IAEA-TECDOC-1346

Input data for quantifying risks associated with the transport of radioactive material

Final report of a co-ordinated research project 1996–2000

INTERNATIONAL ATOMIC ENERGY AGENCY

March 2003

The originating Section of this publication in the IAEA was:

Radiation Safety Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

INPUT DATA FOR QUANTIFYING RISKS
ASSOCIATED WITH THE TRANSPORT OF RADIOACTIVE MATERIAL
IAEA, VIENNA, 2003
IAEA-TECDOC-1346
ISBN 92-0-101403-1
ISSN 1011–4289

Printed by the IAEA in Austria
March 2003

FOREWORD

The worldwide production and use of radioactive material (RAM) and radiation sources in various facets of modern life (energy production, industry, medicine, science, and technology) involves, inevitably, their transport in the public domain and therefore the hazards and the risks associated with RAM transport.

In 1959 the United Nations Economic and Social Council (ECOSOC) charged the International Atomic Energy Agency (IAEA) with the task of establishing recommendations on the transport of radioactive material. More specifically, the IAEA is authorized, under Article III.A.6 of its Statute:

"*to establish or adopt… standards of safety for protection of health and* ***minimization of danger to life and property…*** *and to provide for the application of these standards… services, equipment, facilities, and information made available by the Agency or at its request or under its control or supervision.*"

The assessment and the analysis of the risks associated with the transport of radioactive material have always been in the focus of the IAEA. At the beginning of the 1990s, a Co-ordinated Research Project (CRP) on "The Probabilistic Safety Techniques Related to the Safe Transport of Radioactive Material" was established. Within that CRP, a computerized package named INTERTRAN2 was developed for risk assessment on transport of RAM.

At the eleventh meeting of the IAEA Standing Advisory Group for the Safe Transport of Radioactive Materials in 1995, to cover the maintenance of the software and review data collection issues, it was decided to start a new CRP which was called "Development of Relevant Accident Data for Quantifying Risks Associated with the Transport of Radioactive Material".

This TECDOC represents the final outcome of the work done for this CRP by ten countries, which was co-ordinated by the IAEA in a number of meetings which were spread over five years. A list of contributors to the CRP, including drafting and review of this report can be found at the end of this TECDOC.

The IAEA wishes to acknowledge the efforts of all those who took part in this CRP. The IAEA officer responsible for this publication was X. Bernard-Bruls of the Division of Radiation and Waste Safety.

CONTENTS

1. INTRODUCTION

At the beginning of the 1990s, a Co-ordinated Research Project (CRP) on "The Probabilistic Safety Techniques Related to the Safe Transport of Radioactive Material" was established. Within that CRP, a computerized package was developed for assessing the risk posed by the transport of radioactive material (RAM). This package contained computer codes and some advisory documentation called INTERTRAN2.

During the preparation and development of the INTERTRAN2 package it was felt that some work needed to be done to develop advice for users on how input data should be determined. Therefore, it was agreed to establish a second CRP dealing with the modalities for the collection, analysis and processing of relevant input data and the selection of databases. More specifically, these data covered such items as package characteristics, accident environments and package behaviour under accident load conditions. The CRP was also intended to give advice as to how to present the risk assessment results and how to quantify the uncertainty inherent in the predicted consequences and risks. This CRP started in 1995 and was called "Development of Relevant Accident Data for Quantifying Risks Associated with the Transport of Radioactive Material".

As the INTERTRAN2 Computer Code System was originally developed for the DOS operating system, it was felt that it should be rewritten for Microsoft Windows®. Therefore, in connection with this second CRP a Windows® version of the INTERTRAN2 Computer Code System was developed.

The following countries participated in the CRP and contributed to the development of INTERTRAN2: Canada (Ontario Hydro), China (China Institute of Radiation Protection), France (Institut de Protection et de Sûreté Nucléaire), Germany (Gesellschaft für Anlagen- und Reaktorsicherheit mbH), India (Bhabha Atomic Research Centre), Japan (Institute of Nuclear Safety), Romania (Institute for Nuclear Research), Sweden (AMC Konsult AB), United Kingdom (AEA Technology Consultancy Services) and United States of America (US Department of Energy).

2. SCOPE, OBJECTIVES, LIMITATIONS AND DEFINITIONS

The worldwide production and use of radioactive material (RAM) and radiation sources in various facets of modern life (e.g., energy production, industry, medicine, science, and technology) involves, inevitably, their transport in the public domain. The hazards of RAM transport may be characterized by two distinct conditions of transport and the subsequent risks associated with such transport: i.e., risks associated with incident-free transport as well as those resulting from possible incidents and accidents and the potential to affect people, property, and the environment. A broad understanding of the type, nature, and magnitude of radiological hazards associated with the carriage of RAM in the public domain is important for the following reasons:

- It is an essential input to the continuous regulatory and revision process of the provisions and requirements used to judge the adequacy of the safety principles underlying the 'IAEA Transport Regulations' (Regulations for the Safe Transport of Radioactive Material – 1996 Edition (Revised) – Requirements, IAEA Safety Standards Series No. TS-R-1 (ST-1, Rev.) 2000).
- The IAEA Transport Regulations require periodic assessments to be carried out to demonstrate that the safety objectives are met for all conditions of transport including transport and handling incidents/accidents, and

- Accidents that may occur during transport of RAM might be severe enough to represent a challenge to the package containment and shielding integrity. Such potential severe accidents are a matter of public concern. Thus, reporting of accurate information related to the nature of hazards associated with such activities is important for decision makers and for addressing public needs.

Transport risk assessments require many different and complex subjects to be addressed, including (a) shipment information, (b) radiological, physical and chemical characteristics of the material's constituent isotopes, (c) physical characteristics of the packagings and conveyances, (d) exposure parameters for the transport workers, (e) routing data and population characteristics, (f) frequency and severity of accidents for a given mode of transport, (g) package response and release behaviour, and (h) estimation of the dose to members of the public and transport workers.

The collection and generation of such input data generally represents a challenge to the risk analyst, as the types of information that must be gathered cover many technical disciplines. In addition, collection or synthesis of input data may require a significant investment of resources (both time and funding) to develop a reasonable and defensible data set to adequately address the actual transport environment. Finally, the risk analyst must have a detailed understanding of the modelling assumptions associated with risk assessment tools, to properly assess the applicability of existing compilations of data to the specific risk assessment problem under consideration.

Frequently, the risk analyst encounters difficulty in the collection and compilation of relevant information because available data may have been collected for purposes other than transport risk analysis. For example, available data may be for conditions that are different from the current risk assessment and may require personal judgement to either apply these data in a credible manner, or to disregard certain data when not applicable.

2.1. Principal objectives

The primary objective of this TECDOC is to assist the risk analyst by providing support on assessment techniques and potentially relevant information resources available internationally that may be employed in addressing the complex tasks involved in assessing transport risk. The typical approaches available for collection, compilation, and evaluation of input data for transport risk assessment may be broadly categorized in the following way:

- Use of empirical data collected from the vast body of national and international experience in the transport of RAM that is representative of the transport operation being considered (see for example the PATRAM Conference documentation), or

- Use or synthesis of data from a wide range of technical disciplines (e.g., science, technology, and economy) with relevance to the event or process of study (e.g., structural performance of the package in response to varied thermal or mechanical stresses), or

- Use of scenario specific data that provide a basic description of transport operation (e.g., size of the package, number of drivers, radiation dose rate).

Whenever possible, explicit data and information resulting from transport operations or practices that are the same or similar to the transport scenario under investigation should be used. However, it is also essential that the risk analyst convey an understanding of the potential uncertainty implicit in the risk estimates and other related issues to assist in establishing confidence (by decision makers and the public) in the evaluation of risks associated with the transport of RAM in the public domain.

The INTERTRAN2 transport risk assessment package has been assembled to provide tools for calculating risk estimates for incident-free transport of RAM and for incidents and accidents that may occur during shipping. Transport risk assessment involves the quantification of both the potential for, and the radiological consequences of, transport operations in the public domain, under incident-free and accident conditions. Due to changing conditions associated with transport activities e.g., variations in population density over specific routes or inability to predict the location (and therefore the specific characteristics) of an accident, transport risks are calculated over a spectrum of accident environments.

Transport risk assessment involves consideration of the variability of certain parameters over the transport routes as well as the statistical nature of transport incidents and accidents, with two components to be quantified: (1) the expected frequency of occurrence of some initiating event leading to an adverse consequence and (2) the magnitude (or severity) of the potentially adverse consequence resulting from transport accidents. The consequence of incident-free transport is an exposure to a low level of radiation from the package; the probability of such exposure is 1.

In line with the broad range of applications of INTERTRAN2 to the many types of shipments, the following data requirements and potential sources of information and assessment techniques currently available to the risk analyst are considered in the present publication:

- Incident-free transport data needs,
- Transport accident frequency and severity analysis data,
- Uncertainty of the transport risk estimates and the sensitivity of the various parameters within the framework of the risk assessment model,
- Implications of human error that increase the probability of an accident, and
- Quality assurance requirements.

2.2. Limitations

The risk analyst must be aware of the limitations of transport risk assessments, both in terms of the inherent assumptions upon which the computational models were developed, as well as limitations associated with the input data needed by the computational models.

The computational models are controlled by a series of input variables that can take a wide range of real-world values (e.g., mode of transport, route lengths, package dimensions, or population densities along the route). Some variables strongly influence predictions of transport risks associated with movement of RAM, while others are less significant. Some variables are fixed or only vary over a narrow range, while others can vary widely. Still other variables are country or region specific. While generally fixed, country-specific data include a series of parameters (e.g., population data, shielding factors for buildings, assumptions about land use, or roadway widths) that are unique to a particular area. Incorrect selection of these parameters may affect the overall accuracy of the calculated risk, including the possibility of underestimating the actual risk.

Relative to the task of preparing input data for risk assessment calculations, the risk analyst must collect, generate, or synthesize a great deal of information in order to correctly evaluate the radiological risks associated with the transport of RAM.

The risk analyst must be aware that the computational algorithms, in many cases, apply simplifications to model the transport operations, and require generalized (average) input parameters. Even if more precise data are available, it may be impractical for the analyst to use this information explicitly, without first calculating an average value of the subject parameter. For example, the analyst may be aware that the planned shipment will require six different inspections (with two inspectors each), with each inspection requiring 10 minutes each. From the standpoint of the input data, assuming a single, 60-minute inspection with two inspectors may be sufficient to estimate this radiological risk. It is then up to the risk analyst to correctly document these details during the final, risk evaluation, phase.

The risk analyst must also be cognizant of the many sources of data that are available. Some input data that describe the package and transport operations, such as the package size, number of crew members, type of transport vehicle, mode of transport, velocity of the transport vehicle, and the length of the route, can be readily determined as part of the definition of the problem. Other data, such as that describing the population density along the route, and certain characteristics about the transport system (e.g., traffic volumes, vehicle occupancies, and number of pedestrians) must be derived from experience and careful examination of the transport system. Still other data must be determined using either complicated computer models (radionuclide inventories of spent fuel) — using ORIGEN [1], or dose rates from packages — using shielding codes or derived from existing tabulations and 'rules-of-thumb'. And other data, such as the release rates from packages in response to severe mechanical and thermal stresses, or the fractions of release material that would be available in a dispersible form or of a size that could be inhaled, must be determined either using results from rigorous experimental testing or by use of computer models that simulate the package response under mechanical and thermal damage events.

2.3. Definitions

The risk analyst must be familiar with certain terms associated with transport risk assessment:

- **Package, Packaging, Conveyance…** — are defined in the IAEA Transport Regulations.

- **Mode** — a term to describe the method of transport (i.e., road, rail, air, sea, inland waterway), which involves different assumptions regarding interactions with the population over the route. For example, transport by truck over public highways results in risk to the people located along the route, while transport by ship in a sea generally limits risk to those personnel (crew and handlers) involved in the transport.

- **Incident-free** — the normal shipment of RAM, under which the shipment is completed without incident but including minor mishaps.

- **Accident (or incident)** — an unlikely event that could lead to material damage to the package and may (if sufficiently severe) lead to the partial or complete loss of its safety functions, e.g. degradation of the containment system with release of RAM, degradation of the shielding ability, degradation of the heat dissipation capability, or, if the package contains fissile radioactive material, degradation of the criticality safety function.

- **Probability** — the likelihood of an event (e.g., transport accident) occurring.

- **Consequence** — the adverse outcome from a transport accident event, and for the most severe accidents, the resultant exposure to the RAM released from the package.

- **Risk** — is a term that is internationally not uniquely defined, but generally comprises two basic elements, i.e. (1) the probability of occurrence of some adverse consequences and (2) the magnitude (or severity) of those consequences. In the USA the term 'risk' is generally understood to represent the product of event probability times consequence, expressed, for example, in terms on population dose (in units of man-Sv).

- **Severity** — a term used to distinguish the variation in package damage caused by an accident. Less severe accidents result in no release and no dispersion of RAM, while very severe (but less likely) accidents may result in the release of all RAM from a package.

-

3. INTERTRAN2 TRANSPORT RISK ASSESSMENT TOOL

3.1. The INTERTRAN2 Computer Code System

INTERTRAN2 contains analysis tools used for assessing radiological consequences and risks associated with the transport of RAM by land, air and sea. INTERTRAN2 comprises a series of calculational models in the form of a Computer Code System that determine radiological consequences and risks by combining user-supplied data with radiological information provided by the code system. The principal components are the file handler [2], RADTRAN 4 [3], and TRANSAT [4]. The models in RADTRAN 4 are shown in Fig. 1.

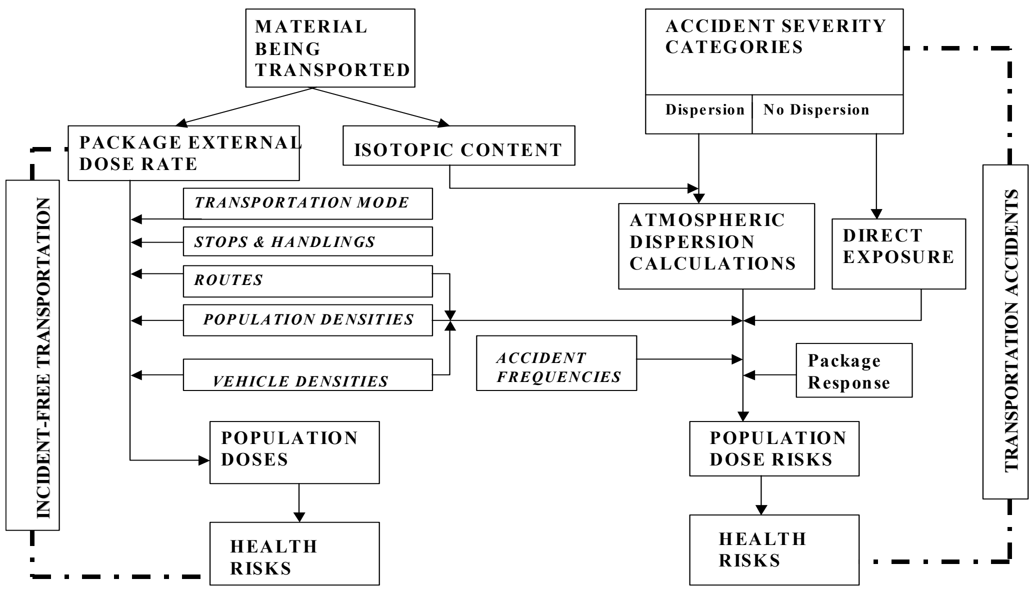

FIG. 1. Flow chart for the modelling of transport risk assessment.

Transport is defined in this TECDOC to mean the shipment of RAM in the public domain via air, water, rail and road including vehicle stops, inspections, intermodal transfers (handlings) and intermediate storage of packages. Transport related activities, including package preparation, marking, labelling, loading and maintenance of packages are, however, not normally assessed as part of a transport risk assessment.

The transport conditions provided by the code system include both incident free transport and the occurrence of abnormal transport conditions including incidents and accidents that may or may not result in radionuclide releases and subsequent dispersal in the environment or increased radiation levels outside the package.

The INTERTRAN2 Computer Code System allows the user to adjust the analysis to the specific problem being analysed including modelling of multi-modal shipments. It covers the broad range of radionuclides being used in medicine, science and technology as well as nuclear materials and radioactive waste.

The INTERTRAN2 Computer Code System also provides an advanced atmospheric dispersion code, TRANSAT, which may be used by experienced users dealing with complicated weather situations.

The transport incident centerline dose calculation program TICLD (Transport Incident Centerline Dose) and LHS module (Latin Hypercube Sampling program [5]) are not included in the standard version of the INTERTRAN2 Computer Code System, but may be downloaded separately or provided on request.

The INTERTRAN2 Computer Code System provides a versatile tool for:

- Applying specific transport impact analysis studies
- Transport risk assessment
- Comparison of shipment options
- Supporting decision making processes
- Optimization of transport concepts and technologies from the viewpoint of radiation protection.

The INTERTRAN2 Computer Code System is available for downloading from the Web at AMC Konsult AB homepage (http://www.amckonsult.se). The INTERTRAN2 Computer Code System is written in Visual Objects, which is a 32 bit object oriented language for Windows® 95/98/2000 and NT. The INTERTRAN2 handler is used to assemble and manage input databases, construct input files for INTERTRAN2-RT4, and execute INTERTRAN2-RT4 cases.

The INTERTRAN2-RT4 program is based on the RADTRAN4.019IOSI program (20 July 2000), which is a SI-unit version of RADTRAN4. INTERTRAN2-RT4 is a modified version of the mainframe code RADTRAN4.019IOSI and has been compiled for PC use.

The supporting documentation including the user guides for all related computer codes are available for downloading at the address given above.

There are also some limitations in the INTERTRAN2 Computer Code System that the user should be aware of. The RADTRAN4 computer code, which is the basis of the INTERTRAN2-RT4, is not intended for on-site transport risk analysis. Also, chemical hazards, such as those from uranium hexafluoride, are not included in the risk assessment model. It should also be mentioned that at present the health effect model included in RADTRAN4 is out of date. Efforts are underway to update this health effect model. A more detailed discussion of the limitations of the INTERTRAN2 Computer Code System can be found in the Advisory Material published together with the computer code system.

3.2. INTERTRAN2 risk assessment methodology

This section briefly discusses the principal features of the transport risk assessment methodology incorporated in the INTERTRAN2 Computer Code System and the associated data needs and requirements.

3.2.1. Incident-free transport risk assessment

Incident-free transport is defined as the transport activity in which no accident or other incident occurs. The radiological risk associated with incident-free (or routine) transport results from the potential exposure of people to low levels of external radiation (mostly gamma and/or neutron radiation) emerging from loaded shipments. The radiation exposures to persons from loaded shipments, however, are not limited to those persons who are engaged in transport operations but also include those who may incidentally be present in the shipment 'path'.

The INTERTRAN2 Computer Code System considers, in particular, radiation exposures of the following population groups:

- Persons residing along the route of transport (off-link population)
- Persons sharing the route of transport (on-link population), i.e. persons in vehicles travelling on the transport route
- Persons at stops
- Crew members and handlers, including aircraft flight attendants.

The INTERTRAN2 Computer Code System calculations are based on the strength of the package's radiation field as a function of the distance between the source and receptor point and a number of input parameters describing and characterizing potential exposure situations typically encountered in transport operations. The parameters involved in land transport include, for example, duration of exposure, vehicular speed, stopping time, traffic density, route characteristics and population density. If a homogeneous population zone characterized the shipment path and if the speed of the vehicle were uniform, the calculation would be fairly straightforward. However, the code package takes into account different populations densities and vehicle velocities in up to three different population density zones, e.g. urban, suburban and rural.

The expected dose to workers and to members of the public along the transport route is for normal conditions of transport (incident-free case) calculated as collective dose, also taking into account handling operations. In addition to the collective dose of different population groups, the code calculates hypothetical maximum individual doses to a person living close to the highway or railroad track. Figure 2 illustrates one of the incident-free pathways modelled in the INTERTRAN2 Computer Code System. The incident-free dose for persons along the transport route is directly proportional to the external dose rate of the package and inversely proportional to the speed of the vehicle transporting the RAM and to the distance (r) between the vehicle and the receptor. The population dose, referred to as off-link dose, is integrated over all receptor distances (r) out to a predefined maximum r (bandwidth) for a uniformly distributed population to give the total off-link population dose.

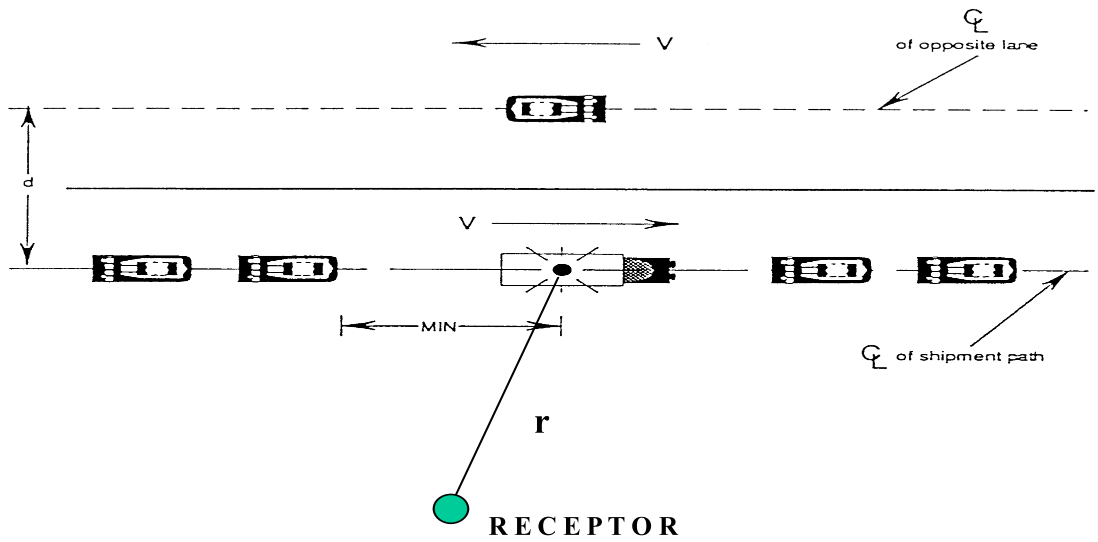

FIG. 2. Dose to persons along the transport route (off-link). V is the shipment speed. The distance between the radioactive shipment and the receptor is r; radiation dose is calculated by integrating from r = -∞ to r = ∞ (adapted from [6]).

The other incident-free pathways are modelled similarly using the package dose-rate at 1 m from the external package surface, distance, populations, and taking into account exposure times and velocities. In the absence of specific information, the analyst may choose to model the regulatory limit of external radiation dose for each type of shipment, although experience indicates that the external dose rate is well below the regulatory limit in many shipments. The modeled incident-free dose is independent of the isotopic content or radioactivity of the material being shipped, and depends only on the external package radiation dose rates.

The most relevant input parameters to be provided by the user in the input file of the INTERTRAN2 Computer Code System for calculating the radiological impact attributable to incident-free transport include the following:

1. Package dose rate at 1 m, i.e. the TI value.
2. The fraction of radiation that is gamma radiation. The remainder will be the fraction that is neutron radiation.
3. Number of packages and number of shipments.
4. Characteristic package dimension. This value is generally the largest dimension of a package.
5. Distances travelled.
6. Vehicle speed.
7. Population densities including numbers of people at stops and at any intermediate storage locations.
8. Mode of transport (e.g., road, rail…).
9. Route characteristics (e.g., city street, highway, waterway, railway).
10. Traffic densities.
11. Number of handlings if intermodal transfers are involved.
12. Number of crew members.
13. Length of time for stops or in-transit storages.

14. Fraction of route that will be travelled during rush hour travel (only used with the aggregate method).

Further information and advice on the derivation of these input parameters and associated sources of information are given in the subsequent chapters.

3.2.2. Modelling of transport accident risks

The assessment and appraisal of risks arising from transport accidents involving RAM shipments differ from the incident-free transport risk assessment approach because incidents and accidents are unexpected events (incident-free transport is the normal or baseline expectation). Depending on the event severity, a transport accident or incident may or may not result in a release of RAM. The most probable accidents are generally the least severe. As accident severity increases, the probability of occurrence generally decreases, so that the most severe accidents are the least likely to occur.

The RAM being shipped, and their associated activities, become important in the transport accident assessment module. The risks from a release of some fraction of the radioactive package contents or from loss of shielding of packages are modelled and calculated. The principal environmental exposure pathways contributing to accidental consequences, e.g. the dose to a member of the public, and considered in the INTERTRAN2 Computer Code System, are groundshine (aerosols deposited on the ground), inhalation (respirable particles inhaled into the lung), resuspension (respirable particles initially deposited and then resuspended and inhaled), cloudshine (aerosols in the cloud before deposition) and ingestion (deposited amounts incorporated into the soil and food). Dose to a receptor may then be calculated from any acceptable set of dose conversion factors. Health risk to the receptors may similarly be calculated with any acceptable set of conversion factors [7, 8].

The set of all possible accidents with a damage potential above some relevance limit or probabilities less than an explicit or implicit cut-off value is generally divided into subsets, each having a particular probability of occurrence and with varying degrees of damage to the radioactive package. Probabilities of accidents of a particular severity may be based on event-tree analysis of accident responses. The set of accidents always includes a subset for no release and no loss of shielding (by far the most likely type of accident event) and a subset for loss of shielding only (i.e. no actual release of material), unless the event database has been screened appropriately to exclude irrelevant events from analysis. The probability of occurrence of an accident depends on the mode of transport (for example, a vehicular accident per vehicle km travelled) and the associated consequences on the population density zone (e.g., in the USA a larger fraction of accidents occur in urban areas, but the radiological consequences are minor, if any at all). An illustrative example of a set of severity categories for road and rail transport is described in Table 1.

The amount of RAM released depends on the physical-chemical nature of the material and its constituent radionuclides. The dispersability is also based upon the physical and chemical properties of the individual radionuclides released. Consequently, release fractions depend on the physical and chemical nature of the radionuclides present in the RAM (e.g. volatility, particle size).

The atmospheric dispersion of airborne particulate releases or gaseous constituents is modelled within the TRANSAT module. The spatial distributions generated within the TRANSAT module depend on the atmospheric stability and wind speed and include curves of constant radionuclide concentrations (isopleths), which describe the downwind radionuclide concentration and deposition pattern. In general, the isopleths are elongated ellipses, because the predominant movement of airborne material is downwind. The crosswind concentration decreases very rapidly (exponentially) with distance from the plume centerline. Outside of the ellipses there will be virtually no airborne radioactivity or radionuclide deposition. Within these isopleths population groups may be potentially exposed to groundshine, cloudshine, inhalation and resuspension.

TABLE 1. ILLUSTRATIVE EXAMPLE OF ACCIDENT SEVERITY CATEGORIES (adapted from Ref. [9])

Severity category	**Severity category description**	**Fraction of accidents in category**		
		urban	suburban	rural
1	Conditions do not exceed those for Type A packages; no release of contents	0.604	0.602	0.603
2	Conditions equal to those for Type B packages; no release of contents	0.393	0.394	0.395
3	Seal damage creates leak path; but fuel is undamaged; CRUD could be released	0.003	0.004	0.002
4	Impact damage great enough to cause damage to spent fuel; fuel particles and fission gases may be released	3.8E-7	4.0E-6	3.0E-6
5	Impact damage to seals plus fire severe enough to cause release of fission gases, volatiles, and particulates	2.5E-7	3.0E-6	5.0E-6
6	Severe impact damage plus fire severe enough to cause fuel oxidation with greater release of particulates than category 5	1.3E-7	2.0E-6	7.0E-6

Two factors independently affect the modelled (collective) dose to the population under the ‘plume footprint’. These two factors are:

1. the maximum downwind distance modelled, and
2. the concentration of dispersed material within the isopleth pattern.

The dataset often used in RADTRAN4 consists of an isopleth pattern that extends out to 80 km downwind of the scene of the accident. This value is used because it is the maximum distance usually considered in US regulations governing air quality. It should be noted that the concentration of airborne respirable material decreases very sharply as one moves away from the source.

Structuring input data for the accident module is a somewhat sequential, multistep process. The parameters needed are:

1. The probability that an accident will occur — likelihood that a package and vehicle/conveyance experiences an accident event.

2. The radionuclide content of the package or packages that would produce a health hazard if released.

3. The conditional probability that an accident event will have a certain severity (i.e., conditional on that particular accident occurring), and:

   - the number of different types of accidents that could happen (number of accident severity categories),
   - the probability that an accident is of a specified severity. This probability does not include the probability of an accident occurring.

4. The fraction of the radioactive contents that would be released in each severity category.

5. The fraction of released material that would be aerosolized.

6. The fraction of aerosolized material that would be in the respirable size range (i.e. material having an aerodynamic particle diameter less than 10μm).

7. The meteorological conditions under which airborne material would be dispersed.

8. The parameters needed to calculate radionuclide deposition.

3.2.3. Potential sources for data input

The following section identifies some potential sources of input data for both incident-free transport and accidents.

1. Census reports (printed or electronic) are the best source of population density data.

2. A geographic information system (GIS), routing codes, and/or sufficiently detailed maps or atlases may be used to determine shipping distances, and hence to derive travel times (with user-supplied speed values) and crew exposures. Reference [10] contains an example of the use of a GIS to obtain INTERTRAN2 Computer Code System input data. An example of a routing code is TRAGIS, which gives travel times and distances as direct outputs for travel on highways and railroads in the USA [11].

3. Speed limits may be used to establish maximum vehicle speed, but the average travel speed is frequently below the speed limit. When trucks are outfitted with governors and when trains or ships or other conveyances are subject to speed controls by mechanical or regulatory means, an operational maximum may be used instead, if distinct from and lower than the speed limit in a particular link.

4. Vehicle density (vehicles per unit distance) may usually be obtained from a national or provincial transport regulatory or traffic agency. In the USA this information is usually available from State Police, Highway Patrol, or State Departments of Transport.

5. Data on receptor-source distances and population densities at stops and intermodal transfer stations (truck stops, inspection stations, rail yards, ports, etc.) usually can be obtained by a combination of observation and analysis. The parameter values often used in the USA as input for RADTRAN 4 (e.g., 50 people at 20 m from the shipment for truck mode) are averages determined by actual observations at stops, like truck stops and rest areas [12, 13]. In many cases, stop times also may be derived from commercial vehicle operators, rail company operational requirements, and freight forwarders' records, as well as actual observations.

6. Accident frequency data for highway, rail, ship and barge, and air are usually available from local, regional, and national transport authorities.

7. Release fractions describe the behaviour of packages under accident conditions of varying severity and are related to the physical-chemical nature of the RAM being transported. Moreover, these data are independent of mode, as well as of the country in which an accident may occur. The USA, the United Kingdom, Canada, Japan, and Germany run package testing facilities, and all of these countries have amassed data on package behaviour [14–16]. Other countries may also have comparable data.

8. Aerosol fraction and aerosol particle size (which determines the respirable fraction input parameter) are related to the physical and chemical nature of the RAM. This information is generally available in the international literature for many types of RAM, but is not exhaustive and may have to be developed by analysis or testing for unusual shipments.

4. INCIDENT-FREE TRANSPORT RISK DATA DEVELOPMENT CONSIDERATIONS AND INTERPRETATION OF ASSESSMENT RESULTS

The INTERTRAN2 Computer Code System calculates the radiation dose received by the various population groups described in Section 3. The code assumes that only external exposure is likely to occur during incident-free conditions of transport. Some packages are designed for continuous release of RAM with provisions for mechanical or manually operated pressure relief systems, albeit, in accordance with the applicable regulations. The internal exposure resulting from the transport of such packages is, however, not computed by the INTERTRAN2 Computer Code System under incident-free conditions of transport.

As in conventional radiological safety computations the parameters relevant for any calculation of the exposure received by individuals are based on five basic parameters, namely, (1) dose-rate at unit distance from the 'radiation source', (2) distance from the 'radiation source', (3) duration of exposure, (4) availability of shielding between the 'source' and the exposed persons, and (5) number of persons exposed.

The INTERTRAN2 Computer Code System requires in addition a number of input parameters to be provided by the user in the input file. Some of the important individual parameters are listed below. The code can handle ten different types of transport (e.g. road, rail, passenger air, cargo air, barge, ocean-going ship, etc.). The following parameters need to be defined for each type:

Fraction of travel in rural zone, f_R

Fraction of travel in suburban l zone, f_S

Fraction of travel in urban zone, f_U

Velocity of the shipment in the rural zone, V_R

Velocity of the shipment in the suburban zone, V_S

Velocity of the shipment in the urban zone, V_U

Number of crew on the shipment

Average distance from radiation source to crew during the shipment

Number of handlings per shipment

Stop time for shipment (hours/km)

Minimum stop time per trip (hours)

Zero stop time per trip (hours) [applicable for rail mode only]

Minimum number of rail inspections [applicable for rail mode only]

Number of persons exposed while shipment is stopped

Average exposure distance while shipment is stopped (m)

Storage time per shipment

Number of persons exposed during storage

Average exposure distance while shipment is stored (m)

Number of persons per vehicle sharing the transport link

Fraction of urban travel during rush hour

Fraction of urban travel by city streets

Fraction of rural and suburban travel by freeways

One way traffic counts in rural zones

One way traffic counts in suburban zones

One way traffic counts in urban zones

The values for fraction of travel in particular population density zones are used only if the aggregate method is used, in which case the fractional values are used to determine the distance travelled within a population density zone. When using the route-specific method, the actual distances travelled are entered for each route segment. The fractional values indicating travel during rush hour, on city streets and on freeways are not used for the route-specific method. These fractional values are used to determine changes to velocities and traffic counts when using the aggregate method. Additionally, the traffic counts are entered on a per-route basis if the route-specific method is used.

When using the route-specific method the users must be aware that the stop and storage doses will be calculated for each link. The times may need to be altered accordingly so that these will not be overestimated.

4.1. Package/vehicle dose rate level

In the calculation of dose to people, the dose rate level at 1 m from the external package surface serves an important role. The dose rate calculated as a function of the distance from a point source is taken as the basic principle in the code.

If the radiation level at unit distance from the shipment were X (1 m) then the dose received by a population at distance r from the shipment path due to the transport of the RAM can be calculated as described below.

The radiation level at a distance r from the package or radiation source is given by:

$$X(r) = K\, e^{-\mu r}\; B(\mu r) / r^2$$

where $X(r)$ is the dose-rate at a distance of r meter (mSv/h)
r is the distance from the radiation source (m)
μ is the linear absorption coefficient of air (m^{-1}).
$B(r)$ is the build up factor in air, a dimensionless quantity
K is the dose rate factor (mSv m^2/h).

This point source approximation is acceptable for distances r that are much larger than the maximum dimension of the package. For this purpose, K, the dose rate factor, is introduced in the mathematical relationship. Now K is given by

$$K = K_0\ TI$$

where TI is the transport index of the package and
K_0 is defined with reference to the package dimension as

$$K_0 = (\,1 + 0.5\ d_{eff})^{\,2}$$

where $d_{eff} = 2\,(\,1 + 0.5\ d_{act}\,)^{0.75} - 0.55$; if $d_{act} >= 4$ m
$d_{eff} = d_{act}$; if $d_{act} < 4$ m
d_{eff} is the effective dimension of the package
d_{act} is the actual maximum dimension of the package.

The advantage of this expression is that it allows a package of definite dimensions to be approximated to a point source at large enough distances, say, three times the maximum dimension of the package. At shorter distances, this approximation overestimates the radiation level significantly and hence the predicted dose rate would be conservative. The above expression is useful in determining, for example, the dose received by the vehicle crew and cargo handlers.

The user must provide a value for the characteristic dimension of the package, d_{act} (input keyword PKGSIZ), in meter for each package type. For a cylindrical package, PKGSIZ would usually be the length unless the diameter of the package is greater than its length, in which case the diameter would be PKGSIZ. For rectangular containers PKGSIZ should be set equal to the longest diagonal dimension.

In the incident-free analysis, the dose rate at 1 m from the packages or vehicle is used by the code to calculate the radiation levels around the shipment. This quantity is used to calculate the dose received by persons beside the transport link (off-link), e.g. the population living along the route and the dose received by persons sharing the transport link (on-link). If the shipment consists of a single package, the package and the shipment dose rates are the same.

In a multiple package shipment, the user provides the dose-rate for each package and the code multiplies the individual dose-rate by the number of packages of each type. Because of shielding provided by the packages to one another, this will result in an overestimation of the vehicle dose rate. Therefore the user should make an adjustment. One way to overcome this problem is to treat the shipment itself as a single package. Then a single effective dose rate can be measured or calculated and the number of packages per shipment set to unity. However, with this approach must be remembered that doses to cargo handlers and persons at storage areas are calculated at the package level. If calculation of these doses is required, a separate package level would be required to properly estimate dose values for handlers and warehouse personnel.

As was seen in the description of the various parameters in this section, one has to estimate the radiation level at specified distances from the vehicle or from the path of the shipment. An expression for the integrated dose received by a person at a distance of r from the path of a radioactive shipment with dose rate factor K travelling with a velocity of V is given by

$$D(r) = 2 \, (K/V) \, I(r)$$

where $I(r) = \int_{r}^{\infty} \frac{(e^{-\mu Y}) \, B(\mu Y) \, dY}{Y(Y^2 - r^2)^{1/2}}$

and V is the speed (km/h) of the conveyance carrying the radioactive consignment.

It is this value of I(r) that is used in the code in determining the dose received by the persons carrying out the shipment and the dose to the public living along the route of the shipment.

4.2. Importance analysis

A problem that may be faced by the user in preparing the input file is that it may not be known how accurate the values of the various input parameters are. For example, if the rural population density is given as 300 persons per km^2 and the correct figure is 4000, then what is the influence of this error? The code provides an importance analysis of nearly forty input parameters used in incident-free dose calculations. From this analysis the user can find out which of the modelling parameters are most sensitive. (It would generally be seen that time, distance and the number of exposed persons are quite important.) The user's efforts at determining the values of the parameters can be optimized on the basis of the importance analysis. The importance analysis is carried out varying the value of each input parameter by 10% and determining the difference it makes in the dose value.

The dose value D depends upon a number of parameters.

$$\text{i.e. } D = D(p_1, p_2, \ldots p_n)$$

The code introduces an increment in each p_i of 10 per cent.

$$\text{i.e. } \Delta p_i = 0.1\, p_i$$

That is the code calculates for each parameter p_i and the resulting variation in the dose value, i.e.,

$$\delta D / \delta p_i$$

The relative importance of all the parameters is reported in a tabular form in the incident-free analysis output file.

4.3. Critical groups for the transport of RAM

Within a risk analysis, it is necessary to identify relevant critical groups: individuals receiving the highest effective dose or equivalent dose by the given exposure pathway from the given exposure source. For the transport of RAM under incident-free conditions, the groups of people likely to be exposed to the radiation of the package are:

- Population surrounding the shipment,
- Population travelling near the shipment,
- Population near the transport vehicle whilst it is stopped, and
- Transport workers: crew, handlers, inspectors, warehouse personnel whilst the vehicle is stopped.

It is important to reiterate that exposure of the workers during packaging and unpackaging operations are not normally modelled. These tasks are considered on-site operations and are not a part of transport.

For incident-free conditions, the user should remember that the main exposure pathway is the irradiation from the package. Consequently, for the assessments, the important input parameters are the dose rate at 1 m from the package, the size and number of the packages, and likewise the time of the exposure and the distance away from the exposure for the persons exposed.

The INTERTRAN2 Computer Code System calculates ***individual*** doses for members of the ***public*** exposed to shipment of RAM. Generally, the transport related individual public doses are low, and therefore significantly lower than the dose limits (1 mSv/a).

For the ***workers***, the INTERTRAN2 Computer Code System calculates a ***collective*** dose (unit in man-Sv). But, considering that the exposure is relatively homogenous for the workers, the user can divide the collective dose by the number of exposed workers, which provides an order of magnitude estimate of individual dose.

4.4. Expected collective dose

Within the permanent optimization process for the level of protection, the magnitude and likelihood of exposure and the number of individuals exposed have to be as low as reasonably achievable, within the restriction that the doses to individuals delivered by the source are subject to dose constraints. The collective dose could be considered as a useful indicator in the optimization process. As a whole, the collective dose is a relevant indicator in the radiological risk assessment approach.

With estimation based on probabilistic safety assessment (PSA) techniques, the annual collective dose receivable under normal conditions of transports can be estimated by determining the dose from the practice of transport of RAM through public domain. Likewise, INTERTRAN2 can be useful for comparing collective radiation exposures for different means of transport or different routes.

The incident-free calculations made by members of the CRP have indicated that the highest collective dose to the population is generally received during the stops of the transport, especially for the long routes, which requires longer stops. The collective dose received by the population surrounding the transport link can also be significant. In a densely populated urban environment (example of Mumbai, India), the collective dose related to the public living along the transport route could be about 1 man-Sv per year. Generally, transport by air results in less collective dose than by rail or road for a given RAM.

Therefore, for these calculations, besides the parameters mentioned in the previous section, the data used for the stop time and the population densities may be very important. The user must also remember that the population dose assessment is possible only by means of calculations, since individual monitors are unlikely to record any measurable dose values.

Previous calculation results have also shown that the workers with the highest exposure are the package handlers. For the workers at the consignor's and the consignee's establishments, if they are occupationally exposed to radiation, they would be subject to routine personal monitoring. In this case, the user can make interesting comparisons between the INTERTRAN2 calculations and the measurements.

4.5. Presenting incident free assessment results

In presenting results, consideration should be given to both the purposes of the analysis and the intended audience, e.g. regulators, industry, the public, or an environmental assessment panel. Either way, results from INTERTRAN2 should be summarized clearly.

Generally, all relevant input data used for analysis should be available with the assessment results. It should be clear what groups of the public or workers are represented in the dose calculations. The significance of the doses calculated may be discussed and compared with regulatory limits and other national criteria.

INTERTRAN2 output includes an importance analysis which calculates the sensitivity of each input parameter in terms of the percentage change in collective dose for a 10 per cent change in the input parameter. It should be noted that for certain parameters, the variation of dose is not linear, and the effect of changes in input parameters values in excess of 10 per cent cannot be scaled. The results of the importance analysis should be discussed and attention drawn to any parameters of particular interest.

5. TRANSPORT ACCIDENT DATA DEVELOPMENT

In spite of all measures taken to ensure the safe transport of RAM, there is still a finite probability that accidents[1] involving RAM packages may occur during transport in the public domain. Such events may occur for a number of reasons with different outcomes depending, for example, on the severity of the accident, the type and magnitude of degradation or failure of the package integrity and the radiological and physical characteristics of the material conveyed. Although it is generally understood that the safety requirements embodied in the IAEA Transport Regulations ensure a high level of protection of people, property and the environment in the transport of RAM, severe accidents with the potential to compromise the package integrity are consistently a matter of concern to the public, the regulators, decision makers and the transport community. In particular, unlikely accidental occurrences resulting in failure of the containment integrity of the package and the subsequent dispersal of its radioactive contents into the environment represent a focal point of the public debate.

To adequately address these concerns and for allowing informed decisions to be made, for example, as to the suitability of a given package design, a thorough understanding of how transport incidents and accidents occur and an assessment and appraisal of the resultant (radiological and non-radiological) hazards associated with and risks arising from the transport of RAM on publicly accessible transport routes is of crucial importance.

The general literature provides several applicable (computerized and non-computerized) assessment approaches relevant for judging the hazards and risks to people and the environment arising from potential accidents involving RAM shipments. These approaches include the analysis of past experience (i.e. lessons learned from reported RAM transport accidents) and the quantification and evaluation of the potential consequences and risks of RAM transport. In this section emphasis will be on the development and application of computerized probabilistic transport risk assessment methods and on providing guidance on the use and development of related databases for applications in probabilistic risk assessment (PRA), with particular reference to INTERTRAN2.

A systematic transport accident assessment typically requires a structured analysis approach to be applied and involves several or all of the following crucial elements to be addressed:

- Identification and description of the transport operations.
- Identification and characterization of the type, severity and frequency of accident events or sequences of events for the given mode of transport (i.e. mechanical and/or thermal load conditions to be encountered in an accident event).
- Analysis of the structural package response and release behaviour under accidental load conditions.

---

[1] The term 'accident' is internationally not so well defined. In this section 'accident' designates the occurrence, outside the realm of normal transportation, of any unusual event in the transport or handling of a package, which entails safety implications above some level of severity and that may or may not breach package integrity. The terminology in the USA distinguishes between 'incidents' and 'accidents'. An 'incident' is any event that is not part of normal, routine transportation. An 'accident' is defined as an event during transportation in which there is loss of life, injury, or vehicular damage severe enough that the vehicle cannot move under its own power. The universe of incidents includes accidents.

- Quantification of the environmental (radiological and non-radiological) consequences, e.g. description of atmospheric dispersal and deposition of radionuclide releases and the resulting radiological impact to persons and their environment, costs, etc.

- Assessment and evaluation of the transport risks, i.e. estimation of radiological adverse impact (e.g. dose to the population or environmental contamination) and the expected probability of occurrence of the accidental event.

Each of these issues will be examined in this section with respect to the methods and procedures relevant to probabilistic transport risk assessment and guidance be given as to the needs, sources and methods available or useful to consult for the development of databases applicable to the assessment of transport accidents.

5.1. Transport accident severity and frequency assessment

This section (1) reviews and describes current assessment methods and procedures for evaluating the expected frequency and severity of transport accidents and (2) provides guidance as to the development and application of both empirical accident event databases and accident assessment approaches applicable to transport risk assessment. The material and illustrative examples presented in this section draw upon a recent analysis and comparison of event frequency and severity assessment methods applicable to transport risk assessment [17].

The open literature offers a wide range of analysis approaches of differing complexity related to transport accident (or risk) assessment. Nevertheless, this section is primarily concerned with the identification, definition and characterization of the type, severity and frequency of transport accident scenarios (accident environments) encountered in RAM transport and the development and use of related data for applications in probabilistic safety assessment (PSA). PSA, consistent with the statistical nature of transport accident events, principally involves two components to be quantified: (1) the probability (or frequency) of the occurrence of some adverse impact and (2) the type and severity of the undesired outcome (e.g. impact or fire load, material/personal damage or radiological consequences) [18].

A structured analysis of the type, severity and frequency of transport accidents involving RAM shipments should address the following issues:

- Accident assessment approaches and related data requirements
- Accident identification
- Accident severity categorization
- Accident event frequency estimation
- Reliability of accident assessment model predictions.

Each of these issues is examined and discussed below.

5.1.1. Accident assessment approaches and related data requirements

There are two overriding considerations governing the development and application of transport accident assessment approaches: (1) the principal objectives of the transport accident (or risk) assessment to be undertaken and (2) the type and quality of event data describing the severity and frequency of transport and handling accidents available to the risk analyst. Within this limiting framework there are two basic approaches available for the development of a thorough understanding of how transport accidents occur and the estimation of the frequency and severity of transport accidents. These are:

- Use of historical accident event data representative for the field of transport operations being considered or event data adapted from similar transport conditions, and

- Synthesis of the accident frequency from an analysis of the combination or sequences of events which could cause the accident, together with data for their likelihood of occurrence.

Application of historical (or empirical) event data is generally the preferred analysis method and widely used for transport accident assessment when representative accident event data are accessible and available, thereby allowing consideration of the wide range of conceivable causes and consequences of (movement and non-movement related) transport incidents and accident. The term 'representative event data' is used to mean the description of accident events with reasonable accuracy for the mode of transport being considered in terms of the type (e.g., impact, crush, fire, immersion…), severity and the likelihood of occurrence. The event database forms the principal basis, for example, for derivation of distributions of different fault sequences, e.g. fire and non-fire environments, event categorization by damage potential and estimation of the probability of occurrence of a given accident event category. The event database also enables the construction of probability distributions of the potential adverse outcome vs. the probability of occurrence. Whenever possible, transport accident data from the same type of transport operations or practices performed under similar conditions should be used for transport accident or risk assessment. For comparatively rare events, however, recorded event data are difficult to acquire and it may be necessary to use generic data. In this case eventual differences between the type of operations and practices from which the data have been gathered must be considered and evaluated very carefully.

In situations where historical event data are scarce or completely lacking, a predictive approach for analyzing event probabilities will be required. Analysis may, for example, be based on a logical combination (or synthesis) of base events to represent a conceivable sequence of events using fault or event tree analysis techniques. The predictive method requires the identification and definition of a specific event sequence for quantifying the likelihood of occurrence and severity of a conceivable transport accident event, for example, a train derailment associated with sufficient lateral displacement to strike, for example, a bridge abutment, resulting in an assumed amount of vehicular damage (cf. Annex I and Annex II for further details). Applying this method generally involves complex event sequences to be broken down into 'quantifiable' base events for which frequency data are available or may be derived. The principal sources of information for estimation of base event frequencies and severities may include, for example, empirical transport accident related databases, or the source may be engineering judgement. Transport event data can be complemented by information about route hazards. This information may be obtained from surveys of representative transport route sections or studies of survey maps to arrive at probabilities of specific line or route hazards.

Accident frequency and severity assessment based on historical event data has been the preferred method for conducting comprehensive probabilistic transport risk assessment studies by describing the broad range of conceivable transport accident events and the associated adverse outcomes including low and high probability events that need to be taken into account in transport risk assessment. Examples of applications of this assessment approach are the Final Environmental Statement on the Transport of Radioactive Material by

Air and other Modes [19], the Transport Programmatic Environmental Impact Statement [20], the Canadian Nuclear Fuel Waste Management Program [21], and the Konrad Transport Study [22, 23].

The predictive approach using fault tree analysis techniques has, for example, been widely employed in the UK for quantifying the risk of radioactive waste transports by rail [24, 25]. The same approach has been employed in the USA in essentially every environmental assessment or impact statement published by the US Department of Energy. In practical applications of the predictive approach, both low impact events with insignificant consequences and 'beyond regulatory test' accident scenarios with an attendant low probability of occurrence should be accounted for in quantitative analyses.

Occasionally, historical event data may be difficult to use because generally available accident event data are often collated for purposes other than risk analysis and may be expressed in terms of human casualties or financial loss rather than damage to vehicle or cargo, so that they are not directly applicable to the study problem. Even generic data relating directly to very severe credible accidents with serious consequences are often at best sparse. Therefore, risk assessments frequently use combinations of the two principal methods. Illustrative examples of applications of the two assessment approaches are included in Annex II.

5.1.2. Accident identification

Transport risk assessment generally deals with the wide range of unusual safety related events during transport above some level of severity (relevance limit) that may or may not threaten the package integrity. Of particular importance to transport risk assessment, however, are abnormal occurrences identified by a condition which may occur during handling and transport of RAM package consignments with the potential of causing degradation or failure of a packaging's safety functions, i.e. loss of shielding, confinement and heat dissipation integrity. In practice, identification of these conditions relies on a thorough analysis of conceivable events or event sequences (resulting in high energy impact and/or thermal loads) by the assessor for a given mode of transport or operation and may include movement and non-movement related accident conditions, i.e. off-site handling accident (package drop), impact due to conditions as bridge collapse, explosion due to flammable gas buildup inside package, sabotage, etc. By its very nature this abnormal condition depends upon the type of packaging being considered.

The structure and quality of the event database and other resources available to the assessor also bear upon grouping and categorization of accident events or event sequences. Depending upon the type of transport operation under consideration, the very broad accident categories may be further refined where appropriate in order to identify and quantify specific hazard features, for example, of a transport route that may challenge a packaging's safety. This analysis approach allows account to be taken of the potential hazard features of the actual route of transport.

For illustrative purposes, two scenario checklists are shown in Table 2 defining the principal classes of accident events for rail transport operations which were considered for analysis in previous transport risk assessment studies (adapted from [17]). It is seen from Table 2 that accident scenarios may be grouped in various ways, the examples shown in the table are grouped in two principal categories: initiating (or root) cause and event sequence.

TABLE 2. GENERIC EVENT SCENARIO CHECKLIST OF TRANSPORT ACCIDENTS (adapted from [17])

Primary event class	**Secondary event criteria**
I. Accident scenarios by initiating cause:	
• Main line freight train accidents resulting in vehicular damage in excess of some relevance limit	• Derailment • Collision (rail/rail vehicle interaction) • Impact (rail/object interaction) • Crash (rail/road vehicle interaction) • Fire/explosion
II. Accident scenarios by event sequence:	
• Interaction of package vehicle with some *fixed* feature of the transport route	• Incidents following sufficient lateral displacement of the package vehicle from its normal safe envelope of travel (derailment alone, derailment followed by collision, drop, roll, etc.) • Running line collisions (i.e. line side object in track clearance, buffer stops) • Impact due to failure of line side feature i.e. bridge collapse
• Interaction of package vehicle with some *non-fixed* feature of the transport route	• Train derails and collides with package train • Package train derails and is struck by or strikes another train • Train collisions on same running line (end-on, side-on) • Collisions with other forms of transport following displacement of either from their normal safe envelope of travel (e.g. level crossing collisions, side-on collisions)
• Fire	• Minor fires occurring on the package vehicle • Collision with fixed feature containing flammable substance • Collision with fuel tanker train (following derailment of either) • Collision with road tanker (at level crossing)
• Off-site handling incidents	
• Explosion due to flammable gas buildup in package	
• Multiple combination events (same line collision on a bridge)	
• Sabotage	

5.1.3. Accident severity categorization

Accident severity categorization schemes define the type and severity of accidental loads (accident environments), e.g. by specifying the conceivable mechanical impact and thermal loads that a package may experience in an accident event, to allow quantitative assessment of the broad range of outcomes of possible accident environments for a given mode of transport. Accident environments may vary significantly in severity and frequency for the various transport modes, i.e. road, rail, air, and sea, and, therefore, mode specific categorization schemes prevail in practical applications of transport risk assessments. Definition of an accident event category or a sequence of events is generally left to the assessor and can be achieved, for example, by dividing the set of all relevant historical accident events into subsets, each representing a logical group of accident environments (scenarios).

The accident environments defined by a given categorization scheme are especially expected to reflect the type and range of accident environments, e.g. in terms of the conceivable damage potential of the suite of fire, crush, impact and puncture forces typically encountered in this mode of transport. The categories and range of conditions also relate to the structural package response and the dispersability characteristics of the package contents under accident load conditions. These parameters are crucial for accident consequence assessment and determine the magnitude of a potential environmental package release. Constraints, however, may result from the quality and accuracy of the empirical data available for analysis and quantification of the event frequency and severity.

In most practical applications the range of accident impact loads represented by a severity categorization scheme has been quantified based on (1) the potential speed of a package as it impacts on a target surface or an object and (2) the temperature and duration of a severe fire. This pattern of accident loads is generally represented in a two-dimensional matrix showing the package impact speed range vs. the type of accident loads (e.g. impact only environment, combined impact and fire environment). The fire temperature and duration and, consequently, the related thermal load is most frequently selected to be within or beyond the IAEA regulatory fire test requirements for Type B packages, i.e. a 30 minute, fully engulfing 800°C pool fire. The mechanical impact loads, e.g. from static and dynamic impacts, and related impact speed ranges assumed for analysis by various assessors often differ significantly depending on the transport operations being considered, but have frequently been inferred from the IAEA regulatory drop test requirements for Type B and non-Type B packages or are based on engineering judgement.

Table 3 illustrates an accident severity categorization scheme for rail transport. The generic severity categorization system relates the magnitude of mechanical impact and/or thermal loads threatening a package to the impact speed and the fire duration and temperature. The scheme defines a fixed number of impact categories (speed) and a fixed number of thermal load categories (fire duration) to represent combined mechanical/thermal load conditions that a RAM package may encounter in freight rail transport accidents. The severity categories designated by either M0 or F0 represent accidental sequences involving mechanical-only (from M1/F0 to M4/F0) or fire-only (from M0/F1 to M0/F2) accident environments of different severity. All other categories — except for category M0/F0 — define accident events or sequences of events which involve the combined occurrence of a specific set of impact and fire loads. The speed, fire durations and the temperature were selected to correspond broadly to the IAEA regulatory testing requirements for different package types (industrial, Type A and Type B packages). The main features of the scheme are:

TABLE 3. GENERIC ACCIDENT SEVERITY CATEGORIZATION SCHEME
(adapted from [17])

Impact Category	Impact speed				
	No mechanical impact	4.9 m/s (17.6 km/h) ~ 1.2 m drop	13.3 m/s (47.9 km/h) ~ 9 m drop	27 m/s (97.2 km/h) ~ 37 m drop	40 m/s (144 km/h) ~ 85 m drop
Mechanical, impact No fire	M0/F0	M1/F0	M2/F0	M3/F0	M4/F0
< 30 min. 800°C fire	M0/F1	M1/F1	M2/F1	M3/F1	M4/F1
> 30 min. 800°C fire	M0/F2	M1/F2	M2/F2	M3/F2	M4/F2

- The matrix is suitably detailed in order to distinguish between events with different outcomes. It takes account of fires occurring without impact as well as impact without fire.

- The scheme allows separation of minor incidents which most frequently do not have the potential to threaten the containment integrity of Type B and most non-Type B package categories from more severe freight rail accident events which need to be reasonably accounted for in transport risk analyses. Thus, the scheme is particularly suitable for analysis of event databases which have not been screened otherwise, for example, by application of relevance limits or some other damage criteria, to separate minor incidents from major accidents.

- Some of the speeds reflect the validation criteria for Type B and non-Type B packages, e.g. the impact velocity of 4.9 m/s corresponds to the terminal velocity of the 1.2 m free drop distance for testing Type A packages weighing less than 5000 kg to normal conditions of transport. Different speeds appropriate to the particular type of package(s) under scrutiny should be adapted where practicable.

- The concept of different fire scenarios associated with impact events is accommodated and fires are grouped as either exceeding Type B regulatory test criteria (30 minutes) or not.

Categorization and estimation of the probability and severity of accident events often requires engineering judgement. Assumptions generally need to be made in a conservative manner, i.e. to err on the safe side. Other problems may arise from limitations and uncertainties that inevitably exist in any event database. A notable example is that frequently, precise event specific information describing the package (or cargo) impact speed onto a target surface or object, the package impact orientation, the impact target characteristics, etc. is unavailable. These parameters are, together with other variables, key factors for analysis of the package response and release behaviour under accidental load conditions [7, 26, 27]. In lieu of such event-specific information, the vehicle speed preceding the accident event may be adapted for approximate severity categorization and frequency estimation. It is recognized that the vehicle speed may only be loosely related to the package impact speed, but the assumption is considered to be conservative — if not overly conservative — by ignoring any mitigating factors that may be involved in the assessment of dynamic package impact loads, e.g. by interaction of a package with yielding structures. A description of structural package response and release behaviour is beyond the scope of this section and will be addressed in Section 5.2.

5.1.4. Accident event frequency estimation

The probability of occurrence of an event or a sequence of events and their associated outcome, e.g. a given accident load, is a key factor for quantifying the risk of transport accidents involving RAM shipments. The relevant event frequency and severity are generally evaluated within the framework of accident environments and impact forces typically encountered in the mode of transport being considered and are a component of the respective accident severity categorization scheme.

The event frequency is formally defined as the number of package vehicles — normalised to some unit quantity — expected to suffer damage from a given accident event and may be derived from event databases or other statistically relevant information. This quantity is also known as accident rate and may for movement-related accident events, for example, be expressed in terms of 'events per vehicle-km' or 'events per train-km'. The frequency of occurrence (f) per unit of travel distance where a package vehicle experiences a given accident event (e.g. fire) can be estimated from relevant historical base event data by dividing the number of package vehicles suffering damage from fire accident events by the cumulative travel distance of the package vehicles in the survey period.

If f_i is the frequency of occurrence of an accident (e.g. fire) of severity i per vehicle-km, the conditional probability of occurrence of an accident (e.g. fire) of severity i is $p_i = f_i / \Sigma f_i$ given that an accident occurred. For very broad categories of accident events the event database must be broken down into logical subsets to better reflect the differing (absolute or conditional) frequencies of occurrence of various accident environments, e.g. in fire and non-fire environments, groups of multiple affected wagons or by impact load intensity.

In situations where the number of vehicles affected in an accident is not recorded, an approximate frequency estimate may be derived based on the recorded number of accident events. (Note: a collision between freight trains results in two trains suffering accidental damage and, therefore, the event has to be counted twice in the event database to arrive at the correct event probability).

An illustrative example of an analysis of the frequency of principal subsets of accident environments (or scenarios) is depicted in Fig. 3 based on a 10-year record of general mainline freight train accidents (marshalling yards excluded) severe enough to cause vehicular damage in excess of DM 3000 (approx. US $1700) [28]. Accident event categorization and the associated event frequency have been based on the vehicle speed immediately preceding the accident event and the fire environments inferred from the IAEA regulatory test fire for Type B packages and represent the characteristics of the general freight train traffic and railway network. Consequently, the probability estimates are generic in nature.

While applying these general railway network data to other specific railway routes (or set of routes), due consideration must be given regarding the representativeness of the estimated frequencies of occurrence for the given railway route, for example, based on an analysis and evaluation of relevant route characteristics, to ensure that the hazard features of this route are comparable with the relevant features of the general railway network.

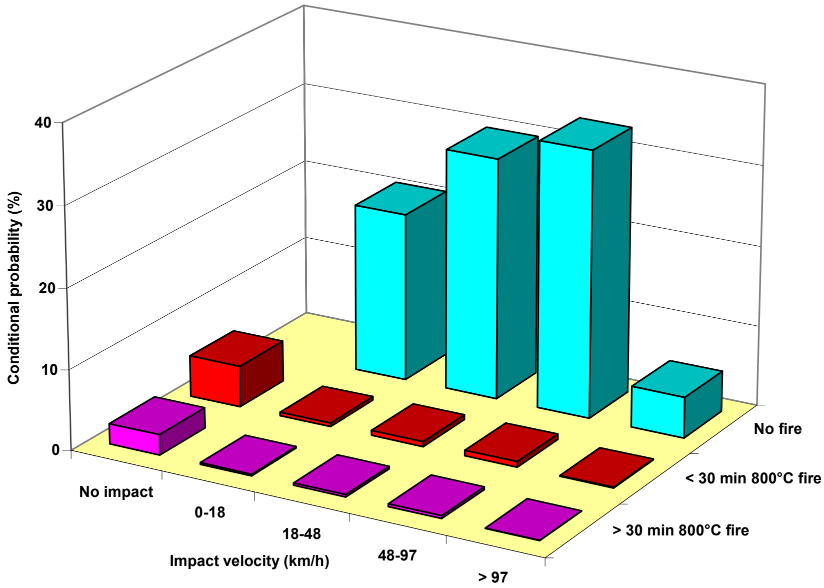

FIG. 3. Conditional probability of occurrence (%) of accident environments in mainline freight train accidents in Germany.

An important consideration in collections or compilations of historical base event data is the quality and representativeness of the event related information. This requires generally that the event data be collated over a sufficient period of time to gain confidence that all credible base events are adequately represented in the survey data. This may be particularly problematical in collections of route or region specific base event data where the number of base events is too limited for a meaningful statistical analysis. In this instance, sampling a probability distribution may offer an alternative, for example, by combining event data derived from other relevant sources of information such as a shipping route with comparable characteristics.

Similar considerations apply to very rare (high consequence) base events. Special efforts and approaches may be required to ensure that the principal base events are adequately reflected in the event database. In a transport accident analysis published in 1992 [23], the observed number of some very rare base events were considered to be the random result compatible with the lower limit of the 95% confidence interval of a Poisson distribution. The expectation value (mean) of this Poisson distribution was taken to best represent such rare events in the event database. An approximate estimation of the event frequency can also be based upon statistical information available for complementary base events. For example, the upper bound frequency for the event “collision of two railway vehicles following derailment” may be derived from the complementary information that such a collision did not occur in a given time period [29].

5.1.5. Reliability of accident assessment model predictions

The application of models in transport accident and risk assessment results in predictions that are always subject to uncertainty [30–34]. In this context the term ‘uncertainty’ is intended to describe the transport accident model’s realism and its predictive capabilities. Modelling uncertainties arise from a number of sources, most of which are related to (a) elements of the real world not accounted for in the model structure, (b) uncertainties in the model input parameters, and (c) lack of knowledge or the lack of data. Model input parameter uncertainties may arise as a result of both natural or stochastic variability in time and space and the difficulty in obtaining an exact measurement of the parameter as defined by the model.

Quantification of the uncertainty in model prediction is best determined through model validation. Model validation involves testing predictions against a series of independent data representative of the range of conditions over which application of the model is intended and to quantify the potential magnitude of predictive error. Unfortunately, the difficulty or impracticality of measuring the predicted quantity, e.g. rare event frequencies, long term performance, etc., precludes attempts to validate transport accident assessment models in their entirety. Often, very few independent experimental data exist to permit quantification of all model parameter values as a function of time, space, accident load, transport mode, etc. Sometimes, only portions of a model can be subject to model validation or calibrated against historical data, but there is principally no guarantee that past relationships will continue to hold in the future. So the question is not whether a model is true but, rather, how best to establish confidence in the model predictions.

In the absence of model validation data, confidence in the adequacy of a prediction model, its model input parameters and the accuracy of the resultant model predictions rests primarily on scientific judgement that may be developed by means of qualitative and quantitative methods. The literature suggests a number of pertinent methods and procedures of differing complexity for the evaluation of the model reliability. These include: (a) examination of the formulation of the conceptual and mathematical model, (b) rigorous examination of the adequacy and quantification and reporting of the uncertainty of the model input parameter values, (c) application of alternative conceptual models (model intercomparison), (d) performing a parameter sensitivity and uncertainty analysis, and (e) conduct of a peer review.

Not all of these general methods may be readily applicable to transport accident (or risk) assessments or available to analysts engaged in assessment modelling to come up with analysis results in a form which includes some quantitative statement of the associated uncertainty because of the resources and time required for this effort. Guidance and advice on the applicability and use of these principal methods can be found elsewhere, for example, in Refs [32, 35–39].

5.2. Package response and release behaviour

This section considers a possible radwaste transport operation and it is assumed that the packages, i.e. Type A and Type B packages, would be transported on suitable vehicles. It is also assumed that the vehicle's speed will be limited to legal limits in accordance with current safety provisions, but it is not an important assumption for this approach.

5.2.1. Package performance requirements

The package (Type B) typically consists of an outer container which provides the impact and thermal protection for a resealable inner container. To reduce the possibility of a release of the contents due to accidental damage during loading and unloading, the inner container is enclosed at the top and at the bottom by a protective impact ring. The package contents — the RAM inventory — is assumed to be known for each package. Type B packages are used to transport larger quantities of RAM. They are tested to withstand severe accident conditions with a maximum release of no more than A_2 in a week and a dose rate following the tests of no more than 10 mSv h^{-1} at 1 m from the external package surface.

The package design has to be shown to comply with the impact and fire performance requirements of the IAEA Transport Regulations for a Type B package. The principal IAEA tests to simulate accident conditions in transport are as follows:

- A 9 m drop (13 m/s) onto an unyielding target,
- A 1 m drop onto a punch target,
- A thermal test environment of a fully engulfing pool fire of 800^{o}C for 30 minutes, and
- An immersion test under a head of 15 m of water for 8 hours.

Most targets likely to be encountered by the package in a road accident are softer than the regulatory unyielding surface. Impact velocities well in excess of 13 m/s would be necessary to achieve the test level of damage for a package impact with these relatively soft targets. Most road fires are of shorter duration and lesser severity than the regulation test because of lack of fuel, non-uniform flame temperature distribution over the package surface and fire brigade intervention.

Therefore, the package can be expected to survive most road accidents without loss of containment or shielding integrity. It must be recognised, however, that high speed impacts with hard surfaces or probes, or prolonged fires, can conceivably cause a loss of containment.

Design margins ensure that the package containment will not be lost in most accidents with an impact of a severity greater than the design limits of 13 m/s impact against an unyielding target and a 30 minute engulfing pool fire.

For the purposes of this approach, it may pessimistically be assumed that the package will fail under impact conditions only slightly in excess of 13 m/s against an unyielding target, and under fire conditions only slightly more severe than the 30 minute fully engulfing pool fire test.

Type A packages are used for medium quantities of RAM with no requirements on distribution of the radioactivity throughout the material. They must withstand the IAEA Transport Regulations tests for normal transport with no loss of radioactive contents and no more than a 20% increase in external surface radiation level. In addition, Type A packages for liquids must survive a 9 m drop test on an unyielding surface. The maximum activity of RAM, other than special form radioactive material, permitted per package is $A_{2.}$ Type A packages can be expected to survive normal transport environments, but are likely to fail in severe accidents. However, the maximum environmental dose in severe accident conditions is limited by the A_2 cap on contents. The doses to exposed people in such an accident are expected to be limited to 50 mSv. The tests are designed to be representative of severe transport accident conditions, but also to be controlled and repeatable.

The design of a package and its associated operating maintenance procedures provides a performance that is acceptable to regulatory authorities for off-site transport (movements). Any potential on-site accident is likely to be less severe due to lower movement speeds, increased emergency service availability, reduction in potential hazardous environments, etc. Therefore, operations associated with IAEA approved packages on-site are controlled in such a way to present a very low accident hazard and are not to be considered as a part of this approach.

5.2.2. *Aerosol generation and airborne release fractions*

The packaged RAM is not expected to be immobilized in a binding agent for transport from the consignor to the consignee. It is therefore assumed that, following packaging containment failure, the radioactive contents become available for air entrainment. This approach is conservative as it neglects the retention of activity by large particles and pieces of the package contents and by the remaining packaging. An upper bound release factor of 10^{-3} for solid material is recommended for use in screening assessment. Further mitigating factors are recommended to take into account the limited containment of a damaged container. The value is used here for the total fraction of solid material which is released from the package in an impact accident.

The entrainment of particulate material is covered in the literature, where Ref. [40] provides a comprehensive review. Appropriate data are those of Mishima and Schwendiman, summarized by Mishima [41, 42]. The largest release fractions reported by Mishima occur for freshly dispersed powder on a sandy soil surface. Much of the contamination from the contents of a package may be expected to attach to relatively large pieces of smooth material (plastic, metal, rubber, etc.). The use of upper-bound fractions is therefore conservative. The release fraction clearly increases with the wind. Conservative assumptions are made here about the package's surface exposed. In practice, the majority of the package's surface is unlikely to be directly exposed to high speed wind. Sutter et. al. have conducted experiments generating aerosols by allowing powders (including uranium dioxide) to fall under their own gravity from a height of between 1 and 3 m [43]. The results display a good deal of variability. The authors recommended the adoption of the largest observed airborne fraction of 1.2×10^{-3}. Many results were an order of magnitude less than this, particularly for uranium dioxide; the fraction of airborne particles (less than 10 μm) was $(0.3–0.8) \times 10^{-3}$ for all the experiments.

For this approach two impact release source terms are defined. The first is for low wind speed and the second is for high wind speed conditions. In each case the fraction of solid material released from the package in an accident is taken to be 10^{-3}. The fraction of this released material that is entrained before reaching the ground is taken to be 1.2×10^{-3}. The fraction of the deposited material, which is subsequently entrained, is taken as 2.4×10^{-3}, for low wind speed conditions and 9.8×10^{-2} for high wind speed conditions. A respirable release fraction of 10^{-3} is taken for low level radioactive waste under impact accident conditions during transport in industrial packages.

The study results of the Konrad Waste Transport Risk Assessment Study are suggested for further advice on the development of source terms and associated release fractions for a variety of low and medium level waste packages (e.g. cylindrical and cubical concrete, cast iron and sheet steel waste container) for road or rail transport accident environments under mechanical and thermal load conditions [22, 23]. Release fraction values for spent fuel and vitrified waste transport casks may be found in two more recent studies including the Transport Risk Assessment Study for Reprocessing Waste Materials to be returned from France to Germany [44] and Re-examination of spent fuel shipment risk estimates [42].

5.2.3. *Fire release fractions*

Many cellulosic and plastic materials to be found in a waste package have an ignition temperature in the range of 300–600°C, with decomposition temperatures somewhat lower. Mishima and Schwendiman report full scale active release experiments in which eleven cartons of combustible waste were separately ignited [40]. The waste (mostly cardboard, paper, cloth and plastic) was in some cases sealed in a single plastic bag and in other cases double sealed in two bags. These were placed in the standard container then in use — a cardboard box of 0.45 m × 0.45 m × 0.6 m. A hole was punched in one side, and an oil soaked fuse inserted. The cardboard box was allowed to burn to extinguishment in a large containment. The measured airborne released fractions of UO_2 in fire conditions are given below:

Source material	Fire release fraction
Measured airborne, ≤ 10μm AED*	
Uranium dioxide powder	$4.8 \times 10^{-4} - 2.4 \times 10^{-4}$
Air dried uranium nitrate	$1.2 \times 10^{-4} - 2.6 \times 10^{-5}$
Maximum measured airborne, all size particles (uranium dioxide powder)	5.3×10^{-4}
Potential calculated maximum	2.3×10^{-3}

*AED = Aerodynamic equivalent diameter.

In most experiments more than 80% of the released uranium was in the form of particles ≤ 10 μm AED. The potential maximum airborne release was calculated from wall deposition. It is suggested that this may be unduly high because of the inclusion of ash on the floor which never became airborne. The recommended maximum release fraction is 5×10^{-4}. In a later summary report, Mishima quotes release fractions of 1.5×10^{-3} for burning contaminated materials under static conditions, but up to 0.38 in a 5 m/s air flow. However, these conditions are not considered by the reviewers to be representative for large scale real waste fire, so the value of 5×10^{-4} is recommended for such fires. The accident scenarios and corresponding release fractions are shown below:

Scenario	Release mechanism	Respirable release fraction
Impact failure > 13 m/s, unyielding impact, no fire, low wind speed	Release from package, direct entrainment during release (1.2×10^{-3}) and entrainment following deposition (2.4×10^{-3})	4×10^{-6}
Impact failure > 13 m/s, unyielding impact, no fire, high wind speed	Release from package (10^{-3}), direct entrainment during release (1.2×10^{-3}) and entrainment following deposition (9.8×10^{-2})	1×10^{-4}
Impact failure > 13 m/s, unyielding impact, fire, low air speed	Loss of package containment, entrainment during fire (5×10^{-4})	5×10^{-4}
Impact failure > 13 m/s, unyielding impact, fire, high wind speed (bounding worst case)	Loss of package containment, entrainment during fire (1×10^{-1})	1×10^{-1}

6. HEALTH EFFECT MODELLING

INTERTRAN2 users should be cautioned that the internal health effect model incorporated in the INTERTRAN2 Computer Code System is out of date and should not be used. Results should be obtained as dose risk. Current conversion factors from ICRP 60 [8] or another source may be applied with dose-risk values to yield up-to-date health effects risks.

The default dose per unit intake values in INTERTRAN2 for inhalation and ingestion are for Committed Effective Dose Equivalent (CEDE) which is the appropriate dose for use with the dose risk conversion factor from ICRP 26 (1.25×10^{-2} fatal cancers Sv^{-1}) [45]. INTERTRAN2, however, allows the user to modify these values in the input data file. Committed Effective Dose (CED) per unit intake factors can therefore be entered in place of the CEDEs. These are appropriate for use with the dose risk conversion factors from ICRP 60 for the whole population (5×10^{-2} fatal cancers Sv^{-1}). CEDs can be obtained from, for example, ICRP 68 [46].

The above approach is acceptable provided the individual doses are sufficiently low that there are no early effects. If there is a potential for early effects the Dose and Dose Rate Effectiveness Factor need to be modified.

7. UNCERTAINTIES

This section addresses some basic concepts related to uncertainty. Parts of this section examine differences between uncertainty and variability, types of uncertainties, and methods and considerations for evaluating and presenting the uncertainty associated with transport risk assessment. The available data needed for transport risk analyses generally include a great deal of uncertainty. Therefore, understanding the uncertainties implicit in parameter value estimates will increase confidence in decisions on transporting RAM.

It is desirable, where possible, to use statistical distributions rather than point estimates of important transport related parameters because point estimates are often merely the means, medians, or maxima of such distributions. For example, average traffic density is a point estimate derived from one or more databases created by highway departments and/or police departments in a country, province or city.

7.1. Difference between uncertainty and variability

Uncertainty indicates a lack of fundamental knowledge about factors affecting risk assessment whereas variability arises from true heterogeneity across people, places or time. Uncertainty can lead to inaccurate or biased parameter estimates, whereas variability can lead to imprecise estimates and can affect the degree to which they can be generalized. Uncertainty can be addressed by additional fundamental information; variability can be addressed in principle by exhaustive study. Uncertainty can take the form of random error, systematic error, or lack of an empirical basis for making an estimate. It can be addressed, but not necessarily reduced, by better measurements. Major sources of uncertainty should be identified early in any analysis, as decisions cannot be rational without knowing the effects of uncertainties on the ultimate quantitative estimate of risk.

7.2. Types of uncertainty

Theoretically, uncertainties can be classified on the basis of bias, randomness and true variability. However, the US Environmental Protection Agency (EPA) has classified uncertainty into three broad categories: one relates to missing or incomplete information needed to fully and accurately analyse risk assessment (Scenario Uncertainty), a second, to the uncertainty in the values of some parameters used in the assessment (Parameter Uncertainty); and the third, to appropriateness of the models used in the risk assessment (Model Uncertainty, e.g. mathematical representation) [2].

In order to reduce uncertainty, it is necessary to identify the sources of uncertainty in the risk assessment process. Table 4 is extracted from the US Environmental Protection Agency [47] and indicates the potential types and sources of uncertainty in risk assessment activities.

TABLE 4. TYPES OF UNCERTAINTIES IN MODEL PREDICTIONS AND ASSOCIATED SOURCES AND EXAMPLES

Type of uncertainty	Source	Example
Scenario uncertainty	Descriptive errors	Incorrect or insufficient information
	Aggregation errors	Spatial or temporal approximations
	Judgement errors	Selection of an incorrect model
	Incomplete analysis	Overlooking an important pathway
Parameter uncertainty	Measurement errors	Imprecise or biased measurements
	Sampling errors	Small or unrepresentative samples (a small number of) observations may not be representative
	Variability	In time, space or activities (uniform population distribution vs. actual)
	Surrogate data	Structurally related chemicals data
Model uncertainty	Relationship errors	Incorrect inference on the basis for correlation
	Modelling errors	Excluding relevant variables

The INTERTRAN2 Computer Code System contains idealized mathematical models of transport environments. Risk calculations using these models yield generally conservative estimates of integrated population dose in a way that can be supported by available data. Inherent conservatisms in the models limit effects of uncertainty on the calculated risk values. Since the majority of parameters are user-definable, the user has a great deal of flexibility in

[2] It should be noted that the technique of performance assessment identifies two types of parameter uncertainty: (1) uncertainty in a parameter value because of lack of knowledge, and (2) inherent uncertainty in a parameter value because the value can never be determined with greater certainty.

performing analyses. Therefore, parameter uncertainty is the most significant of the uncertainties listed in the Table 4, and is addressed in the following sections. To produce a distribution of the model output based on possible values for parameters in the models used in a risk assessment and turn the results into a quantitative estimate of uncertainty, it is relatively straightforward to estimate the effect of input parameter uncertainty on the predicted risk value using 'Monte Carlo' or other numerical techniques. However, it is clear from the table that there are other potential sources of uncertainty in risk results, which are more complicated to describe on a quantitative basis, and some which can only be evaluated qualitatively based on judgement.

7.3. Approach to quantitative analysis of uncertainty

7.3.1. Use of data distributions and sampling methods

Several approaches could be used to characterize uncertainty in parameter values. This section focuses on certain examples of probabilistic uncertainty analysis.

Results of an analysis (e.g. the accidental radiological consequences and their attendant probability of occurrence for a transport risk analysis) can generally be expressed in two ways: (a) by providing a point estimate of the predicted quantity (whether realistic, 'best estimate,' conservative, or ultra-conservative) and (b) by specifying a potential range of input values. A range of input values includes the range of uncertainty. Point estimates of input values will yield point estimates of the results (dose, risk), while a range of input values, expressed as probability distributions, will yield a probabilistic result. The latter is usually expressed as a cumulative distribution function (CDF) or a complementary cumulative distribution function (CCDF) that expresses the functional relationship between a particular outcome and the probability of that outcome. Model input parameter values for even advanced probabilistic risk assessments have usually been realistic (best or conservative) point estimates; e.g., the probability of occurrence of a given event sequence represented in an event tree. This section describes a relatively efficient method for incorporating uncertainty in modelling parameters, in place of a best estimate. The method is basically applicable to input data for both incident-free transport and transport accident risk analysis.

The most common example of probabilistic uncertainty analysis is the 'Monte Carlo' method. Monte Carlo is a general designation for any sampling method that is based on generating a random number and applying that number to a sampling scheme. Monte Carlo sampling can be constrained in various ways, usually by defining and limiting the regions to be sampled ('stratified sampling') or by separating sampling regions by a system of fractals ('fractal grouping'). The most unbiased representation of data would be obtained by completely unconstrained Monte Carlo sampling: in which a random number between zero and one is generated along the probability axis of a distribution. The point on the distribution that corresponds to this number on the probability co-ordinate then constitutes the sample. Because the sampling is completely random, a large number of samples (usually 100 or more per variable) must be taken to ensure that all sections of the distribution are sampled.

Unconstrained Monte Carlo sampling requires a large number of samples to ensure a fair sampling. The Latin Hypercube sampling method (LHS) provides a constraint that ensures that the entire distribution is sampled with a relatively small number of samples and ensures capture of the 'tails' of a distribution. In LHS the distribution to be sampled is divided into segments (e.g., into four segments). Each segment is then randomly sampled in the same manner as in the random sampling method. The constraint is that each segment of the distribution is sampled with equal frequency. LHS sampling always includes the 'tails', even if only a few samples are taken. For example, if only 20 samples are taken, and the distribution has been divided into four segments, there will be five samples from each segment. Thus LHS can be somewhat more efficient than random sampling, but tends to overemphasize the tails of a distribution.

Other sampling schemes are not as appropriate for the distributions of transport risk parameters. Stratification methods other than LHS are inappropriate because they would introduce excessive bias. A fractal sampling scheme would be appropriate only for much larger distributions and much larger uncertainties, and would require many hours of computer processing time.

Unconstrained Monte Carlo sampling and LHS will each yield slightly different results. Both methods require about the same computational time for the same number of samples, although far fewer samples may be needed for LHS. LHS has an advantage over unconstrained Monte Carlo sampling in that the resulting point spread is not so great as with random sampling, although the 'tails' of the distribution being sampled are given more weight than in random sampling. Both methods have inherent inaccuracies. In LHS, the 'tails' are over-emphasised, while in unconstrained Monte Carlo sampling; one or both 'tails' may not be sampled at all if the number of samples is not very large.

In setting probabilistic regulatory standards in the USA, tails of distributions are taking on increasing importance. Emphasis on the extreme end of a normal or lognormal distribution suggests that LHS is a more appropriate sampling method than unconstrained Monte Carlo sampling. Similar reasoning can be applied to any standard or guideline involving radiation dose to the public. As a result, LHS is often the preferred sampling method.

7.3.2. Application of LHS and random sampling methods

For very large areas of some continents and some large countries (e.g., Africa, the Russian Federation), specific information may be sparse or non-existent. A possible approach to population density data development may be outlined as follows, with the Russian Federation used as an example:

Good roads, rail links, and population census data may exist for most of Russia west of the Ural Mountains ('European' Russia), but data for large areas of Russia east of the Urals may be difficult to obtain. However, one may take the population data along some segments of the road and rail routes in 'European' Russia to represent the data as distributions (e.g., Gaussian distributions) and sample the resulting distributions to provide data for appropriate parts of Russia east of the Urals.

Population data along the rail route from St. Petersburg to Kirov (about 1100 km) is, for example, quite well developed. Rural and small town (called 'suburban' in this discussion) population density from Kirov to Krasnoyarsk (about 3000 km) is not as reliable. Population density distributions (cumulative distributions), taken from the 1990 Rand-McNally World Atlas for suburban and rural segments of the St. Petersburg-to-Kirov route are shown in Figures 4 and 5.

Figures 4 and 5 demonstrate the uncertainty (or variability) associated with estimates of population density. These cumulative probability distributions reveal the uncertainty and show how the population density is distributed, but they do not yield a firm number for population density.

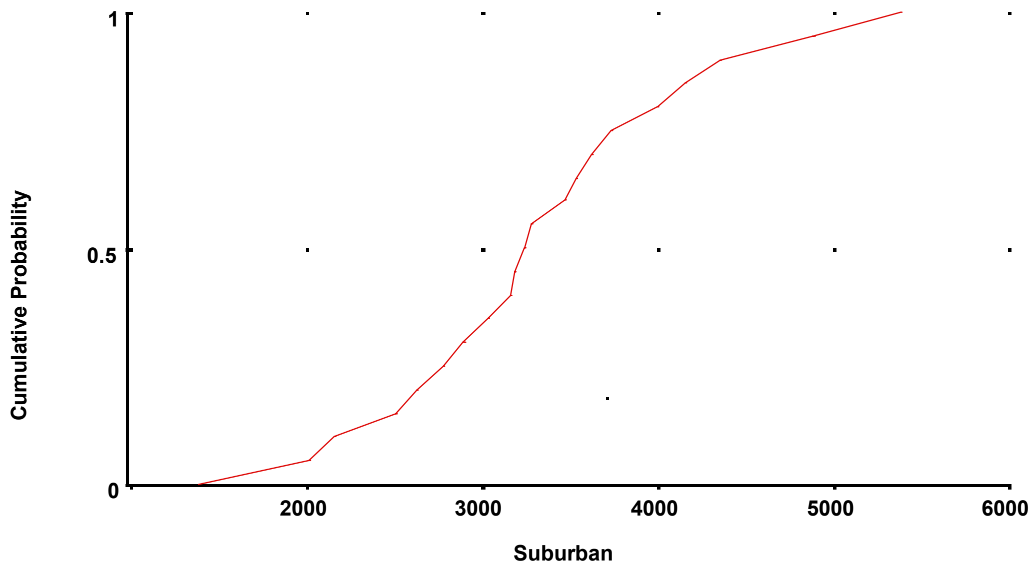

FIG. 4. Suburban population density (person/km^2) for the St Petersburg-to-Kirov rail route.

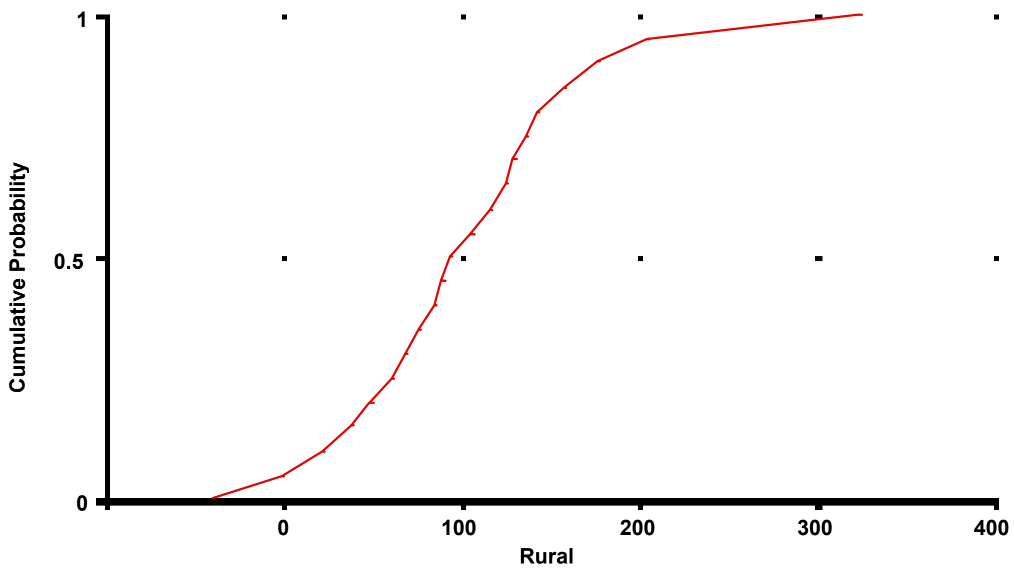

FIG. 5. Rural population density (person/km^2) for the St Petersburg-to-Kirov rail route.

Figure 6 shows unconstrained Monte Carlo sampling of the 'suburban' distribution in Fig. 4. Each dot in the figures corresponds to a population obtained by taking a random sample of the suburban population distribution shown in Fig. 4. As Fig. 6 shows, the suburban population density is most probably between 2500 and 4000 persons/km^2. This region yielded the largest concentration of points. An analysis that can incorporate all of the sampled points in an output distribution would give a more accurate and precise picture of populations and population doses than a single number like a mean or particular percentile.

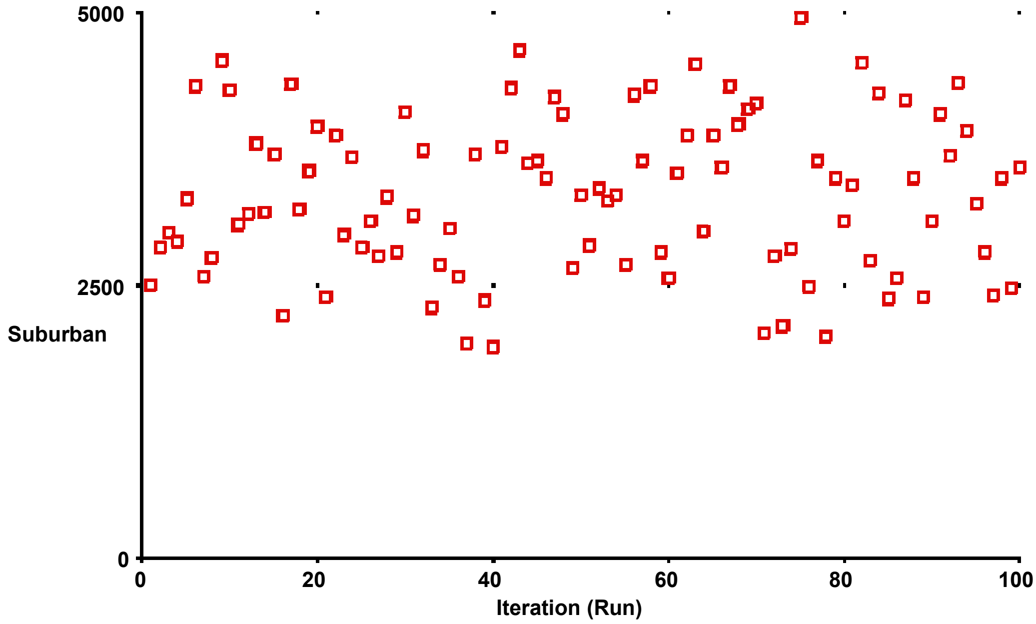

FIG. 6. Unconstrained Monte Carlo sampling of suburban population density (persons/km²) as depicted in Fig. 4.

Figure 7 shows the results of Latin Hypercube sampling of the population distribution of Fig. 4. The resulting point spread is not so great as with unconstrained Monte Carlo sampling. As for with Fig. 6, each population density in Fig. 7 can be used in a separate run and the results presented in CCDF format. However, this capability is not currently available in the INTERTRAN2 Computer Code System, but there are a number of commercially available statistics and mathematics programs that include LHS sampling, such as Analytica™, Crystal Ball™, and Minstat™. The output of this type of program can then be used as input to INTERTRAN2 or other codes.

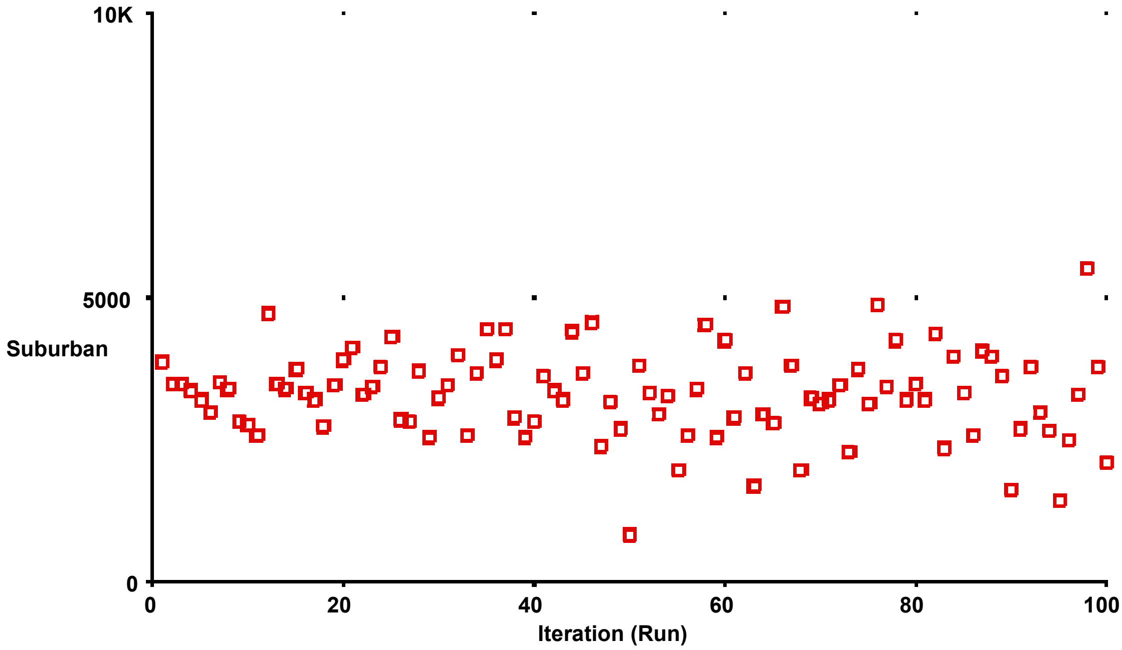

FIG. 7. Latin Hypercube sampling of suburban population density (persons/km²).

Within INTERTRAN2, iterative runs can be done, one for each sample of a parameter value. The resulting population doses can be plotted as in the example of Fig. 8, which shows a CCDF of population doses. (Note that this is an example only, and is not related to any actual calculation.) The interpretation of Fig. 8 is that, for example, it is certain (100% probability) that the population dose is 10^{-8} man-Sv or less; there is about a 95% probability that the population dose is less than 10^{-7} man-Sv; there is about a 25% probability that the population dose is less than 10^{-6} man-Sv; and there is essentially no probability that the population dose will exceed 10^{-5} man-Sv.

FIG. 8. Example result of the population dose presented as a Complementary Cumulative Frequency Distribution (CCFD).

Several approaches are available for obtaining statistical distributions, including data elicitation and the use of geographical information system formats. Census data have also been used to develop methods for dealing with the impact of meteorological conditions that vary, wind direction (and statistical uncertainty in wind direction), population distribution, and the impact of in- and out-migration on the potential impacts of long-term transport campaigns. These methods can be applied to all countries with digitized census data. The risk analyst may need to digitise census data. Sampling and incorporation of uncertainty can be done by manual calculation if necessary, although this is cumbersome and slow.

The degree of highway or rail network development in a country may be correlated with total accident rate, accident-severity frequencies, or emergency response time. The ratio of total paved road mileage to total country area, for example, could be used to extrapolate or estimate emergency response time. ‘Indicator’ or ‘signature’ features might be developed that would allow relevant properties of a country’s transport infrastructure to be estimated reliably, thereby enhancing the global applicability of collected data.

Transport corridors connect cities or population centres. Thus, urban populations of both large and small cities along RAM transport routes normally will be quite well characterized. Reliable data would be lacking primarily for rural areas.

7.4. Presentation of uncertainty

A good understanding of uncertainty is a key feature in providing the decision maker and the public with an understanding of the confidence that should be placed in the decision made based on the risk assessment. Risk assessors have a responsibility to present not just numbers, but also a clear and explicit explanation of the implications and limitations of their assessments. If an analysis involves various alternatives for transporting RAM, it is the analyst's responsibility to assure that documentation clearly shows whether the risk or impact for one alternative is significantly different than that for others.

8. HUMAN ERRORS

8.1. Introduction

Quantitative risk assessments of RAM transport operations have generally not explicitly considered human factors. Instead, they have assumed that human errors are implicitly included in the base event/accident data used to support such assessments. However, scrutiny of RAM transport incident databases reveals a large number of operational incidents and minor accidents that could have been avoided if more attention had been paid to human factors issues, for example in the development of operating procedures. There are recorded instances in the same databases, of where this has been achieved, for example, in the packaging of industrial radiography sources and the handling of Type A packages at airports.

Given the high profile of human factors as the root cause of many serious transport incidents, such as the Clapham rail incident (UK, 1988) and the Herald of Free Enterprise maritime accident (Zeebrugge, Belgium, 1987), failing to consider human factors explicitly in the hazard identification and quantification phases of an assessment could undermine the credibility of such assessments.

This section helps to identify sources of existing guidance on the identification and quantification of human factor related risks and thus illustrates how more credible quantitative risk assessments can be carried out. RAM transport operators should also find this information useful in identifying potential human factor concerns associated with their operations and hence be able to more effectively focus their risk management efforts.

8.2. Data gathering

Reviews of published incident records have proved useful in identifying the types of human error encountered during RAM transport. The following areas have been identified as important contributors to RAM transport accidents:

- Incorrect application of procedures,
- Poor handling,
- Inappropriate or insufficient managerial controls,
- Error in documentation,
- Organizational factors.

Package design clearly acts to mitigate many of these errors. Consideration should be given at the design stage to making the package less susceptible to human error; however, attention should also be given within companies to the promotion of risk perception of operators and to the quality of:

- Procedures,
- Training,
- The management systems for controlling the transport of RAM,
- Guidance available to designers and operators.

The body of incident data is not sufficiently large to support direct estimation of human errors specific to RAM transport operations. Instead, a number of human reliability assessment techniques are available to enable assessors to quantify the probability of errors of omission or commission occurring during RAM transport operations.

8.3. Human reliability analysis

Human reliability analysis (HRA) is a formal method for examining human performance in industrial tasks. Various techniques are used to examine these tasks, to identify human error opportunities in those tasks and to assign probabilities of error to those errors if required. Specialists in this field regard the quantification of human errors as highly speculative as none of the available quantitative techniques has ever been convincingly validated. Nevertheless, the techniques are valuable in focusing attention closely on human factors issues.

This section outlines the general procedures to be followed in an HRA study. There is a distinct benefit in using these techniques to better understand human errors in RAM transport and to apply focused remedial actions.

An example of where the methodology has been applied within a UK safety case is given below. The safety case derived frequencies of accidents arising during the loading and movement of a radioactive material transport package. The probability of failure to correctly secure the package lid was calculated using the Human Error Assessment and Reduction Technique (HEART).

The HEART technique encompasses both the quantification and reduction of human error. The methodology allows for consideration of ergonomic and environmental aspects of the task on performance. Each factor may be considered separately and then combined to produce an overall human error probability.

Initially the task is categorized according to a list of generic task descriptors. The nominal human unreliability figure assigned already incorporates a portion of the factors that may affect performance. The nominal figure is then modified to reflect the more specific effect or error producing conditions that prevail. The assessor uses his/her judgement to decide what portion of the effect may apply to the particular circumstances. The figures obtained by this methodology are multiplied to produce a human error probability.

The methodology also includes provision of remedial actions that may be effected in order to reduce the potential for human error. Each remedial action may be considered independently, allowing the assessor to assess the effect that each remedial action may have on its own or in combination, in order to bring the potential for error to an acceptable level.

The steps in obtaining a figure for human error potential are detailed in Table 5. Task G is defined as “completely familiar, well designed, highly practised, routine task occurring several times per hour, performed to the highest possible standard by highly motivated, highly trained and experienced person, totally aware of the implications of failure, and with time to correct potential error, but without the benefit of significant job aids. The process demonstrates that RAM transport tasks, like those detailed in the task analysis presented earlier, are amenable to assessment by human reliability methodology.

TABLE 5. EXAMPLE HEART TABLE: HUMAN ERROR PROBABILITY DURING PACKAGE LID CLOSURE OPERATION

Generic task type	Nominal probability	Error producing condition	HEART effect	Assessed proportion of effect	Conditions that allow for reduction of HEART effect
G	0.0004	Little or no independent checking of output	3	0.3	Lids are checked for looseness prior to being accepted for movement but torque is not checked independently
		No diversity of information input for veracity checks	2.5	1	No independent check on torque with which lids fastened
		Risk misperception	4	0.3	Trained operator, classified person — should have good perception of risk associated with failure to complete task properly

The resulting human error per demand is 1.5×10^{-3} and was reduced in the safety case by a factor of 10 to 1.5×10^{-4}, to reflect a supervisory element which existed to ensure the task was completed but did not include checks as to adequacy. The validity of this reduction may be questioned, it is acceptable for the figure to be adjusted by the assessor to take account of mediating factors; however, the assessor has not fully referenced the source for this figure. It may have been more appropriate to reduce the error producing condition — 'little or no independent checking of output'. The error potential per demand was claimed for each single lauding operation, assuming the same individual under the same conditions. Thus, a pessimistic probability was claimed.

The exercise of Human Reliability Analysis (HRA) also allows the assessor to recommend remedial steps that may be taken and to quantify their effects on the overall human error probability. Independent checking of torqueing operations is indicated as one way of reducing such errors.

HRA follows a number of discrete steps, the key steps being those outlined below:

Task analysis

Task analysis is used to provide the analyst with a thorough understanding of the task under scrutiny. The methodology uses several techniques, hierarchical task analysis, timeline analysis and link analysis, the basis of which are to decompose the task in order to collect, analyse and represent information in a usable form.

Hierarchical Task Analysis (HTA) is probably the most widely used form of task analysis. The methodology deconstructs the task into the system goal and the constituent sub-tasks required to complete the goal. To achieve this the analyst is usually assisted by a domain expert who can provide details of the task. The analysis describes the task from a top-down approach with the top level containing the goal and the lower levels containing increasingly detailed descriptions of operations. The results may be used for other purposes than human error analysis such as design of manuals and procedures and interface design.

Error identification/reduction

Using the results of Hierarchical Task Analysis, the potential human errors may be identified using either brainstorming techniques, a technique akin to HAZOP in which key words are suggested, or an AEA Technology proprietary technique known as the Systematic Human Error Reduction and Prediction Approach (SHERPA). This latter method uses flow charts to guide the user through a series of questions about each task and describes the type of error that could arise and the underlying 'psychological mechanism' likely to be responsible for the error.

This information provides the basis for making improvements to reduce the influence of these psychological mechanisms. An example is 'place losing error' in which an operator could, through a lapse of attention or distraction, skip a line in a procedure and thus miss an important step. Remedial action would be focused on, for example, introducing checking at the end of critical tasks or improving the design of procedures to include a tick list or other compelling method for place keeping.

Error quantification

Human Error Probabilities (HEPs) can be defined as 'the probability that an operator will fail to perform a required function within a specified time interval', or the

HEP = Number of errors occurred / Number of opportunities for error

Human error quantification methods fall into two main categories: data-based and expert-judgement-based.

The first type derives its HEP figures by using a database of probabilities contained within the methodology, the second uses the judgement of experts to derive a human error probability.

The leading database techniques are the Human Error Analysis and Reduction Technique (HEART) and the Technique for Human Error Rate Prediction (THERP). Both consist, briefly, in selecting a basic human error probability from a table, and adjusting this probability according to the impact that certain human factors are felt to have on the basic figure. Thus, there remains an element of expert judgement even in these methods. The most well-known expert-judgement technique is Absolute Probability Judgement (APJ) and consists in making a direct expert judgement of the probability of error in a given task performed under a given set of conditions. It is a very simple technique in principle and appears to produce results that tally with observed data under test conditions.

8.4. Task analysis

Hierarchical Tsk Aalysis (HTA) is a method whereby a high level description of a task is successively decomposed, from the task goal into a lower level of description of operations (actions required to achieve the goal), resulting in a complete and detailed description of the task. It is a key stage in human reliability assessment and is also useful in developing procedures and training materials for the task. It is also possible to gather information on the design of equipment used, workplace layout and management systems, although other task analysis techniques are available specifically for gathering information on these items.

8.5. Conclusion

The evidence of the task analysis and human reliability review supports the view that these methodologies are relevant and valuable to RAM transport activities. A more structured approach to human error along these lines would strengthen the credibility of RAM transport safety assessments.

9. QUALITY ASSURANCE

Quality assurance (QA) applied in the field of RAM Transport has increased significantly owing to the recognition by experts in the field of the importance and the value of a QA Programme in enhancing safety for all aspects of transport. The main responsibility for achieving safety and quality in transport of RAM rests with those assigned the task and not with those seeking to ensure by means of verification that it has been achieved.

Similarly, when using computer software in safety-related applications it is necessary to implement quality criteria for the best evaluation and estimation of the input/output data used by INTERTRAN2. A rigorous and consistent application of recommended quality criteria will lead to quality results when using the INTERTRAN2 Computer Code System.

9.1. Maintenance of the INTERTRAN2 Computer Code System

The INTERTRAN2 Computer Code System provides tools, for specific shipment studies, national assessments, comparison of shipment options and supporting decision making process and optimisation of transport concepts and technologies from the viewpoint of radioactive waste protection safety. Activities in the software life cycle of the INTERTRAN2 Computer Code System are operation, maintenance and modification. Modifications may be made to remove errors, or to add new requirements or to improve operations.

9.2. QA requirements for user data collection

In order to assure a high quality and a significant high confidence level of the results obtained with the use of INTERTRAN2 in the assessment of risk for a transport programme, the following quality criteria for input and output data should be applied, as appropriate:

- The source of input data should be clearly identified and selected, taking into consideration that only an insignificant number of accidents that have occurred during the transport of RAM have been reported. Therefore, the assessment of risks and radiological consequences for RAM transport depends on calculation, i.e. on the quality of the input data used for INTERTRAN2.

- The input data should be evaluated, e.g., an independent assessment by using a recognized statistical database or by comparison and evaluation with similar cases. For critical situations and for uncertainty cases a direct observation of the RAM transport operation is applicable and recommended.

- The input and output data used in calculations have to be in SI units.

- To increase the confidence level in the results obtained, a comparison between the results of the analysis obtained and those provided by the IAEA and Sandia National Laboratory (SNL) databases should be available.

- The source of input data (such as: government, national, province, local or other competent authorities) should be hierarchized, such as the user to have his own responsibility in use.

- If some components of the INTERTRAN2 Computer Code System have been improved, the user has to be sure that these modifications are tested and validated by recognized institutions, such as the IAEA or SNL. Also, the user has to be sure that the QA software requirements have been fulfilled.

- Every country using INTERTRAN2 Computer Code System should generate and use, as appropriate, its own input database such as to obtain results that are adequate and of a high quality. However, the statistics should be used with a certain circumspection considering the conversion of the different accident rates used.

- Accident scenario and hazard identification must be carried out in the most rigorous, structured and methodological way, with a strong scientific background to ensure that all the relevant hazards associated with the RAM transport are defined in a proper manner.

- The default data and range limits should be printed out.

- Feedback data arising from direct investigations and audit of the transport route will be most beneficial in improving the QA system and preventing further problems of a similar nature.

- As appropriate and where possible, every country should use the same typical accident rate.

- The use of a methodical assessment of risks in order to: (1) identify risks, their sources and consequences, (2) prioritize risk reduction needs, and (3) select risk reduction measures.

- Use of applicable databank scenarios which have already been considered is recommended, if any.

Annex I

ACCIDENT SCENARIOS, EVENT TREES, AND SEVERITY FREQUENCIES

I-1. Introduction

An accident will lead to the release of RAM to the environment only if it is severe enough to cause the RAM packaging to fail and the contents to escape and then only if the escaped material enters the environment (as opposed, for example, to remaining in a trailer or other outer containment structure). Accident scenarios that allow the release of RAM to the environment can be examined by constructing event trees. An event tree depicts a series of events that may occur. By looking at the possible sequences of events, accident scenarios that would lead to a release can be identified. Then, if the probabilities of each of the possible events in the sequence can be estimated, scenario probabilities can be calculated as the product of all of the probabilities for the events that lie on a specific scenario path.

To illustrate these ideas, consider the transport of radiopharmaceuticals as aqueous solutions in a delivery van, with other non-radioactive cargo. Many radiopharmaceuticals are aqueous solutions of a RAM, often a salt (e.g., sodium iodide where the iodine is radioactive). Assume that the delivery van has some accident rate for reportable accidents and that such an accident has occurred. For a release of RAM to the environment to occur, at least some of the cargo in the van must be damaged, the radiopharmaceuticals package must be part of the damaged cargo, and the spilled aqueous radioactive solution must be suspended as droplets or evaporate quickly. Otherwise, all of the radioactive salt will be left inside of the van.

The illustrative event tree presented in Fig. I-1 depicts this sequence of events. The column headers in bold are called top events. The first top event, **Accident**, is assumed to have occurred. The remaining four top events, **Cargo Damage, RAM Package Damage, Fire,** and **Vaporization** may or may not occur. On the event tree, illustrative and arbitrary probabilities of occurrence and non-occurrence for each of these events have been placed on the branches of the tree that apply to each of these top events. The chance that some cargo is damaged during a reportable accident is taken to be 0.9. The chance that the RAM package is among the damaged cargo is taken to be 0.1 (i.e., the average van accident is assumed to damage only 10 percent of the packages on the van). The chance that the accident initiates a fire is assumed to be 0.05. Given that a fire has started, the chance that the fire burns hot enough and lasts long enough to cause the spilled aqueous solution of the radiopharmaceuticals salt to boil vigorously is taken to be 0.9. Finally, if no fire has occurred, the chance that the ambient temperature at the time of the accident is so high that vigorous boiling occurs without a fire starting is taken to be 0.01. Note that the sum of the probabilities that connect to a single branch point is always 1.0. For example, if the chance that the accident initiates a fire is 0.05, then the chance that the accident doesn't lead to a fire must be 0.95. Also, note that the sum of the probabilities of all of the scenarios is 1.0.

Consider the highest scenario path on the tree, the path where cargo is damaged, the RAM package is among the damaged cargo (i.e., the glass vial is shattered), and a fire starts and burns long enough and hot enough to energetically boil the spilled aqueous solution of the RAM, which causes some of the dissolved salts in the solution to be converted to gasborne aerosols that are carried out of the smashed van to the environment; in this case, into the air. The probability of this scenario is given by the product of all of the probabilities of the events that lie on this scenario path. Therefore, the probability of Scenario No. 1 on this illustrative event tree is (0.9)(0.1)(0.05)(0.9) = 0.00405.

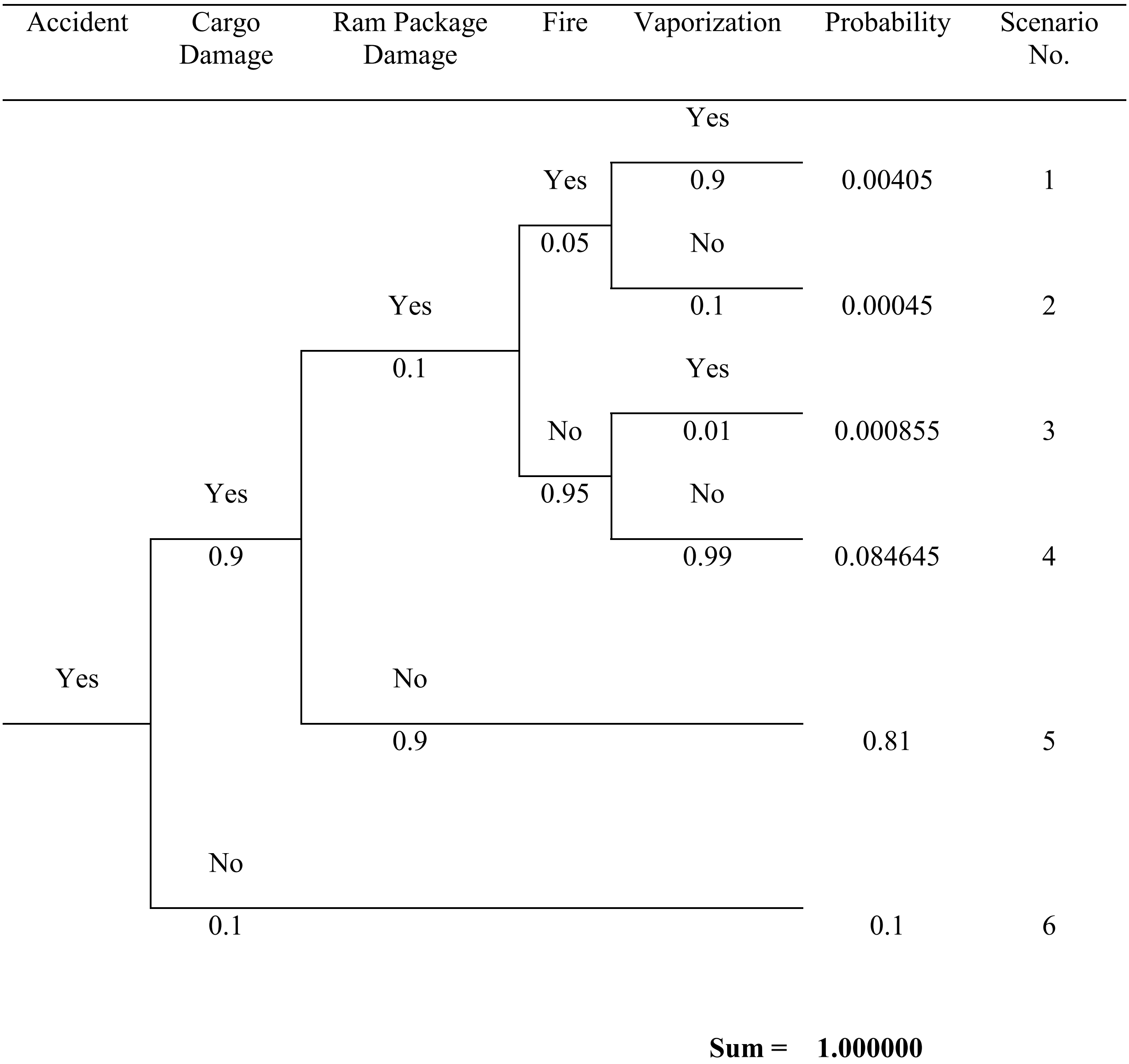

FIG. I-1. Illustrative event tree for delivery van accidents.

Note that several of the paths on this event tree lead to the same final state. Scenarios 1 and 3 both lead to RAM package leakage and vaporisation of at least some of the leaked contents. All of the remaining scenarios either don't involve RAM package failure or, if the RAM package fails, its spilled contents do not vaporise (e.g., all of it is absorbed by packing material), so no release occurs. So for this event tree there are only two endpoints, release to the environment which has an occurrence probability of 0.004905 = 0.00405 + 0.000855, and no release which has an occurrence probability of 0.995095 = 1 – 0.004905 = the sum of scenarios 2, 4, 5, and 6. Thus, the six scenarios on this event tree reduce to two accidents bins, a release bin with an occurrence probability of 0.004905 and a non-release bin with an occurrence probability of 0.995095. Of course, by definition, these probabilities are conditional on the occurrence of some reportable delivery van accident. Moreover, since they are conditional probabilities, they are also by definition, the severity fractions for these two accident bins.

This approach to the construction of accident scenarios has two great strengths. First, it allows a set of representative accidents to be defined by constructing accident scenarios and combining scenarios that lead to the same set of accident conditions, and second it defines the conditions that apply to each group of scenarios that lead to essentially the same set of accident conditions. Defining the accident conditions that applies to each unique group of accident scenarios is important because once the conditions have been defined, the physical and chemical properties of the RAM can be used to estimate the fraction of the material that is released to the environment by exposure to those conditions. Thus, definition of the conditions that apply to each group of scenarios allows release fractions to be developed for each scenario group.

I-2. Databases

Several accident and incident databases maintained by the IAEA and the USA are presented in this annex.

I-2.1. IAEA accident and incident database

A structured RAM transport analysis requires access to effective data on the numbers and types of packages transported annually and the total distance travelled by vehicles carrying these packages, as well as numbers of transport incidents and accidents. In 1988, the IAEA initiated data collecting activities and created the EVTRAM database for accidents and incidents related to RAM transport. The IAEA also established the SHIPTRAM database to collect RAM shipment data. The main objectives of the databases are to provide information to support evaluations of the effectiveness of the IAEA's Regulations for the Safe Transport of Radioactive Material and to provide a means of information exchange for any lessons learned. These databases, if maintained effectively, can provide data for constructing event trees.

I-2.2. USA databases and experience

The United States Department of Transport (USDOT) (http://www.dot.gov) maintains a database of national transport statistics that includes detailed tables on the transport system, transport economics, safety, and other related areas. The USDOT Bureau of Transport Statistics (http://www.bts.dot.gov) provides data on all modes of transport.

The USDOT Federal Motor Carrier Safety Administration (http://www.fmcsa.dot.gov) provides information on, and access to, accident and other databases that can be used to analyse safety issues, safety statistics, ratings, and other statistical information. The USDOT also maintains the HMIR database (http://hazmat.dot.gov/files/hazmat/hmisframe.htm) for transport accidents and incidents, involving all hazardous materials, including RAM.

Lawrence Livermore Laboratory and Sandia National Laboratories have developed detailed truck and rail event-trees for several package types in the USA. Because of their universality, all countries could use these mode-specific event trees with little or no modification. Severity categories derived from these event trees are available via TRANSNET [48] and the RADTRAN Web site (http://ttd.sandia.gov/risk/radtran.htm). TRANSNET also provides access to the Radioactive Materials Incident Report (RMIR), an extensive database of transport accidents and incidents involving RAM.

Annex II

TRANSPORT ACCIDENT SEVERITY AND FREQUENCY ASSESSMENT METHODS

II-1. Introduction

Section 5 of this TECDOC is related to transport accident assessment and (1) reviews and describes the probabilistic safety assessment methods, database requirements and practises currently in use for quantifying the type, severity and frequency of transport accident events and (2) provides guidance as to the development and application of these assessment approaches.

This annex presents illustrative examples of the two principal probabilistic assessment approaches which where identified to prevail in attempts to assess and evaluate the potential radiological risks arising from the transport of RAM. The illustrative examples have been adapted from a recent review [17] of assessment methods for analysis of the frequency and severity of the associated adverse outcome of rail transport accidents, e.g. in terms of impact load, material damage, etc., and represent the standard probabilistic analysis methods developed and used by AEA Technology (UK) and Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH (Germany) for quantifying the risks associated with waste transport operations. Thus, these two assessment approaches are referred to throughout this Annex as AEA- and GRS-method.

The GRS method is a full scale probabilistic assessment methodology allowing account to be taken of the potentially broad range of conceivable transport accident events including low and high probability events based on a complete set of historical rail event data. The AEA methodology is a predictive approach and involves identification, definition and analysis of particular sequences of base events and analyses each event sequence in terms of the severity and likelihood of occurrence of the associated outcome using event tree analysis techniques. Further information on these methods may be found elsewhere [17, 28].

In addition a calculational approach is provided for estimation of road transport accident frequencies consistent with the data requirements of the INTERTRAN2 Computer Code System using information most likely available to risk assessors in many countries.

II-2. GRS probabilistic accident assessment methodology

The GRS probabilistic transport accident assessment methodology described below has been developed for and applied to the transport of (low and intermediate level) radioactive waste to the designated Konrad Repository [22] and other destinations, with the objective of quantifying the radiological risks arising from potential rail transport and handling accidents. The probabilistic accident assessment methodology was particularly designed to account for a wide range of transport accidents and the associated adverse consequences. It is recognised that the harmful consequences of transport related accidents can be measured in various ways, but throughout the Konrad Transport Study the radiation dose to persons in close proximity to the accident site has been used as the preferred means of describing the adverse radiological consequences, including low probability high consequence events as well as high-probability events with insignificant consequences — if any at all. The transport risk assessment results are generally presented in terms of cumulative complementary frequency distributions (CCFD) and provide, for example, a relationship between the potential radiation exposure of members of the public (critical group individuals) subsequent to an accident and the expected frequency of occurrence at a specific level of exposure.

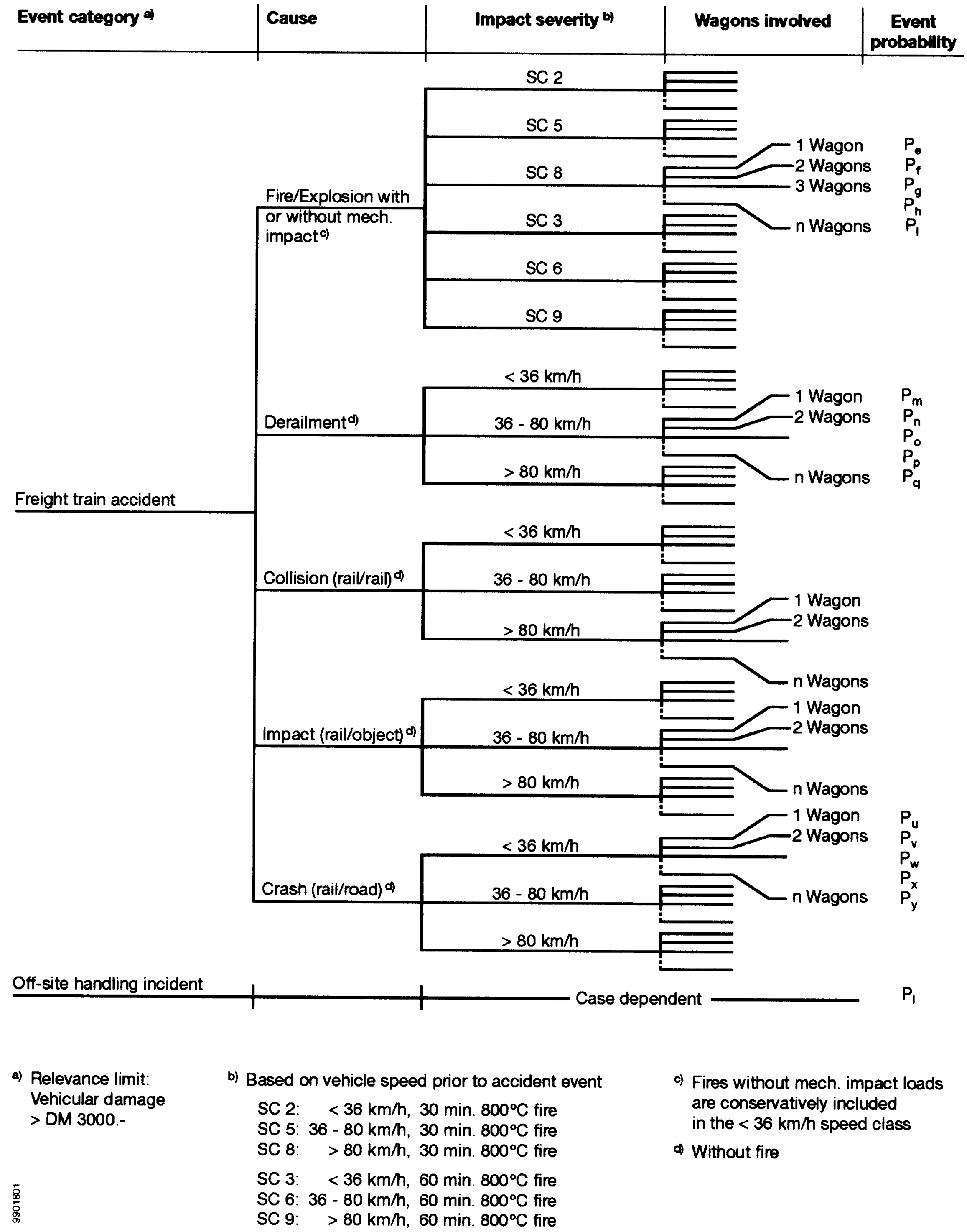

FIG. II-1. GRS probabilistic accident frequency and severity assessment approach.

This annex relates to the elements of the overall assessment methodology concerning the definition of accident events, assignment and categorization of event severity, estimation of the likelihood of occurrence of accident event categories and the sources of information being used with relevance to rail transport. The elements of the PRA methodology not related to these topics are not covered in this annex.

Assessment approach characteristics

The modelling approach of the GRS accident severity and frequency assessment method is primarily driven by the type and nature of freight rail event data available nationally and clearly guides the way in which the analysis is structured. The analysis method considers a suite of event sequences grouped by initiating cause and quantifies the adverse outcome depending on the number of wagons affected and the event severity, i.e. the damage potential for packages. The principal structure of this model is shown in Fig. II-1. The assessment relies on recorded event data compiled by German Railways (DB) and offers the advantage of fully encompassing the wide range of categories and severities of accidental events which need to be considered in transport risk assessment including low and high probability and severity events. It makes the analysis flexible in terms of considering different shipping conditions, i.e. single or multiple package shipments, package types and regions.

Identification and definition of transport accidents

The analysis of causes and consequences of rail transport accidents events has been derived from a 10-year record (1979–1988) of mainline freight train accidents (marshalling yards excluded) on the German Railways network. This extensive and detailed database of freight train accident events on the German Railway network has been acquired for analysis and offers the unique advantage of identifying and quantifying the wide range of all conceivable categories and severities of freight train accident events, e.g. by the initiating cause (derailment, collision, etc.), and the related frequency of occurrence. Accidents involving shunting units, however, are included only in the survey data if they refer to collisions between a shunting unit and freight train.

Low severity freight train accident events have been effectively screened out from the analysis by adopting a relevance limit for vehicular material damage of DM 3000 (approx. US $1700). Accidents resulting in less material damage were not considered to be severe enough to challenge a packaging's containment integrity. For similar reasons accident events with personal damage only, e.g. injuries resulting from being struck by a rail vehicle, have deliberately been excluded from the analysis.

For this analysis categorization is made between the following principal initiating event classes (or root causes):

- *Derailment* occurs when a railway vehicle[1] runs off or lifts off the track or runs on two different pairs of tracks.
- *Collision* is defined as one railway vehicle impacting another railway vehicle.
- *Impact* is defined as a railway vehicle hitting a foreign object other than a railway vehicle within the track clearance, e.g. running into buffer stop, hitting an obstacle in the track clearance, etc.
- *Crash* is defined as (a) an accident at a level crossing between a moving railway vehicle and a road user or (b) an accident at a level crossing between a motor vehicle and a stationary railway vehicle.
- *Fire/explosion* occurring in or caused by a moving vehicle and any accidents caused by a moving vehicle that cannot be assigned to anyone of the other categories.

---

[1] Throughout this annex the term "railway vehicle" refers to either the power unit and one or several wagons/railcars, whereas the IAEA Transport Regulations define "vehicle" as "… a railroad car or railway wagon".

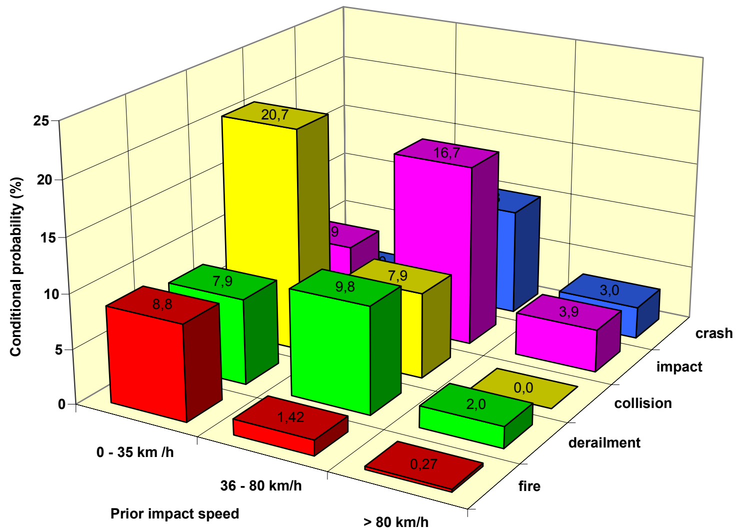

FIG. II-2. Type and initiating event probabilities of mainline freight train accidents in Germany (1979–1988).

Based on this survey of accident events the frequency of occurrence of mainline freight train accidents severe enough to cause material vehicular damage above DM 3000 (approx. US $1700) has been estimated related to the initiating event classes defined previously and the vehicle speed preceding the accident; the result is shown in Fig. II-2.

Application of this database has the advantage that there is no conflict between the accident category used and the data that is used as an input to derive the frequency of events in that category. Thus complex distributions of different fault sequences for each accident event category are derived and form the basis for transport risk assessment. Generally these frequency distributions take no account, however, of the actual route of transport involved. They are derived from a large body of information which covers accident events for the entire German Railway (DB) network. Therefore, the methodology as presented does not consider the effects on the overall risk of route specific features. Consequently, application of this generic set of information to a specific transport route must generally be complemented by considerations ensuring that the hazardous features of this specific route are comparable with the relevant hazardous features of the total rail network.

Additional data available from German Railways (DB) also allow a full quantitative analysis of other fundamental accident characteristics, e.g. the number of wagons involved. The relevant statistical event data are presented in Fig. II-3. It can been seen that the material damage to railway vehicles in excess of the relevance limit is in approximately one half of the freight train accident events limited to the power unit while the rail wagons suffer only insignificant damage — if any at all (cf. “0 wagons affected” entry in Fig. II-3). The accidents referred to in this category represent accident sequences where damage is exclusively limited to the power unit or where the damage to at least one or several rail wagons is below the relevance limit of DM 3000 (approx. US $1700). This can be attributed to the fact, that in impact accidents (i.e. interaction with obstacles) wagons are not affected in over 80% of events; for crashes (at level crossings) this applies to over 90% of events. For derailments and collisions events (between railway vehicles) the probability of several wagons being adversely affected is greater. Derailment is the sole accident category in which damage only to the train engine is not the most frequent case.

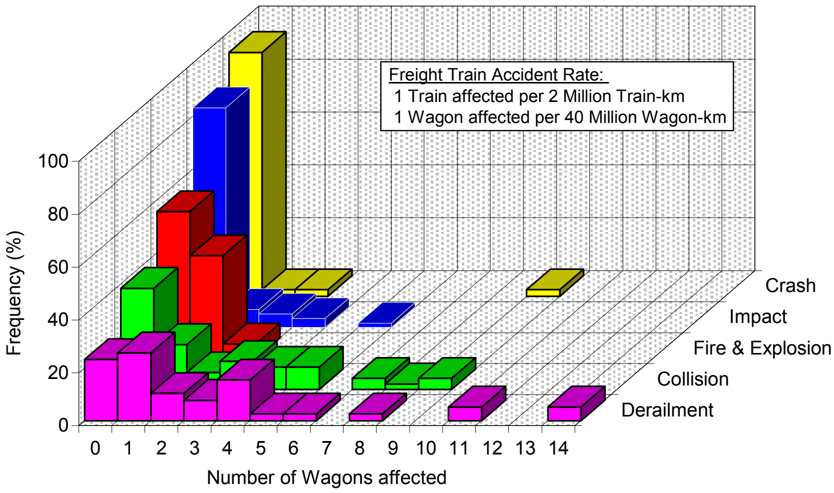

FIG. II-3. Number of wagons affected in mainline freight train accidents.

For fire-only freight train accident events, the most common occurrences are fires on the power unit, mostly caused by the electrical system. More than half of the fire incidents is of this nature. It is also evident that even severe fires rarely spread to other wagons in the train.

Accident severity categorization

The scope and complexity of the accident severity categorization schemes used by the GRS assessment approach is presented in Table II-1 and is typical for analysis of land-based transport operations, i.e. road and rail. The severity categorization scheme has adapted speed bands, which reflect performance criteria of the waste packages considered or are based on engineering judgement. The severity scheme assigns two potential fire scenarios (30 minute and 60 minute fully engulfing 800°C fire) to each impact speed banding. The selected thermal loads reflect the exposure conditions defined by the IAEA regulatory test fire for Type B packages and account for even more extreme fire environments. Note that fire events on freight vehicles where there was no mechanical impact have been included in the 0–35 km/h speed band for estimation of the event frequency to keep the number of categories to the lowest practicable level.

For frequency estimation each accident has been assigned to one of the selected three speed ranges and fire scenarios and it is these bandings and fire scenarios which form the basis for the GRS accident severity categorization scheme. Assignment of each accident event to a severity category has been based on the initiating cause and the speed recorder measured vehicle speed (potential package impact speed) immediately prior to the accident event as severity estimator (damage potential). It is seen from Table II-2 that non-fire environments are prevailing in about 90 percent of rail accidents events and the remainder of about 10 per cent involve fire (without or combined with mechanical impact loads).

Given that a fire has been recorded there is, however, frequently insufficient information within the accident record to categorize precisely the severity of the fire event. Thus, the fires are based on analysis and judgement assumed to be 800°C with two thirds corresponding to a 30 minute and one-third to a 60 minute fully engulfing fire. The size of the event data set used gives confidence in the proportion of trains that were travelling within each speed band. For impact response analysis it is conservatively assumed that all incidents within each

TABLE II-1. ACCIDENT SEVERITY CATEGORIZATION SCHEME ADOPTED FOR TRANSPORT RISK ANALYSIS

Impact Velocity	No fire	800°C fire 30 min	800°C fire 60 min
0–35 km/h (0–9.7 m/s)	SC 1	SC 2	SC 3
35–80 km/h (9.7–22.2 m/s)	SC 4	SC 5	SC 6
>80 km/h (>22.2 m/s)	SC 7	SC 8	SC 9

TABLE II-2. CONDITIONAL PROBABILITY OF OCCURRENCE OF ACCIDENT EVENTS BY SEVERITY IN THE MAINLINE FREIGHT TRAIN TRAFFIC ON THE GERMAN RAILWAYS (DB) NETWORK

Impact velocity	No fire	30 min 800ºC fire	60 min 800ºC fire
0–35 km/h	SC 1: 0.36	SC 2: 5.9×10^{-2}	SC 3: 2.9×10^{-2}
36–80 km/h	SC 4: 0.45	SC 5: 9.5×10^{-3}	SC 6: 4.7×10^{-3}
>80 km/h	SC 7: 8.4×10^{-2}	SC 8: 1.8×10^{-3}	SC 9: 8.8×10^{-4}
Total	89.4×10^{-2}	7.0×10^{-2}	3.5×10^{-2}

banding occurred effectively at the upper speed in the respective speed range. In the vehicle speed range above 80 km/h a package impact speed of 110 km/h was assumed for package response analysis.

Accident frequency estimation

Based on the survey and analysis of the 10 year record (1979–1988) of mainline freight train accidents on the German Railways (DB) network (marshalling yards excluded) the frequency of occurrence of a regular freight train to experience an accident with the potential to cause material damage to railway vehicles in excess of DM 3000 (approx. US $1700) is about 0.5 per 1 million train km, i.e. one accident event per 2 million train km. The freight train accident rate of 0.5 per 1 million train km has been determined by dividing the number of regular freight trains involved in mainline railway accident events (marshalling yard operations excluded) and suffering vehicular damage in excess of DM 3000 (approx. US $1700) by the cumulative freight train travel distance in the 10 year survey period and by making appropriate corrections to account for accident events involving auxiliary, service and exchange trains.

It is important to note that the estimated accident rate per train km is in accordance with the characteristics of the survey data i.e. the frequency estimate is generic in nature. Application of this frequency of occurrence for a specific railway route would require an analysis and evaluation regarding the representativeness of this value for this specific route, for example, by ensuring that the hazard features of this route are comparable with the relevant features of the general railway network.

From the information presented in Fig. II-3, it can be estimated that the number of freight wagons — power unit excluded — suffering damage above the relevance limit is on average 1.54 railwagons in mainline freight train accident events. Consequently, the conditional probability of occurrence (P_w) that a specific wagon will be affected in a mainline railway accident is about 5.13 per cent (= 1.54/30) for freight trains travelling on average with about 30 wagon per train. Combining this information with the freight train accident rate referred to above results in an accident rate per wagon-km of 2.56×10^{-8} accident events ($1.54/30 \times 0.5 \times 10^{-6}$). In other words: The frequency of occurrence of a railcar travelling in the regular freight train traffic of the German Railways Network to suffer damage in excess of the relevance limit in a mainline railway accident — marshalling yard accidents excluded — is about one in about 40 million wagon km.

The survey data cover a broad range of accidental sequences and are broken down according to the initiating cause (or root cause) of the event and the vehicle speed prior to the accident to indicate the package damage potential. The principal event classes considered in the survey and the respective conditional probabilities of occurrence of running-line freight train accidents are shown in Fig. II-2.

Event probability estimation for mixed cargo freight train accidents

For dedicated trains carrying only cargo with the same characteristics, e.g. hazardous material, the probability of occurrence of accident events of a given severity and involving a given number of affected wagons and, thus, resulting in the same consequences, can be taken directly from the database underlying Fig. II-3. For mixed cargo freight trains, however, which generally carry a number of hazard cargo and non-hazard cargo wagons, it is necessary to consider other factors including the random nature of wagons to be affected in an incident, which are detailed in this section.

For determining the risk associated with the transport of hazard and non-hazard cargo wagons, the number of wagons of each type being affected in an accident event has to be taken into account. In this way, different probabilities of occurrence can be assigned to the range of potential accidental consequences, e.g. the environmental package release, which result from different numbers of wagons being affected. Fig. II-3 shows the frequency of occurrence with which a specific number of wagons are affected in freight train accidents but no distinction is made between wagons carrying hazardous cargo (more generally: wagons with a particular characteristic) and non-hazardous cargo. For risk assessment only the hazard (e.g. radioactive) cargo wagons contribute to the (radiological) risk.

Using combinatorial statistics [49] the conditional probability of occurrence of accident events can be estimated, that r affected wagons having the particular characteristic are among the total number of w affected (hazard and non-hazard) wagons in a railway accident, while travelling in a mixed cargo freight train with a total of N (hazard and non-hazard) wagons, of which R wagons have the particular (hazard) characteristics. Since a specific number (r) of affected wagons with the particular (hazard) characteristic can result from accidental sequences involving different numbers (w) of affected (hazard and non-hazard) wagons, the total conditional probability of a specific railway accident sequence, e.g. the case of three affected hazard cargo wagons, is the sum of the weighted conditional probabilities of all potential accident event sequence combinations. For example, the event sequence 'three hazard cargo wagons affected' can result if only the three hazard cargo wagons travelling in a freight train are affected but also if 3 out of a total of $w = 4$ involved wagons, 3 out of a total of $w = 5$ involved wagons, etc. are affected. The conditional probabilities for these freight train accident event sequences have been calculated for the nine severity categories defined in

Table II-I (SC_k, k = 1–9) and for up to 10 hazard cargo wagons (R = 1 to 10) travelling in a regular freight train with a total of 30 wagons (N = 30) and are given elsewhere [28]. These statistical data form the input data for the simulation program for determining representative accidental consequences, e.g. radioactive source terms, and their frequency of occurrence as described in the Konrad Transport Study [22].

II-3. AEA probabilistic accident assessment methodology

The AEA accident frequency and severity methodology is a predictive approach and is based on a thorough consideration of conceivable sequences of events which can occur during rail transport with the potential of compromising the containment or shielding integrity of a RAM package (through high energy impacts and extreme thermal conditions). Depending upon the type of operation under consideration, the broad categories are further subdivided, where appropriate, in order to identify and quantify specific hazard features of the railway route which may threaten the package integrity. This approach therefore allows account to be taken of the actual routes under consideration when considering potential hazardous events. Further, once the events have been identified, it allows quantification of the frequency of an event which relates directly to the existence of a particular hazard along the route in question by using event tree analysis techniques.

The assessment and evaluation of the frequency and severity for each accident event sequence is determined using the same approach 1999 [17]:

- Identify event sequences in accordance with identified scenarios
- Assign damage category(s) using severity categorization scheme
- Assess frequency associated with each damage category event using event tree
- Ensure that frequency of specific event that has a particular consequence is included in the total frequency assessed for that consequence from all events.

The initiating frequency of an accident event is quantified using historical freight rail accident data. The likelihood of interaction with a feature on the route (for some events) is based upon actual routes. In practice, judgement may be required as to the extent to which actual routes are surveyed. For a scooping assessment it is likely that a typical number of hazards per route km can be assigned based on studies of similar routes. Generally actual route studies can be carried out using maps (actual surveying of line side hazards along a rail route is impractical compared, for instance, with route surveys carried out for road transport). For the purposes of assessment features which do not have an obvious ‘length’ (tunnel portal, bridge support, etc.), a distance of track prior to the feature is assumed within which it is considered that the initiating event may result in interaction with the feature.

For lower frequency events the methodology relies upon the assignment of conservative event frequencies which are applied to the event sequence at each node in the event tree analysis. Event values used in the assessment generally include the:

- Probability of train interacting with feature following derailment (displacement from track)
- Probability of impact speed prior to derailment exceeding a particular value to achieve an assumed level of damage (as defined in the severity categorization)
- Probability of impact speed prior to collision exceeding a particular value to achieve an assumed level of damage (as defined in the severity categorization)

- Probability that installation contains enough material to sustain fire for 30 minutes
- Probability of ensuing fire
- Probability of fire engulfing package
- Probability of fire duration exceeding 30 minutes
- Probability of most threatening impact orientation (side on/end on).

Examples of the application of these event specific sequences in order to determine the frequency of specific events are given in Fig. II-4. (Note: n/a indicates that the outcome of this scenario is not considered in the consequence assessment or is not a relevant scenario in its own right).

In summary the AEA methodology is event specific and covers principally both low probability high consequence events as well as higher probability low consequence events. In practice, however, for most RAM transport operations for which risk assessments have been carried out (i.e. for Type B packages) low consequence events have been effectively screened out from further assessment by the severity categorization assignment. Consequently, in such risk assessments there is often some emphasis on low probability, high consequence events and these are included in their own right because of the event specific nature of the assessment approach and conversely low consequence events are not considered quantitatively for obvious reasons. At each stage of the assessment conservative assumptions are generally used such that the overall risk will be an overestimate. However, care has to be exercised in cases where an event probability is estimated by combining several conditional probabilities in a multiplicative way to avoid an accumulation of parameter conservatism's which may render a result to be overly conservative.

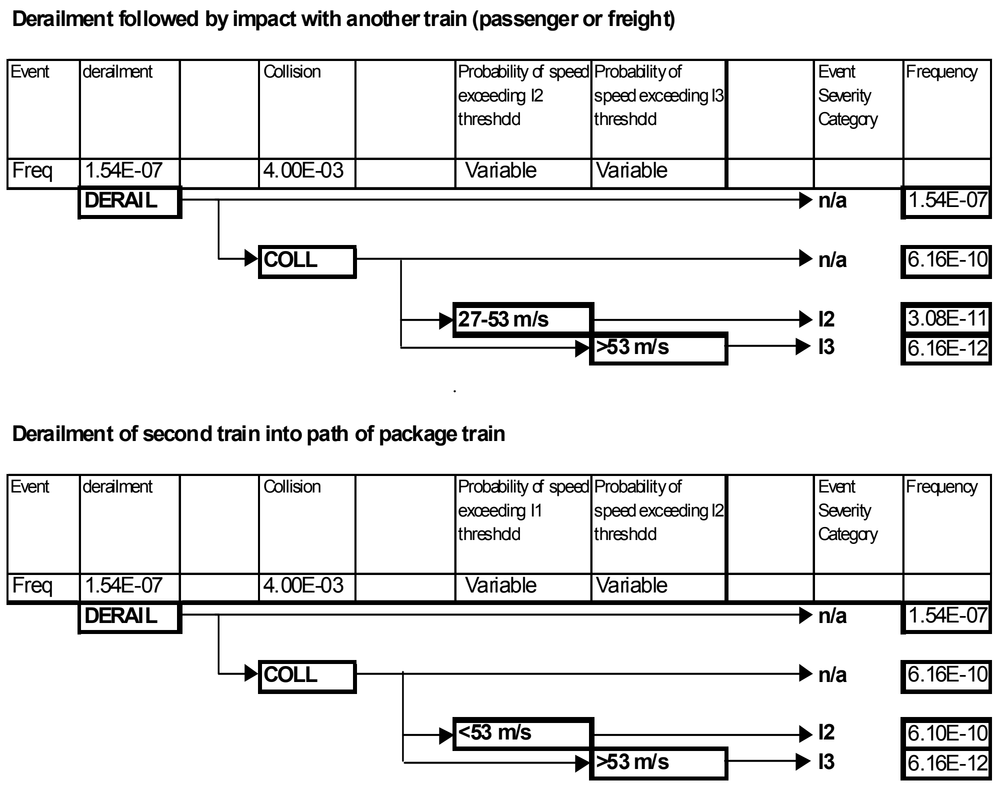

FIG. II-4. AEA accident frequency derivation examples (adapted from [17]).

II-4. Frequency estimation for road transport accidents

INTERTRAN2 requires users engaged in road transport accident assessment to furnish the frequency of occurrence of road transport accidents of different severities and occurring in different population zones. In order to generate the data in a form readily applicable in the INTERTRAN2 Computer Code System, the analyst requires the following principal information:

		Model parameter
1.	The number of registered (package) vehicles in a given time period.	N
2.	The number of reported (package) vehicles affected in road transport accident events in a given time period: (Often accident events are graded according to severity of their consequence. Thus let a_i be the number of vehicles affected in accidents of severity category, i, in a given time period. Then $A = \Sigma a_i$).	A
3.	Average distance (km) travelled by a (package) vehicle in a given time period.	d
4.	Number of reported (package) vehicles affected by accident events in population zone, j, in a given time period. Now, $A = a_j$.	a_j
5	Number of reported (package) vehicles affected by transport accidents of severity, i, occurring in zone, j: ($a_i = \Sigma a_{ij}$ summed over, j, all three population zones) ($a_j = \Sigma a_{ij}$ summed over, i, all severities of accidents).	a_{ij}
	With the above defined quantities, it is now possible to state the following:	
6.	Frequency of occurrence of a (package) vehicle to experience a road transport accident events (all severities) per vehicle-km.	$f = A/(N \cdot d)$
7.	Frequency of occurrence of a (package) vehicle to experience an accident of severity category, i, per vehicle-km.	$f_i = a_i/(N \cdot d) = f \cdot a_i/A$
8.	Frequency of occurrence of a (package) vehicle to experience an accident of severity, i, in population zone, j, per vehicle-km.	$f_{ij} = a_{ij}/(N \cdot d) = f_i \cdot a_{ij}/a_i$

In many circumstances, such accident data may be available on a national basis and provide physical description of the accident conditions which would enable the analyst to quantify the impact of the accident on a package. On the basis of the assessed response of the package to certain known physical impacts, such as mechanical or thermal impact, the response of the package to an accident event of defined severity can be evaluated. There would be some amount of approximation in all these estimates, but they are understood to form a basis for probabilistic safety assessment.

Annex III

DOSE ASSESSMENT TECHNIQUES

III-1. Introduction

The radiation dose calculations carried out for accident conditions are different from those related to incident-free transport conditions. The source term governed by the package response and release behaviour can strongly vary with the conditions of the accident. Indeed, besides enhanced radiation levels caused by potential loss of packing shielding, there is a finite probability of occurrence of a radionuclide release into the environment. In this case, the critical population group is the population near the site of the accident, which could be exposed to both radionuclides from possible radionuclide releases and/or to enhanced radiation from loss of shielding. An atmospheric dispersion and deposition model is necessary to evaluate the atmospheric dispersion and ground deposition of radionuclides released by the accident (determination of a dilution factor). Then, several exposure pathways resulting in a dose to the population have to be considered.

The interested reader is particularly referred to the following reference documents on internal and external dose assessment published in the IAEA Safety Standards Series No. RS-G-1.1, RS-G-1.2 and RS-G-1.3 [50–52].

III-2. Potential maximum individual dose

Individual dose limits do not apply in the case of accident conditions. In fact, ICRP 63 [53] and IAEA Safety Series No. 109 [54] propose intervention levels based on the principle that the intervention should be optimised so as to maximise the net benefit of the intervention and reduce the build up of deterministic effects. These intervention levels are expressed in terms of individual dose. Therefore, the individual doses are to be used as a relevant indicator in the evaluation. Additional indicators like specific organ doses (thyroid, skin, and lung for example) can be of interest too, depending on the content of a damaged package. The chemical form of the RAM can determine the tissues and organs that are likely to be primarily affected following the intake of the radionuclide.

In order to assess individual doses under accident conditions, the user can perform the calculations with TICLD (Transport Incident Centreline Dose), a tool provided for INTERTRAN2 on request (see Section 3.1).

Overall, deterministic effects to the public are unlikely to occur in the context of the transport of RAM for many accident conditions. Deterministic effects may become relevant only in the case of accident conditions of very high severity.

III-3. Potential collective dose

In order to estimate the stochastic effects, computation of the collective dose — and not individual doses — would be meaningful because of the statistical nature of the manifestation of the biological effects for which no threshold dose are defined. Thus, a quantitative assessment of the radiological risk associated with transport of RAM requires computation of collective dose. With estimation based on probabilistic assessment techniques, the annual collective dose incurred from normal transport or the potential dose from transport accidents can be estimated by determining the dose from ’the practice of transport of RAM through public domain’. INTERTRAN2 evaluates the collective dose of populations located downwind the site of the accident.

Influence of population densities

The collective dose depends on the type of the population zone (urban, suburban or rural) where the accident occurs and on the population density of this zone. Indeed, the collective risk is directly derived from the product of the expected dose and the population density of the affected zone. The population density is often difficult to estimate precisely and can vary significantly in a country or area. So, the user must focus on population density values and select the best data corresponding to the transport route.

III-4. Exposure pathways

There are several potential exposure pathways contributing to the dose of the population.

Direct radiation

There are generally three ways of external radiation exposure:

- Cloudshine (submersion dose): an external exposure to radiation from the plume during the passage of the radioactive clouds considered for exposure. The dose is derived from the atmospheric dispersion factor determined at the receptor point multiplied by a suitable external dose conversion coefficient depending of the radionuclide released.
- Groundshine: an external exposure to radiation from the radioactive substances deposited on the ground (dry or wet deposition). The dose from groundshine is calculated from the activity concentration per unit of ground surface multiplied by a suitable external dose conversion coefficient depending of the radionuclide released. The integrated dose can be calculated for different periods following the deposition (for example, from 1 h to 50 years). The choice of the integration period depends on the type of assessment carried out. Short term assessment is interesting for judging the necessity of sheltering and evacuation; long term assessment is relevant for the evaluation of long term effects and decisions being made about permanent relocation.
- Direct exposure to radiation from the damaged package of a person located in close proximity of the accident site caused by degradation (or complete loss) of the package shielding integrity (mechanical or fire accident).

Under accident conditions, INTERTRAN2 allows estimation of the external dose received by cloudshine and groundshine, but only calculates the inhalation dose received from direct exposure to radiations from degraded package shielding.

Inhalation

Inhalation of airborne RAM during the passage of the radioactive plume or from resuspended radionuclides following an environmental release may results in internal exposure of tissues or organs. The dose is assessed by multiplication of the volumetric radionuclide concentration at the location with the breathing rate of the individual and an appropriate dose conversion coefficient. It is important to recognise that the respirable fraction is linked to the aerosol particle size and to the physical and chemical nature of the RAM released. It is widely accepted that an aerosolized material is respirable if the medium aerodynamic diameter (AMAD) is less than 10–20 µm. Moreover, the value of the dose conversion coefficients used in the calculation depend of the size of the AMAD (1 µm or 5 µm for example) and the physical and chemical form of the radionuclide which determine the absorption behaviour from the lungs (fast, moderate, slow).

Ingestion

This is an internal exposure caused by consumption of contaminated foodstuff and water. This pathway is linked to the calculation of specific activity concentrations in various foodstuffs, as a function of time (see groundshine). The activity concentration of foodstuff and water can be a relevant indicator to compare with the values proposed by ICRP 63 or IAEA Safety Series No. 109 for judging the necessity of agricultural countermeasures (ban of foodstuffs). The ingestion dose is obtained by multiplying the specific activity in food with the human consumption rates and the relevant dose conversion coefficient.

The dose conversion coefficients for inhalation and ingestion have recently been revised. IAEA Safety Series No. 115 [55] provides the most up to date values of dose coefficients for workers and members of the public of various age groups. If the user does not have at his disposal precise information on the radionuclides released (size, chemical form), it would be better to select the most restrictive values for the dose conversion coefficients.

III-5. Presentation of results

As in the case of incident-free transport, consideration should be given to both the purpose of the analysis and the intended audience. Radiological consequences should be put in perspective by a discussion of the magnitude of dose and the associated frequency of occurrence.

REFERENCES

[1] OAK RIDGE NATIONAL LABORATORY, ORIGEN: Isotope Generation and Depletion Code System Matrix Exponential Method, RSIC CODE PACKAGE CCC-217, Oak Ridge Natl Lab., Oak Ridge, TN.

[2] ERICSSON, A.M., JÄRNRY, C., INTERTRAN2 Transportation Risk Assessment Package User's Guide, AMC Konsult AB, Stockholm (2000).

[3] NEUHAUSER, K.S., KANIPE, F.L., RADTRAN 4: Volume 2; Technical Manual, SAND89-2370, Sandia National Laboratories, Albuquerque, NM (1993).

[4] PAGES, P., RANCILLAC, F., TRANSAT User Manual, CEPN, Fontenay-aux-Roses (1992).

[5] WYSS, G.D., JORGENSEN, K.H., A User's Guide to LHS: Sandia's Latin Hypercube Sampling Software, SAND98-0210, Sandia National Laboratories, Albuquerque, NM (1998).

[6] NEUHAUSER, K.S., KANIPE, F.L., RADTRAN 4: Volume 3; User Guide, SAND89-2370, Sandia National Laboratories, Albuquerque, NM (1993).

[7] EVANS, J.S., et al., Health Effects Model for Nuclear Power Plant Accident Consequence Analysis, NUREG/CR-4214, Nuclear Regulatory Commission, Washington, DC (1985).

[8] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Pergamon Press, Oxford (1991).

[9] US DEPARTMENT OF ENERGY, Environmental Assessment of Urgent-Relief Acceptance of Foreign Research Reactor Spent Nuclear Fuel, DOE/EA-0912, USDOE, Washington, DC (1994).

[10] NEUHAUSER, K.S., MILLS, G.S., Urban risks of truck transport of radioactive material, Risk Analysis **18**(6) (1998) 781–785.

[11] JOHNSON, P.E., MICHELHAUGH, R.D., Transportation Routing Analysis Geographic Information System (WebTRAGIS) User's Manual, ORNL/TM-2000/86, Oak Ridge National Laboratory, Oak Ridge, TN (2000).

[12] MADSEN, M.M., et al., "Truck transportation of radioactive materials", Proc. 7th Int. Conf. on the Packaging and Transportation of Radioactive Materials (PATRAM'83), Vol. I, New Orleans, LA (1986) p. 724.

[13] GRIEGO, N.R., et al., Investigation of RADTRAN Stop Model Input Parameters for Truck Stops, Waste Management '96, Tucson, AZ (1996).

[14] GOGOLIN, B., et al., "Drop-tests program with the German 'POLLUX' cask for final disposal of spent fuel", Proc. 11th Int. Conf. on the Packaging and Transportation of Radioactive Materials (PATRAM'95), Las Vegas, NV (1995).

[15] LUDWIGSEN, J.S., AMMERMAN, D.J., "Analytical determination of package response to severe impacts", Proc. 11th Int. Conf. on the Packaging and Transportation of Radioactive Materials (PATRAM'95), Las Vegas, NV (1995).

[16] LAWRENCE, G., GAFFKA, A.P., "Design and approval testing of the D3705 Type-B and D3726 Type-A 'nested' containers", Proc. 12th Int. Conf. on the Packaging and Transportation of Radioactive Materials (PATRAM'98), Paris (1998).

[17] HEYWOOD, J.D., SCHWARZ, G., FETT, H.J., Analysis of Rail Accident Frequencies and Severities for the Assessment of Radioactive Material Transport Risk, European Commission Research Contract DG XVII 4.1020/D/97-005, AEA Technology, Risley (1999).

[18] HEALTH AND SAFETY EXECUTIVE, The Tolerability of Risk from Nuclear Power Stations, HSMO, London (1992).

[19] US NUCLEAR REGULATORY COMMISSION, USNRC, Final Environmental Statement on the Transportation of Radioactive Material by Air and other Modes, NUREG-0170 (1977).

[20] MONETTE, F., et al., "Transportation radiological risk assessment for the Programmatic Environmental Impact Statement: An overview of methodologies, assumptions and input parameters", Waste Management Conference (WM'94), Tucson, AZ (1994).

[21] KEMPE, T.F., GRONDIN, L., "Radiological impact on the public of transportation for the Canadian Nuclear Fuel Waste Management Program", Proc. PATRAM '89 (1989).

[22] LANGE, F., GRÜNDLER, D., SCHWARZ, G., Transportstudie Konrad: Sicherheitsanalyse des Transports radioaktiver Abfälle zum Endlager Konrad (in German), Gesellschaft für Reaktorsicherheit (GRS) mbH, Cologne GRS-84 (1991).

[23] LANGE, F., GRÜNDLER, D., SCHWARZ, G., Transport Study: Safety Analysis of the Transport of Waste to the Konrad Waste Disposal Site, RAMTRANS Special Issue Vol. 3, No. 4 Nuclear Technology Publishing, Ashford (1992).

[24] DUTTON, T., MILLOY, C., "The application of probabilistic assessment methods in irradiated fuel transport", PSA/PRA for the Nuclear Industry (Conference Documentation), 1/2 (1993).

[25] APPLETON, P.R., "Probabilistic safety assessment for the transport of radioactive waste to an UK repository at Sellafield", Developments in the Transport of Radioactive Waste, IAEA-TECDOC-802, Vienna (1995).

[26] DENNIS, A.W., et al., Severities of Transportation Accidents Involving Large Packages, Sandia National Laboratories, SAND77-0001 Albuquerque, NM (1977).

[27] FISCHER, L.E., et al., Shipping Container Response to Severe Highway and Railway Accident Conditions, NUREG/CR-4829 (Vols 1 and 2), Sandia National Laboratories, Albuquerque, NM (1987).

[28] FETT, H.J., LANGE, F., Frequency of Railway Accidents on the German Federal Railways (Deutsche Bundesbahn DB) Network: Goods Traffic and Shunting Operations (Marshalling Yard Braunschweig), Gesellschaft für Reaktorsicherheit (GRS) mbH, GRS-85, Cologne (1992).

[29] MARTZ, H.F., WALLER, R.A., Bayesian Reliability Analysis, Krieger Publishing Company, Malabar, FL (1982).

[30] SHAEFFER, D.L., A Model Evaluation Methodology Applicable to Environmental Assessment Models, ORNL-5507 Oak Ridge National Laboratory, Oak Ridge, TN (1979).

[31] GESELLSCHAFT FÜR UMWELTÜBERWACHUNG mbH, GUW, "General aspects of accuracy in dose calculation (Working group report)", Accuracy in Dose Calculations for Radionuclides Released to the Environment (Proc. Workshop, Aachen) (LINDACKERS, K.H., BONNENBERG, H., Eds), GUW Gesellschaft für Umweltüberwachung mbH, Aldenhoven (1980).

[32] INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluating the Reliability of Predictions Made Using Environmental Transfer Models, Safety Series No. 100, IAEA, Vienna (1989).

[33] NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENT, Uncertainty in NCRP screening models relating to atmospheric transport, deposition and uptake by humans, NCRP Commentary No. 8, Bethesda, MD (1993).

[34] MORGAN, M.G., HENRION, M., Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis, Cambridge University Press, Cambridge (1990).

[35] COVELLO, V.T., et al. (Eds), Uncertainty in Risk Assessment, Risk Management, and Decision Making, Plenum Press, New York (1987).
[36] BOHN, M.P., et al., Approaches to uncertainty analysis in probabilistic risk assessment, Sandia National Laboratories, SAND87-0871 RX (NUREG/CR-4836) Albuquerque, NM (1988).
[37] INTERNATIONAL ORGANIZATION FOR STANDARDISATION, Guide to the Expression of Uncertainty in Measurements, ISO/TAG 4/WG 3: 1992 First Edition, Geneva (1992).
[38] PAULA, H.M., et al., Analysis of uncertainties in interactive probabilistic safety analysis (PSA) models, Risk Analysis, Vol. **13** 2 (1993) 165.
[39] KLOOS, M., HOFER, E., SUSA, E., The PC version of the software system for uncertainty and sensitivity analysis of results from computer models, User's guide and tutorial, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Cologne (1998).
[40] MISHIMA, J., SCWENDIMAN, L.C., Some Experimental Measurements of Airborne Uranium (Representing Plutonium) in Transportation Accidents, BNWL-1732 (1973).
[41] MISHIMA, L., Potential Aerosol Generation Mechanism from Damaged Shipping Packages, BNWL-SA-5742, (1976).
[42] SPRUNG, J.L., et al., Reexamination of Spent Fuel Shipment Risk Estimates, NUREG/CR-6672 Sandia National Laboratories, Albuquerque, NM (2000).
[43] SUTTER, S.L., et al., Aerosols Generated by Free-fall Spills of Powders and Solutions in Static Air, PNL-3786, Rep. NUREG/CR-2139, Battelle Pacific Northwest Laboratory, Richland, WA (1981).
[44] FETT, H.J., LANGE, F., LOMBARD, J., RAFFESTIN, D., RECULEAU, J.Y., SCHNEIDER, T., SCHWARZ, G., Transport Risk Assessment Study for Reprocessing Waste Materials to be Returned from France to Germany. GRS-141 Report, jointly prepared by IPSN/GRS/CEPN (1998).
[45] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, Publication 26, Annals of the ICRP 1(3), Pergamon Press, Oxford (1977).
[46] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Dose Coefficients for Intakes of Radionuclides by Workers, ICRP Publication 68, Annals of the ICRP 24(4), Pergamon Press, Oxford.
[47] EPA Office of Research and Development "Exposure Factors Handbook", EPA 600 P95/002Ba, SAB Review Draft (1996).
[48] CASHWELL, J.W., ERICKSON, C.E., KERN, E.A., TRANSNET: Online Transportion Risk Analysis for Public Use, SAND88-0568, Sandia National Laboratories, Albuquerque, NM (1988).
[49] HARTUNG, J., ELPELT, B., KLÖSENER, K.H., Statistik, Lehr- und Handbuch der angewandten Statistik, Chapter IV, Section 3.2, ISBN 3-486-24984-3 (1999).
[50] INTERNATIONAL ATOMIC ENERGY AGENCY, Occupational Radiation Protection, Safety Guide, Safety Standards Series No. RS-G-1.1, IAEA, Vienna (1999).
[51] INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of Occupational Exposure Due to Intakes of Radionuclides, Safety Guide, Safety Standards Series No. RS-G-1.2, IAEA, Vienna (1999).
[52] INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of Occupational Exposure Due to External Sources of Radiation, Safety Guide, Safety Standards Series No. RS-G-1.3, IAEA, Vienna (1999).

[53] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Principles for Intervention for Protection of the Public in a Radiological Emergency. ICRP Publication 63, Pergamon Press, Oxford (1991).
[54] INTERNATIONAL ATOMIC ENERGY AGENCY, Intervention Criteria in a Nuclear or Radiation Emergency, Safety Series No. 109, IAEA, Vienna (1994).
[55] INTERNATIONAL ATOMIC ENERGY AGENCY, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources: Safety Series No. 115, IAEA, Vienna (1996).

CONTRIBUTORS TO DRAFTING AND REVIEW

Armingaud, F.	Institut de Protection et de Sûreté Nucléaire, France
Bernard-Bruls, X.	International Atomic Energy Agency
Blalock, L.	International Atomic Energy Agency
Blenkin, J.	AEA Technology Consulting, UK
Ericsson, A.M.	AMC Konsult AB, Sweden
Fett, H.-J.	Gesellschaft für Anlagen- und Reaktorsicherheit, Germany
Järny, C.	AMC Konsult AB, Sweden
Juanola, M.	Institut de Protection et de Sûreté Nucléaire, France
Kanipe, F.	Sandia National Laboratories, United States of America
Kapoor, A.	US Department of Energy, United States of America
Kempe, T.	Ontario Hydro, Canada
Lange, F.	Gesellschaft für Anlagen- und Reaktorsicherheit, Germany
Mitake, S.	Institute of Nuclear Safety, Japan
Nobe, J.	Mitsubishi Research Institute, Japan
Nandakumar, A.	Bhabha Atomic Research Center, India
Neuhauser, S.	Sandia National Laboratories, USA
Raffestin, D.	CEPN, France
Schwarz, G.	Gesellschaft für Anlagen- und Reaktorsicherheit, Germany
Sprung, J.	Sandia National Laboratories, United States of America
Vieru, G.	Institute for Nuclear Research, Romania
Wang, J.	China Institute for Radiation Protection, China
Weiner, R.	Sandia National Laboratories, United States of America
Wangler, M.	US Department of Energy, United States of America
Wilkinson, H.	AEA Technology Consulting, United Kingdom

Research Co-ordination Meetings
Vienna, Austria: 8–12 July 1996, 2–6 November 1998,
29 November – 3 December 1999

Consultant Service Meetings
Vienna, Austria: 31 July – 4 August 2000, 7–11 August 2000