fires, wood crib fires simulating cargo hold fires, and pool fires staged for comparison to land-based regulatory fire results. Primary instrumentation for the tests consisted of two pipe calorimeters that simulated a typical package shape for radioactive materials packages. These fire tests were then modeled with the methods of computational fluid mechanics to confirm that analytical models can successfully predict the shipboard fire environment. In addition, analytical studies of fire spread were conducted to improve the ability to predict hold-to-hold fire spread for break-bulk freighters. Also in this section, a simple hold-to-hold fire spread model based on methods developed by the fire protection engineering community is briefly described, and a typical event tree for break-bulk freighter fire spread is outlined and discussed.

5.1. FIRE TESTS

The tests were conducted aboard the *Mayo Lykes*, a World War II Victory class cargo ship, maintained by the United States Coast Guard at Mobile, Alabama, specifically for the purpose of fire testing. Two holds, holds 4 and 5, at the aft end of the ship were selected for the tests. Level 1 of these holds, immediately below the weather deck, was used for all fires and measurements. In all cases the fires were set in hold 4. Steel pipe calorimeters representing simulated radioactive materials packages were placed in both holds 4 and 5. Fires included ignited heptane sprays impinging on the steel bulkhead between holds 4 and 5, and wood crib fires representing combustible cargo fires. The general experimental arrangement is shown in Figure 5-1.

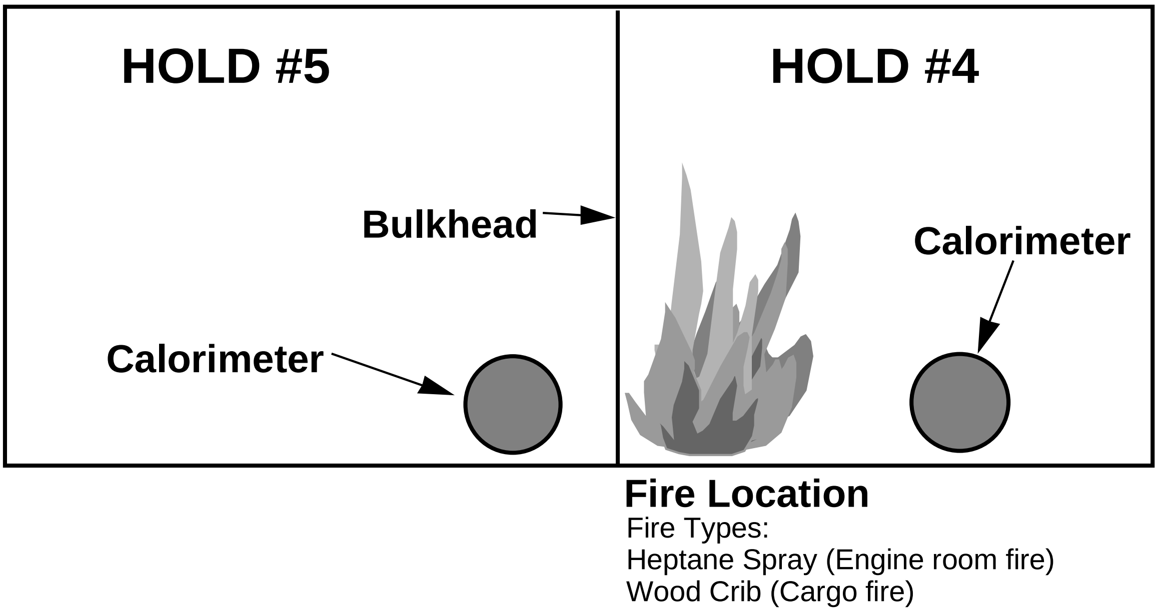


Figure 5-1. Fire test arrangement.

The sequence of eight fires conducted aboard the *Mayo Lykes* is shown in Table 5-I. A brief description of each type of fire and major fire characteristics follows. Hold 4 measures 17.6 m wide by 21 m long by 3.8 m high. Hold 5 dimensions are 17.6 m wide by 16 m long by 3.8 m high. all tests the calorimeter in hold 5 was located with its centerline 0.4 m above the deck and 2 m aft of the hold 5-5 bulkhead. Detailed descriptions of the ship holds involved and instrumentation locations are included in Koski, et al [5-1].

To avoid potentially explosive conditions with the heptane spray and in-hold pool fires, adequate oxygen was supplied to hold 4 via openings in the hull. Measurements indicate that oxygen levels in the vicinity of the fire were usually near normal atmospheric content. In sealed shiphold fires at sea, oxygen would be more limited, leading to smoldering fires with even lower heat flux levels than experimentally measured. The experimental fires reported here represent conditions more typical of a fire that could occur during ship loading or unloading in port.

TABLE 5-I. FIRE TEST SEQUENCE

Test Number	Date, Time and Duration	Type of Test	Peak Thermal Power, MW
5037	9/12/95, 2:09 PM CDT, 60 Minutes	2 burner heptane spray test	2.2
5040	9/14/95, 9:13 AM CDT, 20 Minutes	Wood crib fire test with 17 L heptane accelerant	4.1
5041	9/14/95, 12:21 PM CDT, 60 Minutes	2 burner heptane spray test with diesel fuel in drip pans for smoke	2.2
5043	9/15/95, 8:26 AM CDT, 20 Minutes	Wood crib fire test with 17 L heptane accelerant	4.1
5045	11/13/95, 12:02 PM CDT, 60 Minutes	4 burner heptane spray test	5.6
5046	11/13/95, 2:46 PM CDT, 60 Minutes	4 burner heptane spray test with diesel fuel in drip pans for smoke	5.6
5048	11/14/95, 3:09 PM CDT, 27 Minutes	Diesel pool fire in hold 4	15.7
5049	11/15/95, 2:20 PM CDT, 32 Minutes	Diesel pool fire on weather deck	18.8

5.1.1. Heptane spray tests

The heptane spray fires were intended primarily to simulate a fire in an adjacent ship compartment. For the first series of tests heptane in a pressurized reservoir was fed through nominal 3/8 inch stainless steel tubing to two nozzles located in hold 4. Stainless steel BETE model P54 fine atomization spray nozzles were used to create a 90˚ cone shaped fog spray that was manually ignited with a propane torch. The nozzles were located 0.91 m to either side of the hold centerline. The nozzles were located 1 m above the deck, 1 m from the bulkhead between holds 4 and 5, and were aimed at the bulkhead at an angle of 45˚ above horizontal. For the estimated 0.21 MPa pressure difference across each nozzle, a 0.024 kg/s mass flow rate was calculated. For heptane with a heat of combustion of 44.6 MJ/kg, this gives a thermal output of each nozzle for full combustion of 1.1 MW. The two nozzle configuration doubles this to a total thermal output of the fire to 2.2 MW.

After inspecting the calorimeter results from the first series of two-burner heptane spray tests, a second series with larger nozzles in a four-burner arrangement was conducted. For these tests, in addition to the nozzle locations 0.91 m to each side of the ship centerline, nozzles were located 3.05 m to each side of the centerline. As with the two burner tests, nozzles were 1 m above the deck, 1 m from the hold 4 and 5 bulkhead, and aimed at the bulkhead at an angle of 45˚ above horizontal. For the test, the larger BETE P66 nozzles were used with a 0.55 MPa pressure maintained at the fuel reservoir. This gives an estimated nozzle pressure difference of 0.17 MPa and a flow from each nozzle of 0.031 kg/s. This yields an estimated power release of 1.4 MW for each burner, and a total release of 5.6 MW total for all burners.

5.1.2. Wood crib fires

Wood cribs built from clear Douglas fir were used to simulate a cargo fire immediately adjacent to the simulated radioactive cargo. The general wood crib design is based on UL Standard 711, [5-2], and is consistent with the size designated as 20-A in that standard. To estimate the heat release from the crib, equations were taken from Walton, [5-3]. Application of these equations gave a heat release of 2.4 MW. The UL standard also specifies that to initiate the fire, 17 L of heptane accelerant are to be ignited in a 1 m square pan under the crib. Observation of the experimental data indicated that this accelerant burned for about five minutes giving an experimental recession rate of 0.038 kg/(m^2s), and a corresponding output of 1.7 MW. Combining the heat release of the wood crib and the heptane accelerant gives an initial thermal output of 4.1 MW for the first 5 minutes of the fire, then a steady heat release of 2.4 MW as the crib alone burns. Inspection of the data for the calorimeter in hold 4 indicates that the wood crib heat release decreased rapidly 15 minutes after ignition indicating that most of the wood had burned.

5.1.3. Pool fires

For this test a 3 m × 3 m pool was constructed on the ship centerline at the aft end of hold 4, and the steel pipe calorimeter moved to be centered above the pool in a manner consistent with land based regulatory testing.

During the test a 7.6 cm depth out of a total depth of 13 cm of diesel fuel was burned before overhead temperatures exceeded the previously agreed upon maximum of 540˚C at 24 minutes into the test. At 27 minutes the fire extinguishment with foam was complete. From this information a fuel recession rate of 0.0443 kg/(m^2-s) was calculated. With a typical diesel heat of combustion of 42.75 MJ/kg this leads to an average heat release of 15.7 MW during the test.

For comparison to the in-hold fire test, a 3 m × 3 m pool was built on the weather deck of the *Mayo Lykes* on the port side amidships. The pool was constructed to closely follow the dimensions of the pool built in hold 4. The calorimeter from hold 5 was centered above the pool, 1 m above the fuel surface at the start of the test. A depth of 13 cm of diesel fuel gave a 32 minute burn, typical of a regulatory pool fire. Calculation of the recession rate for this fire led to an estimated average thermal output of 18.8 MW.

5.1.4. Experimental results

Temperature and heat flux results for the first four-burner heptane spray test designated test 5045 are given in Figures 5-2 and 5-3. These results are typical of the one-hour four-burner heptane spray fires conducted. For these tests the calorimeter located in the adjacent compartment, hold 5, was heated about 25˚C during the one hour duration of the test as shown in Figure 5-2. The inverse heat transfer computer code SODDIT [5-4], with use of both inside and outside thermocouples at each angular position, estimates maximum heat fluxes of about 0.8 kW/m^2 on the side of the calorimeter facing the hot bulkhead between holds 4 and 5 (see Figure 5-3).

Results for the calorimeter located immediately adjacent to the burning wood crib (Calorimeter 1) for the first wood crib test designated as Test 5040 are shown in Figures 5-4 and 5-5. During this test the calorimeter increased in temperature about 200˚C. The initial rapid temperature increase at the start of the test is caused by the heptane accelerant used to start the fire. This initial transient results in an initial peak of about 25 kW/m^2 on the calorimeter surface (see Figure 5-5) as estimated with SODDIT with the use of the interior thermocouples only.

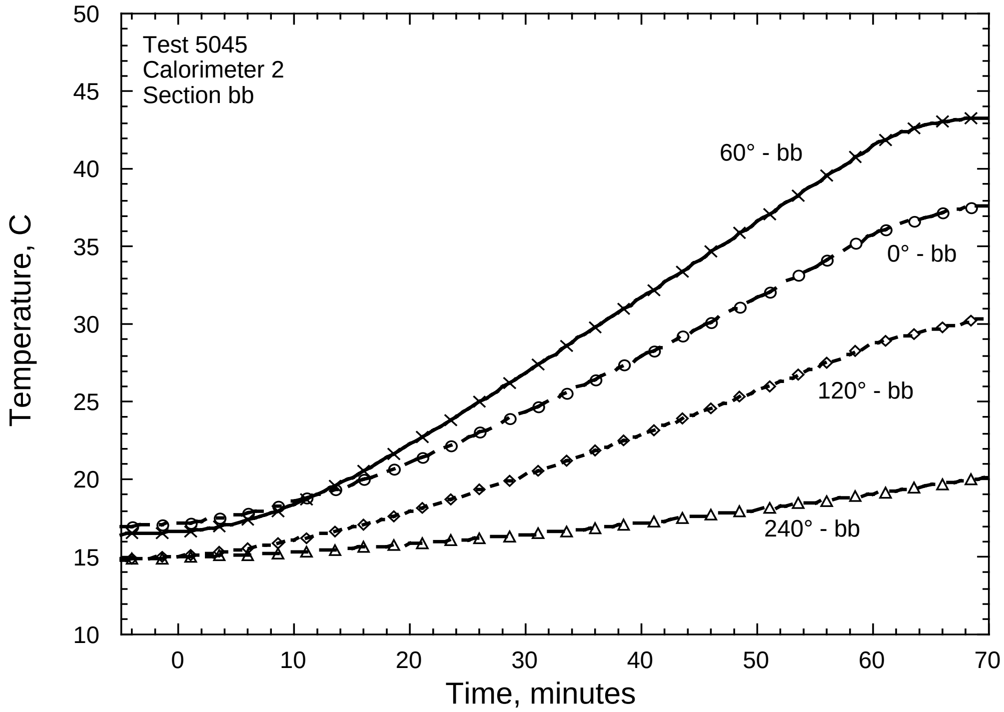


FIG. 5-2. Hold 5 calorimeter temperatures for four-burner heptane spray. All angular locations are measured from the top of the calorimeter with the 90° location facing toward fire.

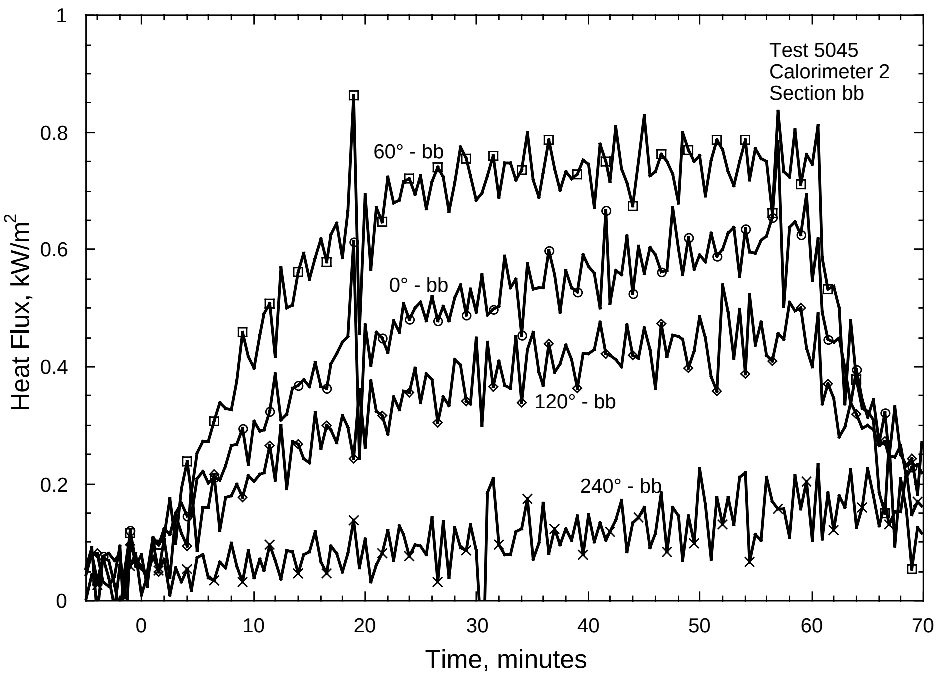


FIG. 5-3. Hold 5 calorimeter heat fluxes for four-burner heptane spray. All angles are measured from top of calorimeter with 90° location facing toward hot bulkhead.

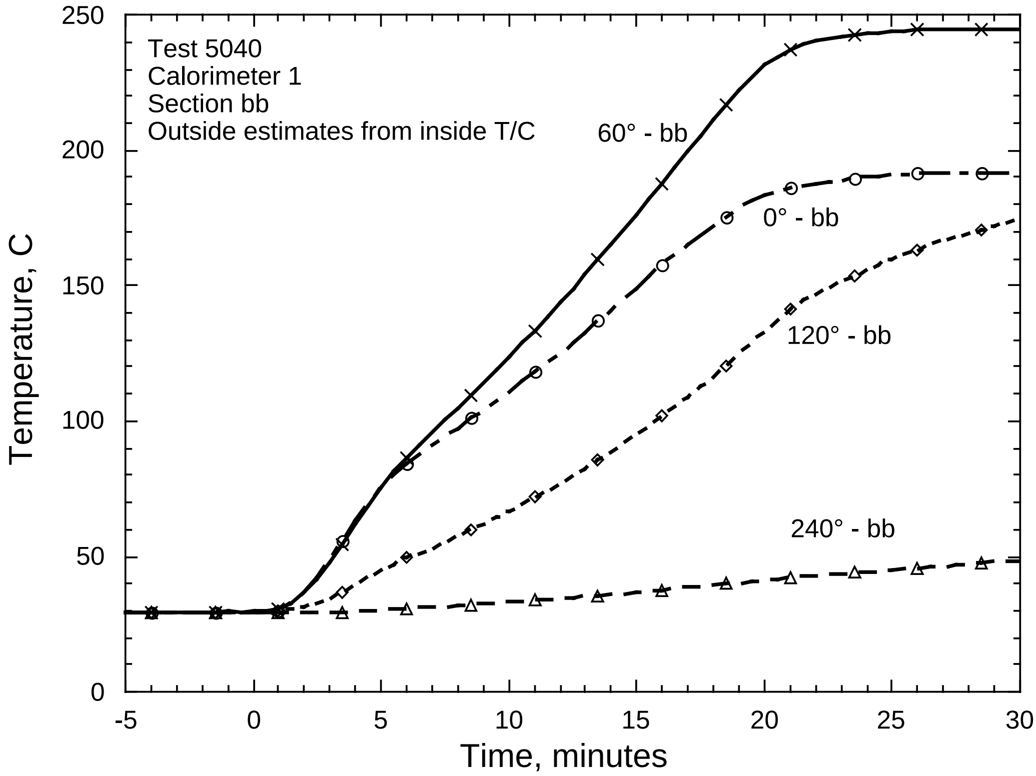


FIG. 5-4. Typical calorimeter temperatures for wood crib test.

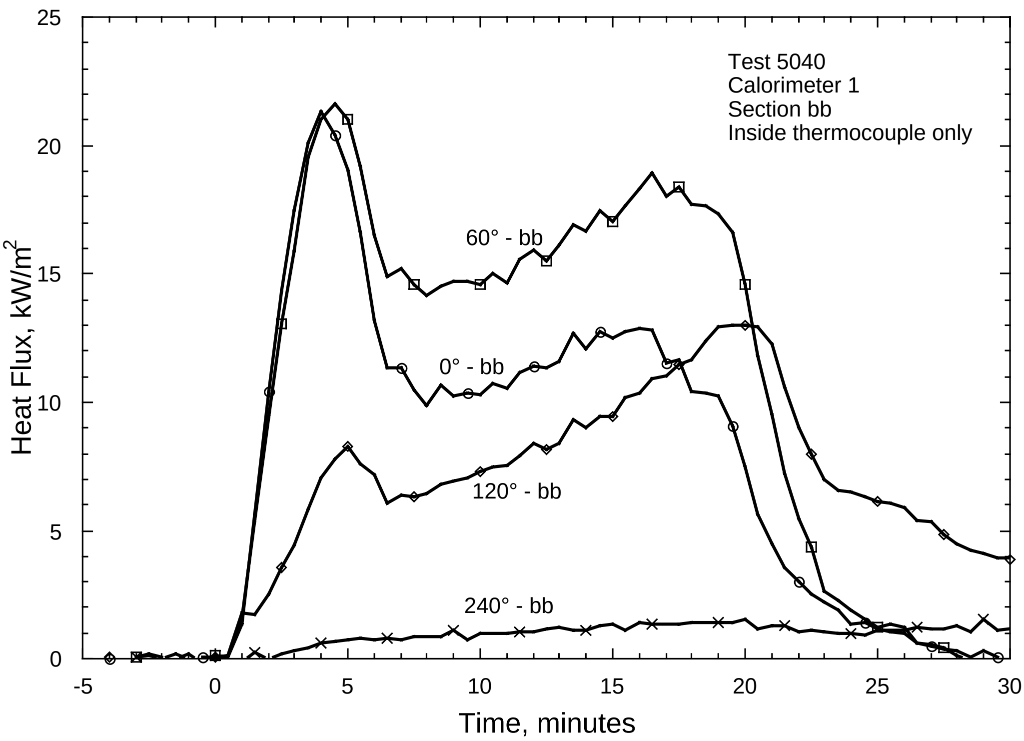


FIG. 5-5. Typical hold 4 calorimeter heat fluxes for wood crib test.

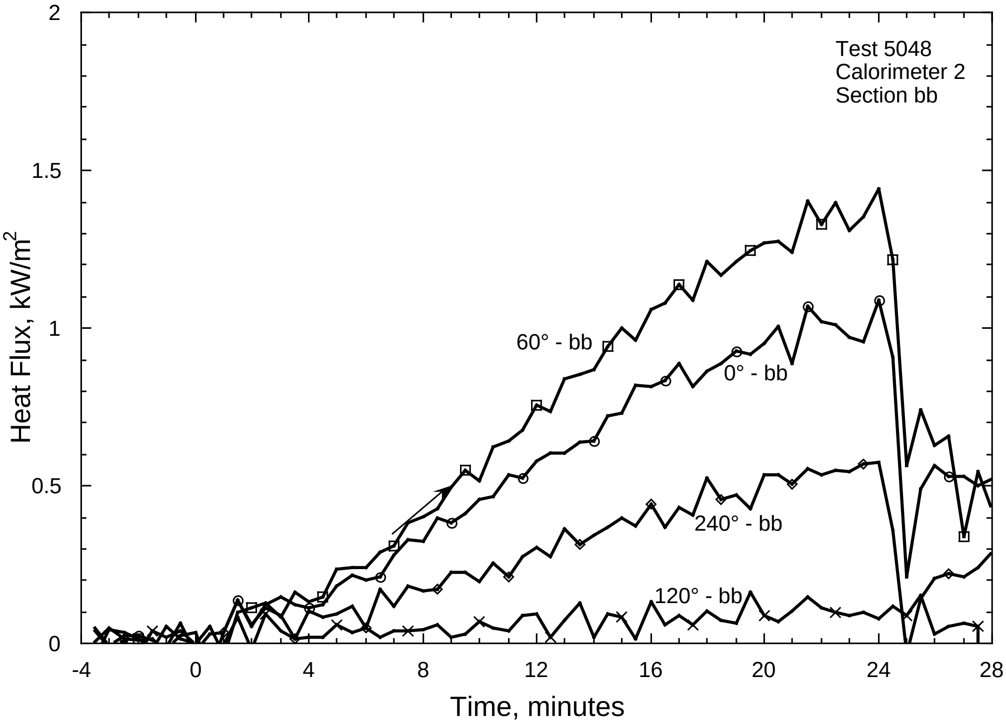


FIG. 5-6. Hold 5 calorimeter heat fluxes for in-hold pool fire test.

For the fire in hold 4, the calorimeter was completely engulfed in flames. The heat fluxes to the calorimeter in hold 5 adjacent to the fire compartment remain at about the 1 to 1.5 kW/m^2 level as shown in Figure 5-6. At about 24 minutes, a decision to extinguish the fire was made to avoid damaging the deck immediately above the fire zone.

Because the on-deck outdoor pool fire was conducted during a strong wind, these data are not directly comparable to typical regulatory outdoor pool fires conducted under low wind conditions. For this reason, these data are not presented here. A complete summary of the data is provided in Koski, et al, [5-1].

5.1.6. Discussion and conclusions

The fire tests yielded several results that support the concepts held prior to testing. First, the overall heat flux level in typical adjacent-hold and combustible-cargo ship fires is considerably below the initial 65 kW/m^2 heat flux levels implied by the 800°C flame temperature and 0.9 flame emissivity of regulations such as Safety Series 6, 1990. Even for the in-hold pool fire, initial heat flux levels to the calorimeter over the fire were comparable to values measured in land-based regulatory fires (see Gregory, et al, [5-5]). For hold 5, adjacent to the fire hold, the heat fluxes to the calorimeter never exceeded 1.5 kW/m^2, even with the large 15.7 MW pool fire near the hold 5-5 bulkhead in hold 4.

For both the heptane spray and wood crib fires, analysis of the calorimeter heat flux plots shows that the absorbed heat fluxes are much higher on the side facing the fire. This indicates that thermal radiation is the dominant heat transfer mechanism since convection would lead to a more uniform heating with hot gases flowing around the entire circumference of the calorimeter. Accurate fire simulations with computer models can aid in determining the partitioning of the heat transfer mechanisms involved.

Analysis of the data does not indicate that shipboard fires are likely to lead to increased heat transfer when compared to land based regulatory fires. In general, the heat transfer seems to be lower than for the fully engulfing pool fire considered for land based accidents.

These experimental results are primarily intended to serve as a means of confirming and refining analytical heat transfer models of shipboard fires. No general conclusions regarding the adequacy or inadequacy of regulatory tests as applied to the shipboard fire environment can be drawn directly from the tests. Any risk assessment model of fires must also include the probabilities of initiating events, as well as details of crew response and allowances for use of fire suppression systems. The testing here applies primarily to the break-bulk freighters typically used to transport radioactive materials. The work does not apply to container ships, where the IMDG rules on cargo separation differ from those applied to break-bulk ships.

5.2. MODELING OF THE FIRE TESTS

To better understand shipboard fire environments, a computational study simulating the fires in holds 4 and 5 of the *Mayo Lykes* was conducted at Sandia National Laboratories to demonstrate that modern computational fluid dynamics (CFD) tools can adequately model such fires in enclosed volumes. These simulations are more completely discussed discussed in [5-6]

The simulation of the wood crib fire in hold 4 was calculated using 24052 finite volume cells. Cell size varied from very small in regions near the fire to very large in the far reaches of the hold. Simulations with twice the number of cells produced little change in the solution convergence. Comparisons of temperatures and heating rates show that with computational fluid dynamics models, useful results can be obtained with fairly rudimentary models of the fire. With modifications the computational model could be extended to estimate heat flux to a cask during a hold fire involving other cargo. More comprehensive fire models, especially with improved smoke models, should yield even better agreements with experiments.

The CFD model of ship hold 5 was a three-dimensional symmetric model and contains 64,352 cells. Heat conducting solids were used to include the thermal capacitance of features such as the hold bulkheads, deck and overhead, the calorimeter and the king post. A weakly compressible buoyancy model, which means only density is a function of temperature, was used since any flow will be induced by natural convection. The model also used a turbulent flow formulation for calculating fluid flow. The temperature and heat flux values calculated in the hold 5 analysis are comparable to what was observed from tests. The reasonable calculated temperature and heat flux values indicated that the thermal response of a ship hold with an adjacent hold fire can be predicted.

The calculated circumferential temperature and heat flux patterns for hold 5 were also similar to the experimental results. The patterns build confidence that a ship hold thermal response can be successfully modeled. The model also confirmed that the predominant mode of heat transfer near the hot bulkhead is thermal radiation. The large time scale for heating components also indicates that radiation is the dominant heat transfer mechanism. However, convection is present and can be a larger factor in transferring heat away from the hot bulkhead.

5.3. BULKHEAD FIRE SPREAD MODEL

When performing risk analyses for maritime shipments of radioactive materials, accidental fires aboard ships must be considered. In most cases such fires will originate at a location other than the hold where the radioactive materials package is stored. The risk analyst must then determine the probability that the remote fire will spread from the hold of origin to threaten the package. To spread the fire must cross steel bulkheads and ignite cargo in holds adjacent to the fire. The purpose of the computer code constructed under this task was to permit a quick estimate of the time required for a fire to ignite a combustible cargo near the steel bulkhead in the hold adjacent to a fire. The code relies on methods developed in the fire protection engineering community (Janssens, [5-7]), and applies the methods to a likely worst-case geometry consisting of a wood shipping crate located near the hot bulkhead separating the fire from the crate. The detailed model is discussed in the full report [5-8].

5.4. FIRE SPREAD ON BREAK-BULK FREIGHTERS

5.4.1. Break-Bulk Freighters

Figure 5-7 presents a side view of the layout of the 14,478 tons deadweight (TDW) break-bulk freighter for which ship collision penetration depths were estimated in Section 3.2.5 using the revalidated, modified Minorsky correlation.

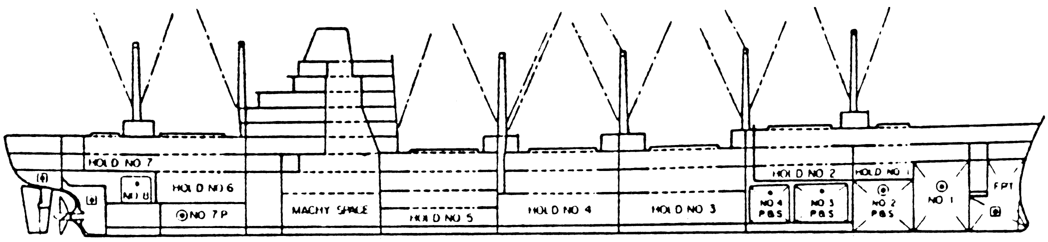


FIG. 5-7. Side view of a 14 478 tons deadweight break-bulk freighter.

Inspection of Figure 5-7 suggests that a break-bulk freighter may be viewed as a set of holds (h) and Decks (d) that define the locations (L_{hd}) of a set of compartments. For example, if superstructure is ignored, the machinery space is treated as a hold, and each hold is assumed to have four decks, then, as is shown in Figure 5-8, the break-bulk freighter depicted in Figure 5-7 can be represented as a 4 by 8 matrix of compartments.

	4	**L_{84}**	**L_{74}**	**L_{64}**	**L_{54}**	**L_{44}**	**L_{34}**	**L_{24}**	**L_{14}**
Decks (d)	**3**	**L_{83}**	**L_{73}**	**L_{63}**	**L_{53}**	**L_{43}**	**L_{33}**	**L_{23}**	**L_{13}**
	2	**L_{82}**	**L_{72}**	**L_{62}**	**L_{52}**	**L_{42}**	**L_{32}**	**L_{22}**	**L_{12}**
	1	**L_{81}**	**L_{71}**	**L_{61}**	**L_{51}**	**L_{41}**	**L_{31}**	**L_{21}**	**L_{11}**
		8	**7**	**6**	**5**	**4**	**3**	**2**	**1**

Holds (h)

Figure 5-8. Schematic representation of the holds and spaces on a break-bulk freighter.

5.4.2. Fire spread model

Suppose that the break-bulk freighter depicted by Figures 5-7 and 5-8 is transporting a RAM cask on the bottom deck of hold 3 (location L_{31}) and that the collision causes a fire to start on the second deck of hold 2 (location L_{22}) hold, which spreads to compartment L_{31} by the Path $L_{22} \rightarrow L_{32} \rightarrow L_{31}$. The probability that fire spread along this path leads to an engulfing fire in compartment L_{31} which damages the RAM transportation cask or its contents is given by

$$P_{Fire} = P_{St,L_{22}} \left(P_F P_{O_2} P_{Ex}\right)_{L_{22}} \left(P_F P_{O_2} P_{Ex}\right)_{L_{32}} \left(P_F P_{O_2} P_{Ex}\right)_{L_{31}} P_{Csk,L_{31}} \quad (5\text{-}1)$$

where $P_{St,L_{22}}$ is the probability that the fire starts in compartment L_{22}, $P_{Csk,L_{31}}$ is the probability that the RAM cask is located in compartment L_{31}, $P_F = P_{enough\ fuel} P_{good\ fuel}$ is the probability that enough of a good fuel is present in the indicated compartment L_{hd} to support a significant fire, P_{O_2} is the probability that the air required to support free burning is available in the indicated compartment, $P_{Operate}$ and $P_{Ex} = 1 - P_{Operate}$ are respectively the probability that the fire system operates and fails to operate in the indicated compartment, and for example $\left(P_F P_{O_2} P_{Ex}\right)_{L_{22}}$ is the probability that the fire in compartment L_{22} is not extinguished by the operation of the fire suppression system and has enough of a good fuel and enough oxygen to place heat loads on the compartment walls that allow fire spread to compartment L_{32}.

But the fire need not start in compartment L_{22} and the cask may not be stowed in compartment L_{31}. A general equation, that expresses the fact that the cask may be stowed in any compartment and the fire may start in any compartment and spread to any other compartment, can be developed by summing over all possible fire start locations and fire spread paths,

$$P_{Fire} = \sum_{\substack{\text{All Start} \\ \text{Locations} \\ \text{and Paths}}} P_{St,L_{hd}} \left[\prod_{\text{Path k}} \left(P_F P_{O_2} P_{Ex}\right)_1 \ldots \left(P_F P_{O_2} P_{Ex}\right)_{n_k} \right] P_{Csk,L_{hd}} \quad (5\text{-}2)$$

where Path k is a sequence of compartments (e.g., L_{22}, L_{32}, L_{31}) of length n_k, $P_{St,L_{hd}}$ is the probability that the fire starts in the first compartment on Path k, and $P_{Csk,L_{hd}}$ is the probability that the cask is located in the last compartment on Path k. Now, as is likely, if unique values of the probabilities $P_{St,L_{hd}}$, P_F, P_{O_2}, P_{Ex}, and $P_{Csk,L_{hd}}$ are not available for individual compartments, and therefore average values must be used, then Eq. 5-2 reduces to

$$P_{Fire} = P_{St} P_{Csk} \left\{ \sum_k N_k \left(P_F P_{O_2} P_{Ex}\right)^{n_k} \right\} \quad (5\text{-}3)$$

where P_{St} and P_{Csk} are the respective probabilities that the fire starts and the cask is located in a random compartment, N_k is the number of paths of length n_k that connect a random fire start location through n_k–2 intervening holds to a possible cask location, P_{Ex} is the probability that the fire suppression system fails to operate in compartment L_{hd} when called upon, and P_F and P_{O_2} are the probabilities that the compartment contains enough of a good fuel and enough air to support a fire of a size large enough and duration long enough to damage a RAM cask located in the compartment or to place heat loads on the compartment's walls that allow fire spread to a neighboring compartment.

5.4.3. Parameter values

Fire spread on the break-bulk freighter depicted in Figure 5-7 for fires that occur in ports was examined by Sprung et al. [5-9] who estimated the following values for the probabilities that enter Equation 3: $P_{enough\ fuel}$ = 0.95, $P_{good\ fuel}$ = 0.9, $P_{operate}$ = 0.8, and P_{O_2} = 0.17 where this value for P_{O_2} reflects the fraction of time that the hold and tween-deck covers of a break-bulk freighter are open for loading or unloading during a port call and thus is a maximum value.

Fire spread paths are not likely to be contorted. For example, if fire spread from compartment L_{22} to compartment L_{32} by the path L_{22}, L_{23}, L_{33}, L_{32} is possible, then spread by the direct path L_{22}, L_{32} should also be possible and should be more probable. Thus, if only minimum length fire spread paths are considered, then for each n_k in Eq. 5-3 there is a single value for N_k. Specifically, for $n_k \geq 2$, $N_k = 4\left(\sum_i b_i - 1\right)$, where $\{b_i\}$ is the set of binomial coefficients obtained by expanding $(x+a)^{n_k-1}$ and the 4 accounts for the fact that, for an infinite matrix of compartments, for any value of n_k, there will always be four identical sets of compartments for the fire to spread to, one set in each of the four quadrants that border the compartment in which the fire starts. For example, for fire spread from compartment L_{32} by any path of length $n_k = 3$, there is only one path (L_{32}, L_{33}, L_{34}) to compartment L_{34}, but there are two paths (L_{32}, L_{33}, L_{43} and L_{32}, L_{42}, L_{43}) to compartment L_{43}. Thus, the number of fire spread paths from compartment L_{32} to compartments L_{34} and L_{43} is [(1+2+1) − 1] = 3, where 1, 2, and 1 are the binomial coefficients of a polynomial of order $n_k - 1 = 2$. But the same analysis applies to fire spread from compartment L_{32} to compartments L_{52} and L_{41} or to compartments L_{12} and L_{23} or to compartment L_{21} and the compartment that would be below compartment L_{31} if the freighter had five decks instead of four. Therefore, for a freighter with five decks (or for an infinite matrix of compartments), if $n_k = 3$, then N_k = 4[(1+2+1) − 1] = 12. For Figure 5-7, because there isn't a compartment below compartment L_{31}, the exact value of N_k for spread of fires that begin in compartment L_{32} along paths with lengths $n_k = 3$ is 11 rather than 12. Finally, Table 5-2 presents values for N_k, for the first six terms of the summations in Eq. 5-3, and for the sums of those terms.

TABLE 5-2. VALUES OF N_K, INDIVIDUAL TERMS, AND SUMS OF TERMS FOR EQUATION 5-3 FOR AN INFINITE MATRIX

n_k	N_k	$N_k\left(P_F P_{O_2} P_{Ex}\right)^{n_k}$
1	1	0.02900000
2	4	0.00336400
3	12	0.00029267
4	28	0.00001980
5	60	0.00000123
6	124	0.00000007
		$\sum_k N_k\left(P_F P_{O_2} P_{Ex}\right)^{n_k} = 0.03267778$

The 4 deck, 8 hold break-bulk freighter being considered here contains 32 compartments. Therefore, P_{Csk} = 1/32 = 0.031. As stated above in Section 2.1, the 15 years of Lloyds' collision data contains 702 port collisions, 11 of which led to fires. Therefore, given that a port collision has occurred, P_{St} = 11/702 = 0.016. Accordingly,

$$P_{Fire} = P_{St} P_{Csk} \left\{ \sum_k N_k \left(P_F P_{O_2} P_{Ex} \right)^{n_k} \right\} = 0.016(0.031)\{(0.033)\} = 1.6 \times 10^{-5}$$

which is almost two orders of magnitude smaller than the value of 10^{-3} previously estimated by Sprung et al. [5-9] for the probability that a RAM transport cask will be subjected to a severe engulfing fire following a ship collision.

5.4.4 Illustrative applications

The preceding derivation assumed that the matrix of compartments is infinite in extent, and that fire start locations, collision locations, and cask locations are random. This section examines those assumptions.

Use of binomial coefficients to derive values for N_k in Eq. 5-3 is strictly correct only for a matrix of compartments that is infinite in extent. N_k values can be developed by inspection for the 32 compartment finite matrix used above to represent a break-bulk freighter. Because the value of the summation in Table 5-2 is set by the first three terms in the summation, only these three terms are reevaluated.

For fire spread paths that contain two compartments (n_k = 2), the 4 × 8 compartment matrix contains 12 compartments (L_{22} through L_{72} and L_{23} through L_{73}) that have all 4 of the fire spread path termini predicted by the binomial coefficient formula, 16 compartments (L_{21} through L_{71}, L_{24} through L_{74}, and L_{12}, L_{13}, L_{82}, and L_{83}) that have only 3 of the 4 termini predicted by the binomial coefficient formula, and 4 compartments (the corner compartments of the 4 × 8 matrix) that have only 2 of the 4 termini predicted by the binomial coefficient formula. An average number of termini (N_k value for an average compartment in the matrix) for fire spread paths that contain two compartments (n_k = 2) can be constructed as a weighted sum of the fraction of compartments in the matrix that have 4, 3, or 2 termini. Thus, (12/32)(4) + (16/32)(3) + (4/32)(2) = [1/32][4(12) + 3(16) + 2(4)] = 3.25.

Construction of a similar weighted sum for three-compartment fire spread paths, paths where n_k = 3, yields an average value for N_k of 7.75. Of course, N_k = 1.0 for one compartment fire paths. If these N_k values for an average cell in a finite matrix are divided by the values of N_k calculated for a compartment matrix of infinite extent and the resulting fractions are used as weights to correct the values of the terms in the summation presented in Table 5-2 for a matrix of infinite extent, a value of 0.03196 = 1(0.0290) + (3.25/4)(0.0034) + (7.75/12)(0.0003) is obtained for the summation for the limited matrix. But this value is almost identical to the value obtained for the infinite matrix. Thus, because the probability of fire spread is dominated by short fire spread paths, the probability of fire spread through real matrices that are limited in extent will be well represented by the value calculated for an infinite matrix.

If a ship collision initiates a fire on the struck ship, the compartment where the fire starts may not, as was assumed above, start on any deck in any hold of the struck ship (that is in any compartment on the matrix). Instead, fire start may be limited to holds near the struck hold. Suppose that the chance of a fire starting is significant only in the struck hold or in the two holds immediately adjacent to the struck hold (the holds on either side of the struck hold). In addition, assume that the struck hold has at least three holds on either side of it. Then, if the RAM cask is located in the struck hold, a value for P_{Fire} can be estimated for fire paths that contain one, two, or three compartments (n_k = 1, 2, or 3) by using path dependent values for P_{Csk} to recalculate the values for P_{Fire} that were calculated in Section 9.5.1 for a limited compartment matrix.

For fire paths that contain only one compartment (n_k = 1), the chance that the fire starts and therefore also terminates in a compartment in the struck hold is 4/12 and the chance that the cask is in this compartment is 1/4 because there are four compartments in that hold. Thus, P_{Csk} = (4/12)(1/4) = 0.083 for the first term in the summation in Eq. 5-3. For fire paths that contain two compartments (n_k = 2), the chance that the neighboring compartment to which the fire spreads contains the RAM cask is 0.083 = [(2/12)(2/4) + (4/12)(1/4) + (6/12)(1/3)][1/4], because two of the twelve compartments in the three holds where fire start is significant have four neighboring compartments of which only two are in the struck hold; four have four neighboring compartments of which only one is in the struck hold; and six have three neighboring compartments of which only one is in the struck hold. Thus, P_{Csk} = 0.083 for the second term in the summation in Eq. 5-3. For fire paths that contain three compartments (n_k = 3), a similar analysis yields P_{Csk} = 0.055 for the third term in the summation in Eq. 5-3.

If P_{Fire} is recalculated assuming that the striking ship strikes the RAM hold, that the fire starts in either the struck hold or in one of the two holds immediately adjacent to that hold, and that P_{Csk} values are path dependent, then

$$P_{Fire} = 0.016\{[(0.083)(1)(0.029) + (0.083)(3.25/4)(0.0034) + (0.055)(7.75/12)(0.0003)]\} = 4.2 \times 10^{-5}$$

If the RAM hold is struck and the probability of fire start is significant only in the struck hold, a similar analysis yields path dependent values for P_{Csk} of 0.25, 0.073, and 0.039 respectively for fire spread paths that contain one, two, and three compartments, whereupon substitution of these values into the preceding equation gives

$$P_{Fire} = 0.016\{[(0.25)(1)(0.029) + (0.073)(3.25/4)(0.0034) + (0.039)(7.75/12)(0.0003)]\} = 1.2 \times 10^{-4}$$

Thus, for break-bulk freighters that are carrying combustible cargo (e.g., wood, plastics, ets.) and are equipped with a fire suppression system, $2 \times 10^{-4} \geq P_{fire} \geq 2 \times 10^{-5}$.

RAM casks are frequently shipped in charter freighters, for example the *Marsis*. For purposes of fire spread, the Marsis may be viewed as a three hold, one deck matrix, where one hold, the stern hold, is the equipment hold (the hold that contains the ship's engines) and the other two holds are cargo holds, only one of which will be used if only one cask is being shipped. Because the freighter has only three holds, fire spread paths are short and few in number. When used to transport a RAM cask, a charter freighter usually carries no other cargo. Thus, the only time a combustible material is present in a cargo hold is when the ship collision breaches the fuel tank in the double bottom of the that cargo hold releasing bunker or diesel fuel into the hold.

A value for P_{Fire} for a charter freighter like the *Marsis* can be estimated using Eq. 5-3 for collisions that strike one of the two cargo holds and thus might fail the cask if it is stowed in the struck hold. The estimate is developed assuming that any collision may initiate a fire in the engine compartment, but that only a collision with a cargo hold can initiate or allow a fire to spread through that hold because the fuel tank in the double bottom of a cargo hold is unlikely to be breached if that hold is not directly struck. Accordingly,

$$P_{Fire} = \frac{1}{3} P_{St} P_{Csk} \left[\left(P_F P_{O_2} P_{Ex}\right)_{L_3} \left(P_F P_{O_2} P_{Ex}\right)_{L_2} + \left(P_F P_{O_2} P_{Ex}\right)_{L_2} + \left(P_F P_{O_2} P_{Ex}\right)_{L_1} \right]$$

where the first term in the brackets represents a collision with hold 2 (compartment L_2) that initiates a fire in the engine hold (compartment L_3) that spreads to hold 2, the second term represents a collision with hold 2 that initiates a fire in hold 2, and the third term represents a collision with hold 1 that initiates a fire in hold 1. When the first cargo hold (compartment L_1) is struck, fire spread from the engine compartment through the second cargo hold to the first cargo hold is neglected, because the double bottom of the second cargo hold should not have been failed by the collision and thus there will be nothing combustible in the second cargo hold to support fire spread through that hold. Collisions with the engine compartment are also neglected because these collisions are not expected to fail the double bottom bunker fuel tank in either of the two cargo holds and thus fire start in the cargo holds or fire spread from the engine compartment to these holds are both very unlikely. Finally, $P_{Csk} = 0.5$ and the leading 1/3 expresses the fact that a collision with any of the three holds is equally likely.

The Minorsky calculations described in Section 3.0 indicate that the small mass (5 ktons) of typical charter freighters means that, if struck by another ship, only one time in ten will the hull of the charter freighter be penetrated. However, because almost all collisions (9 of every 11) that penetrate the hull of a charter freighter will also lead to deep enough penetration to breach the double bottom of the struck hold, when the cargo hold of a charter freighter is struck, for that hold, $P_F = (1/10)(9/11) \approx 0.1$. Therefore, since $P_F = 1.0$ for the engine compartment, $P_{St} = 0.016$, and $P_{O_2} = 0.5$ because while in port hold covers will be off perhaps half of the time [5-9],

$$P_{Fire} = (0.33)(0.5)(0.016)\{[(1.0)(0.5)(0.2)][(0.1)(0.5)(0.2)] + [(0.1)(0.5)(0.2)] + [(0.1)(0.5)(0.2)]\} = 5.5 \times 10^{-5}$$

for port fires on small INF2 charter freighters initiated by collisions.

The preceding estimates of P_{Fire} values were developed using approximate values for P_{O_2} and P_F where $P_F = P_{enough\,fuel} P_{good\,fuel}$. Better estimates of P_{Fire} can be made if better values can be developed for P_{O_2}, $P_{enough\ fuel}$, and $P_{good\ fuel}$. Oxygen availability depends on air availability which depends on the size of the openings (ventilation shafts, bulkhead doors, holes produced by the ship collision) in a hold and the fraction of time that each hole is open on average. The types and amounts of cargo required to support a fire that burns hot enough and long enough to allow the fire to spread to a neighboring hold or to threaten a cask colocated with the fire can be estimated using a compartment fire model and the combustion characteristics and typical shipment quantities of the various types of cargo transported on freighters. Thus, the ship and cargo data and fire models required to support the development of more precise values for P_{O_2}, $P_{enough\,fuel}$, and $P_{good\,fuel}$ are all available.

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6. ILLUSTRATIVE CONSEQUENCE CALCULATIONS

6.1. INTRODUCTION

Should the break-bulk freighter depicted in Figure 4-X be involved in a severe ship collision while transporting spent fuel in a Type B cask, cask failure and/or loss of the cask into the ocean might occur. If cask failure leads to the release of radioactive species to the atmosphere, gasborne transport of these species from the sea to land would cause population along the overland transport path to be exposed to radiation. In addition, deposition of gasborne radioactivity onto the ocean surface or the loss of the failed cask into the ocean would introduce radioactivity into marine food pathways, whereupon people who consume the marine foods contaminated as a result of the accident would also be exposed to radiation.

This section describes illustrative consequence calculations performed using the MARINRAD [6-1], RADTRAN [6-2,6-3], and MACCS [6-4,6-5] consequence codes. MARINRAD was used to model a ship accident that occurs in the open ocean during a transocean voyage, RADTRAN to model a ship accident that occurs while sailing a coastal route at a distance from shore of several tens of miles, and MACCS to model a ship accident that occurs in a port at a known location.

6.2. SOURCE TERMS AND SOURCE TERM PROBABILITIES

The illustrative consequence calculations all assumed transport of spent fuel in a TN-125 cask. Table 6-1 presents the TN-125 cask inventory after cooling for three years.

Table 6-1. TN-125 Cask Inventory

Radionuclide	Inventory (Bq)	Radionuclide	Inventory (Bq)	Radionuclide	Inventory (Bq)
CO-58	3.64E+10	TE-127	3.54E+12	PR-143	2.07E-07
CO-60	1.71E+15	TE-127M	3.62E+12	ND-147	2.58E-13
KR-85	1.73E+15	TE-129	1.28E+06	NP-239	3.73E+12
SR-89	6.89E+10	TE-129M	1.96E+06	PU-238	5.47E+14
SR-90	1.52E+16	CS-134	1.35E+16	PU-239	6.81E+13
Y-90	1.52E+16	CS-136	9.40E-10	PU-240	1.03E+14
Y-91	7.07E+11	CS-137	2.12E+16	PU-241	2.24E+16
ZR-95	2.99E+12	BA-140	7.33E-09	AM-241	1.34E+14
NB-95	6.65E+12	LA-140	8.43E-09	CM-242	6.97E+13
RU-103	1.69E+09	CE-141	3.11E+07	CM-244	4.03E+14
RU-106	1.60E+16	CE-144	2.02E+16		

The MARINRAD calculation assumed that the ship collision caused the TN-125 cask to be lost into the sea and that the entire cask inventory was released into ocean waters over time periods ranging from 3 to 300 years. Source terms for the RADTRAN and MACCS calculations were constructed for two bounding ship collision scenarios, a ship collision that leads to a small failure of the TN-125 cask seal, and a much more severe collision that leads to a double failure of the cask and also initiates a fire that spreads to the hold where the spent fuel cask is stored, and there engulfs the cask and burns hot enough and long enough to significantly increase the release of radioactive material from the spent fuel to the cask interior. For these two hypothetical accidents, the amount M_i of radionuclide i released to the atmosphere was calculated using the equation $M_i = I_iF_i = I_iF_{mci}F_{cei}$, where I_i is the amount of radionuclide i in the TN-125 cask, F_{mci} is the rod-to-cask release fraction and F_{cei} is the cask-to-environment release fraction.

For accidents that don't lead to a fire, transport of aerosols and fission product vapors from the cask interior to the environment was modeled using the MELCOR code [6-6]. These calculations showed that the small seal failure areas expected for credible impact, crush, or fire accidents will lead to cask-to-environment release fractions (F_{cei} values) of order 10^{-2} and that cask-to-environment release fractions increase as cask leak areas increase, which is to be expected since, after cask pressurization due to the failure of fuel rods, cask depressurization times decrease as cask leak areas increase. Thus, a large leak area means a short depressurization time, little time for fission product deposition to cask interior surfaces, and consequently large cask-to-environment release fractions. For the severe ship collision that initiates a severe fire in the where the spent fuel cask is stowed, uneven heating of the cask was assumed to cause combustion gases and air to flow through the cask and this gas flow was assumed to oxidize involatile RuO_2 to volatile RuO_4 and also to carry all species released to the cask interior out to the atmosphere. Therefore, for the collision-plus-fire scenario, $F_{cei} = 1.0$ for all species.

Rod-to cask release fractions (values of F_{mci}) for accidents that don't involve fires were taken from Wilmot [6-7], rod-to-cask release fractions for Cs and Ru due to vaporization during fire accidents were taken from Sprung et al. [6-8], and release fractions for CRUD from fuel rod surfaces to the cask interior were based on estimates of CRUD spallation fractions under accident conditions developed by Sandoval et al. [6-9]. Finally, Table 6-2 presents the release fraction values used to calculate consequences for the collision-only and the collision-plus-fire scenarios that lead to release of radioactivity from the failed cask into the atmosphere.

Table 6-2. Release Fractions for Two Bounding Ship Accident Scenarios

Chemical Element Class		Scenario					
Name	Symbol	Collision-Only (1 hole)			Collision-plus-Fire (2 holes)		
		F_{mci}	F_{cei}	F_i	F_{mci}	F_{cei}	F_i
Noble Gases	Kr	0.2	0.8	0.16	0.2	1.0	0.2
CRUD	Co	0.3	1×10^{-2}	3×10^{-3}	0.3	1.0	0.3
Cesium	Cs	2×10^{-6}	1×10^{-2}	2×10^{-8}	1.6×10^{-3}	1.0	1.6×10^{-3}
Ruthenium	Ru	2×10^{-6}	1×10^{-2}	2×10^{-8}	1.6×10^{-6}	1.0	1.6×10^{-6}
Particulates	Part	2×10^{-6}	1×10^{-2}	2×10^{-8}	2×10^{-6}	1.0	2×10^{-6}

6.3. ACCIDENT SCENARIOS AND SCENARIO PROBABILITIES

For the MARINRAD calculation, sinking of the break-bulk freighter or loss of the cask into the ocean was assumed to occur while the ship was sailing through the Grand Banks. The RADTRAN calculation examined the shipment of a spent fuel cask by a coastal route from New London CT to Charleston SC. The MACCS calculation estimated the consequences of a severe ship collision that might occur during a port call at New York NY (Port Elizabeth). Table 6-3 lists the event probabilities that determine the probability of each of these accident scenarios.

Inspection of Table 6-3 shows that the probability cask failure and loss of a cask into the ocean due to the sinking of the break-bulk freighter following a severe ship collision that occurs while traversing the Grand Banks is about 6×10^{-13}; that the probability of a severe ship collision that leads to failure of the cask seal due to cask crush is about 9×10^{-10} while sailing the urban portion of the New London CT to Charleston SC coastal route and about 1×10^{-8} while making a port call at Port Elizabeth; and that the probability of a severe ship collision that causes a double failure of the cask (both seal failure and a puncture or shear failure) and also a severe fire is about 4×10^{-15} while sailing the urban portion of the New London CT to Charleston SC coastal route and about 5×10^{-14} while making a port call at Port Elizabeth.

Table 6-3. Values of Scenario Event Probabilities

Event	Probability	Value
A ship collision occurs while Sailing through the Grand banks (400 nmi) Sailing the urban portion of the New London to Charleston coastal route (72 nmi) Making a port call at Port Elizabeth	$P_{collision}$	 2.7×10^{-6} 1.4×10^{-5} 1.6×10^{-4}
The RAM ship is the struck ship	$P_{RAM\ ship\ struck}$	0.5
The strike location is midship	$P_{strike/midship}$	0.38
The RAM cask location is midship	$P_{cask/midship}$	1.0
The RAM hold is struck	$P_{RAM\ hold\ struck}$	0.33
Crush forces are applied to the cask	$P_{crush\ forces}$	0.1
Cask crush causes the cask seal to fail	P_{crush}	0.01
Cask puncture or shear occurs	$P_{puncture/shear}$	0.1
A severe fire occurs	$P_{severe\ engulfing\ fire}$	4.6×10^{-5}
The ship sinks	P_{sink}	3.6×10^{-3}

6.4. ACCCIDENTS AT SEA (MARINRAD CALCULATION)

The MARINRAD code was used to estimate the radiological consequences that might result if a severe ship collision led to cask failure and the sinking of the RAM transport ship while the ship was sailing through the Grand Banks, a major fishing region located off of the southern coast of Labrador. The MARINRAD codes models transport of radionuclides between ocean compartments by ocean currents, deposition of radionuclides onto compartment sediments, uptake of radionuclides from these sediments and/or ingestion of suspended radionuclides by seaweed, plankton, crustaceans, mollusks, and larval fish, bioaccumulation of radioactivity due to predation in marine food chains, and radiological exposures caused by ingestion of marine foods and desalinized seawater, inhalation of seaspray, swimming in contaminated seawater, and exposure to contaminated sediments. As Figure 6-1 shows, for these calculations transport of radionuclides by ocean current and deposition onto ocean sediments was modeled by dividing the world's oceans into 19 compartments. The calculations assumed that the entire inventory of the TN-125 cask was released into the Top Labrador compartment (the compartment that contains the Grand Banks fishing region) over time periods of about 3, 30, or 300 years. The calculations used values for pathway concentration factors, predator gut adsorption factors, predator biological turnover rates, and marine food usage factors adapted from previous studies [6-10,6-11]. As expected, the calculations showed that radiological exposures were largely determined by the ingestion pathway and were largest for individuals who consumed seafoods taken exclusively from the Top Labrador compartment. The variation of yearly individual doses with time for this compartment is presented in Figure 6-2. This figure shows that near-term individual doses increase as the radionuclide release time decreases; that, if release takes place over three years, yearly individual doses reach a maximum value of about 180 millirem five years after the sinking of the RAM transport ship; and that, after 100 years, yearly individual doses have fallen to 40 millirem if release occurs over 300 years and to 1 millirem if release occurs over three years. For the Top North American, Top Guiana, and World Ocean compartments, radionuclide release over 30 years produces the largest values for one-year individual dose, specifically 5 millirem at 40 years for the Top North American compartment, 1.3 millirem at 100 years for the Top Guiana compartment, and 0.04 millirem at 100 years for the World Ocean compartment.

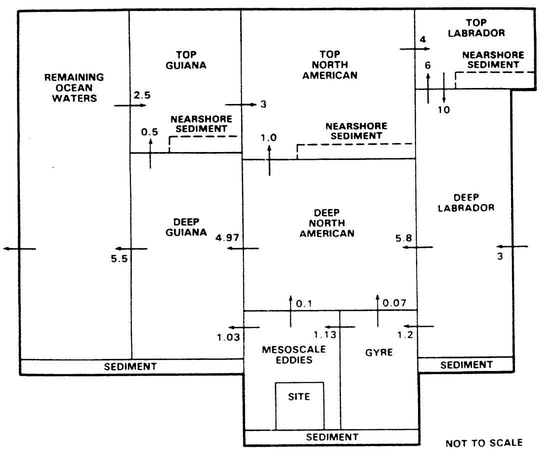

Figure 6-1. Nineteen compartment ocean model showing intercompartment flows (10^6 m^3 sec^{-1}).

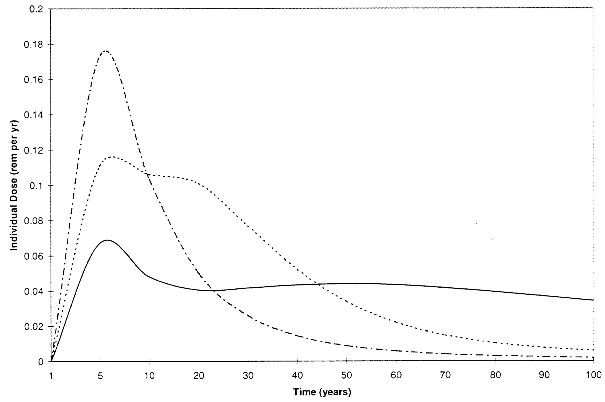

Figure 6-2. Average yearly individual doses in the top labrador compartment (release period: · —· – 3 yrs, ···· 30 yrs, — 300 yrs).

6.5. ACCIDENTS WHILE SAILING A COASTAL ROUTE (RADTRAN CALCULATION)

The RADTRAN transportation risk code was used to model the consequences that might be caused if either of the two hypothetical transportation accidents occurred while spent power reactor fuel was being transported in a TN-125 cask from New London CT around Long Island and then down the east coast of the United States to Charleston SC at a distance of approximately 40 km from the coast. These calculations used three aggregate route segments (one urban, one suburban, and one rural segment), the inventory presented in Table 6-1 and the release fractions presented in Table 6-2. Table 6-4 presents the lengths and average population densities of these three aggregate route segments as calculated using the HIGHWAY code and the following coastal highway route: State Highway 27 from Montauk Point on Long Island to New York City; US 9 from New York City through Cape May, New Jersey, and Lewes, Deleware, to US 13; US 13 to Norfolk, Virginia; and US 17 from Norfolk, Virginia, to Charleston, South Carolina.

Table 6-4. Aggregate Coastal Route Segment Lengths and Population Densities

Segment	Urban	Suburban	Rural
Length (km)	133	415	902
Population Density (people per km^2)	2780	386	13.5

Consequences were calculated for each of the two hypothetical accident scenarios described in Section 6.3, the one hole collision-only scenario and the two hole collision-plus-fire scenario by differencing two RADTRAN calculations: a 0-to-121 km calculation and a 0-to-40 km calculation. By differencing the results of these two calculations [6-12], the 40 km near-field open ocean region between the sailing route and the shoreline was subtracted from the results of the standard RADTRAN calculation, thereby obtaining an estimate of the consequences that occurred in the 40-to-121 km distance range, which comprises the first 81 km of land next to the shoreline. Table 6-5 presents the results of these RADTRAN calculations.

Table 6-5 shows that deposition of radioactive materials, onto the surface of the 40 km wide region of ocean between the sailing route and the shoreline, reduces the estimated population dose by a factor of about three. Thus, correcting for the presence of a near-field region that is devoid of population produces a significant reduction in estimated population dose. Of course, some of the radioactivity that deposits onto the ocean surface will eventually cause population dose via marine food pathways. However, because contaminated seafoods reach individuals in the general population through the commercial food distribution system, the individual doses caused by consumption of these contaminated seafoods will always be very small, much smaller than normal background exposures, and thus of little significance.

Table 6-5. Fifty-Year Population Doses (Sv) Calculated by RADTRAN for Three Distance Ranges for the New London to Charleston Coastal Shipping Route

Source Term	Collision-Only (1 hole)			Collision-plus-Fire (2 holes)		
Route Segment	Urban	Suburban	Rural	Urban	Suburban	Rural
0-to-121 km	1110	255	8.9	106 000	24 400	855
0-to-40 km	795	183	6.4	72 900	16 700	586
40-to-121 km	315	72	2.5	33 100	7 700	269

Although the 50-year 33,100 Sv urban population dose calculated for the collision-plus-fire accident scenario seems to be very large, in fact it is about 20 times smaller than the 590 000 Sv background dose that the 3.3 million people in the exposed population would accumulate during the 50 years that follow the hypothesized accident. Thus, even an unusually long epidemiological study of a large portion of that exposed population would not be expected to be able to detect any radiological consequences (e.g. cancer fatalities) attributable to the accident. Finally, not only are the radiological consequences of this extremely severe collision-plus-fire accident unlikely to be capable of epidemiological detection, but also, as Table 6-5 shows, the probability that this accident will occur while sailing off of urbanized shoreline during a voyage from New London to Charleston is so small (4×10^{-15}) that the accident is almost not credible.

6.6. PORT ACCIDENTS (MACCS CALCULATION)

Table 6-6 presents consequence estimates for the two hypothetical ship accident scenarios described in Section 6.3 assuming that these accidents occur in the port of New York (Port Elizabeth). Both calculations assumed that the break-bulk freighter was carrying other cargo besides the spent fuel cask and both used the inventory presented in Table 6-1, the release fractions presented in Table 6-2, one year of variable meteorological data recorded at the New York City National weather Service Station, and a population distribution constructed from 1990 census data using POPSEC90 [6-13]. Although no short term emergency response actions (evacuation, sheltering) were assumed to take place, post-accident relocation of population from and decontamination and/or condemnation of significantly contaminated property was assumed to take place. The results of these MACCS calculations are presented in Table 6-6.

Table 6-6. MACCS Predictions of 50 Year Population Dose and Cancer Fatalities for a Port Accident

Source Term	Probability (per port call)	Population Dose (Sv)	Cancer Fatalities
Collision-Only (1 hole) Collision-plus-Fire (2 holes)	1.0×10^{-6} 4.0×10^{-12}	857 2.4×10^{4}	37 1.0×10^{3}
50 Year Background Dose		$>1.8 \times 10^{6}$	
50 Year Cancer Fatalities			$>1 \times 10^{5}$
Exposed Population		$\sim 1 \times 10^{6}$	

Table 6-6 shows that the normal background radiation doses and normal rates of cancer deaths among the population predicted to be exposed to radiation as a result of these two hypothetical ship accidents exceed by factors of about 10^2 to 10^5 the MACCS predictions of mean population dose and cancer fatalities among the same population that might be caused by these two bounding port accident scenarios.

6.7. DISCUSSION

The illustrative consequence calculations described in this section have one result in common. They all predict doses that are very small when compared to the average annual dose normally incurred by individuals due to exposure to natural (e.g., comic rays, radon, terrestrial radionuclides) or routine man-made (e.g., medical X rays) sources of radiation. Thus, these illustrative calculations suggest that the radiological consequences that might result if a ship transporting a Type B package were involved in a severe maritime accident are not of great concern.

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