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CENTRE D'ETUDE SUR
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DANS LE DOMAINE NUCLEAIRE

Gesellschaft für Anlagen-
und Reaktorsicherheit
(GRS) mbH

Transport Risk Assessment Study for Reprocessing Waste Materials to be Returned from France to Germany

Final Report

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I. Preface and Acknowledgements

The transport risk assessment study presented in this report is a collaborative effort of the Institut de Protection et de Sûreté Nucléaire (IPSN), France, the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Germany, and the Centre d'étude sur l'Evaluation de la Protection dans le domaine Nucléaire (CEPN), France.

The study has been conducted on behalf of the Institut de Protection et de Sûreté Nucléaire (IPSN), France, the Federal Ministry of Environment, Nature Protection, and Nuclear Safety (BMU), Germany, and the Directorate-General for Environment, Nuclear Safety, and Civil Protection (XI-A-I) of the European Commission.

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II. Executive Summary

A transport risk assessment study has been completed on behalf of the Institut de Protection et de Sûreté Nucléaire (IPSN), France, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Germany, and the Directorate-General for Environment, Nuclear Safety and Civil Protection (XI-A-I) of the European Commission with the objective to provide an overview on the type, quantity, and characteristics of radioactive waste resulting from reprocessing of German spent nuclear fuel at Cogema's La Hague Reprocessing Plant and to quantify the radiological risks associated with the transport of this radioactive waste from France to Germany.

The radiological risks entailed in the transport and handling operations of the reprocessing waste materials considered in the study include the following:

- Radiation exposure of the public and transport personnel from routine (incident-free) transportation of radioactive material (expected exposure).
- Transport incidents and accidents resulting in radiation exposure of the population and/or contamination of the environment and the likelihood of occurrence of such consequences (potential exposure).

Type and Quantity of Waste Return Shipments:

Overall four kinds of radioactive waste arising from reprocessing of German spent nuclear fuel at the La Hague Reprocessing Plant have been identified and will be returned to the country of origin at due time: (1) Vitrified high-level radioactive waste, (2) hulls and end caps, (3) bituminous waste (immobilised sludges etc.), and (4) intermediate-level and low-level solid technological waste. This transport risk assessment study, however, concerns transportation of waste over a time period of about 7 - 8 years from now which has been generated from reprocessing of 4650 Mg(HM) of spent nuclear fuel within the first 10-year reprocessing contract (1985-1995) between Cogema and its German customers (utilities).

Based on current planning the types of waste expected to be returned from France within the studied period, i.e. from approx. 1995 - 2003, for interim storage at the Interim Storage Facility Gorleben (TBL) include:

- Vitrified high-level radioactive waste (1995 - 2003)

- Intermediate-level bituminous waste (1997 - 2003)

The other radioactive waste streams, i.e. hulls/end caps and solid technological wastes, are according to currently available information considered to be suitable for supercompaction and will most likely not be returned within the studied period and are, thus, not covered by this study.

The vitrified high-level radioactive waste (HAW) contains the bulk of fission products and transuranic elements - except uranium and plutonium - of the spent nuclear fuel immobilised in a solid glass matrix and encapsulated in a 175 l stainless steel canister. The canister radioactivity inventory is about 30 000 TBq (nominal), primarily Beta/Gamma-emitting radionuclides. The 175 l stainless steel canisters will be shipped in accordance with the relevant Transport Regulations in heavy shielded casks known as CASTOR HAW 20/28 CG and TS 28 V. Approximately 2 800 glass canisters are expected to be returned in about 120 casks leading to an average of 15 shipments per year over a time period of about 8 years. The conservatively estimated average 1m-dose rate of the casks is approximately 0.11 mSv/h for the CASTOR HAW 20/28 CG and slightly lower for the TS 28 V.

The low- and intermediate-level radioactive liquid plant effluents are generally purified by coprecipitation or evaporation and the resulting sludges are ultimately immobilised in bitumen and filled into 225 l stainless steel drums. Lower radionuclide inventories are present in bituminous waste materials with a nominal total activity of about 2.2 TBq per drum (99% Beta/Gamma-emitting radionuclides). The steel drums will be shipped in a cubical cast iron Container VII having a capacity of 5 steel drums. A total volume of 3 600 drums has conservatively been assumed to be returned from France. This corresponds on average to about 50 railcars shipments per year (assuming a shipping period of 7 years (1997 - 2003) and a loading capacity of 2 transport containers per wagon). The container dose rate has conservatively been estimated to be about 0.2 mSv/h at 1 m from the container surface.

Routine transportation:

The first part of the report concerns the radiological consequences from routine (incident-free) transportation with the following results:

As far as the detailed schedule for the shipment is not yet fixed, it has been assumed that during the period from 1995 - 2003 an average of about 115 waste transport casks or containers per year will be shipped from France to Germany. This corresponds to a volume of about 65 railway wagons per year to be shipped.

The primary mode of transport for all waste products is by rail with regular freight trains. Road transportation will be limited to a small fraction of the journey between the La Hague Reprocessing Plant and the Valognes loading terminal (road-rail transfer) and, similarly, between the Dannenberg loading terminal (rail-road transfer) and the Interim Storage Facility Gorleben. It is generally assumed that each waste consignment is limited to a maximum of 3 waste wagons per train, with an average of 2 railcars. The journey covers a distance of about 1400 km (almost equally distributed in length between France and Germany) along a route with an average population density of about 358 persons/km².

Using the computer code INTERTRAN II (IAEA reference code) for the assessment of radiation exposure, the collective effective dose has been estimated to about 0.02 man-Sv/yr for the rail-crew, approximately 0.01 man-Sv/yr for the personnel at each of the loading terminals at Valognes and Dannenberg, and 0.03 man-Sv/yr for the general population along the transport route (performing the dose calculation over a distance of 800 m on each side of the transport path).

The conservatively predicted individual doses to members of the public and the transport personnel (critical group individuals) from routine transportation are up to about:

- 0.01 mSv/yr for residents/by-passers living in close proximity (5-10 m) to the transport path and 0.02 mSv/yr for workers of a scrap metal yard located close to the siding tracks of the Ehrang (Trier) railyard;
- 0.03 mSv/yr for residents (i.e. critical group) at the Valognes loading terminal and even lower values at the loading terminal of Dannenberg;
- 0.03 - 0.2 mSv/yr for railway personnel, i.e. train driver, shunters, escorts, and inspectors;
- 0.7 - 1.7 mSv/yr for handlers, crane operators, and health physicists of the Dannenberg and Valognes loading terminal.

The annual collective dose estimates attributable to the transportation of reprocessing waste material are clearly below the occupational and public radiation exposure predicted in previous studies for waste transports to the Centre de l'Aube (0.48 man-Sv/yr), France, and the designated Konrad Repository (ca. 0.3 man-Sv/yr) in Germany.

The conservatively predicted individual doses for members (critical group) of the public represent only very small fractions of the applicable dose limit of 1 mSv/yr of the IAEA Transport Regulations or the dose limit recommended by the International Commission on Radiological Protection (ICRP-Publ. 60). Moreover, the doses are well within the range of variation of the natural radiation exposure in member states of the European Union, which is generally considered as an acceptable level of exposure. For personnel involved in the transport operations, the predicted individual doses to the critical groups of workers are well below the applicable dose limits of the ICRP and the IAEA Transport Regulations and rarely exceed the dose limit of 1 mSv/yr for members of the public.

Transport or Handling Accidents:

Accidents and incidents associated with the transportation and handling of return shipments of radioactive reprocessing waste from France to Germany pose a potential risk to man and his environment. There are several kinds of operations contributing to the overall radiation risk: rail transport, road transport, marshalling yard and rail-road transfer operations. However, it has been concluded from the information available, that transportation by rail is predominant and, thus, emphasis has been placed on quantifying the radiological risks related to waste transportation by rail.

The risks associated with transport accidents and incidents have been quantified in terms of the radiological consequences of potential railway accidents and the expected probability of such accidental events for the given volume of waste to be shipped from the La Hague site to the Interim Storage Facility Gorleben (Germany). The probabilistic method adopted for the study involves a five-step analysis approach: (1) Characterisation of the type and quantity of waste shipments, (2) analysis of the type and probability of occurrence of railway accidents, (3) assessment of the structural system response of the transport packagings and the waste product to specific impact load conditions, (4) estimation of the radioactive release and frequency of occurrence taking into account the broad range of shipping patterns and accident severities, and (5) assessment of the potential radiological consequences for the spectrum of weather conditions encountered along the transport route.

The transport container activity inventory was generally assumed to have nominal characteristics, but for 10 percent of the transport containers upper (guaranteed) limit values were conservatively adopted for the study. Nine accident severity categories including three mechanical (non-fire) and six combined mechanical-thermal accident environments have been defined for rail transportation to represent the impact load conditions typically encountered in railway accidents on the basis of an analysis of a 10-year historical record of freight train accidents provided by German Railways. The structural waste package response and subsequent fractional release have been evaluated on the basis of experimental information including drop test experiments and engineering analysis taking into account the physico-chemical behaviour of the (vitrified and bituminous) waste product under mechanical and thermal impact loads. Based on this information the broad range of conceivable shipping patterns and mechanical and thermal load conditions potentially experienced by a waste package have been determined using a Monte Carlo simulation approach. As much as 1000 load-shipment configurations for each severity category have been simulated for the study each repetition resulting in a radionuclide-specific source term for the simulated accidental sequence. Subsequently, the numerous different source terms have been consolidated into 10 representative **release categories** including 5 release categories representing non-fire accident environments and 5 release categories representing combined mechanical-thermal accidental sequences.

Potential radiological consequences, expressed in terms of the 50-year committed individual dose of the population (critical group) and the 25 km-radius collective dose under the condition of **absent mitigative actions**, have been calculated using the probabilistic accident consequence code COSYMA developed under the auspices of the European Commission. The relevant exposure pathways considered in the estimation of the dose include: cloudshine, groundshine, inhalation, and ingestion. The results of the COSYMA code are generally presented as cumulative complementary frequency distributions (CCFD) and show the frequency of a specified outcome, e.g. the dose of critical group individuals at a given distance (250m, 1150m, and 6250m) from the scene of the accident or the 25 km-radius collective dose.

The risk assessment results refer to the total volume of waste transports of about 120 railcars with vitrified waste and 360 railcars each carrying two transport containers with bituminous waste which are shipped in regular (non-dedicated) freight trains from Valognes near Cap de La Hague to Dannenberg near Gorleben over a distance of 1414 km within the projected time period from 1995 to 2003. The assessment results are presented as cumulative complementary frequency distributions (CCFD) of the 50 year-effective dose below the plume centerline at various distances versus the expected frequency of occurrence that a given dose may be exceeded. The potential individual 50 year-dose has been calculated for a hypothetical individual being permanently located at the specified receptor point during the passage of the radioactive cloud (inhalation, cloudshine) and from exposure to ground deposits and the intake of contaminated foodstuff under absent mitigative actions. The following conclusions can be drawn from the accident analysis:

- For the total volume of vitrified and bituminous waste transports to be shipped within the time period from 1995 - 2003, the estimated probability of an accident resulting in some damage to a waste wagon and its load is about 0.016 (i.e. a chance of 1 in 64 that at least one waste wagon experiences an accident somewhere on the 1400 km shipping route during the shipping campaign period of about 7 - 8 years).

- The waste transport casks and containers are all Type B packages which have to fulfil stringent test requirements and which have, as far as the casks transporting vitrified waste are concerned, substantial safety margins above the regulatory requirements. Based on a conservative approach it has been estimated for the total volume of transports of vitrified and bituminous wastes that in 1 out of 16 railway accidents where a waste wagon is affected the impact forces onto the cask/containers may be severe enough to result in a release of radioactive material. Consequently, the chance for an accidental release somewhere along the shipping route is about 1 in 1010 for all waste shipments.

- In most cases, however, the accidental radioactive releases and associated consequences would be quite small. Only in very few of all accidents the potential radiological consequences, expressed as 50-year committed individual dose, could approach values of 50 mSv close to the accident location in down-wind direction if no counter-measures are assumed at all.

- For the total volume of waste transports the probability of occurrence of a release of radioactive matter with potential radiological consequences at a down-wind distance of 250 m approaching 50 mSv is below 1 in 10 millions.

Potential radiological consequences decline fast with distance from the accident site and therefore accidents with release of radioactive matter would have quite localised consequences.

- The radiological transport risks are dominated by accidents involving transport containers with bituminous waste. Even with the quite conservative approach of the risk analysis rail accidents which could result in some release from casks with vitrified waste are much rarer and releases in those cases much lower than for bituminous waste.

The results of the risk assessment are broadly consistent with previous transport risk assessment studies, which have, for example, been conducted for projected waste transports to the Centre de l'Aube, France, or the designated Konrad Waste Repository in Germany if differences in the waste volume and other characteristic factors are appropriately taken into account.

Concluding Statement:

The results of the analysis of the causes, consequences, and associated probabilities indicate that the potential radiological impact associated with the return shipments of radioactive waste within the next 7 - 8 years from France to Germany do not pose a significant risk to man and his environment.

The results reflect the appropriate level of protection and safety provided by and embodied in the national, international and IAEA Transport Regulations, the Waste Acceptance Criteria of the Interim Storage Facility, and the anticipated shipping practices for reprocessing waste materials.

III. Table of Contents

1 Introduction

Twenty nuclear power units having a capacity of about 22.4 GW(e) are currently operational in the Federal Republic of Germany. The fraction of nuclear generated electricity provided to the public power supply system was in the range of 30 - 35 percent over the recent years.

In the late 70's and early 80's the utilities operating the nuclear power stations opted to close the back end of the nuclear fuel cycle by reprocessing of the spent light water reactor fuel. Reprocessing contracts were signed accordingly with Cogema in France and British Nuclear Fuels Limited (BNFL) in the United Kingdom.

The quantity of spent fuel of German origin being processed under the contracts signed with Cogema, France, totals to about 6000 t (HM). The first 10-year contract covers a quantity of about 4650 t (HM) to be reprocessed within the time period from 1985 - 1995 while a second 10-year contract with Cogema relates to reprocessing of spent fuel from 1995 - 2005.

The contracts signed with Cogema (and BNFL) generally require the return of the radioactive waste resulting from reprocessing of foreign fuel to the country of origin at due time. Current planning[1] calls for return of the reprocessing related radioactive waste generated within the first 10-year contract beginning in 1995 and being completed not later than 2003 /JAN 91, JAN 92/. This approach is consistent with the French legislation which mandates the complete return of the radioactive waste resulting from reprocessing of foreign fuel from the French territory. Nevertheless, a new process will be implemented within the next few years at the Cogema reprocessing plant, it consists of supercompaction of hulls and end caps and technological waste. This procedure will delay the return of the relevant waste for about 10 years.

The safety of the transboundary transports of packaged waste materials from France to Germany is of major importance to the reprocessors, utilities, and governmental bodies since it takes place in the public domain and may affect the public. The transport of the radioactive waste material has to be conducted in flasks or containers designed and approved in accordance with the national and international Transport Regulations and must conform to the safety requirements specified in:

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[1] The analysis and results presented in this report reflect the waste mangement strategy and developments as of middle 1995.

- Council Directive No. 92/3/EURATOM of 3 February 1992 on the supervision and control of shipments of radioactive waste between Member States and into and out of the Community and, for the shipments carried out before 1.1.1994.

- Council Regulation (EURATOM) No. 1493/93 of 8 June 1993 on the shipments of radioactive materials between Member States.

To give adequate assurance that the radiological impact attributable to the transboundary transports of radioactive waste to be returned from France to Germany is within acceptable levels and that the safety requirements of the relevant regulations can be met for shipments of packaged waste materials, a transport risk analysis study has been conducted on behalf of the Institut de Protection et de Sûreté Nucléaire (IPSN), France, the Federal Ministry of Environment, Nature Protection and Nuclear Safety (BMU), Germany, and the Directorate-General for Environment, Nuclear Safety and Civil Protection, (XI-A-I) of the European Commission.

The specific purpose of the study is to quantify the **expected and potential exposure of workers and members of the public** that may be associated with the transport of radioactive waste materials from France to Germany with the earliest shipments expected in 1995. Not included in the study are shipments of spent fuel from Germany to France and return transports of uranium and plutonium recovered from the spent fuel.

The radiation risks entailed in transport and handling operations of reprocessing waste materials are twofold:

- Expected radiation exposure of the public and the transport personnel from routine (incident-free) transportation of radioactive material

- Potential exposures of man and his environment to radiation/contamination arising from transport incidents and accidents

The radioactive waste arising from reprocessing of spent fuel and being returned from France to Germany include a variety of waste types:

- Vitrified high-level radioactive waste

- Bituminous intermediate-level waste

- Cemented hulls and end caps
- Technological waste from different operational areas of the La Hague Reprocessing Plant (Zone 2/3, Zone 4)

The vitrified high-level radioactive waste (HAW) contains the bulk - up to 99 percent - of fission products and transuranic elements - except of uranium and plutonium - of the spent fuel which are incorporated into a solid glass matrix encapsulated in a 175 l stainless steel canister. The vitrified waste is heat-generating with a thermal power of up to 2 kW per canister at the time of transport.

The low- and medium-level radioactive liquid effluents produced at various stages of the chemical separation processes applied at the La Hague plant are purified by co-precipitation of the radioactive constituents or evaporation and the resulting sludges are currently immobilised in a bituminous matrix and poured into 225 l steel drums. The production of bituminous waste, however, will be discontinued in the near future due to modifications in chemical process design and complete recycling of liquid effluents /LED 94/.

The waste stream referred to as "hulls and end caps" comprises the structural metallic material of the fuel bundle such as the fuel cladding, spacing elements, nozzles, end fittings etc. and can contain up to 3 percent of the spent fuel activity inventory. The metallic waste material is currently cemented into 1500 l steel drums and classified as intermediate-level radioactive waste (ILW).

The technological waste stream includes a broad range of solid low-level and intermediate-level contaminated items such as components, tools, filters, protective clothing, paper, plastic sheeting, laboratory bins etc. from plant operations, repair and maintenance. Depending on the operational area two kinds of waste are distinguished: low-level technological waste (LLW) from Zone 2/3 and intermediate-level alpha-bearing technological waste (ILW) from Zone 4. The solid technological waste is collected and encapsulated by cementation into fibre concrete containers (CBF).

On account of the implementation of supercompaction, these last two categories (hulls and end caps, technological waste) will not be considered in the study.

Some of the previously mentioned primary waste packagings - particularly those for LLW - are designed to conform directly to the national and international transport regulations while the primary packagings for HAW and ILW require additional radiation shielding, containment and protection for the purposes of transport.

This report provides an overview on the information available related to the type and volume of waste material being shipped, the packaging and transport system and the mode and conditions of transport. The first part of this report is concerned with the assessment of the radiation exposure from routine (incident-free) transportation of radioactive waste generated at Cogema's reprocessing plant in La Hague within the first 10-year contract (1985 - 1995) while the second part deals with the assessment of the potential radiological consequences of potential transport and handling accidents and the expected frequency of occurrence of such events.

For the purpose of this study it has been assumed that all waste types to be returned from France will be shipped to and stored on the Interim Storage Facility site at Gorleben. We note, however, that some of the waste transport packages have not yet received final approval for interim storage at the Gorleben facility. Second, the total projected volume of reprocessing waste to be returned from France may exceed the storage capacity of the Gorleben facility. But these principal limitations have not been accounted for in this study for several reasons. One important aspect in mind is, that the operating licence of the Gorleben Facility is currently under review with the objective to broaden the range of containers acceptable for storage and to enhance its storage capacity. But depending on the time required for granting a new licence contingency plans need to be developed including the provision of storage capacity at alternative sites. Such plans are currently under development.

A further important assumption has been made by adopting that the radioactive waste will be conditioned and packaged in multi-purpose containers meeting the safety requirements of the Transport Regulations, the interim storage facility, and - where relevant - of the final repository. This assumption is consistent with the waste management strategy pursued by the utilities in order to minimize any effort that may otherwise be required for potential reconditioning, repackaging, handling, and transportation of the radioactive waste. The multi-purpose capability of the transport containers greatly increases the operational flexibility of the utilities and is considered to be more cost effective.

The information and data used for the assessment of radiation exposures from routine transportation reflect the current status of procedures, decision processes and the waste management strategy in France and Germany up to middle 1995. Substantial progress has been made over recent years at the La Hague Reprocessing Plant by modifications in the process design and the implementation of stringent procedures in the waste management program to reduce the production of radioactive waste or to completely eliminate specific waste streams. Additional changes in procedures and the process design to further reduce the production of waste are expected to be effective in the near future. A notable example is the envisaged use of supercompaction for conditioning of the hulls and end caps and the technological waste. Because of the expected reduction of the types and volume of radioactive waste on the one hand and various pessimistic assumptions on the other hand the study results are believed to be reasonably conservative.

2 Description of the assessment method

The radiological risks attributable to the transportation of reprocessing waste products may be divided into two broad categories:

- Transport workers and members of the public may be exposed to ionizing radiation emanating from the waste packages during routine (incident-free) transportation.

- Potential transport and handling accidents which affect the package integrity resulting in increased package radiation levels and/or the release and subsequent dispersal of radioactive material in the environment.

2.1 Routine transportation

Radioactive material carried in transport containers or packages can cause radiation exposure of members of the public or the transport personnel while being handled at loading terminals and marshalling yards or being conveyed on public or publicly accessible transport routes to its destination. The radiation exposure is generally due to gamma-rays and/or neutrons penetrating through the container walls to persons residing in close proximity of the transport package such as railway personnel, truck drivers, or bystanders.

The magnitude of the external radiation exposure incurred from routine transportation depends on the intensity of the radiation field at the receptor location and the associated dose rate and the duration of exposure.

Radiation exposure received by internal exposure from incorporation of radionuclides into the human body needs not to be considered for routine transport operations due to the complete containment of the radioactive material by the packaging structures.

In this study radiation exposures will be examined and quantified for the population and transport personnel surrounding the transport paths of the waste materials in terms of:

- individual doses and

- collective doses.

Individual doses to member of the public and the transport personnel are important from the radiation protection point of view and serve the purpose of showing compliance with existing dose limits. In accordance with standard dose assessment practices doses to individuals from routine transportation will be considered who are specifically affected by the waste shipments as a result of their living habits or their occupational functions. This dose assessment approach is widely used for radiation protection purposes and referred to as critical group concept.

Doses to individuals other than critical group individuals can reasonably be expected to be lower, if not substantially lower, than the dose estimates for the critical group individuals.

The collective dose is used as a mean of expressing the overall radiological impact that is collectively incurred by the public and the transport personnel for the volume of waste shipments considered in the study.

The dose assessment approach applied within the study has been derived from several sources including the INTERTRAN II computer code which was derived from the RADTRAN 4 computer code /NEU 93/. INTERTRAN II is an internationally available computer program package developed and distributed by the International Atomic Energy Agency (IAEA) for calculation of collective doses to various population groups from routine transportation and potential accidents. The basic calculational approach for dose estimation used by the code has been adapted for estimation of doses to critical group individuals. This dose assessment approach generally represents packages as a point source and uses the external package dose rate at 1 m from the surface, a modifying shape factor which depends on the physical package dimension and the inverse square relationship for the estimation of doses at greater distances.

The site specific data required for the estimation of dose have been collected from site visits and other relevant sources and reflect the current stage of planning and present standard transport practices.

2.2 Transport and handling accidents

Transport and handling accidents may occur for a number of reasons and pose a risk to man and his environment. Particularly, individuals may eventually be exposed via a number of pathways to radiation from material that might be released into the environment during the accident. The magnitude of such a release and the related frequency of occurrence depend on a number of factors including the type and volume of waste being shipped and the severity of an accidental sequence.

Because the occurrence of an accident is statistical in nature, a probabilistic assessment method has been adopted for the study with the objective to quantify the potential environmental radiological consequences and the expected frequency of occurrence of such accidental sequences. The probabilistic assessment method conceptualized in Fig. 2.1 has been used in previous studies /LAN 92, FET 93/ and involves typically a five-step analysis approach:

- Description of the type, quantity and mode of transport
- Analysis of transport accidents and the associated mechanical and/or thermal impact load conditions and the expected frequency of occurrence for the mode of transport being considered
- Assessment of the system response of the packaging and waste product to specific accidental load conditions, e.g. impaction, fire etc., and the subsequent environmental release
- Estimation of the environmental release and frequency of occurrence considering the range of shipping patterns and accident severity's
- Assessment of the environmental radiological consequences for different meteorological conditions

The transport risk assessment method requires a complex modelling effort and is specifically designed to describe the broad range of shipping arrangements and credible transport and handling accidents including low-probability accidents with high consequences and higher-probability accidents having - if at all - low radiological consequences. Accident frequencies for the study have been derived from historical records of road and railway accidents or have been adopted from the general literature.

The radiological consequences can be measured in various ways, but the potential individual dose to members of the public and the collective dose to the population within the 25-km radius region surrounding the site of the accident will be used as the preferred means in quantifying the radiological consequences. The calculation of individual and collective doses employs models that quantify the population exposure following the dispersal of the released radioactive material into the environment under different environmental and meteorological conditions. The potential exposure pathways considered include external exposure to the passing cloud (cloudshine) and contaminated ground (groundshine) and internal exposure from inhalation of airborne contaminants and ingestion of contaminated food under absent mitigative actions, i.e. no clean-up activities or dose reduction measures were assumed for the dose calculations.

The (maximum) individual potential dose resulting from accident related releases is considered to be a useful quantity for the evaluation of the risks posed to individuals and may be compared directly to regulatory dose limits and other relevant standards as well as with the individual dose from natural background radiation.

The collective dose arising from potential transport and handling accidents is a measure of risk posed to the society as a whole. It can directly be compared to the collective dose from routine transportation (which has a probability of occurrence of unity), if the probability of occurrence of such accidental sequences is appropriately taken into account.

Modelling of complex accidental sequences and calculation of the resulting radiological consequences require a number of assumptions, simplifications and generalizations. Throughout the transport risk assessment study described herein such simplifying assumptions and generalizations have generally been made in a conservative manner. Therefore, the assessment results are believed to overestimate the accidental radiological consequences and related frequencies of occurrence of such sequences although the overall magnitude of conservatism in the assessment is difficult to quantify. Further details related to the assumptions and simplifications in the risk prediction models are given in the following chapters.

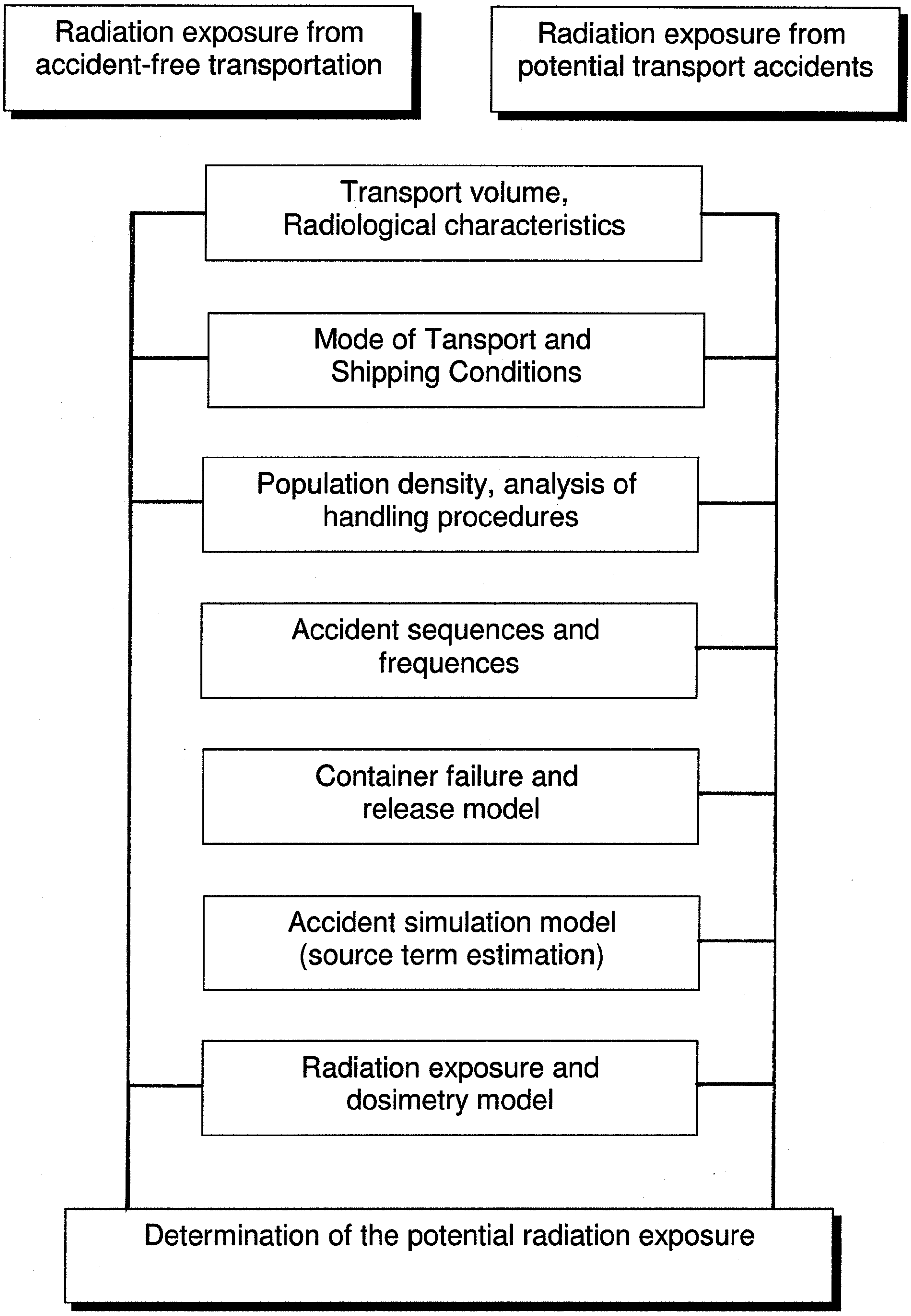

Figure 2.1: Schematic Representation of the Analysis Approach for Determining the Potential Radiological Consequences of Transports of Radioactive Waste

3 Type and quantity of radioactive materials to be transported

3.1 Data base

The German spent fuel to be reprocessed in the Cogema plant at La Hague represents about 6000 tons of uranium. Reprocessing of the spent fuel is planned within two time periods: the first contract period is from 1985 to 1995 while the second contract period refers to the time period from 1995 to 2005. The second contract period will not be considered in this study. The return of waste to the Interim Storage Facility, Gorleben (Germany), corresponding to reprocessing of 4650 t (HM) within the first 10-year contract period will be effective from 1995 to 2003 (except for technological waste and hulls and end caps which would be returned a decade later).

3.2 Waste characteristics and transport containers

As the transportation of reprocessing waste will begin in 1995, the primary packages are defined while some transport containers to be used are open to modification. Currently, two options could be adopted, from the one hand, the consignor point of view (Cogema), and from the other hand, the GNS Gesellschaft für Nuklear Service which is responsible for managing the waste return and interim storage and has to take account of storage constraints. The final decision will be taken within the next years for all streams. It is important to point out that the choice of the transport containers mainly affects the assessment of risks associated with accidental situations. In practice, the way of conditioning drums or canisters in a transport container does not significantly modify the result in terms of collective dose as far as accident free conditions of transport are concerned.

According to the information provided by GNS and Cogema principally four kinds of waste have to be considered: vitrified high-level waste, hulls/end caps, bituminous waste and technological waste. But a new process will be implemented within the next few years at the Cogema reprocessing plant, it consists of super-compaction of hulls and end caps and technological waste zone 2/3. The major changes affecting transportation will be a reduction of the volume, the need for adapted packages and a period of about 10 years of delay before returning the considered waste. On account of these considerations, the vitrified waste and the bituminous waste will only be considered in this study.

Vitrified waste: The vitrified waste will be transported in 175 litres (outer dimension) stainless steel canisters Ø 430 mm x 1335 mm with a wall thickness of 5 mm; each canister has a capacity of 150 l of glass. The canisters could be transported either in CASTOR HAW 20/28 CG or TS 28 V casks, their outer dimensions are respectively Ø 2.5 m x 5.9 m and Ø 2.4 m x 6,6 m with a gross weight of 112 tons. These two containers are broadly equivalent with respect to geometry and mechanical behaviour, slight differences exist concerning the internal cavity pressure, temperature and shielding arrangements. Depending on the thermal power or the dose rate of the glass canisters 20 or 28 canisters can be transported.

Bituminous waste: The bituminous waste shall be transported in 225 litre (outer volume) steel drums (Ø 586 mm x 883 mm, empty weight 20 kg), 210 litre inner volume, placed in a cubical cast iron Container VII (1.6 m x 2.0 m x 1.45 m, weight < 20 tons) with a capacity of 5 steel drums. The alternative Cogema solution could be container type RD33 with a capacity of 12 steel drums.

The waste packages and containers are described in Appendix I.

3.3 Amount and volume of waste transports

The quantity of reprocessing waste corresponds to a total of about 4650 tons of reprocessed uranium. The return of waste is planned from 1997 - 2003 except for vitrified waste for which transports are envisaged from 1995 - 2003.

The expected volumes of waste transported related to a reference and average year are as follows:

Vitrified waste: About 2800 canisters containing vitrified high-level waste are forecast. Thus, considering an average value of 24 (range 20 to 28) canisters per CASTOR HAW 20/28 CG or TS 28 V, approximately 120 casks could be transported in total. With one CASTOR HAW 20/28 CG or TS 28 V cask per railway wagon, on average 15 railcars will be shipped per year over a time period of about 8 years.

Bituminous waste: 1300 drums (225 l) will be produced by the UP3 plant of La Hague reprocessing plant, as the production of the UP2 plant is yet unknown, a total conservative number of 3600 drums containing bituminous waste from both plant units have been considered. This amount leads to 720 Containers VII and to an average value of

50 railway wagons per year (2 Containers VII per wagon) to be transported within a time period of about 7 years.

The information concerning the number of transports, the package types and the expected dose rate of the transport containers is summarised in the Table 3.1.

Table 3.1: Type and Volume of Reprocessing Waste Shipments to be returned from France to Germany

Waste Type	Primary Waste Package Type/ outer Volume (m)	Transport Container Type (m)	Projected Total Number of Primary Packages	Total Number of Transport Containers	Total Number of Railway Wagons	Average Annual Number of Railwagons/ (Shipp. Period)	Transport Container 1m-Dose Rate (mSv/h)
Vitrified Waste (HAW)	Canister 175 l Ø 0.43m x 1.34m 5 mm thickness	Castor HAW 20/28 CG Ø 2.5 m x 6.8 m 112 tons TS 28 V Ø 2.4 m x 6.8 m 112 tons	2 800	120 20 or 28 canisters per container (avg. 24)	120 1 Castor HAW or TS 28 V per wagon	15 (8 years)	0.11 (avg.)
Bituminous Waste	225 l drum Ø 0.586m x 0.883m 20 kg (empty)	Container VII 1.6m x 2m x 1.45m Cast Iron (20 t)	3 600	720 5 drums per Container	360 2 Container VII per wagon	50 (7 years)	0.2 (max.)

4 Radiological characteristics of the reprocessing waste material and transport containers

The radiological characteristics of the waste material and containers used for transport and interim storage are an essential element for the assessment of the radiation exposures from routine transportation and radiation risks associated with potential transport and handling accidents. Several sources have been exploited to collect and compile the relevant information for the study purpose including material and data bases provided by the waste producer, consignor and potential carrier. This chapter gives a summary of currently available information with respect to the type and quantity of radionuclides being present in the various waste streams and the external radiation dose rate of the transport and storage containers for reprocessing waste materials. The given information reflects the chemical process design at the La Hague plant (UP2, UP3) and the current stage of planning of transport and storage operations in returning the radioactive waste from France to Germany.

4.1 Sources of information

The radioactive waste materials resulting from reprocessing of spent fuel and requiring transportation to the country of origin are specified in the "Waste Specifications" by Cogema, e.g. /COG 86, COG 91/, in terms of nominal (estimated average) and guaranteed (maximum) parameter values. The information provided in these documents include the physico-chemical characteristics of the waste material, the type and description of the primary packagings enclosing the waste material, the package activity inventory, the radionuclide composition, package dose rate etc. For vitrified waste, additional information has been derived from the Transnucléaire Safety Analysis Report.

Nominal characteristics of components and waste material are based on a variety of assumptions with respect to the spent fuel to be reprocessed (e.g. the average burn-up rate, the cooling time until reprocessing or conditioning, the initial enrichment) and reflect the past operational experience and the chemical process design at the La Hague plant (UP2, UP3). The spent fuel reprocessed within the contractual period, however, differs generally to some extent from nominal spent fuel conditions. Consequently, the quantity and composition of waste may differ from the nominal values but will remain within the range of guaranteed parameter conditions which are given in the

Cogema Specifications. For the purpose of the study the guaranteed parameter values have been widely used for the assessment of the radiation risk as a conservative approach, unless other specific information was available.

In addition, relevant information has been acquired from organisations in France and Germany with responsibilities for loading, packaging, shipping, and interim storage of the waste material. The previously mentioned sources of information form - along with the relevant regulatory requirements - the principal basis of information and have been examined for the purpose of the transport risk assessment study.

4.2 Radioactive material and packaging regulations

The safety requirements applicable to the radioactive materials and packagings for shipment of reprocessing waste materials on public or publicly accessible transport routes and interim storage are regulated in the:

- National and international Transport Regulations, e.g. RID, ADR
- Acceptance Criteria of the Interim Cask Storage Facility, e.g. TBL-Gorleben /BLG 87/
- Preliminary Waste Acceptance Criteria of the Konrad Repository /BFS 93/

The national and international transport regulations are based on the IAEA-Transport Regulations with the latest version being issued in 1990 /IAE 90/.

Among the safety requirements for packages specified in the IAEA-Transport Regulations are the following:

- radioactive contents limits for different package types
- maximum permissible external radiation levels for the package and conveyance
- maximum permissible external package surface contamination levels
- limits on leakage of radioactivity for Type B packages for routine transport conditions
- requirements for retention of shielding, heat dissipation, and containment of radioactive material in accident conditions

Vitrified high-level waste: The radiation levels of casks for transport and storage of vitrified waste are controlled by the safety requirements of the Interim Storage Facility (TBL), Gorleben, where the following limits apply to the radiation level at the external surface of the cask:

	Cask Surface Dose Rate Limits for the Interim Storage Facility (TBL) (mSv/h)
Neutrons *)	0.1
Gamma rays	0.1
Total	0.2

*) Based on ICRP Publ. No. 26

At the external flask surface - excluding the lid and bottom - the dose rate limits are defined and used in terms of the average surface dose rate which is represented by the mean value of the measured dose rate at prescribed locations on the external flask surface. Thus, the given dose rate limits may be locally exceeded. For the lid and bottom the dose rate limits are upper limits which shall not be exceeded at any location.

We note that the limits controlling the radiation level of transport containers for vitrified waste have been set approximately one order of magnitude below the package limits specified in the IAEA-Transport Regulations which are 2.0 mSv/h at the surface and 0.1 mSv/h at a distance of 1 m from the external surface except for packages shipped under exclusive-use. The maximum permissible dose rate at any point 2 m from the external surface of the transport vehicle shall not exceed 0.1 mSv/h.

Intermediate- and low-level radioactive waste: The external package or container dose rates for shipments of intermediate- and low-level radioactive waste materials to be met during transport and interim storage are limited by the safety requirements of the Interim Storage Facility and are given below. These safety standards are consistent with the Preliminary Waste Acceptance Requirements of the designated Konrad Repository /BFS 93/.

	Package/Container Dose Rate Limits (mSv/h)
- Package/Container surface	2.0
- 1 m from external surface of cylindrical packages	0.1
- 2 m from external surface of cubical packages	0.1

4.3 Package activity inventory and radionuclide composition

The package activity inventory and other radiological characteristics of the reprocessing waste material are given in Tab. 4.1 for the following waste streams:

- Vitrified high-level radioactive waste
- Bituminous waste

Vitrified waste qualifies as high-level radioactive waste (HAW) while the other waste type represent intermediate-level waste (ILW).

The parameters and values given in Tab. 4.1 refer to the quantity of radioactive reprocessing waste enclosed in a primary packaging (drum or canister). For transport and interim storage generally several (up to a maximum of 28 canisters of vitrified waste and 5 drums of bituminous waste) primary packages are enclosed in a containers or cask such as the Castor HAW 20/28 CG or TS 28 V. The containers or casks for transport and storage have to offer a high level of protection to the primary packaging which they carry to ensure that there is no release of activity during routine transport and at most a limited release even under severe accidental conditions.

Vitrified waste contains the highest radionuclide inventory - mainly fission and activation products - of about 30 000 TBq (nominal) and up to 37 000 TBq (guaranteed) per stainless steel canister. Lower radionuclide inventories are found in bituminous waste materials with values of about 2.2 TBq (nominal) and up to 3.6 TBq (guaranteed value) per drum.

The radionuclide composition of the waste varies substantially by the type and nature of the waste stream. Radionuclides typically encountered in the radioactive waste material in different quantities include the following and are given below.

The vitrified waste canisters have a nominal surface dose rate of up to 14 000 Gy/h [2] and a maximum (guaranteed) thermal power of 2 kW at the time of transport according to the Cogema Specifications. The surface dose rate of the bituminous waste drums range between 0.75 - 2 Gy/h. The values indicate that these waste forms require adequate shielding for transport to comply with the relevant limits specified in the national and international transport regulations and other applicable safety standards.

The thermal power or decay heat of the vitrified waste is an important factor and determines for example the number of canisters to be loaded into a transport flask such as the CASTOR HAW 20/28 CG or TS 28 V.

Radionuclide	Half-Life (yr)	Radiation Type
H 3	12.3	β
Co 60	5.3	β/γ
Sr 90	28.6	β
Ru 106	1.0	β/γ
Cs 134	2.1	β/γ
Cs 137	30.1	β/γ
Ce 144	0.8	β/γ
Pu 238	87.7	α/γ
Pu 241	14.4	β/γ
Am 241	432.2	α/γ

2 Value adopted from the Cogema Waste Product Specifications. The available experience, however, indicates measured surface dose rates for vitrified waste canisters in the range of 500 - 1000 Gy/h /KUN 97/.

Radionuclide Composition of the Vitrified High-level Waste*) according to the Specifications for Vitrified Residues:

Radionuclide	**Nominal Inventory (Bq/canister)**	**Guaranteed Inventory (Bq/canister)**
Am-241	3.96E+13	4.21E+13
Cm-244	9.99E+13	2.70E+14
Pu-238	9.13E+11	1.26E+12
Pu-239	1.08E+11	1.49E+11
Pu-240	1.56E+11	2.15E+11
Pu-242	5.77E+08	7.93E+08
U-232	8.18E+06	1.86E+07
U-233	1.06E+03	2.41E+03
U-234	1.14E+08	2.59E+08
U-235	3.96E+06	9.00E+06
U-236	3.04E+07	6.91E+07
U-238	2.39E+07	5.43E+07
Th-228	3.31E+06	7.52E+06
Sub-Total (Alpha)	1.41E+14	3.14E+14
Ru-106	1.62E+15	1.97E+15
Rh-106	1.62E+15	1.97E+15
Sr-90	3.37E+15	4.63E+15
Y-90	3.37E+15	4.63E+15
Cs-137	5.61E+15	6.66E+15
Ba-137	5.61E+15	6.66E+15
Cs-134	1.82E+15	2.16E+15
Ce-144	1.58E+15	1.96E+15
Pr-144	1.58E+15	1.96E+15
Pm-147	3.11E+15	3.56E+15
Sm-151	2.11E+13	2.33E+13
Eu-154	2.43E+14	2.69E+14
Eu-155	2.59E+14	2.91E+14
Pu-241	3.84E+13	5.28E+13
Sub-Total (Beta/Gamma)	2.99E+16	3.68E+16
Total	**3.0 E+16**	**3.7 E+16**

*) Initial enrichment 3.5% U 235, average burn-up 33000 MWd/t (U), reprocessing 3 yrs after unloading from reactor, vitrification 4 yrs after unloading from reactor

Radionuclide Composition of the Bituminous Waste:

Radionuclide	Nominal Inventory (GBq/drum)	Guaranteed inventory (GBq/drum)
Pu 238	12.37	15.72
Pu 239	1.46	1.85
Pu 240	2.05	2.61
Am 241	7.84	9.96
Cm 242	0.22	0.28
Cm 244	1.56	1.98
U 235	2.55E-04	3.24E-04
U 238	2.55E-03	3.24E-03
Sub-Total (Alpha)	25.5	32.4
Co 60	10.96	19.99
Ru 106	370.5	675.77
Rh 106	370.5	675.77
Sb 125	26.13	47.66
Cs 134	28.85	52.61
Ce 144	110.49	201.52
Pr 144	110.49	201.52
Pm 147	9.7	17.69
Eu 154	10.78	19.67
Eu 155	5.23	9.53
Cs 137	146.97	268.07
Ba-137 m	146.97	268.07
Y 90	35.5	64.75
Sr-90	35.5	64.75
H 3	1.42	2.59
I 129	0.01	0.03
Tc 99	0.01	0.03
Pu 241	765	972
Sub-Total (Beta/Gamma)	2 185	3 562
Total	**2210**	**3594**

4.4 External dose rate of the transport and storage containers

Gamma-rays and/or neutrons released by the radioactive waste material have the potential of penetrating through the wall of the cask or container and may cause radiation exposure of members of the public and transport personnel. Consequently, the wall material and thickness have to be designed to limit the dose rate below the applicable limits.

The magnitude and distribution of the external radiation field depend on various factors such as the type, energy and intensity of the radiation and the shielding efficiency of the waste immobilisation and shielding material.

The dose rate-distance relationship shown in Fig. 4.1 clearly illustrates that the external dose rate declines rapidly as the distance increases. One should note that the dose rate in Fig. 4.1 is normalised to 0.1 mSv/h at 1 m from the external surface of a cubical container.

The dose rate values presented in this chapter for all waste streams are based on shielding design calculations using radiation transport codes such as ANISN, MICROSHIELD a.o. or have been derived from relevant information in safety assessment studies for containers considered for shipment of reprocessing waste material. The assessment results are presented in Tab. 4.2 in terms of the maximum package/container dose rate at the centerline of the container surface, and at a distance of 1 m and 2 m from the external surface.

Generally waste package activity inventories were assumed for the dose calculations equivalent to or slightly above of the guaranteed activity inventory. Thus, the dose rate estimates tend to be upper estimates.

The assessment results given in Tab. 4.2 indicate that under the assumptions made, the dose rate estimates generally closely approach the applicable limits which are 0.2 mSv/h (total) at the external surface of flasks for vitrified high-level radioactive waste and 0.1 mSv/h for all other waste stream packages at 1 m for cylindrical and 2 m for cubical containers. Although data relevant for evaluating the degree of overestimation of package dose rates are needed, such information is at the present stage of the study not available.

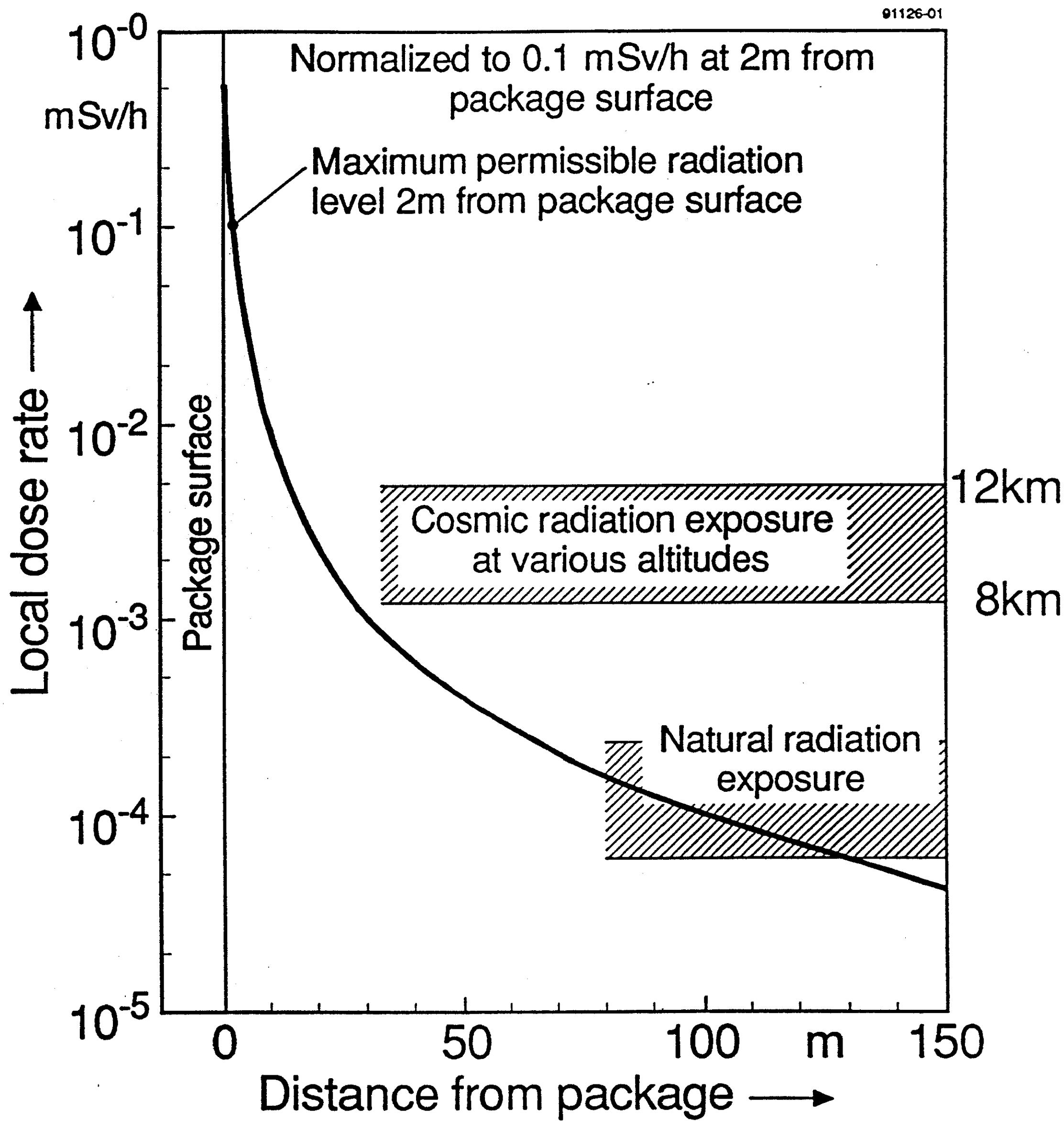

Figure 4.1: Spatial Distribution of the External Dose Rate of a cubical Container

Table 4.2: External Radiation Levels of Packages of Reprocessing Waste Materials assumed for Dose Assessment Purposes

Note: Values are based on Shielding Design Calculations and represent upper Estimates

Waste Type	Package Type	**Package Centerline Dose Rate (mSv/h)**		
		Surface	at 1 m	at 2 m
Vitrified Waste	Castor HAW 20/28 CG	0.17	0.11	--
	TS 28 V	0.3 [a]	0.04 [a]	--
Bituminous Waste	Container VII (Cast Iron)	0.4	0.2 [b]	0.1

[a] Maximum measured dose rate in region of the trunnions

[b] Approximate dose estimate adapted from Container V shielding analysis

5 Waste transportation

5.1 Transportation scenarios and shipping arrangements

The transport of waste will mainly occur by rail. Road transportation will only be necessary between the La Hague Reprocessing Plant and the Valognes loading terminal and similarly in Germany between the loading terminal in Dannenberg and the Gorleben Interim Storage Facility, because both sites have no direct access to the railway network.

It is assumed that the waste transports are limited to 3 waste wagons per train (non-dedicated trains), with an average of two waste wagons. The position of each waste wagon in the train is left to the responsibility of the Société Nationale des Chemins de Fer (SNCF), but according to present planning, buffer wagons will be included between each of them. On the German railway network, however, the wagons carrying vitrified radioactive waste material will preferably travel immediately behind the locomotive for several reasons with the exception of railcars carrying containerized low-level radioactive waste materials.

5.2 Annual traffic volume

The following average number of waste wagons have been estimated to be shipped annually and are used for the estimation of dose to the public and transport personnel (reference year):

- Vitrified waste: 15 railway wagons/year
- Bituminous waste : 50 railway wagons/year

Assuming an average of 2 railway wagons per train, the 65 railway wagons per year require 33 trains per year carrying waste shipments.

5.3 Routing

From the Cogema reprocessing plant to the loading/unloading terminal at Valognes the waste will be transported by truck over a distance of about 40 km. Then, from the

Cogema loading terminal at Valognes, the train will go to Caen (marshalling yard) then preferably to Sotteville-les-Rouen (marshalling yard), avoiding Paris the train will go to Amiens, Arras, Valenciennes, Hirson, Charleville-Mézières, Thionville and finally to Woippy (marshalling yard) and Apach near the French-German border. It should be noticed that according to SNCF, only four bridges exceeding 9 m have been identified along the French route. In Germany, the journey is expected to continue via Apach, Cologne, Hamburg-Maschen (marshalling yard), Lüneburg (marshalling yard), Dannenberg-Ost (loading/unloading terminal) and then 20 km by truck to the Gorleben Interim Storage Facility site.

From a European database /GAR 81/ containing population data within a grid of 10 km x 10 km, an analysis was performed to estimate the population density along the transport route. The rail routing was characterised by the longitude and latitude of each representative town. From this calculation, an average density of 358 inhabitants per square kilometre was derived for a total length of 1414 km (almost equally distributed in length between France and Germany). If one defines the population density of rural areas from 0 to 165 persons/km^2, suburban areas from 166 to 1650 persons/km^2 and urban areas in excess of 1650 persons/km^2, the fraction of the waste transport route falling in different population density zones is as follows: 78% rural, 21% suburban and 1% urban. Contrary to truck transportation, the train generally does not avoid urban and suburban areas and therefore the population densities along a rail route are generally higher than those of a truck itinerary.

The 10 km x 10 km mesh is relatively large and integrates more rural areas and may not be representative for population densities in the vicinity of the rail route. Therefore, in order to take into account the differences of densities related to the size of the corridor considered in INTERTRAN II (800 m on both sides), the following distribution is assumed: 73% rural, 21% suburban and 6% urban. These values were adopted from an earlier transport risk analysis study /LAN 87/. Moreover, it is important to note that there is a major difference between the average population density along the itinerary in Germany and France, actually 577 persons/km^2 in Germany compared to 219 persons/km^2 in France. Figure 5.2 describes the rail itinerary considered for the assessment.

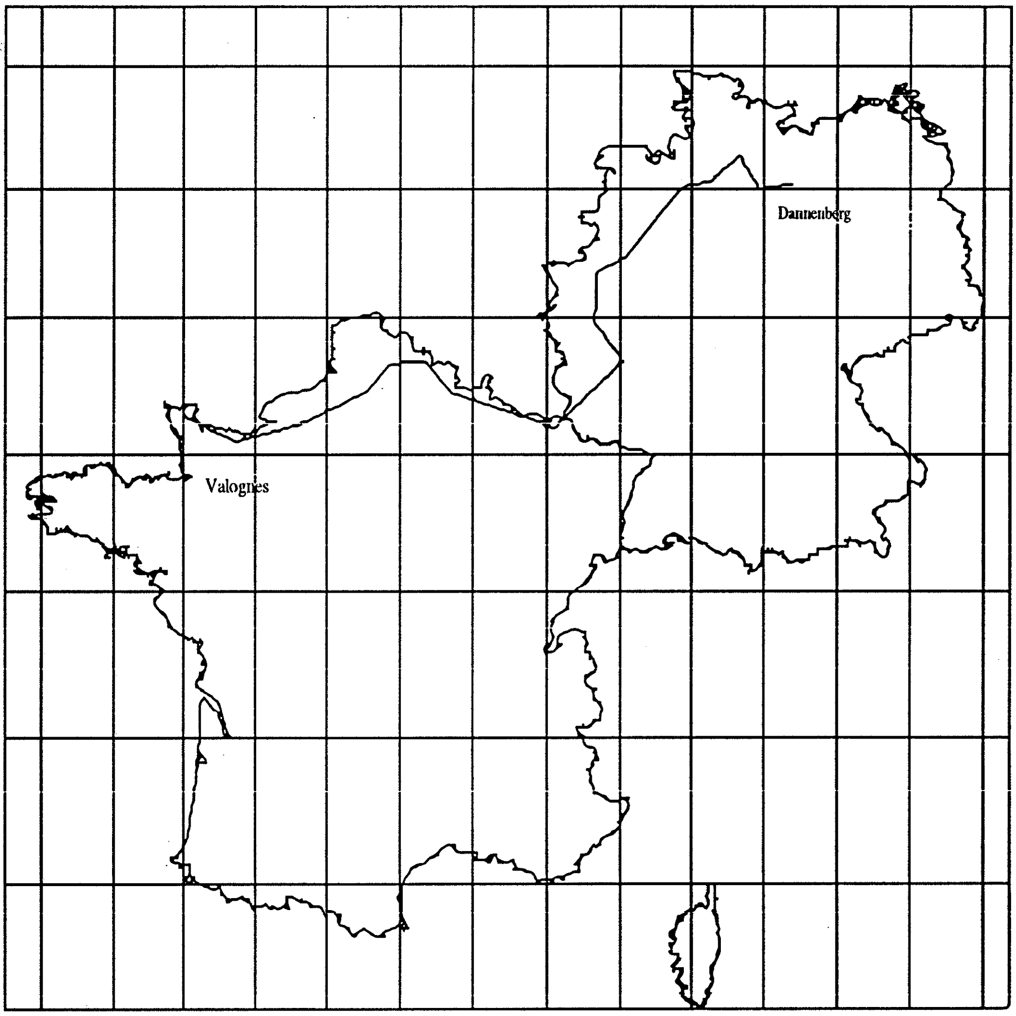

Figure 5.2: Transport route of waste shipments assumed for dose assessment

6 Radiation exposure from routine waste transportation

This chapter provides a brief overview on the dose assessment approach and the basic information used for quantifying the radiation exposure from routine (incident-free) transportation of radioactive waste materials.

6.1 General description

Members of the public surrounding the transport path and the transport personnel involved in handling and transport operations of the waste shipments will be externally exposed to radiation emerging from the waste package. However, it is important to recognise that the radiation exposure to human beings resulting from waste transports is limited to individuals being or working close to the waste packages due to the rapid decline of the radiation dose rate with distance, cp.. Fig. 4.1.

The magnitude of the annual radiation dose at a given location is related to the following parameters:

- the annual route-specific volume of waste shipments;
- the package dose rate of the individual waste shipments;
- the radiation source - receptor configuration, i.e. the distance between the package and the receptor location;
- the time period a person spends in the radiation field at a given location taking into account any shielding effect by structural materials or other components.

The essential elements required for dose estimation have been described in the previous chapters (see chapter 2 - 5) or will be discussed subsequently. Using this information, the radiation exposure attributable to routine transportation of radioactive waste materials has been quantified in terms of individual and collective doses for various population groups at different locations. The dose estimates are expressed as annual effective dose in units of mSv/yr (10^{-3} Sv/yr) or man-Sv/yr.

The collective dose to the population and transport personnel has been determined using the INTERTRAN II computer program. INTERTRAN II permits calculation of collective effective doses to various population groups. Two different population groups have been considered in this study:

- transport personnel
- general population

Transport workers include personnel involved in transport operations such as the truck or train drivers, handlers, and railyard workers.

The general population group comprises residents and by-standers within a corridor of a width of 800 m to both sides of the transport path, people in railcars passing the waste shipments, as well as people exposed at stops of waste transports. To account appropriately for different population densities along the transport route, three population density zones are distinguished: rural areas, suburban areas, and urban areas. The population densities for these areas have been adapted from the European Population Data Base which provides population data on a 10 km x 10 km grid basis /GAR 81/.

The total travel distance between La Hague and Gorleben is about 1414 km, including 60 km by truck (40 km between La Hague and Valognes and about 20 km between Dannenberg and Gorleben). The trucks are routed through low-density population zones at the two ends of the journey, and thus the associated collective dose from routine (incident-free) road transportation is negligible. Therefore the collective dose estimates will concern only the rail mode.

The shipping data have been derived from information provided by the Société Nationale des Chemins de Fer (SNCF) and the Deutsche Bahn AG (DB) and reflect current shipping practices for nuclear material on transport routes relevant for this study. The basic data used for the calculation of collective effective doses are summarised in Table 6.1.

Assessment of <u>individual</u> doses to the population and transport personnel is based on extensive analyses of routine transport and handling operations of waste shipments involving individuals or groups of individuals residing or working in close proximity to the waste packages. To identify such operations along the transport route site visits were made on railyards and loading terminals with emphasis in the region where waste shipment converge, i.e. in the La Hague reprocessing site region (Valognes) and the interim storage site region (e.g., Lüneburg, Dannenberg). The site visits included analysis of standard handling procedures, working schedules, manpower requirements, travel-, handling- and residence times etc. reflecting current transport practices, and a survey of residential and industrial areas that may potentially be affected by the waste shipments.

Routine transport doses to individuals were calculated using the calculational approach similar to that employed in the INTERTRAN II code, but with parameter values reflecting the relevant exposure conditions.

It is important to note that the dose estimates given subsequently refer to critical group individuals, who may be more extensively exposed to radiation emerging from the waste shipments due to their living habits or occupational functions than other individuals. Notable examples are permanent residents at specific locations along the transport path or permanent employees exclusively assigned to specific working areas or tasks, e.g. load/vehicle inspection. Moreover, assumptions required for dose estimation have generally been made in a conservative manner. Thus, the dose predictions are believed to overestimate doses resulting from real movements of waste. The major components of conservatism incorporated into the dose calculations include the following:

- use of upper bound values for the number of waste transports, i.e. current projections of the waste volume indicate that the quantity of reprocessing generated waste to be shipped to Germany may be substantially lower than the values assumed for this study;
- use of upper bound package dose rates, i.e. upper bound package activity inventories have been assumed for radiation shielding calculations;
- use of conservative exposure conditions, e.g. exposure of members of the public to all waste shipments, all-year-around residence of members of the public at the site of interest, exclusive assignment of workers to a specific functional area.

6.2 Collective doses

As two categories of waste will be considered, a single run of INTERTRAN II was performed for each category: vitrified high-level waste and bituminous waste. Moreover, an average year (reference year) in terms of number of transports was considered. The following results are obtained:

Table 6.1: Collective effective dose from routine waste transportation

Type of Waste	Crew (man-Sv/yr)	Public (man-Sv/yr)	Total collective dose (man-Sv/yr)	Total collective dose (%)
Vitrified Waste	2.04E-03	4.85E-03	6.89E-03	16.7 %
Bituminous Waste	1.44E-02	2.01E-02	3.45E-02	83.3 %
Total	1.64E-02 39.6 %	2.50E-02 60.4 %	4.14E-02 100 %	100 %

The largest collective dose fraction is related to the transport of bituminous waste which gives rise to about 83 % of the total collective dose from about three quarters of the volume of all waste shipments (50 out of 65 waste wagons per year). The total collective effective dose for an average year of transportation and accident-free transport conditions has been estimated to about 0.041 man-Sv/yr. Concerning the crew of the train, one train driver was considered at an average distance of 20 meters from the transport containers, except for vitrified waste shipments where a train driver and one escort individual were assumed to be present on the train. On average two waste wagons per train were considered but for the crew members it was assumed that only the closest waste wagon contributed to the radiation exposure (effect of shielding and distance).

The collective effective dose for the loading terminal personnel including the handlers, crane operators, and health physicists at Valognes and Dannenberg has been determined to be approximately 0.013 man-Sv/yr at each site.

6.3 Individual doses

The dose estimates for members of the public and the transport personnel from routine transportation of reprocessing waste materials are summarized in Table 6.2 and Table 6.3. The dose estimates are based on the annually averaged waste transport volume given in Tab. 3.1 and reflect standard shipping practices and exposure conditions at the relevant sites referred to in the tables. Doses at other locations and functional areas tend to be lower than the values given for the critical group individuals at the sites specified in Table 6.2 and Table 6.3.

6.3.1 Members of the public

Several hypothetical groups of individuals, generally known as critical group individuals, were considered with assumed exposure conditions to maximise the resulting individual effective dose from routine transportation by rail and road: a permanent resident/passers-by living close to a traffic light on the road approach to the Interim Storage Facility and a railway user regularly positioned on a station platform while waste containers pass by or stop temporarily in front of the platform or traffic light, and a person living near a rail-to-road transfer point.

To adequately describe the assumed exposure conditions of residents/passers-by along the route of waste transports by road and rail, two exposures contributing to the overall individual dose were taken into account:

- First, an exposure component from all shipments, while the transport vehicle passes by the receptor location at a speed of 35 km/h (road) and 50 km/h (rail) in a distance of 5 m (road) and 10 m (rail).
- Second, an exposure component from 5 percent of all shipments, while the transport vehicle stops at a traffic light or railway signal for 3 - 5 minutes in close proximity to the critical group individual.

Assuming that residents and by-passers (critical group) are exposed according to the conditions mentioned above, results in an unshielded (free-air) radiation doses along the transport route of up to about 0.01 mSv/yr from rail and road transportation.

Doses to members of the public at the various transfer stations, railyards etc. were calculated assuming current working procedures and the locally relevant exposure conditions such as site-specific source-receptor distances, residence- and handling times, and where appropriate, shielding by building structures, assuming a dose rate reduction factor (DRF) of 10 for occupants and an indoor occupancy rate of 75 percent, unless otherwise indicated.

Residents of a farm house located in close vicinity south of the Valognes loading terminal (see Appendix II) are considered as critical group at the terminal site. The minimum distance between the parking position of the loaded railcars and the farm house is approximately 100 m. Shielding is provided by the structural material of the farm house and the on-site service facilities of the loading terminal and, consequently, an enhanced dose rate reduction factor (DRF) of 20 has been assumed for dose calculation. After loading of the wagons the transport flasks or waste container can remain on-site for up to 3 days on the on-site siding tracks.

Assuming that members of the public at the Valognes loading terminal are exposed to the radiation emerging from the waste containers according to the conditions mentioned before can result in doses to nearby individuals (critical group) of about 0.03 mSv/yr for an assumed average on-site residence time of the waste wagons of 1.5 days. The calculational procedure and the site-specific assumptions used for dose assessment are explicitly presented in Appendix II, Chapter 1.3.2.

Similarly, residents of houses located as close as 100 m south of the Dannenberg loading terminal have been identified to represent critical group individuals at this site. Loading operations have been assumed to be completed within 1.5 h for flask shipments and up to 5.5 h for simultaneous shipments of three railcars carrying containerized waste materials. Based on these assumptions, a dose rate reduction factor (DRF) of 10 for the building structure, and an exposure scenario of human beings representative for 75% indoor and 25% outdoor activities, the dose predictions for the critical group are in the range of approximately 0.01 mSv/yr.

The combined effects of the site-specific exposure conditions, e.g. large distances between the waste packages and the receptor point, and the operational procedures at railyards within the German railway network give rise to doses to members of the public (critical group individuals) of not more than of a few hundredth of a mSv per year. Similarly, the workers of a metal scrap yard located in close proximity (approx. 25 - 50 m) to the siding tracks of waste shipments at the Ehrang (Trier) railyard in

Germany may be exposed to doses of up 0.02 mSv/yr based on a five-day-per-week working schedule and no structural shielding.

From the results presented in Tab. 6.2 it can be concluded, that the dose estimates for the general population are well below the applicable IAEA dose limit of 1 mSv/yr and represent only a small fraction of the natural radiation exposure of approximately 5 mSv/yr (including cosmic rays, gamma indoors, gamma outdoors and radon) in France and 3.2 mSv/yr in Germany /CEC 93/. This general conclusion holds for any population group in France and Germany that could be reasonably identified as being exposed to the radiation from reprocessing waste transports.

6.3.2 Transport personnel

The dose estimates presented in Tab. 6.3 for the transport personnel involved in carriage, handling, marshalling, and inspecting the waste shipments vary substantially and are in the range from 0.1 - 1.7 mSv/yr.

The highest doses are found for workers at the loading terminal in Valognes and Dannenberg. Five handlers including the crane operator are generally needed for loading a waste flask like the Castor HAW 20/28 CG from road to rail and vice versa. The tasks to be completed include unfastening of the tiedowns and fittings from the support frame, alignment of the corner fittings while the cask is suspended from the crane, and then securing the fittings and fastening of tiedowns after the flask is lowered into place. Including the time required for removing the protective cover (sliding cover or protective canopy) these individuals spend overall up to 30 minutes within a few meters of the flask. Loading/unloading of containerized waste packages from road to rail is routinely performed using cranes equipped with standardised lifting equipment by not more than two workers, the crane operator and a spotter. The time for handling and radiological inspection in close proximity of the container or overpack rarely exceeds 4 - 8 min.

Other transport workers which may come close to the waste packages and for which dose estimates are presented in Tab. 6.3 are the shunters and inspectors at various railyards. The basic tasks to be completed by railyard personnel generally include disassembling of the train, handling in the classification track and reassembling and inspection of railcars before onward journey of the train. The Ehrang (Trier) railyard in Germany - the frontier station - is probably an exception, where handling of regular freight trains is limited to the change of the locomotive and minor administrative work (inspection). Thus, the average stop time of a freight train at this railyard is generally limited to about half an hour and rarely exceeds 1 hour.

Although the principal tasks and procedures are similar at most railyards the dose to its personnel can vary remarkably depending on the manpower availability and the working schedules followed at each railyard. This is evident, for example, from the dose predictions given for Hamburg-Maschen and Dannenberg. While railyard personnel is numerous at Hamburg-Maschen the workforce at the railyard at Lüneburg/Dannenberg is rather limited and, consequently, results in higher individual doses to the railyard personnel by a factor of 5 compared to workers at Hamburg-Maschen for the same volume of waste shipments.

It is important to recognise that the predicted doses of about 0.1 - 0.2 mSv/yr for the railway personnel involved in waste transports, i.e. the train drivers, escorts and shunters and inspectors at the various railyards, are well within the dose range observed at German Railway Network stations where radioactive material shipments for medical, radiographic and industrial applications were regularly accepted for transport in the past years.

Doses to handlers at the loading terminals at Valognes (Cogema operated) and Dannenberg (Interim Storage Facility operated) are, however, significantly higher. But the predicted doses for handlers in Valognes and Dannenberg are below the level of 5 mSv/yr where, according to the IAEA Transport Regulations, neither special work patterns nor detailed personal monitoring is required /IAE 90/. Nevertheless, the transport and handling personnel at both facilities is routinely qualified as occupationally exposed workers and, thus, subject to individual radiation exposure monitoring programs and special health supervision.

Table 6.1: INTERTRAN II Input Parameters

Input parameter	Parameter value
Average velocity of freight trains in rural areas	100 km/h
Average velocity of freight trains in suburban areas	60 km/h
Average velocity of freight trains in urban areas	45 km/h
Distance from package to crew member	20 m
Average stop time	0.023 h/km
Independent stop time (Valognes loading terminal)	36 h
Loading terminal population density	35 persons/km^2
Number of waste wagons per train	2
Lenght of the journey	1414 km
Average number of passengers per train	160 persons
One way traffic count rural (passenger trains per hour)	1 / h
One way traffic count suburban (passenger trains per hour)	5 / h
One way traffic count urban (passenger trains per hour)	5 / h

Table 6.2: Dose Estimates for Members of the Public from Routine Transportation of Radioactive Waste Material to be returned from France to Germany
Basis: Dose estimates for critical group individuals

Location/Population Group	Distance [a)] (m)	Effective Dose (mSv/yr)
Residents/passers-by along the transport route		
- Rail	10	< 0.01 [b)]
- Road	5	< 0.01 [b)]
Valognes Loading Terminal (Closest residential building)	approx. 100	0.03
Ehrang Railyard (frontier station)		
- Closest Residential Building (south)	approx. 100	< 0.01
- Scrap Metal Yard (Staff)	approx. 25	0.02
Hamburg-Maschen Railyard (Residents)	-	negligible
Lüneburg Railyard (Residents)	-	< 0.01
Dannenberg-East Railyard (Residents)	-	< 0.01
Dannenberg Loading Terminal (Residents)	> 100	< 0.01

a) Radiation source - receptor distance
b) Dose from unshielded exposure of all waste return shipments

Table 6.3: Dose Estimates for Transport Personnel from Routine Transportation of radioactive Waste to be returned from France to Germany

Functional Area	Occupation/ Functions	Effective Dose (mSv/yr)
Rail Transportation (not including the route Lüneburg-Dannenberg)	Escort [a]	approx. 0.1 [b]
	Train driver	< 0.1 [b]
Road Transportation	Truck driver	-- [c]
Valognes Loading Terminal	Handler	approx. 1.7
	Health Physicist	approx. 1.2
	Crane Operator	approx. 0.7
Ehrang Railyard (Frontier Station)	Shunter	< 0.1
	Inspector	< 0.2
Hamburg-Maschen Railyard	Shunter	< 0.03
	Inspector	0.03
Lüneburg / Dannenberg	Shunter	< 0.2
	Train driver	0.2
Dannenberg Loading Terminal	Handler	approx. 1.0

[a] German regulations require escorting for some kinds of waste shipments
[b] Dose from all shipments requiring escorts and assuming an exposure time of 3 hours per trip
[c] Value currently not available

7 Transport accident risk assessment

7.1 Assessment method

In spite of all measures taken to ensure the safe transport of radioactive materials there is still a possibility that accidents and incidents involving radioactive material shipments may take place in the public domain. Although the radiological consequences of reported transport accidents and incidents tend to be very low /LOM 89, HUG 89, SHA 90, HUG 90/, the potential occurrence of transport accidents and incidents is consistently a matter of public concern. Particularly, accidents and incidents with the potential to affect the package integrity and resulting in an increase of the external exposure and/or release of the radioactive package contents present the focal point of the public debate.

Such transport accidents are as other human activities a classical example of exposure situations which, while not certain to occur, can be anticipated to increase the overall radiation risk to man as a result of a practice and have been termed as <u>potential exposure</u> within the unified conceptual radiation protection framework of the International Commission on Radiological Protection (ICRP) /ICR 91, ICR 93/.

Transport accidents and incidents involving radioactive materials may occur for a number of reasons with different outcomes depending, for example, on the characteristics of the packaged waste product, the accident severity, and type and magnitude of failure of the containment function of the transport packaging under accident loads.

Because of the statistical nature of transport and handling accidents and the random characteristics of other variables the risks of accidental events are often quantified in terms of the <u>harmful consequences</u> and the <u>probability of occurrence</u> of such sequences of events. This approach is generally known as <u>probabilistic risk assessment</u> (PRA).

The method is specifically designed to describe the broad range of potential accident environments, package-shipment configurations etc. and the associated outcome including low probability accidents with high consequences as well as higher probability incidents having - if at all - minor consequences. The method has extensively been used in previous transport risk assessment studies, e.g. /APP 90, ERI 92, KEM 92, LAN 92, NEU 92a, TOR 92, DUT 93, FET 93, TOR 93, APP 94, GRA 94, MON 94/

and involves for large volumes of different kinds of waste shipments typically a five-step analysis procedure:

- Description of the type, quantity and mode of waste transports
- Determination of accident rates and frequency of occurrence of typical accident environments, i.e. impact, crash, fire etc., for the transport operations being considered
- Assessment of the system response of the packaging and encapsulated waste product to specific load conditions, e.g. hard surface impaction, fire, crush etc., and the subsequent radioactive package release
- Estimation of the environmental release and frequency of occurrence for the broad range of possible shipping patterns (package-shipment configuration) and accident severities
- Assessment of the environmental consequences for different environmental settings, e.g. meteorological conditions, at the time of release

The harmful consequences of a transport related accident can be measured in various ways, but throughout the study described herein the potential effective dose to individual members of the population and the collective effective dose to the group of individuals within the 25 km-radius region surrounding the site of the postulated accident have been used as the preferred means of assessing the radiological consequences. Calculation of individual and collective doses resulting from an accident employs models for predicting the population exposure following dispersal of the released radioactive material into the environment under a range of meteorological conditions via various exposure pathways including external and internal exposure.

External exposure can result from the plume of radioactive material passing the receptor location as well as from radioactive ground deposits. Internal exposure generally encompasses the intake of airborne contaminants by inhalation and ingestion of contaminated foodstuffs. Protective measures, e.g. clean-up activities, to reduce the dose subsequent a radioactive release have not been taken into account in the calculations of the radiation risks. Consequently, the predicted doses to human beings presented in this chapter are upper (or conservative) estimates that will not likely be exceeded should an accident occur.

There are several kinds of transport and handling related operations having the potential of threatening the package (cask or container) containment integrity thereby contributing to the overall radiological risk:

- rail transportation
- road transportation
- marshalling yard operations
- rail-road transfer by crane.

Each of these transport activities have been considered and evaluated to permit a complete assessment of the magnitude of radiation risks. The major input parameters and assumptions made for the assessment are briefly discussed below:

The likelihood of initiating unwanted events with the potential to threaten the package integrity including vehicle collisions, derailment, fire/explosion etc. has been derived from historical records or has been adopted from the literature. Notably, a 10-year record of causes and consequences of regular freight train accidents on the French and German Railways network were available for the study /FET 92a, RAF 94b/. The analysis results of the historical accident data are expressed in terms of the frequency of occurrence of an undesired event within the time period of interest or unit of practice and are used to predict the future likelihood of such events for the waste shipments while travelling from France to Germany. The railway accident data available include both mainline accidents and those on railyards.

The overall radiation risks, i.e. the predicted doses and related frequency of occurrence, presented in the study refer to the total volume of waste shipments which are shipped on public or publicly accessible transport routes over a distance of approx. 1400 km from La Hague, France, to Gorleben in Germany. It is important to note that the likelihood of transport and handling accidents for the total shipping distance and given volume represents an upper bound value and encompasses specifically accident risks for any fraction of the transport path in France or Germany. In other words, the expected frequency of transport accidents for any part of the travel distance or volume of shipments can under no circumstances be greater, but must be lower than the predicted frequency for the total shipping distance and waste volume.

The transport container activity inventory was generally assumed to have nominal characteristics, but for 10 percent of containers upper (guaranteed) limit values were conservatively adopted for the study (cp. Chapter 4.3). Nine accident severity categories, including 3 mechanical non-fire and 6 mechanical-thermal accident environments, have been considered to describe transport and handling accidents to encompass the broad range of possible accident environments. A conditional probability is assigned to each severity category. The structural system response of the packaging and waste product and the subsequent environmental release has been evaluated on the basis of experimental information and engineering analysis for a broad range of impact load conditions including mechanical (hard surface impact) and thermal (fire) forces in excess of the IAEA Transport Regulations package testing requirements.

For each severity category the associated fractional package release was determined - where relevant - for two physicochemically different types of radionuclides: volatile and semivolatile/nonvolatile radionuclides. Tritium (H3), radiocarbon (C14) and halogens are generally considered as being volatile. Particulate non-volatile radionuclide releases were assigned to four particle size ranges. Based on this information the broad range of package-shipment configurations and possible accident severities, the environmental release of radioactive material (source term) has been determined using a Monte Carlo simulation approach (1000 repetitions for each severity category).

Subsequent appropriate consolidation of the numerous source terms 10 different representative release categories have been defined for assessing the radiological consequences by means of the probabilistic accident consequences assessment code COSYMA developed under the auspices of the European Commission /HAS 93/. COSYMA calculates the downwind dispersion (Gaussian plume model) of a radioactive release and the resulting dose from external and internal exposure to radionuclides as a function of downwind distance for a range of weather conditions.

The complex modelling approach used for predicting the radiation risks of waste transports relies on numerous assumptions and simplifications. The major elements of the accident risk assessment including the modelling approach, the assumptions made and the databases used for quantifying radiation risks are addressed in the following sections and in appendices.

7.2 Mode of transport and shipping arrangements

Waste and packaging characteristics:

Two kinds of reprocessing waste products are considered in the transport risk assessment study described herein: vitrified waste and bituminous waste.
The nature of the high-level radioactive vitrified waste requires heavy shielded casks which are categorized by the IAEA Transport Regulations as Type B packages. The ductile cast iron (DCI) Castor HAW 20/28 CG and the forged carbon steel TS 28 V casks are optionally available packagings specifically designed as reusable dual-purpose transport and storage casks meeting the performance criteria of both the IAEA Transport Regulations and the Interim Storage Facility Gorleben (TBL). The capacity of each dual-purpose cask is 20 or 28 stainless steel canisters depending on the thermal power of the canistered waste product. According to information provided by Cogema and GNS, however, the 28 canister configuration will be the primary shipping mode. The cask cavity is filled with helium at an internal pressure of about 0.5 - 0.8 hPa during transport (and storage) except for the Castor HAW 20/28 CG, where the internal pressure may be as high as the ambient air pressure level or slightly above. The laden casks weigh up to about 113 Mg. The transport casks are equipped for transport with removable impact limiters (steel-sheathed wooden shock absorber) on both ends of the cask, protecting the base and seal area from impact and fire. Further information on the design features and performance criteria of the casks are given elsewhere, e.g. /GNS 88, SER 89, HÜG 91, KIR 94, CAR 95/.

The intermediate-level bituminous waste is anticipated to be returned from France in a so-called Container VII. This is a cubical dual-capability cast iron container for transport and interim storage conforming to the performance criteria of both the IAEA Transport Regulations and the Interim Storage Facility Gorleben. The Container VII is designed to hold up to five 225 l bituminous waste drums. During transport the Container VII is placed into a fully surrounding transport pallet (welded steelplate covered framework) developed by GNS, which serves the purpose of an impact limiter. The Container VII in combination with the transport pallet is designed to conform to the Type B package requirements of the IAEA Transport Regulations. Requests for approval of the package design and certification for transport and storage have recently been submitted to the German competent authority (Bundesamt für Strahlenschutz (BfS), Salzgitter, and Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin). The laden weight of the cast iron Container VII including the impact limiter is up to about 25 Mg.

With respect to the transport cask activity inventory nominal waste product characteristics have generally been adopted for risk assessment, but for 10 percent of the casks and containers upper (guaranteed) limit values were conservatively assumed for the accident analysis. The isotope-specific composition of the reprocessing waste product was adopted as given in Chapter 4.3. Selected data describing the activity inventory for both waste streams are depicted in Tab. 7.1.

Shipping arrangements:

The transport mode of the waste returned from the La Hague Reprocessing Plant (UP2, UP3) site to the Interim Storage Facility at Gorleben is by rail and road. However, road transportation will be limited to a small fraction of the journey from the La Hague Plant to the offsite loading terminal at Valognes (40 km) and, similarly, from the Dannenberg loading terminal to the Interim Storage Facility Gorleben (20 km). The travel distance of the transboundary shipments by rail on the networks of the Societé Nationale de Chemin de Fer (SNCF) and German Railways (DB AG) is about 1400 km and has been used for assessing the occurrence of initiating undesired accident events such as vehicle collisions, derailments etc.

The abnormal high weight of the transport casks for vitrified waste requires specifically designed vehicles and equipment, similar to those used for shipments of spent nuclear fuel (Fig. 7.1a). The bituminous waste transport containers, however, are suitable of being loaded onto standard container railcars (Fig. 7.1b). For the ease of the handling and transfer operations each Container VII including the impact limiter will be placed into a standardized 20' ISO freight container (overpack). Two freight containers per railcar are assumed to be carried on a standard container wagon for the purpose of the study. Similar considerations apply to road transportation, except that the loading capacity of road vehicles for casks/containers considered in this study is typically limited to one package or standard freight container.

According to Cogema the shipping pattern of waste transports will regularly differ from consignment to consignment, but the number of waste wagons being shipped in a regular mixed freight train will generally be limited to a maximum of 3 railcars per train. For the purpose of the risk assessment shipping arrangement comprising 1, 2 and 3 waste wagons were assumed to occur with equal probability, i.e. on average 2 waste wagons were taken to be carried in a regular mixed cargo train.

Specific positions of the waste wagons in a regular freight train are not prescribed by SNCF, but in Germany the type of radioactive materials considered in this study are preferably positioned behind the engine at the front of a train for various reasons including operational considerations. Marshalling operations of waste wagons travelling in the regular freight train traffic are expected to take place on average 6 - 8 times on the journey from France to Germany based on current operational schedules and shipping practices.

Number of movements:

The radiological risk associated with the transport of reprocessing waste has been assessed for the **total** volume of vitrified and bituminous waste to be returned from France to Germany over a projected time period from about 1995 - 2003. The relevant numbers of casks/containers and railcars required for the carriage of the total waste volume are summarized in Tab. 7.1. These values correspond on average to about 65 waste wagons being shipped from France to Germany annually.

Table 7.1: Volume and Characteristics of Reprocessing Waste Shipments used for Risk Assessment

	Vitrified Waste	Bituminous Waste
Total Number of Waste Transport Casks/Containers to be returned:	120	720
Total Number of Railcars required for Waste Transportation:	120	360
Annual Number of Railcars being Shipped (Average over Shipping Period)	approx. 15	approx. 50
Transport Cask/Container Activity Inventory (TBq)	nominal/guaranteed	nominal/guaranteed
- Total activity	840 000/1 000 000	11.1/18.1
- Beta/Gamma Emitters	840 000/1 000 000	11.0/18.0
- Alpha Emitters	4 000/8 800	0.13/0.16
- Cesium 134/137	210 000/247 000	0.88/1.6
- Plutonium (incl. Pu 241)	1 100/1 500	3.9/4.9

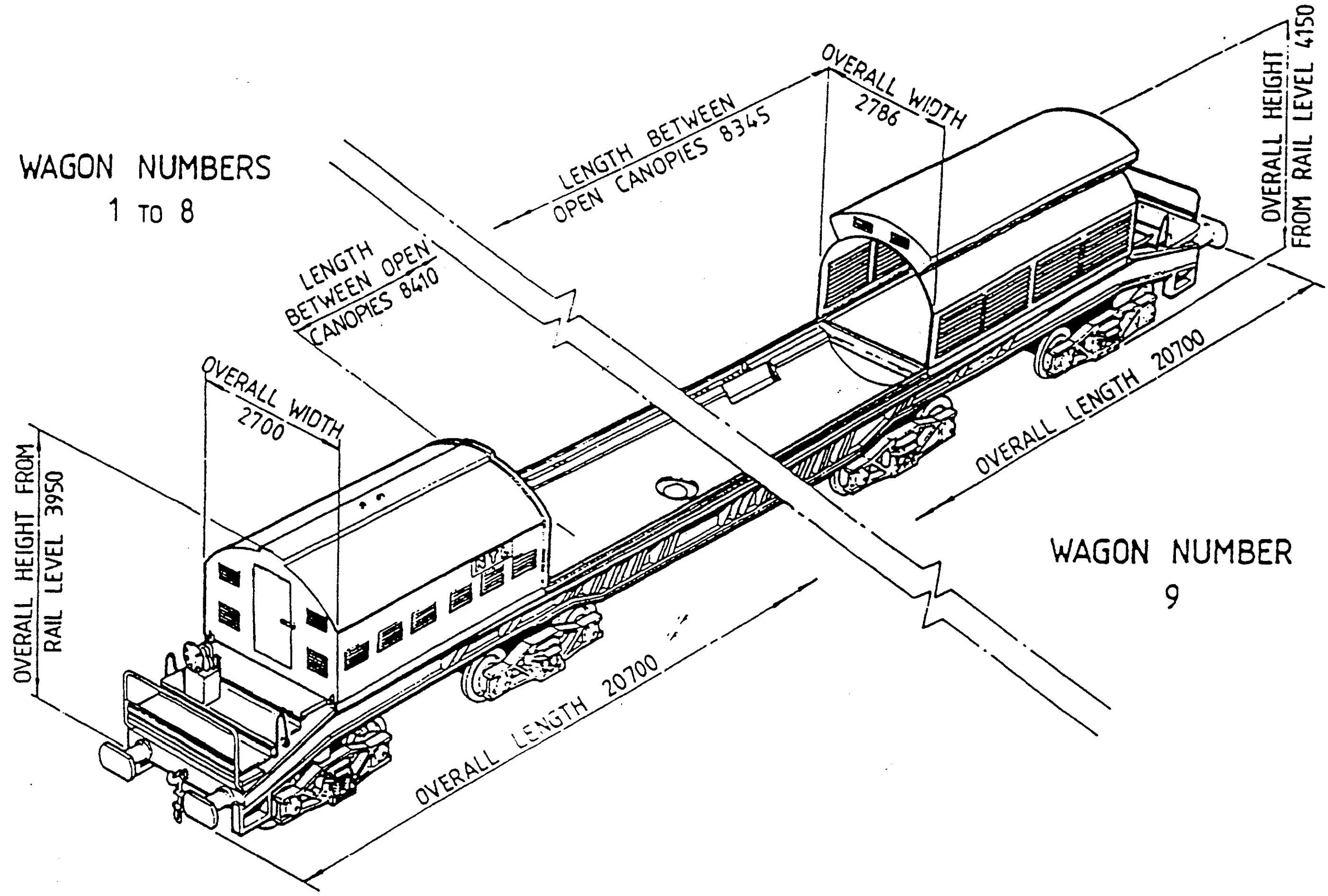

Figure 7.1a: Type of Vehicles being used for Waste Transportation

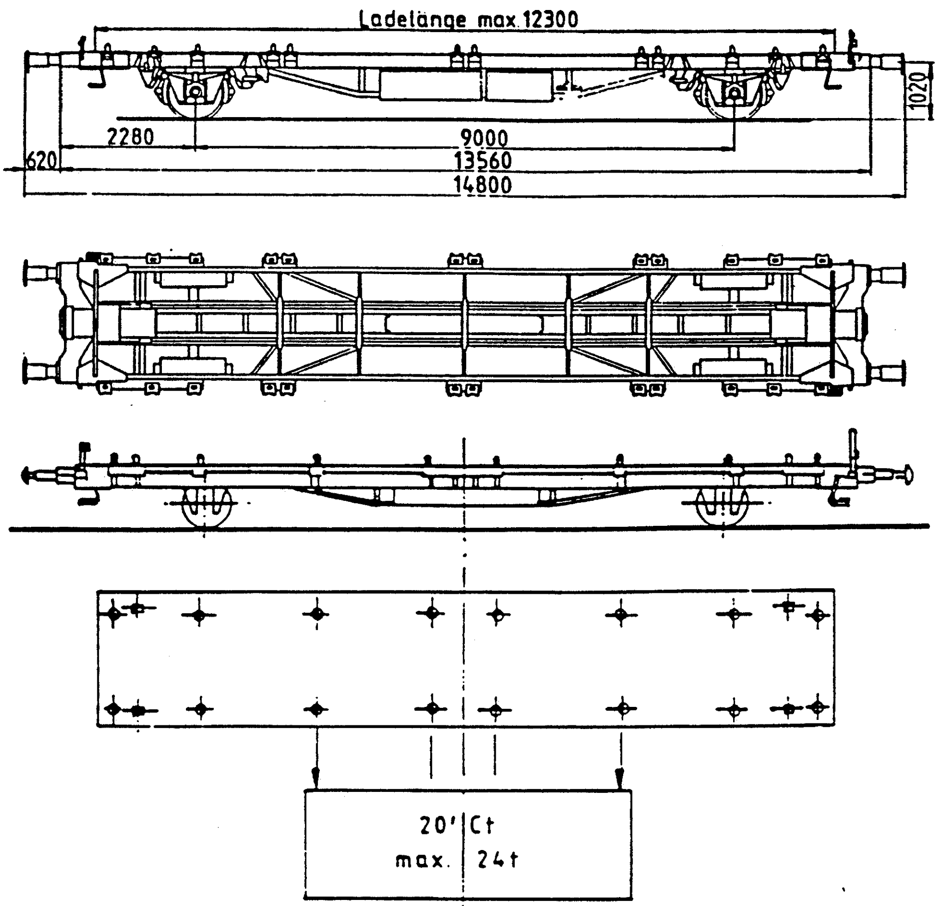

Figure 7.1b: Type of Vehicles being used for Waste Transportation

7.3 Accident rates and accident severities

The likelihood and severity of transport and handling accidents with the potential of compromising the cask or container (package) integrity are key factors in probabilistic transport risk assessment. Very severe, but rare transport accidents might be expected to result in significant releases of the package content, while minor transport related accidents or incidents are unlikely to cause any release at all. Thus, in addition to the probability of occurrence of accidental events for each mode of transport or operation, the credible range of accidental sequences according to severity must be provided.

This section gives a brief overview of the sources of information and data bases used for the definition, categorization and evaluation of accident events with relevance to reprocessing waste transportation. In addition, the application of this information to the relevant transport operations contributing to the overall transport radiation risk including rail transportation, road transportation, marshalling yard operations and rail-road transfer activities and the relative significance of each transport mode or operation to the overall radiation risk will be discussed.

7.3.1 Definition of accident environments

The transport accident severity and associated probability of occurrence have been evaluated within a framework of accident environments and impact forces typically encountered in transport and handling accidents such as fire, crush, impact and puncture forces. For the risk assessment presented herein the broad range of possible transport accident environments has been categorized in terms of the intensity or severity of the potential mechanical impact (e.g. from static or dynamic loads) and the thermal load conditions that a waste transport package may experience in a transport or handling accident. In accordance with the availability of statistical accident data **nine** severity categories (SC) have been adopted with characteristic shown in the accident severity classification scheme given in Table 7.2.

The principal entries of the accident severity categorization scheme depicted in Table 7.2 are the vehicle speed or potential impact velocity of a package and the fire duration and fire temperature. The latter parameters determine the potential heat input into a waste transport package being placed close to or into a fire.

Table 7.2: Accident Severity (SC) Classification Scheme adopted for Risk Assessment

Impact Velocity (km/h)	Fire Temperature / Duration Pattern: No fire	30 min 800°C fire	60 min 800°C fire
< 35	SC 1	SC 2	SC 3
36 - 80	SC 4	SC 5	SC 6
> 80	SC 7	SC 8	SC 9

Three different severity levels were defined to represent the potential mechanical impact forces experienced by a package based on the vehicle speed or potential impact velocity in an accident:

- 0 - 35 km/h
- 36 - 80 km/h
- > 80 km/h.

Three fire severity levels are distinguished to model accidental sequences with combined mechanical and thermal impact forces. These include:

- No fire
- 30 minute 800°C-fire
- 60 minute 800°C-fire

Severity categories SC 1 (impact speed up to 35 km/h), SC 4 (impact speed between 36 - 80 km/h) and SC 7 (impact speed > 80 km/h) represent sequences of events causing only mechanical forces to a waste transport container. All other categories represent accident events where combined mechanical-thermal load conditions exist. To keep the number of severity categories to a minimum, accidental sequences with fire occurring on its own right and without mechanical impact forces have been assigned to severity categories SC 2 or SC 3 which basically represent combined accidental mechanical and thermal load conditions (impact speed < 35 km/h with subsequent fire).

7.3.1.1 Rail transportation

The accident rate for rail transportation has been adopted from a survey of causes and consequences of regular freight train accidents on the German and French railway network /FET 92a, RAF 94a/.

The total railway accident rate (excluding marshalling yard operations) for regular freight trains with the potential to cause material damage to the waste packages was estimated to be on the order of 0.5 accident events per 1 million train-km. This value is consistent with a freight train accident rate of 0.026 per 1 million vehicle-km for an assumed average of 30 wagons per train and is in close agreement with the mainline accident rate of regular freight trains of 0.019 accidents per 1 million vehicle-km on the French railway network of the Société Nationale de Chemin de Fer (SNCF).

For the evaluation of the accident severity a 10-year record of accidents and incidents within the regular freight train traffic on the German Railways (DB AG) network was available for analysis and has been statistically examined /FET 92a, FET 92b/. The data base included a total of 656 relevant (mainline) freight train accidents for the time period from 1979 - 1988 resulting in material damage to railway vehicles in excess of a relevance limit of DM 3000.

Six different kinds of railway accidents have - among other data - been identified by the survey:

- Derailment, i.e. railway vehicle running off the track
- Collision, i.e. impaction of a railway vehicle with others in the same or adjacent line
- Impact, i.e. impaction of a railway vehicle with a foreign object within the track clearance other than a railway vehicle
- Crash, i.e. level crossing collisions
- Fire/Explosion, i.e. fire or explosive damage to or caused by a railway vehicle

The intensity of the mechanical and thermal impact load encountered by a package determines the type and magnitude of potential package damage and the portion of material that may subsequently be released into the environment. Based on the 10-year freight train accident record provided by German Railways (DB) each accident was categorized according to severity based upon the potential impact speed (i.e. the train velocity prior to the accident) and the duration and temperature of fire occurring in an railway accident.

The result of the analysis is summarized in Tab. 7.3 describing the accident severity of freight train accidents and the associated relative frequency (conditional probability) of occurrence.

Table 7.3: Accident Severity of Freight Train Accidents and the related Frequency of Occurrence by Severity Category (SC)

Train Velocity (km/h)	**Relative Frequency**		
	No fire	Thermal Impact 30 min., 800 °C	Thermal Impact 60 min., 800 °C
0 - 35	SC 1: 0.36	SC 2: 5.9E-2	SC 3: 2.9E-2
36 - 80	SC 4: 0.45	SC 5: 9.5E-3	SC 6: 4.7E-3
> 80	SC 7: 8.4E-2	SC 8: 1.8E-3	SC 9: 8.8E-4
Total:	0.89	7.0E-2	3.5E-2

Number of railcars affected:

In addition to the accident severity and probability of railway accidents the number of railcars affected by an accident must be considered for risk assessment. From a subtotal of 196 freight train accidents, which are documented in greater detail, the frequency distribution of the number of affected wagons has been determined. However, the documentation of these accidents was far from being complete, so that conservative upper limit values had to be assumed for the number of affected wagons in some cases. The empirical distribution of the number of railcars affected in a freight train accident is shown in Fig. 7.2.

In approximately 60 percent of railway accidents only the engine is affected ("Zero wagons affected"). The distribution decreases with increasing number of affected wagons. Accidents involving 10 or more wagons occurred in less than 1.5 percent of all relevant accidents. A maximum of 14 affected wagons (with damage above the relevance limit) was reported.

In a more detailed approach characteristic tendencies for the individual accident types are discernible: Wagons are not significantly affected in over 80 percent of impact events (against obstacles, except onto vehicles at level-crossings) and in over 90 percent of crash events (onto vehicles at level crossings). In these cases the engine's large mass generally absorbs the impacts of an accident. Subsequent derailments and collisions (between railway vehicles) the probability of several wagons being affected is greater. Derailment is the sole accident category in which damage only to the power unit is not the most frequent case.

In fire accidents without mechanical impact, the most common incident (50 %) is fire in the power unit, mostly caused by the electrical installation. Only one fire without mechanical impact was reported with two affected wagons, but none with a larger number. This does surely not apply to fires in consequence of an accident with mechanical impact. The statistical data did not allow to generate a distribution curve for this type of accident and a uniform distribution for 0 to 10 affected wagons was conservatively assumed in these cases.

At higher speed, the accident pattern is dominated by impaction to obstacles and crashes into road-vehicles (resulting in smaller numbers of affected wagons), while at lower speeds collisions of trains (resulting in larger numbers of affected wagons) are prevailing. This is due to the fact, that collisions of trains are more likely to occur within station areas where trains cross, while impacts on obstacles and crashes into road-vehicles will occur more frequently on the open line or on railway crossings, respectively, where trains tend to move with high speed. As a result of this, the fraction of accidents in which no wagon is affected rises, as the respective speed range increases, a finding that seems somewhat surprising at the first sight.

In order to use the data in risk analysis, the empirical distributions of the number of affected wagons were determined separately for each velocity category and for fire and then fit with Weibull distribution curves [$F(x) = 1-\exp(-\alpha x^{\beta})$]. The respective fraction of accidents without damage to wagons was not included in the adjustment. Estimated values for the frequency of the occurrence of an accident in each case of one to nine affected wagons, as well as for accidents with more than nine affected wagons, were determined from the calculated Weibull distributions. From these data the matrix of probability for severity categories and associated numbers of affected wagons according to Tab. 7.4 were derived and have been used throughout this study.

Severity Categories	Number of Wagons Affected											Line Total
	0 *)	1	2	3	4	5	6	7	8	9	≥10	
SC 1	17.09	5.12	3.80	2.82	2.09	1.55	1.15	0.86	0.64	0.47	0.35	36.0
SC 2	2.92	2.02	0.35	0.11	0.07	0.07	0.07	0.07	0.07	0.07	0.07	5.9
SC 3	1.46	1.01	0.17	0.05	0.04	0.03	0.03	0.03	0.03	0.03	0.03	2.9
SC 4	29.77	3.15	2.60	2.14	1.77	1.46	1.20	0.99	0.82	0.68	0.55	45.1
SC 5	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.9
SC 6	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.5
SC 7	6.16	0.28	0.26	0.25	0.24	0.23	0.22	0.21	0.20	0.19	0.18	8.4
SC 8	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.2
SC 9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.1
Column Total	57.55	11.74	7.34	5.53	4.36	3.50	2.83	2.31	1.91	1.59	1.34	100

*) i.e. Damage limited to power unit

SC 1 0 to 35 km/h
SC 2 0 to 35 km/h 800°C 30'
SC 3 0 to 35 km/h 800°C 60'

SC 4 36 to 80 km/h
SC 5 36 to 80 km/h 800°C 30'
SC 6 36 to 80 km/h 800°C 60'

SC 7 Above 80 km/h
SC 8 Above 80 km/h 800°C 30'
SC 9 Above 80 km/h 800°C 60'

Table 7.4: Matrix of the Probability of Occurrence of a given Severity Category (SC) and a specific Number of affected Wagons in Freight Train Accidents (in Percent)

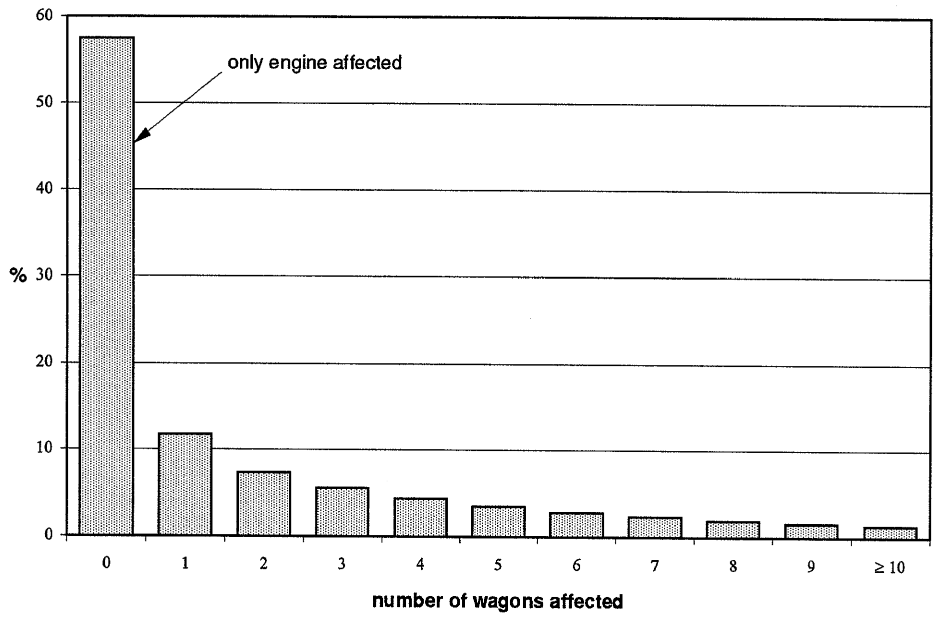

Figure 7.2: Frequency Distribution of the Number of Wagons Affected in Freight Train Accidents

7.3.1.2 Road transportation

Several sources pertinent for estimating the likelihood of road transport accidents have been explored for the transport risk assessment study described herein.

In France an accident rate on motorways and highways of 0.1 and 0.3 accidents per 1 million vehicle-km, respectively, has been used for the evaluation of transport risks /RAF 94a, RAF 94b/. These values are specifically intended for hazardous material shipments using heavy trucks. Relative frequencies of the accident severity (i.e. the conditional probability of occurrence given a truck accident) for truck transportation consistent with the severity category classification scheme described in section 7.3.1 have also been determined and are given elsewhere /RAF 94a, RAF 94b/.

For road-based transports in Germany an accident rate of about 0.5 per 1 million vehicle-km has been used for accidents of heavy trucks on motorways and freeways resulting in material damage in excess of DM 10000. The value is based on 1991 accident data for heavy trucks collected on the motorway Hannover-Berlin (A 2) known of having a fairly high traffic density and accident frequency, but is believed to represent a reasonable approximation for risk estimation.

The relative frequencies of the severity of road transport accidents in Germany are given elsewhere /FET 96/.

7.3.1.3 Marshalling operations

The available information relevant for the evaluation of the radiological risks of waste transport accidents on marshalling yards is based on accident data of the Braunschweig marshalling yard (Germany) for the time period from 1987-1989 /FET 92a, LAN 92/. The total marshalling yard rate of incidents and accidents subjected to a relevance limit of material damage in excess of DM 3000 was found to be about 7.5 accidents per 1 million handled railcars. The value is most representative for the site of the Braunschweig marshalling yard and is believed to be a conservative estimate for most other sites due to topographical factors (natural slope) and operational procedures (partly gravity controlled movement) prevailing at the Braunschweig site. The majority of relevant accidents is attributable to collisions (at low speed) and forceful bumping from the gravity-controlled movement of railcars and rarely to derailment and other causes.

The available accident data also permitted evaluation of the accident severity and number of wagons affected for a specific course of events. The results are given elsewhere /FET 92a, FET 92b/.

7.3.1.4 Transfer operations

The transport and handling operations involving large cranes at the loading terminals at Valognes and Dannenberg are associated with the risk of dropping a cask or container to the ground surface or equipment structures during the movement from road-to-rail and vice versa for various reasons including non-compliance with operational instructions, failure of lifting equipment etc. Based on fault tree analysis for a lifting system (crane) for heavy loads the rate of dropping the load was estimated of being on the order of 1.1E-10 per hour. If one conservatively assumes a handling time of 1 hour per cask/container movement, the drop probability for casks/containers being transferred from road to rail is about 1.1E-10 per movement. NEUHAUSER et al. /NEU 92/ have studied similar transfer operations in ports including loading-unloading operations and have made reference to a drop probability of 2.7E-6 drops per operations (or moves) for ordinary containerized cargo. However, it is pointed out that the drop probability for shipments of the kind considered in this study (heavy casks, trained personnel) might be lower than for ordinary containerized cargo. In summary the information provided indicates that the probability of dropping the lifted cargo from a crane system is fairly low.

Thus, the value for containerized cargo referred to previously has been used for approximate risk estimation of modal transfer operations pertaining to waste transports considered in this study.

7.3.1.5 Significance of different risk contributing transport activities

Transport and handling accidents can not entirely be excluded for waste transports operations considered in the risk assessment study described herein but are expected to differ substantially with respect to the likelihood of occurrence and the potential radiological consequences resulting from such accidents.

This section briefly examines the relative significance of the various transport operations involved in the transportation of reprocessing waste materials from France to

Germany. The information provided is considered to be useful in prioritizing the effort and resources (which are generally limited) required for a comprehensive risk analysis. In other words, high risk transport operations should be scrutinized more thoroughly and subject to a full scale probabilistic risk assessment while obviously low risk operations do not justify the application of such complex and time consuming analysis methods.

The approach used for the evaluation of the relative significance of the various transport operations is based on a semi-quantitative analysis including both the probability of occurrence of an accidental sequence and the potential that the load characteristics stipulated in the IAEA Transport Regulations for Type B packages may be exceeded in such an accident event. The results of the comparative analysis summarized in Tab. 7.5 refer to the total volume of vitrified and bituminous waste to be returned from France and the shipping arrangements described in section 7.2.

The results indicate that for the waste shipping scenario considered in this study, rail transportation is a major risk contributor while the railyard and loading/unloading operations can reasonably be judged as low risk contributors and may therefore be eliminated from a full-scale probabilistic risk assessment. Road transport accidents and train transport accidents involving a waste wagon are basically comparable with respect to the probability of occurrence, but the potential consequences of road transport accidents are definitely lower than the potential consequences of severe train transport accidents due to the different shipping practices. The projected rail transports are, for example, generally multiple-package shipments (up to about 6 casks/containers per shipment) while road transports are generally limited to **one** cask/container per movement due to weight constraints of the vehicles used for transport.

Based on these considerations it has been concluded for the study purpose to place emphasis on probabilistic risk assessment for rail transportation as the dominating risk contributor of the waste transports considered in the study described herein.

Table 7.4: Relative Significance of the various Waste Transport Operations contributing to the Total Radiation Risk
Basis: 840 Waste Transport Casks/Containers resp. 480 Waste Consignments

Type of Operations	Number of Vehicle Movements	Operations per Unit or Transport	Accident Rate	Accident Probability [a]	Potential of Threatening Type B Package Integrity [b]
Rail Transport	480	1400 km	0.026 E-6/vehicle-km	0.02	possible
Road Transport	840	60 km	0.5E-6/vehicle-km	0.02	low
Marshalling	480	6	< 7.5E-6 / vehicle	0.02	very low [c]
Intermodal Transfer	840	2	< 2.7E-6 / move	0.005	very low [d]

a) Rounded to one significant Digit
b) All Casks/Containers used for Waste Transportation are qualified as Type B Packages
c) The operational speed in railyard operations is generally low and limited to a maximum of 25 km/h
d) The potential drop height rarely exceeds H = 9 m

7.4 Cask release behaviour for accident generated load conditions

This section briefly reviews the considerations, models and data bases pertinent for quantifying the system response and release characteristics of the transport casks and waste product for accidental sequences considered in the risk assessment study described herein.

In a shipping accident involving a waste transport container mechanical and/or thermal response can be generated with the potential to damage the packaging to a degree resulting in the subsequent release of the radioactive cask/container inventory. For the massive waste transport casks/containers which all comply to the IAEA Type B package testing requirements very severe impact load conditions will be required to adversely affect the package containment system integrity. Thus, in most transport and handling accidents and considering the physical form of the radioactive waste material, the radioactive release will be limited to small fractions of the package content or will be zero.

The system response of a transport cask or container holding the waste product depends on many factors. Such factors include the mechanical loading generated by the impact velocity and the object or target surface being struck and in events with fire, the heat input generated by the fire temperature and the extent and duration of a fire impact. These factors need to be properly understood within the context of a transport risk assessment study.

7.4.1 Definition of impact load conditions

In estimating the potential impact forces and the associated damage to a package and subsequent release several simplifying assumptions were made for the analysis. The most important example is the assumption, that the package impact speed onto a target surface or object equals the vehicle velocity at the time of or immediately prior to the accident event. This assumption introduces a significant element of conservatism into the assessment of the potential package damage and subsequent release, in that it ignores any deceleration of the package resulting from potential interactions of the package with external energy-absorbing structures or the behaviour of the tie-down equipment.

In addition, the waste transport containers were assumed to impact onto a **hard rigid target surface**, e.g. hard solid rock, with the upper speed of the respective severity category to maximize the potential package damage. For the speed range above 80 km/h, an effective impact speed of 110 km/h was assumed for the assessment of the mechanical impact force. In rare, extremely unfavourable circumstances, this approach possibly underestimates the actual accidental impact loads. In the 0 - 35 km/h speed range, for instance, it could also be possible that heavy objects (e.g. the engine) could fall onto the transport container or that, in the event of a collision, a train travelling at a considerably higher travel speed could strike the container in a very unfortunate position or orientation. In such cases the energy input to the waste container could, in principle, exceed the energy input caused by an impact onto a hard rigid surface at 35 km/h. Impact forces exceeding those postulated can also not be ruled out in the top speed category (assuming an impact speed of 110 km/h). For the assessment of transport risks, however, which requires consideration of a broad range of accident environments, the proposed procedure is considered to be sufficiently cautious since individual incidents are largely compensated for by the following conservative assumptions:

- The use of the upper bound velocity in each severity category - rather than the mean value - generally results in a substantial overestimation of the package impact velocity.

- A reduction of cask/container speed before impacting a target surface or object has not been taken into account as in the case of a wagon sliding after derailment.

- The assumed impact of a package onto a hard solid target surface such as tunnel or bridge abutment is likely to occur in reality only in exceptional circumstances; generally target surfaces are yielding or destructible, such as embankments or building structures.

The **thermal impact** is characterized by a fire of a given duration and fire temperature and by assuming that the waste transport container is totally engulfed by the fire. In estimating the thermal package response, three different accident severity levels are considered:

- No fire

- fully engulfing 30 minute 800°C fire

- fully engulfing 60 minute 800°C fire

Even in experiments conducted specifically for this purpose, fires corresponding to such conditions (30- or 60-minute 800°C fire fully engulfing the transport container on all sides) can be simulated only with great difficulty, especially for large transport containers such as those used for waste transportation. In this respect, fires of 30 minutes duration cover a high percentage of fire loads and the related heat input occurring in reality, and the 60-minute scenario allows for even extreme accidental fire situations. A 30-minute fully engulfing fire of 800°C corresponds to the reference fire to demonstrate compliance with the performance standards specified in IAEA Transport Regulations for Type B packages /IAE 90/.

The accident severity classification scheme covers fires lasting much longer time periods or burning at higher temperatures. Thus, the transport container is exposed to higher temperatures by a fully engulfing 60-minute 800°C fire of than by a fire lasting several hours within close proximity of the waste container, for example, such as could arise from nearby wagons or vehicles with a high fuel load materials (e.g. fuel, coal etc.) burning subsequent an accident.

A similar situation applies as regards the fire temperature. During stoichiometric combustion, temperatures in the high temperature region of the flame are generally considerable above the assumed value of 800°C. The generation of such high temperatures requires generally special equipment, e.g. welding torches. Investigations in conjunction with fire temperature determination reveal that average outdoor fire temperatures are clearly below 800°C. Higher temperatures generally occur only in enclosed spaces with unfavourable thermal radiation geometry. However, these conditions have been accounted for indirectly in the heat transfer calculations by means of conservative assumptions so that, overall, higher waste product temperatures (and therefore releases) are calculated than would be observed in reality.

The most notable conservative assumptions used for the heat transfer calculations, which form the basis for assessment of the package response, include the following:

- Selection of conservative heat transfer parameters such as irradiation numbers, emission coefficients and heat transfer coefficients.

- Disregard of any insulating or shielding structures, e.g. by shock absorbers.

- Cooling and insulating effects of any fire-extinguishing agents during the fire attack are not taken into account.

In conjunction with the assumed fire duration/temperature pattern, the assumptions stated above ensure that the possible heating of the waste containers during fire incidents is adequately covered.

In summary, the stated boundary conditions (i.e. hard solid impact target surface, fire duration/temperature pattern of a fully engulfing fire), together with the severity categorization scheme are believed to be appropriate for the purpose of the study, which conservatively cover the broad spectrum of potential accidental impact environments. This does not include hypothetically conceivable extreme accident events, but these have such a low probability of occurrence, as discussed below, and fall far short of the frequencies of occurrence that reasonably need to be considered.

7.4.2 Package activity release fractions

The release fraction of a package is defined as the fraction of the radioactive package inventory that will be released from the package into the environment instantaneously or over a prolonged period of time, e.g. in a fire, for given accidental impact conditions. Thus, the total environmental radionuclide release related to the accident is the cask activity inventory times the release fraction.

Release fractions vary according to the package type, the physical and chemical form of the waste product, and the accident severity. The radionuclides present in the waste product were grouped according to their physicochemical characteristics in:

- volatile radionuclides
- semivolatile/nonvolatile radionuclides (particulates)

Generally, tritium (H 3), radiocarbon (C 14) and halogens, e.g. I 129, were assigned to the volatile radionuclide category except for vitrified waste, where all radionuclides are expected to be released as solid particulates. Particulate releases resulting from combustion of radioactive waste material such as bituminous waste were generally assumed to be in the respirable size range.

For the assessment of the radiological consequences the semi-/nonvolatile radionuclide releases were assigned to **four** particle size ranges according to the aerodynamic equivalent particle diameter (AED):

0 - 10 µm (AED)
10 - 20 µm (AED)
20 - 50 µm (AED)
50 - 70 µm (AED)

Particles in the size range of less than 10 µm (AED) are ordinarily classified as respirable, particles in excess of 10 µm (AED) as non-respirable and, thus, do not contribute to the dose via the inhalation pathway. However, larger particles are potential contributors to the dose to human beings via groundshine and exposure to radionuclides from the intake of contaminated foodstuffs (ingestion pathway). In addition, particles of diameter > 10 µm (AED) tend to deposit onto the ground surface or vegetation faster than particulates in the size range less than 10 µm resulting in an increased contamination of the vegetation and ground surface.

The escape of radionuclides from a waste transport cask or container into the environment generally requires failure of all of the multiple barriers of the containment system of a package including the:

- solidified waste product
- primary casing (i.e. stainless steel canister or drum) of the vitrified or bituminous waste product
- transport cask containment, i.e. cask/container body and the lid closure system

To cause all barriers of the containment system of very strong transport casks to fail, e.g. by breach of the steel canister and cask body or degradation of the lid closure system etc., requires some intensity of the mechanical and/or thermal impact forces. Thus, for impact loads not exceeding the severity of the IAEA regulatory test requirements of a Type B package (9 m drop onto an unyielding target surface in an orientation to maximize damage followed by a 30 minute fully engulfing 800°C-fire, 1 m puncture test) no release has been assumed to occur and, consequently, a zero-release fraction was taken for the study.

But even for accident severities over a range of loading conditions in excess of the IAEA regulatory test requirements the containment system integrity of very massive casks may be retained because of substantial built-in safety margins incorporated in the design of transport casks/containers.

However, at some level of impact severity loss of containment integrity or leak-tightness of the transport cask/container is expected to occur or has been assumed based on the current level of information on the cask/container performance for a range of loading conditions beyond the IAEA regulatory test requirements. This information has been developed from a literature review and engineering analysis including drop and penetration test experiment results and heat transfer calculations. The containment function of the steel canister or the steel drum forming one of the inner containment boundaries of the multiple barrier system was not explicitly taken into account.

By incorporating the release characteristics of the various waste products into these considerations fractional releases of transport packages for vitrified and bituminized waste materials have been determined for all severity categories defined previously (Tab. 7.2). The results arrived at from this analysis effort are presented in Tab. 7.6 for the vitrified waste transport casks Castor HAW 20/28 CG or TS 28 V and in Tab. 7.7 for the bituminous waste transport Container VII. The release fractions given in Tab. 7.6 and Tab. 7.7 refer to the airborne fraction of radionuclides released into the environment instantaneously or over a prolonged period of time as particulate matter except for tritium (H 3), radiocarbon (C 14) and halogens (e.g. I 129) being present in the bituminous waste matrix.

A complete description of the models and data bases used in the estimation of package release fractions is presented in Appendix II.

The release fractions depicted in Tab. 7.6 and Tab. 7.7 for waste transport packages considered in the transport risk study described herein reflect the following package response and release behaviour:

- Vitrified waste transport cask
    - Gross failure of the package containment of the very massive cast iron Castor HAW 20/28 CG or the forged carbon-steel TS 28 V transport cask with an wall thickness of up to 45 cm is believed to virtually inconceivable over the entire

velocity impact range up to about 110 km/h. However, for impact velocities in excess of 80 km/h damage has been assumed to occur at the cask body - lid interface (degradation of lid closure and sealing system) resulting in an increased leakage of the filling gas and, consequently, of the suspended particulate matter being present in the cask cavity atmosphere.

- The release fractions increase slightly with the accident severity as a result of the assumed pressure increase in the cask cavity in excess of the ambient air pressure level generated by the thermal heat input of a 30 or 60 minute 800°C fire.

- The size-dependent model spectrum of the released particles in the size range up to 70 μm (AED) is dominated by the mass fraction of particles in the respirable size range up to about 10 μm (AED). This observation can be attributed to the particle size-dependent effectiveness of depletion processes of particles taking place inside the cask cavity such as gravitational settling etc. Larger suspended particles are more readily depleted from the cask atmosphere than smaller particles.

- Bituminous waste transport container

  - For accidental impact velocities beyond the IAEA regulatory test requirements for Type B packages structural damage to the cast iron Container VII has conservatively been assumed to occur. The type and degree of damage are supposed to increase with the severity of impact. Impacts in the velocity range from 36 - 80 km/h were assumed of causing structural damage to the cask body, e.g. cracks, but limited in size prohibiting gross access of ambient air into the cask cavity. Thus, combustion of bituminous waste material in an open fire is not expected to occur. For accidental sequences having impact velocities in excess of 80 km/h, however, gross failure of the outer containment boundary was assumed to a degree permitting the escape of that fraction of the bituminous waste product being melted by the heat input. The discharged bituminous waste product can be expected to burn down completely by the fire of such an accident.
    However, no environmental releases have been assumed for mechanical impact only accident categories reflecting the release characteristics of the bituminous waste material under non-fire impact conditions.

- The fractional releases of bituminous waste packages generally increase with the severity of the assumed mechanical and thermal impact forces. The highest release fractions are expected to occur from combustion of the melted fraction of bituminized waste escaping from the container under severe mechanical and thermal impact conditions.

The conditional probability of occurrence assigned to a package release resulting from a given impact severity was taken from Tab. 7.3 describing the conditional probability of occurrence of specific railway accident environments with the potential to give rise to such (mechanical/thermal) impact forces. In real accidents, however, the mechanical / thermal impact conditions differ typically from case to case and are most likely less severe than the conditions assumed for estimating fractional package releases. Thus, the assessment approach is believed to be conservative, because various effects which clearly reduce the package damage and the associated release fractions have not been taken into account for the impact analysis. Such factors include, for example, the actual hardness of the target surface or object struck by the package, the package orientation at impact, and the likelihood of occurrence of specific impact characteristics in real world accidents.

Table 7.6: Fractional Release of Radionuclides of a Vitrified Waste Transport Cask for different Accident Severity Conditions

Severity Category	Impact velocity 1)/ Fire conditions	Particle Release Fraction			
		< 10 µm	10-20 µm	20-50 µm	50-70 µm
SC 1 ... 3	< 35 km/h	No loss of structural cask integrity			
SC 4 ... 6	36-80 km/h	No loss of structural cask integrity			
SC 7	110 km/h, No Fire	7.0 E-10	1,4 E-10	2.1 E-10	7.5 E-11
SC 8	110 km/h, 30 min/800 °C	1.2 E-9	2.3 E-10	3.5 E-10	1.2 E-10
SC 9	110 km/h, 60 min/800 °C	1.4 E-9	2.8 E-10	4.2 E-10	1.5 E-10

1) Impaction onto a hard rigid target surface, e.g. hard rock, solid concrete

Table 7.7: Package Activity Release Fractions of a Bituminous Waste Transport Container VII for different Accident Severity Conditions [1)]

Severity Category	Impact Velocity (km/h)	Fire Temperature-Duration Pattern	Activity Release Fraction [2)] Volatile Radionuclides [3)]	Semi-/Nonvolatile Radionuclides [4)]
1	< 48	No Fire	0	0
2		800°C / 30 min [5)]	0	0
3		800°C / 60 min [6)]	0	0
4	48 - 80	No Fire	0	0
5		800°C / 30 min [5)]	0.38	1.9 E-3
6		800°C/60 min [6)]	0.55	2.8 E-3
7	> 80	No Fire	0	0
8		800°C / 30 min [5)]	0.38	0.038
9		800°C / 60 min [6)]	0.55	0.055

1) Accident consequence mitigation measures have not been taken into account for estimation of the release fractions, e.g. fires were not extinguished and no enforced cooling has been assumed
2) Normalized to the container activity inventory
3) Values assumed for H 3, C 14, and halogens and its compounds
4) Released and dispersed as particles in the respirable size range (AED < 10 µm)
5) Bitumen mass fraction above melting point (85°C) ca. 38% (approx. 15 h after fire)
6) Bitumen mass fraction above melting point (85°C) ca. 55% (approx. 15 h after fire)

7.5 Source term estimation: Transport accident simulation approach

The ultimate quantity of radioactive material that may potentially be released into the environment from a waste transport package subsequent an accident can vary depending on a number of factors including (1) the number and type of (vitrified or bituminous) waste transport packages affected by an accident, (2) the package activity inventory and (3) the type and severity of the accident event. For analyzing the broad range of accidental sequences and associated releases for a large number of projected waste shipments a Monte Carlo simulation approach has been used to simulate the conceivable shipping patterns, i.e. the possible package-shipment-inventory combinations potentially involved in accident events of different severity. The method used for this study is designed to generate a representative set of package-shipment-activity inventory configurations within each severity category and ensures specifically that low probability, higher consequence accident events are adequately represented in the spectrum of simulated accidental sequences /LAN 92a/.

As much as 1000 package-shipment-activity inventory configurations have been analyzed in each accident severity category (SC 1 ... 9) defined in Tab. 7.2 for rail transport accidents. The outcome of each repetition of the simulation program comprises: the environmental release of each radionuclide present in the waste product of all (randomly) selected waste packages involved in the simulated freight train accident event - the source term - and a measure of likelihood of occurrence of this release. The simulated accident events include both accidents resulting in an environmental release and those where the containment integrity of waste transport packages is retained resulting in a zero-release.

Measuring of the likelihood of occurrence of the accident event and associated release (source term) is based on the conditional probability of occurrence - given a freight train accident - of the simulated accident sequence of a given severity and the number of waste wagons being damaged in the simulated accident (see /FET 92a/, Table 3.4 and Appendix C: Table C-1).

Based on information provided by the shipper (carrier) organizations involved in the envisaged transport operations the following assumptions were made for the analysis describing the shipping scenario of railway transports:

- Each individual waste consignment routed to the Interim Storage Facility site at Gorleben is limited to a maximum of 3 waste wagons.

- The load of a railcar was assumed to be either one vitrified waste transport cask (Castor HAW 20/28 CG or TS 28 V) or two bituminous waste transport containers.

- 90 percent of the waste transport containers were assumed of having nominal activity inventories and 10 percent having upper bound (guaranteed) values (see Chapter 4.7).

To permit the analysis of the radiological consequences of potential reprocessing waste transport accidents the numerous radionuclide-specific source terms must be consolidated in a manageable number of **release categories (RC)**. 10 non-zero release categories were selected for risk assessment including 5 release categories representing non-fire accident environments and 5 release categories representing combined mechanical/thermal impact conditions. The simulated zero-release events were grouped and assigned into one separate category.

The consolidating procedure has been performed by combining source terms of similar radiological significance using an appropriately defined radiological hazard index. In other words, the simulated accident events and the associated source terms resulting in the same or approximately the same radiological consequences have been grouped to form one representative release category. The release categories RC 1 - RC 5 refer to non-fire accident environments and release categories RC 6 - RC 10 to combined mechanical/thermal accident impact conditions. The probability of occurrence assigned to each release category has been derived from the conditional probability of occurrence of each individual source term comprised in the release category.

Selected characteristics of the simulated railway accident events and associated releases for the volume (240 consignments by rail) and type of reprocessing waste considered in the study are given below:

- Based on past experience of the type and severity of freight train accidents and the release characteristics of the waste transport casks/containers considered in the study, the conditional probabilities of simulated accidental sequences of different severities involving reprocessing waste shipments - given a freight train accident which may or may not result in environmental releases - are summarized in the table below:

Accidental Sequence	Conditional Probability [a)]
Zero-release accident events attributable to mechanical (non-fire) impact conditions	0.863
Zero-release accident events attributable to combined mechanical/thermal impact conditions	0.074
Release generating accident events attributable to mechanical (non-fire) impact conditions	0.019
Release generating accidental events attributable to combined mechanical/thermal impact conditions	0.043
Total	1.000

a) Given a freight train accident whereby at least one waste wagon experiences material damage in excess of DM 3000

- The data given above reflect the frequency and severity of railway accidents and the release characteristics of the massive waste transport packages (Type B packages) considered in the study and are indicative that accidental environmental releases are rarely expected to occur. In approximately 94 percent of the simulated fire and non-fire accident events no environmental radionuclide release is expected to occur. But based on a conservative assessment approach for about 6 percent of transport accident events an environmental radionuclide release - including minuscule releases - has been predicted.
- The type and nature of transport accident events causing radioactive material to be released into the environment and the likelihood of occurrence of such a release is further detailed in Tab. 7.8. The table gives the characteristics of the previously defined release categories (RC) for mechanical (non-fire) and combined mechanical/thermal accident impact environments and the associated conditional probability of occurrence given a release-generating accident occurs.
- It is obvious that the magnitude of the accidental activity release increases in ascending order of the release categories for both mechanical-only (RC 1 - RC 5) and combined mechanical/thermal (RC 6 - RC 10) accident environments. However, the probability of occurrence of the environmental releases clearly

decreases inversely as the order of the release categories. The high-probability accidental radionuclide releases (RC 1 .. 3 and RC 6 .. 8) tend to be on the order of 10^7 - 10^{11} Bq. Higher accidental radionuclide releases have conservatively been predicted on the order of 10^{12} Bq, but with a very low conditional probability of occurrence in the range of about 10^{-6} - 10^{-3}.

A complete compilation of the radionuclide-specific release categories based on the procedure described above is shown in Appendix II. The data presented in Appendix II describe the radionuclide specific composition of the particulate environmental release in four particle size ranges (AED < 10 µm, 10 - 20 µm, 20 - 50 µm and 50 - 70 µm) associated with freight train transport accidents (marshalling operations excluded) involving reprocessing waste materials considered in the study. In addition, a complete description of the procedure to form the release categories (RC) has been included in Appendix II for the interested reader.

Table 7.8: Characteristics of the Release Categories (RC) related to Railway Transport Accidents involving Reprocessing Waste Shipments

Release Category (RC)	Acitivity Release (Bq)	Conditional Probability of Occurrence [a)]
Mechanical (non-fire) Impact Conditions:		
RC 1	6.6 E+8	1.52 E-1
RC 2	6.7 E+8	1.21 E-1
RC 3	9.3 E+8	2.84 E-2
RC 4	1.4 E+9	1.54 E-3
RC 5	1.5 E+9	2.65 E-5
Combined Mechanical/Thermal Impact Conditions:		
RC 6	6.0 E+ 7	3.48 E-1
RC 7	1.1 E+11	2.79 E-1
RC 8	8.7 E+11	6.61 E-2
RC 9	1.9 E+12	3.47 E-3
RC 10	3.5 E+12	6.83 E-6
Total:		1.00 E+0

[a)] Given a freight train accident resulting in an environmental release. The conditional probability for this category of railway accidents is about (0.0191 + 0.0439=) 0.0631 given a freight train accident whereby at least one waste wagon suffers material damage in excess of DM 3000.

7.6 Expected probability of freight train accidents resulting in an environmental release

For the evaluation of the potential radiological risks associated with the projected waste shipments from France to Germany the expected probability of occurrence of accident events resulting in a specific environmental release must be known and is essential to assign the probability of occurrence to the individual release categories. The considerations relevant for the estimation of this quantity for the total volume of vitrified and bituminous waste are presented in this section:

The number of railway journeys for the total volume of vitrified (120 railcars) and bituminous (360 railcars) waste to be returned from France over a projected time period from 1995 - 2003 is approximately 240 journeys based on the assumption that on average assemblages of 2 railcars (range 1 - 3 railcars) are carried in a mixed freight train. With a shipping distance from Valognes (France) to Dannenberg (Germany) of approximately 1400 km per journey and an accident rate for regular freight trains of 0.5 per 1 million train-km, the probability of occurrence of a freight train accident somewhere on the shipping route during the 7 - 8 year shipping campaign period is:

240 journeys x 1400 km/journey x 0.5 E-6 accidents/train-km = 0.17

However, based on the analysis of accidental sequences involving regular mixed freight trains in many of these accident events the potential damage will be limited to the engine or railcars other than the wagons carrying the waste transport container. For example, from the information presented in Fig. 7.2 it can be concluded, that in about 58 percent of freight train accident events the resultant damage is limited entirely to the engine and, consequently, 42 percent of accidents may affect the railwagons and/or the engine as well.

From a statistical analysis of freight train accidents it is further known /FET 92a, Tab C-1 (Appendix C)/, that the probability p, that in a mixed freight train with an average number of 30 railcars 1, 2 or 3 wagons with specific characteristics (e.g. the waste wagons) are potentially affected in an accident is for a shipping arrangement of:

1 wagon: $p(1 \in 1) = 5.14$ E-2

2 wagons: $p(1 \in 2) + p(2 \in 2) = 9.48$ E-2

3 wagons: $p(1 \in 3) + p(2 \in 3) + p(3 \in 3) = 1.31$ E-1

If in addition the assumption can be made, that assemblages of 1, 2 or 3 waste wagon shipments are equally distributed over the waste volume and the return shipment period, then the relative frequency that at least one (out of 1, 2 or 3) wagon is affected in a mixed freight train accident is given by:

(5.14 E-2 + 9.48 E-2 + 1.31 E-1)/3 = 0.093

In other words: Waste shipping arrangements travelling in regular freight trains as described above are expected to be affected in a railway accident only in 9.3 percent of accident events. Thus, the probability of occurrence that at least one waste wagon is affected in a regular mixed freight train accidents is:

0.17 x 0.093 = 0.016 (i.e., a chance of 1 in 64)

Considering the volume and performance of the waste transport packages to retain the containment integrity in many accident events and the probability and severity of the anticipated mechanical/thermal load conditions a waste package may experience in a freight train accident it has been shown (see section 7.6), that the relative frequency of a package release is approximately (0.0191 + 0.0439 =) 0.063.

In other words: Given a freight train accident event whereby at least one waste wagon is adversely damaged to the extent to result in loss of cask/container integrity and a subsequent environmental release is conservatively expected to occur in 6.3 percent of such accident events. Thus, for the total volume of vitrified and bituminous waste the probability of a freight train accident resulting in radioactive environmental release - including minuscule quantities - is approximately:

0.17 x 0.093 x 0.063 = 9.9 E-4 (i.e., a chance of 1 in 1010)

Combining the likelihood (probability) of a release-generating freight train accident with the conditional probability (Tab. 7.8) - given a release-generating accident event - that a specified quantity of radionuclides is released into the environment, i.e. the release category (RC), provides the (absolute) probability of occurrence which can be assigned to the respective release category. These expected probabilities of occurrence of a specified radionuclide release have been determined based on the approach described above and have been tabulated in Tab. 7.9.

To develop a broader understanding of the risk assessment approach presented above it is important to note that a series of conservative assumptions have been made for a variety of reasons within the framework of the risk assessment analysis. These include:

- When evaluating freight train accident statistics, a cargo wagon was considered to be affected, if the material damage exceeds DM 3000.
- The speed of a freight train prior to the postulated accident event determines the speed range (0 - 35 km/h, 36 -80 km/h and > 80 km/h) to be used for assigning the accident severity category.
- The potential accident impact loads experienced by a cargo wagon were taken to be equivalent to the accident load encountered by the waste container.
- When determining the waste container's behaviour and the resultant release, it is assumed that the accidental impact corresponds to the upper speed limit of the relevant severity category. Accident loads corresponding to an impact at 5 km/h are treated in the same way as an impact at 35 km/h, for example, which has an energy input that is 50 times greater. Furthermore, it is assumed that the waste package impacts against a surface corresponding to a hard solid structure, although this is seldom the case in reality. Similarly, by assuming a fully engulfing fire and an unfavourable combination of fire temperature (800 °C) and duration (30 minutes, 60 minutes), each fire incident is classified as a very serious fire with adverse effect on the large heavy waste containers.

The combination of these conservative assumptions as part of the accident risk analysis has the effect of clearly overestimating the frequency of accidents involving a release and the associated radiological consequences.

Table 7.9: Expected Probability of Occurrence of the Accidental Release Categories (Rail Transportation) for the Total Volume of Vitrified and Bituminous Waste

Release Category	Estimated Probability of Occurrence [a]
RC 1	1.5 E-4
RC 2	1.2 E-4
RC 3	2.8 E-5
RC 4	1.5 E-6
RC 5	2.6 E-7
RC 6	3.5 E-4
RC 7	2.7 E-4
RC 8	6.5 E-5
RC 9	3.4 E-6
SC 10	6.7 E-9
Total	**9.9 E-4**

[a] All values rounded

7.7 Estimation of the radiological consequences

Following an accidental release and subsequent dispersal of radioactive substances in the environment members of the public can be irradiated by a number of routes externally and internally from radionuclides both in the atmospheric cloud and after deposition onto the ground surface. The potential exposure pathways considered in this study include:

- External irradiation from radionuclides in the cloud (cloudshine)

- External irradiation from radionuclides deposited on the ground or vegetation (groundshine)
- Internal irradiation following inhalation of radionuclides
- Internal irradiation following ingestion of foodstuffs contaminated by deposited radionuclides

The first route of irradiation affects only those people while the individual is present in the contaminated plume or as the plume of radionuclides passes overhead and results in short-term exposure. Long-term irradiation can result from exposure to radionuclides deposited on the ground surface and from radionuclides incorporated and retained in the human body over a long period of time.

The magnitude of irradiation of the population resulting from an accidental release into the atmosphere is related to many factors and can vary substantially depending on the atmospheric meteorological conditions prevailing at the time of release such as the windspeed, wind direction, atmospheric stability, precipitation intensity etc. For predicting the radiological environmental consequences of potential transport accidents the probabilistic accident consequence assessment code COSYMA (Version 93/1) developed under the auspices of the European Commission (EC) has been used throughout this study /HAS 93/. COSYMA calculates the downwind dispersion (Gaussian plume model) of a radionuclide release into the atmosphere and employs models to predict the radionuclide transport in the environment and foodchains and the subsequent dose to man as a function of the downwind distance for a range of weather conditions.

To adequately describe the range of atmospheric conditions at the time of an accidental release along the shipping route the meteorological data from a 2-year recording period of the Braunschweig-Völkenrode weather station was selected for the risk and consequence assessment. The decision was made based on a comparative analysis of meteorological key parameters /MÜL 87/ and complementary material with relevance to judge the atmospheric transport and dispersion of airborne constituents for a number of sites along the anticipated shipping route. The result of the comparative analysis was indicative that the relevant meteorological data for the selected sites in North-Central Europe were reasonably representative.

Although the radiological consequences and associated health risk can be measured in various ways the 50-year committed effective dose to individual members of the public (critical group) and the 25 km-radius region collective effective dose to the population have been chosen throughout this study as the preferred means of quantifying the radiological consequences. Protective measures and dose mitigating actions such as clean-up activities, foodban etc. to minimize the population exposure have not been taken into account in the radiation exposure calculations. Consequently, the predicted doses presented in this chapter are upper (or conservative) estimates that will most likely not be exceeded under realistic conditions.

For estimating the collective effective dose in the 25 km-radius region surrounding the accident site a population density of 358 persons per square kilometre has been adopted for the risk assessment study. This value is most representative for the shipping route region of the waste return shipments including northern parts of France and the western and northern region of Germany.

Based on this generalized assessment approach described above accident related radiation doses were calculated for each release category (RC) for given distances up to 25 km by the COSYMA accident consequence assessment code. The following assumptions were made in this context:

- Ground-level releases (H = 2 m) were assumed for the release categories RC 1 - RC 5 representing mechanical (non-fire) accident environments.
- For the release categories RC 6 - RC 10 representing combined mechanical / thermal accident environments the effective release height H was conservatively set to H = 50 m to account appropriately for plume rise generated by a accidental fire.
  For the purpose of the risk assessment, fire accidents are defined as severe fires with respect to fire temperature (800°C), fire extension (fully engulfing) and impact duration (up to 60 minutes). Such fires correspond to a heat output of 20 MW and more, leading to substantial plume rise of the fire-generated hot gases. The assumed effective release height of 50 m is clearly lower than plume rise predictions for hot gases using standard formulae's, e.g. /VDI 87/.
- COSYMA runs were carried out separately for particle releases less than 10 µm (AED) and for the 10 - 70 µm size range and subsequently

superimposed for each release category. This approach allows to take adequately into account the deposition characteristics of particles in the human respiratory tract (particles > 10 µm (AED) are generally non-respirable) and by wet and dry deposition processes on the ground surface.

The numerical results derived from the probabilistic accident consequence assessment code COSYMA are generally presented as cumulative complementary frequency distributions (CCFD) showing the frequency or probability of a specified outcome, e.g. the dose to critical group individuals at a given distance, for example of 250 m, 1150 m and 6250 m from the site of the accidental release. The CCFD's presented subsequently are generated by superimposing the calculated CCFD's of the 10 release categories (RC). In doing so, the probability of occurrence of the individual release categories must be taken into account. The expected probabilities of occurrence have been derived from the probability of freight train accident events and the conditional probability of occurrence of each individual release category - given a release generating accident occurs - shown in Table 7.9.

7.8 Transport risk assessment results: Presentation, discussion and conclusions

The estimated radiological consequences of potential transport and handling accidents related to reprocessing waste return shipments by rail from France have been quantified in terms of potential **individual** and **collective** doses to the population and are shown in Fig. 7.3 and Fig. 7.4. The probabilistic assessment results are presented as cumulative complementary frequency distributions (CCFD) of doses resulting from accidental releases (x-axis) vs. the expected probability that a given (individual or collective) dose may be reached or exceeded.

The individual dose to members of the population is specified in terms of 50-year committed effective dose (adults) below the plume centerline from internal and external exposure to radionuclides under the condition of absent mitigative actions and refers to a hypothetical individual residing permanently at a specified distance (e.g., 250 m, 1150 m and 6250 m) from the accident site. The predicted individual dose estimates are believed to be conservative and will most likely not be exceeded under realistic living conditions anywhere along the shipping route should an accident occur.

The collective effective dose is related to the 25 km-radius region surrounding the postulated accident site and assuming a uniform population density distribution of 358 persons per square kilometer.

The likelihood or probability of a specified outcome (consequence) given on the vertical axis refers to the total volume of vitrified (120 railcars) and bituminous (maximal 360 railcars) waste shipments expected to be returned by rail from France (La Hague) over a projected time period from 1995 - 2003 for interim storage at the Gorleben site.

The following conclusions can be drawn from the transport risk assessment results presented in Fig. 7.3 and Fig. 7.4:

- Based on the accident rate of regular freight trains on the French and German railway network the probability of occurrence of a waste wagon to encounter some level of material damage in a freight train accident is about 0.016, i.e. a chance of 1 in 64 for the total volume of vitrified and bituminous waste transports to be returned from France over a projected time period from 1995 - 2003. In other words: By shipping a waste volume 64 times larger than the volume considered in this study, one railway accident is expected to occur resulting in material damage to (at least one) the waste wagons being carried in a regular freight train somewhere on the 1400 km shipping route.

  The term material damage is used to mean damage to the transport vehicle in excess of DM 3000 arising from a vehicular collision, crash, derailment etc.

- Most railway accidents referred to above, however, will not compromise the structural waste package integrity and, consequently, do not result in a package activity release. Accidents with the potential to affect the integrity of Type B waste transport casks or containers as considered in the study require a high level of intensity of the mechanical and/or thermal accidental impact loads to cause all barriers of the package containment system to fail. The available railway accident data for France and Germany indicate that such high-intensity railway accidents are rarely expected to occur. Based on a conservative approach to describe the structural package response it has been found that 1 out of 16 (1/64:1/1010) freight train accidents result in material damage giving rise to a package release of radioactive material for the total transport volume of vitrified and bituminous wastes.

Consequently, the conservatively estimated chance for an accident-related radioactive package release is less than 1 in 1010 (P = 9.9E-4) somewhere on the 1400 km shipping route for all waste transports being returned within the projected 8-year shipping campaign.

- For a large fraction of accident events giving rise to a package release, however, the quantity of radionuclides escaping from the waste transport cask or container is quite low resulting in predicted doses far below of being a matter of concern even in close proximity of the accident site. For example, the accident-related 250 m-dose below the plume centerline corresponding to a value of one thousandth (1/1000) of the 1-year natural radiation exposure of about 3 mSv (i.e. a dose of approximately $3 \cdot 10^{-6}$ Sv) has conservatively been predicted to occur with a probability of $8 \cdot 10^{-4}$, i.e. a chance of 1 in 1250. In other words, such an accidental sequence is expected to occur with a frequency of not more than once by transporting a waste volume 1250 times larger than the projected vitrified and bituminous waste volume to be returned from France.
- Accidental radionuclide releases in quantities resulting in below-plume-centerline-doses to critical group individuals under absent dose-mitigative actions close or exceeding the natural radiation exposure of **one** year have conservatively been predicted with a likelihood of about $4 \cdot 10^{-5}$, i.e. a chance of 1 in 25 000.
- Radioactive releases and the associated below-plume-centerline 50-year committed effective doses in excess of 50 mSv are not expected to occur even in close proximity of the accident site (250 m) at a probability level as low as 10^{-7}, i.e. a chance of 1 in 10 million for the total volume of vitrified and bituminous waste. If expressed as probability per year, the corresponding value would be well below 10^{-8} per year.
- The potential radiological consequences decline rapidly with distance from the accident site and, consequently, the potentially adverse consequences of transport accidents are generally limited to an area in close proximity of the accident site.
- The predicted radiological risk of transport accidents, i.e. the likelihood of an accident/incident and the consequences, resulting from such an accident/incident is dominated by accident events involving bituminous waste shipments.
  Especially, accidental sequences such as severe freight train accidents resulting in high mechanical loads to the waste container and subsequent fire impact to a multiple-package shipment of bituminous waste have been identified as being

potential low probability, high consequence events, if conservatively no fire-fighting activities are taken into account over the entire post-accident time period. This assumption is quite conservative, since such emergency arrangements are regularly in place close to any location of such transports.

- Similar considerations and explanations as given above apply to radiological risk attributable to waste transport accidents expressed by the collective dose vs. probability. Accidental releases and the resultant collective doses to the population in the 25 km-radius region around the site of the postulated accident generally represent only a small fraction of the radiation exposure of natural origin to the population residing in a corridor of 800 m extending on both sides of the transport path.

Evaluation of the quantitative probabilistic assessment results must take into account the major conservatism's introduced in the assessment approach. Notable examples include:

- The transport cask/container activity inventory was assumed for a major fraction of waste transport packages to have maximum permissible values.
- The response and behaviour of the containment system represented by the packaging and the waste product to the potential mechanical (up to 110 km/h impact onto a hard solid surface or structure) and thermal (up to 60 minute fully engulfing 800°C fire and no fire fighting activities or forced cooling over the entire post-accident time period) impact forces were generally taken to maximize the cask/container damage and the subsequent radionuclide release.
- All casks/containers forming a shipment (up to a maximum of 3 railcars carrying up to 6 waste containers) were assumed to encounter the same level of maximum damage and radionuclide release in a regular freight train accident.
- Estimation of the radiological dose to the population arising from an environmental accidental release is based on the critical group concept (50-year internal and external exposure of a hypothetical individual) under the condition of **absent** mitigative actions.

Overall, these assumptions are believed to result in a significant overestimation of the transport risks, i.e. the radiological dose and the likelihood of occurrence, that will most likely not be exceeded under realistic transport and environmental conditions.

The results of the risk assessment study are broadly consistent with previous transport risk assessment studies, which have, for example, been conducted for projected waste transports to the Centre de l'Aube, France, /RAF 94a, RAF 94b/ or the designated Konrad Waste Repository in Germany /LAN 92/ if differences in the waste volume and other characteristic factors are appropriately taken into account.

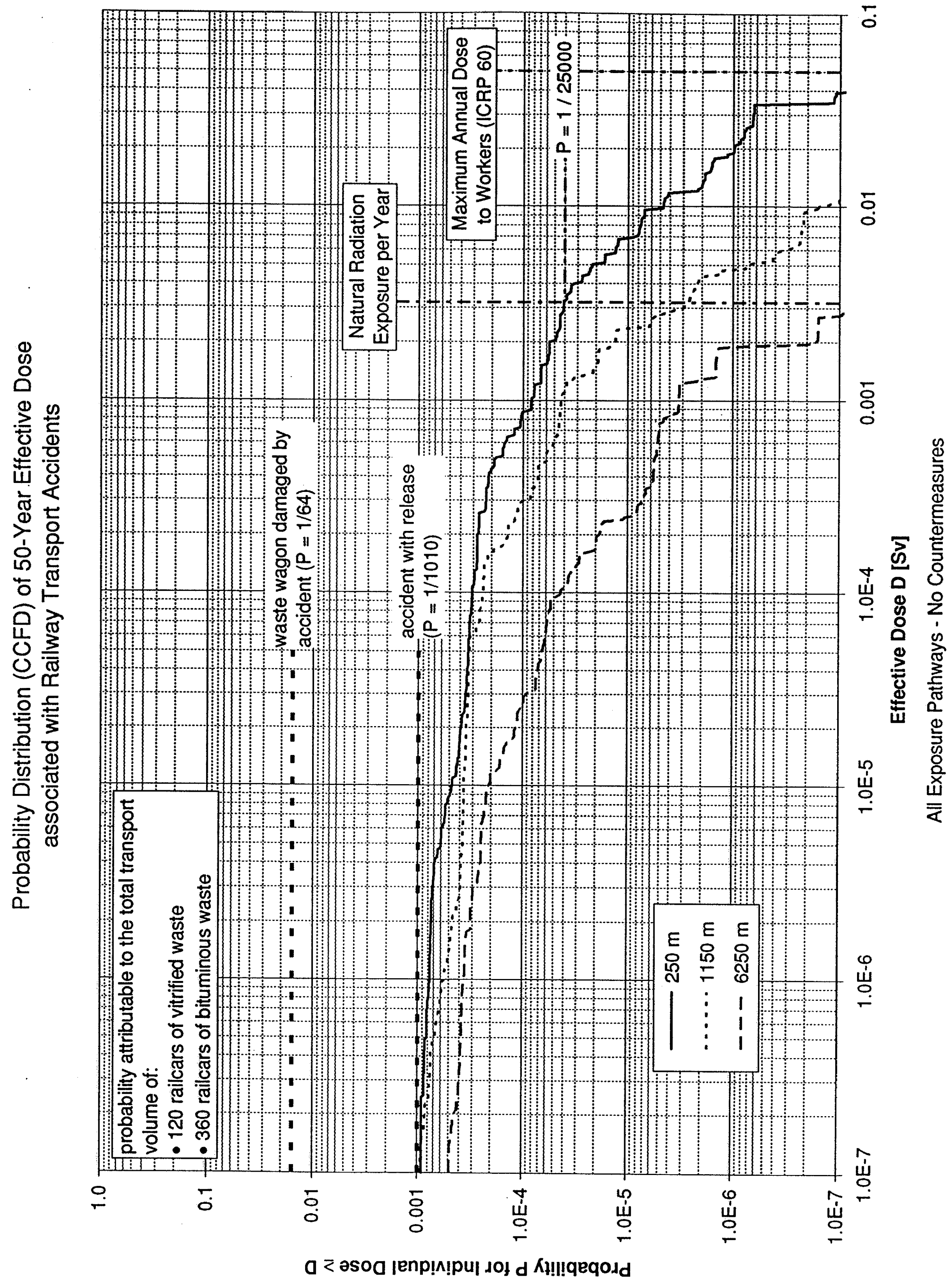

Fig. 7.3: Probability Distribution (CCFD) of the 50-Year Individual Effective Dose attributable to Railway Transport Accidents for the Total Volume of Vitrified and Bituminous Waste to be returned from France

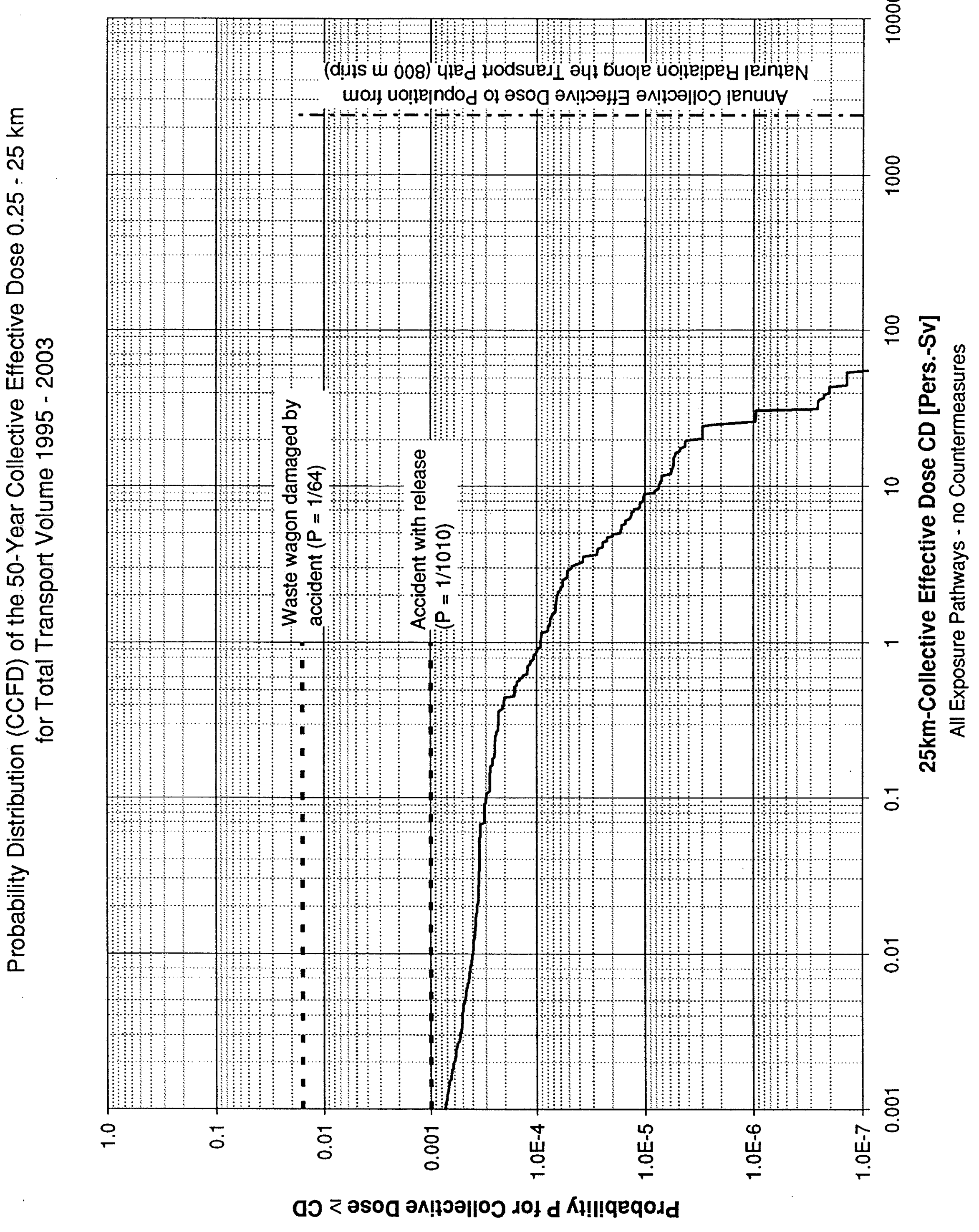

Fig. 7.4 Probability Distribution (CCFD) of the 50-Year Collective Effective Dose attributable to Railway Transport Accidents for the Total Volume of Vitrified and Bituminous Waste to be returned from France

8 Summary and conclusions

The primary goal of the transport risk assessment study is the quantification and evaluation of the radiological consequences associated with accident-free transport and potential transport and handling accidents of return shipments of radioactive wastes from France to Germany generated by reprocessing of German fuel elements. Not considered in the study are return shipments of uranium and plutonium recovered from the spent fuel.

The main results of the study regarding accident-free transportation and potential transport and handling accidents are the following:

- The projected shipping campaign of radioactive waste from La Hague to the Interim Storage Facility Gorleben corresponding to the first 10-year reprocessing contract period (1985 - 1995) is from 1995 to about 2003. During this period, on average up to 115 waste containers will be shipped per year, requiring about 65 railway wagons and about 33 trains per year.
- The collective effective dose has been predicted to be on the order of 0.02 man-Sv/yr for the rail-crew, 0.01 man-Sv/yr for the loading terminal personnel (Valognes and Dannenberg), and approximately 0.03 man-Sv/yr for the general population. Collective effective doses attributable to railyard operations are currently not available.
- Conservatively estimated individual doses (critical group) for the general population have been predicted on the order of: ca. 0.01 mSv/yr for members of the public/residents living close to the transport route, 0.02 mSv/yr for permanently employed staff members of a scrap metal yard located close to the siding tracks of the Ehrang railyard, and 0.03 mSv/yr for permanent residents (critical group) at the Valognes and Dannenberg loading terminal.
- Conservatively estimated individual dose predictions for the transport personnel are on the order of: 0.1 - 0.2 mSv/yr for railway personnel (e.g. the train driver, escorts, shunters, and inspectors), and about 0.7 - 1.7 mSv/yr for crane operators, handlers and health physicists at the Valognes and Dannenberg loading terminal. The information available indicates that the critical group generally represents a very small population group.

It must be born in mind that the reprocessing waste related movements represent a large amount of transports on a single transport path (about 115 waste wagons per year). Furthermore, it is of the same order of magnitude than the domestic annual transports of low- and intermediate-level waste to the French disposal site Centre de l'Aube (about 681 railwagons and 370 trucks) /TOR 92, TOR 93/ or projections made for the designated Konrad Waste Repository in Germany (about 390 trains/yr) /LAN 92/.

Concerning the collective effective dose, the results are of the same order of magnitude as those of the transports to the Centre de l'Aube (0.48 man-Sv/yr, equally distributed between public and workers) and the designated Konrad Repository (approx. 0.3 man-Sv/yr for the public and the transport personnel).

While the public collective dose represents the appreciable fraction of the total collective dose, it should be mentioned that this radiological impact is derived from individual doses quite below the exposure level of 0.01 mSv/yr which is considered as negligible /IAE 88/. However, doses to the public (critical group) at Valognes and Dannenberg terminal are clearly above this value. Furthermore, due to the loading/unloading procedures required by the containers adopted for the return of the German waste, the associated individual dose of the personnel at Valognes or Dannenberg is significant.

However, despite of the conservative nature, the predicted individual doses for the general population (critical group) are well below the dose limits for members of the public of 1 mSv/yr recommended in the Transport Regulations and by the International Commission on Radiological Protection (ICRP-Publ. 60) and represent only a small fraction of the natural radiation exposure of about 3.2 mSv/yr in Germany and 5.0 mSv/yr in France /ICR 91, CEC 93/.

For personnel involved in waste transport operations, the predicted individual doses to the critical group of workers are within the applicable limits of the IAEA Transport Regulations as well as the ICRP dose limits for occupational exposure.

The analysis results of causes and consequences of potential transport accidents arising from shipments of vitrified and bituminous waste from France over a projected time period from approximately 1995 - 2003 support the conclusion, that the reprocessing waste transport accidents do not represent a significant risk to man and his environment.

The transport risk assessment results reflect the high level of safety and protection provided by safety requirement embodied in the national and international Transport Regulations, the waste acceptance criteria of the Interim Storage Facility and the anticipated shipping practice for the reprocessing waste materials.

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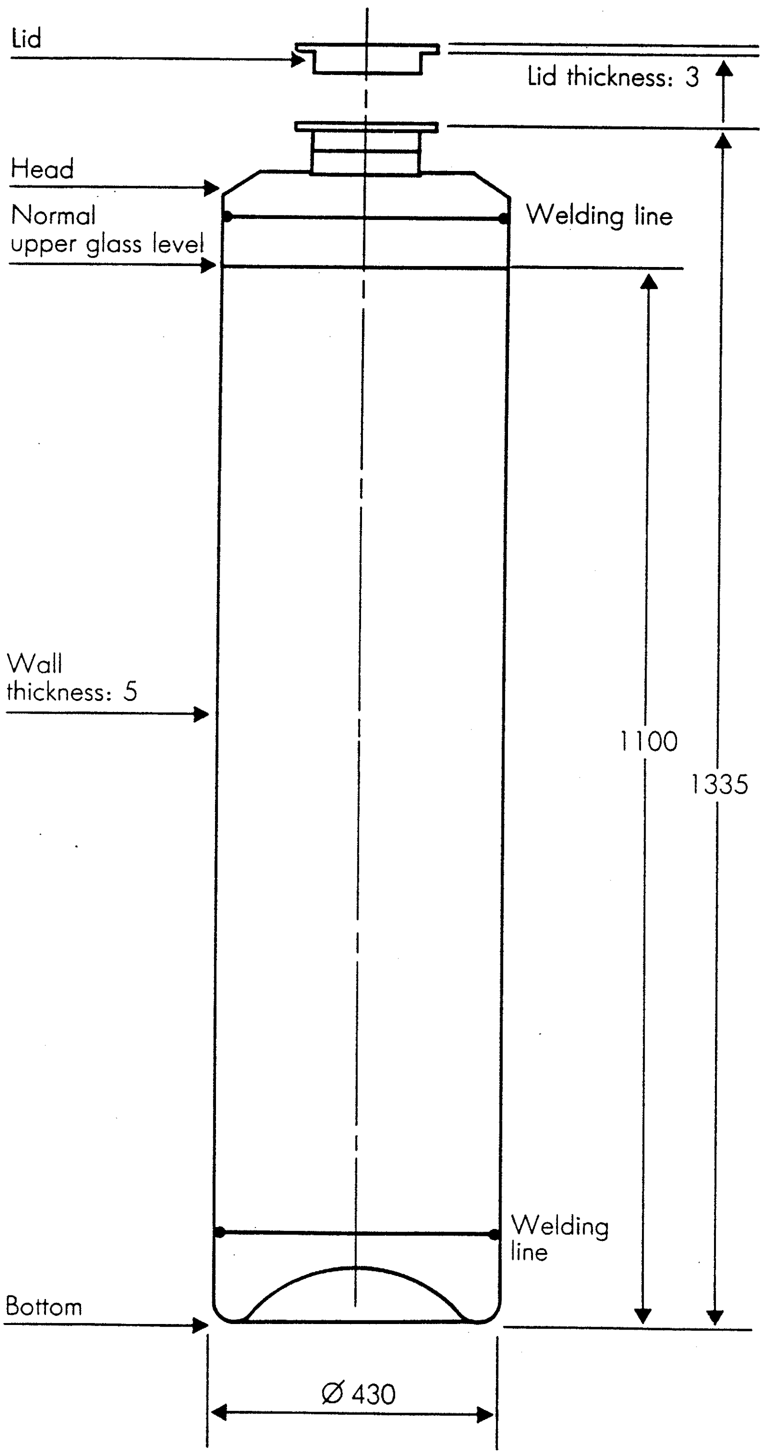
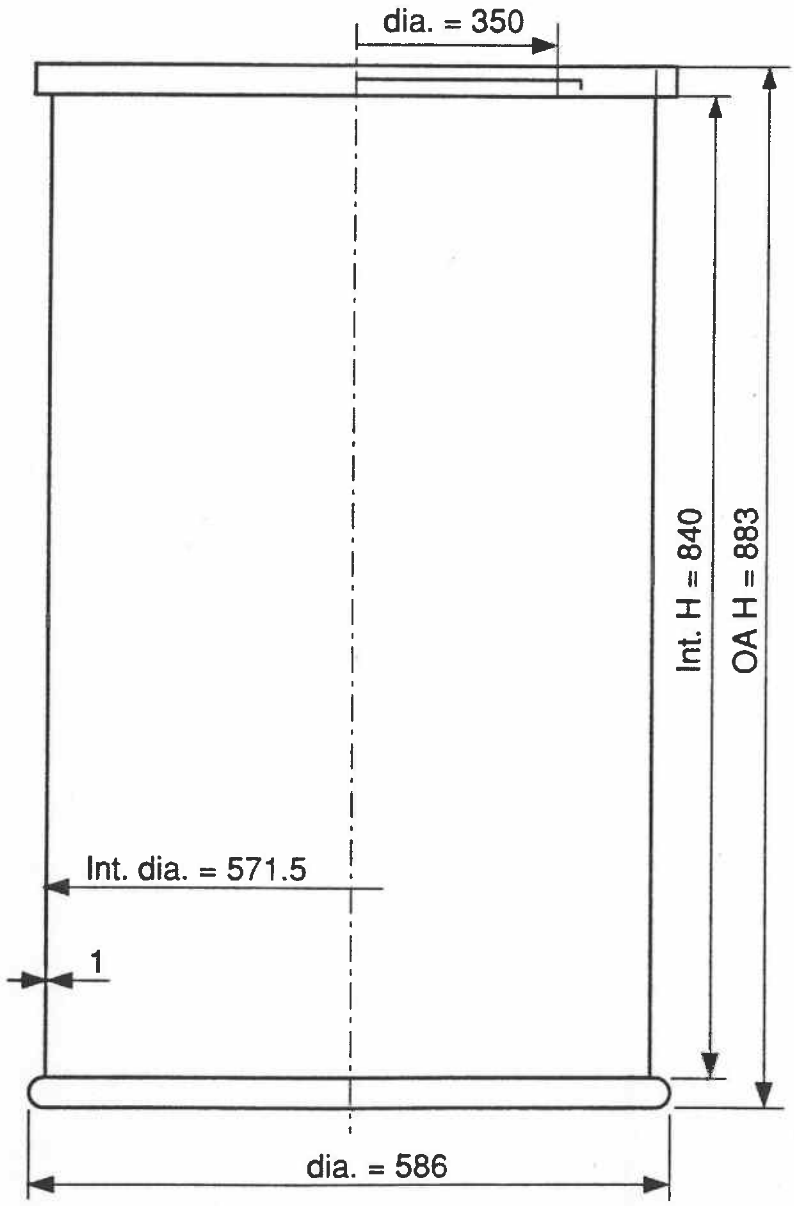
APPENDIX I:

Packagings and Transport Equipment for Reprocessing Waste Materials

DIAGRAM "C"

GLASS CONTAINER UP2 - UP3: OVERALL DIMENSIONS
Container glass volume: 150 l
(all dimensions in mm)

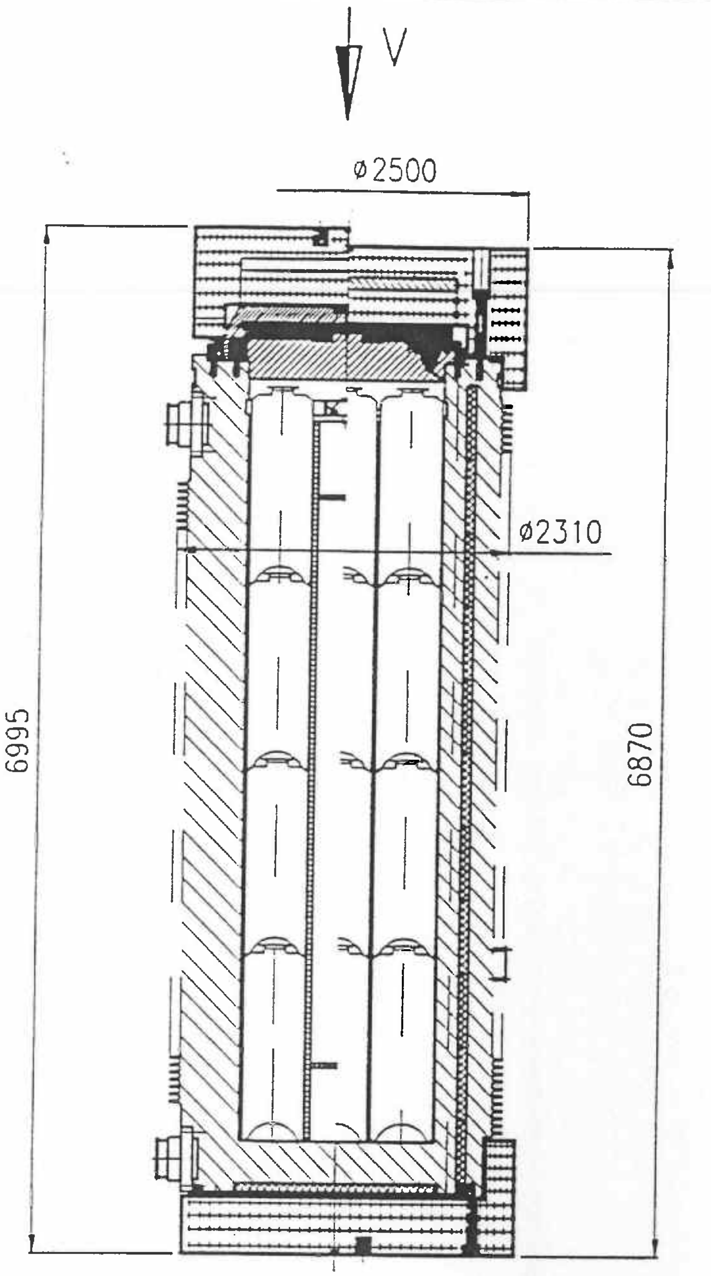




(Dimensions in millimeters)

FIGURE A

DRUM FOR BITUMEN-COATED MATERIAL



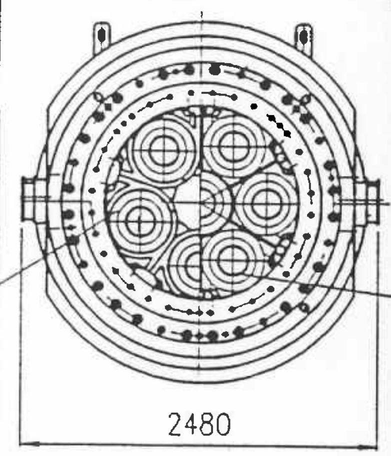
Ansicht V — ohne Deckelstoßdämpfer, Primärdeckel
without TOP SHOCK ABSORBER, PRIMARY LID

Transportmasse unbeladen 108780kg
TRANSPORT WEIGHT LOADED

Transportmasse beladen 111000kg
(mit Stoßdämpfer)
TRANSPORT WEIGHT LOADED
(WITH IMPACT LIMITER)

Transportmasse beladen 114000kg
(mit Stoßdämpfer+Sekundärdeckel)
TRANSPORT WEIGHT LOADED
(WITH IMPACT LIMITER)

Tragkorb / Basket
20 HLW - canister



Transportmasse unbeladen 109780kg
TRANSPORT WEIGHT LOADED

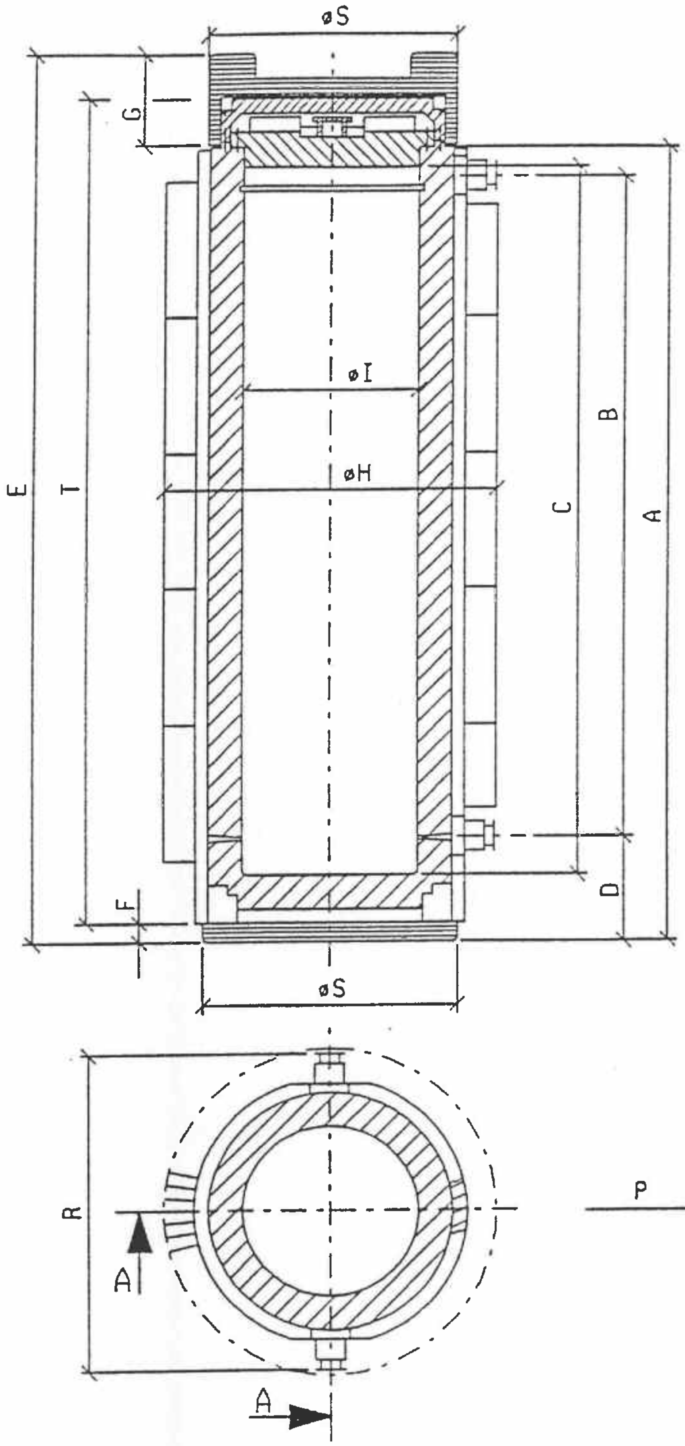
Transportmasse beladen 112000kg
(mit Stoßdämpfer)
TRANSPORT WEIGHT LOADED
(WITH IMPACT LIMITER)

Transportmasse beladen 115000kg
(mit Stoßdämpfer+Sekundärdeckel)
TRANSPORT WEIGHT LOADED
(WITH IMPACT LIMITER)

CASTOR HAW 20/28 CG

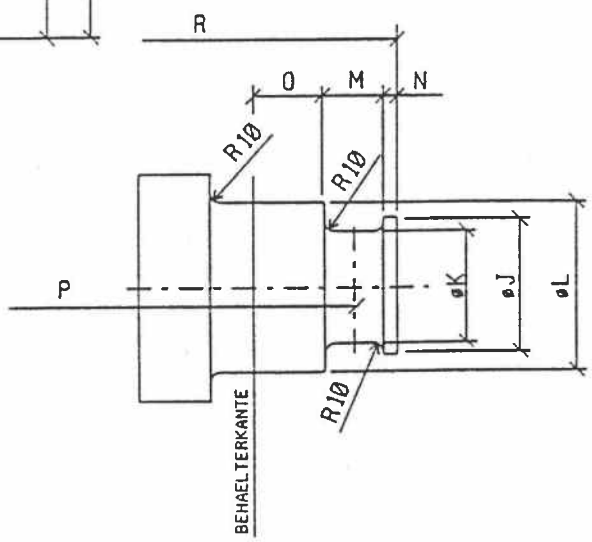
Tragkorb / Basket
28 HLW - canister

SCHNITT A-A



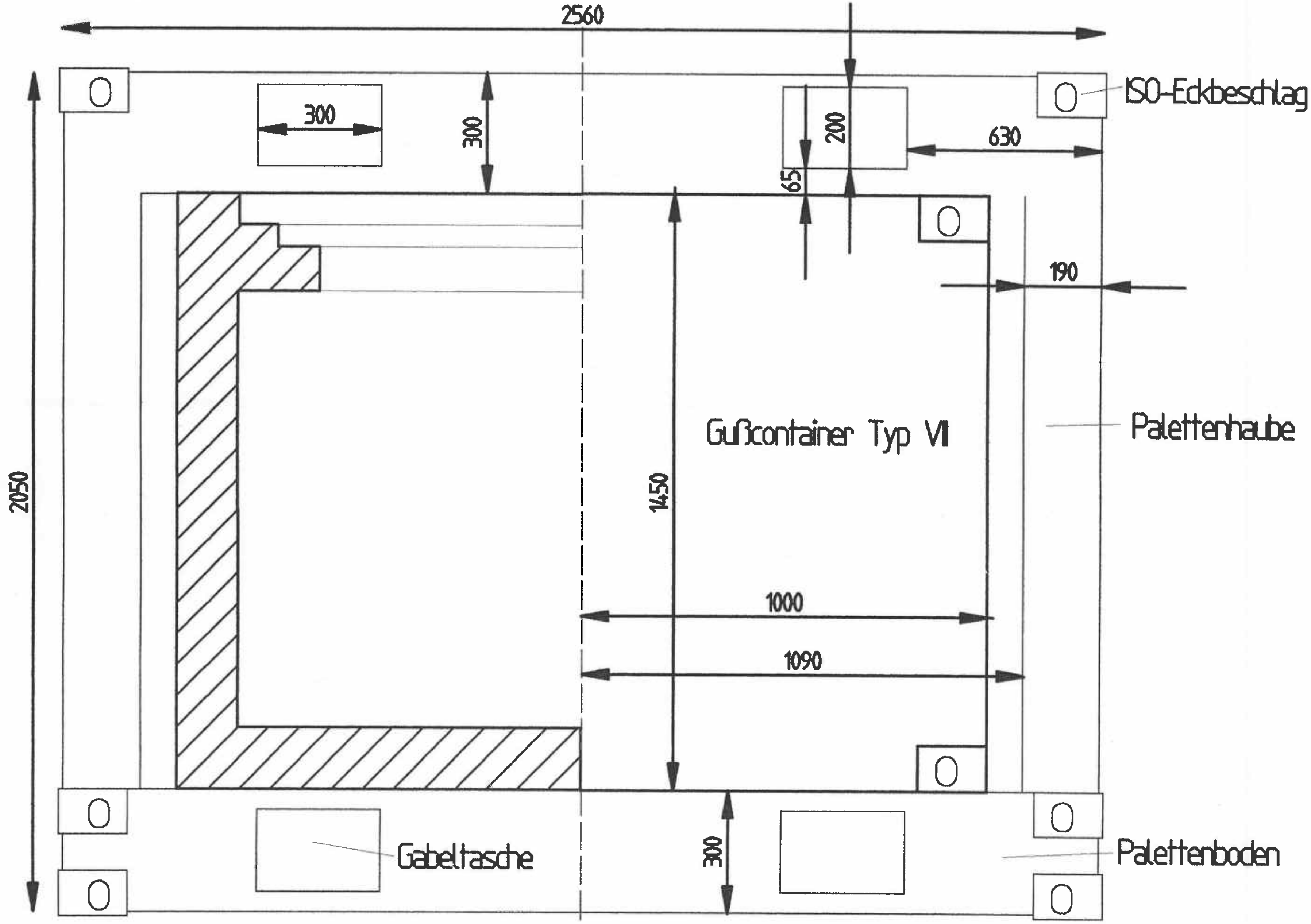
ABMESSUNGEN [MM]			
A	5990	N	10
B	5000	O	85
C	5178	P	2390
D	650	R	2480
E	6866	S	2150
F	170	T	6100
G	906	U	
H	2500	V	
I	1385	W	
J	280	X	
K	250	Y	
L	300	Z	
M	70		

MASSEN [kg]		
	28er KORB	20er KORB
EINSATZKORB	2830	6800
INHALT	14000	10000
VERSANDSTUECK BEI TRANSPORT VOM LAGER	114340	114310
VERSANDSTUECK BEI HANDHABUNG IM LAGER	111710	111680



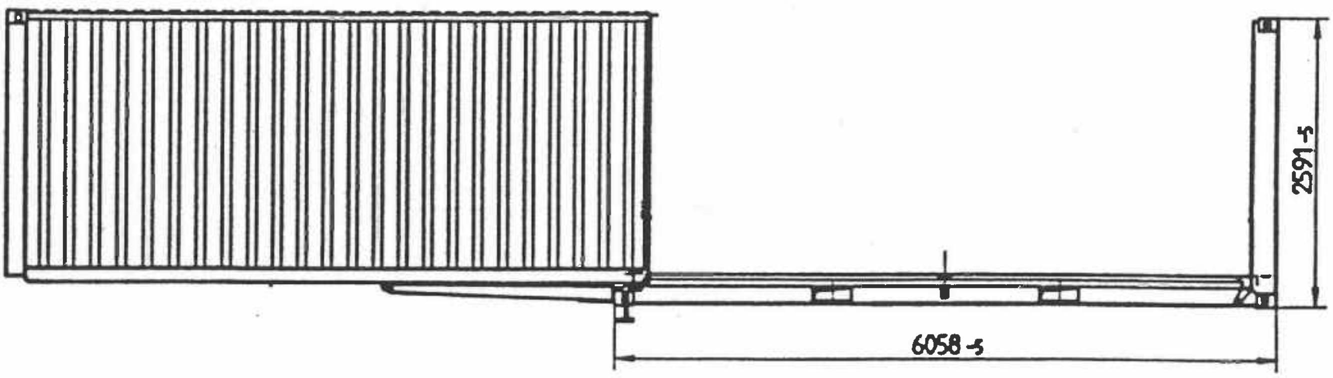
GNB	Datenblatt TS 28 V mit Primär- und Sekundärdeckel	Abb. 2

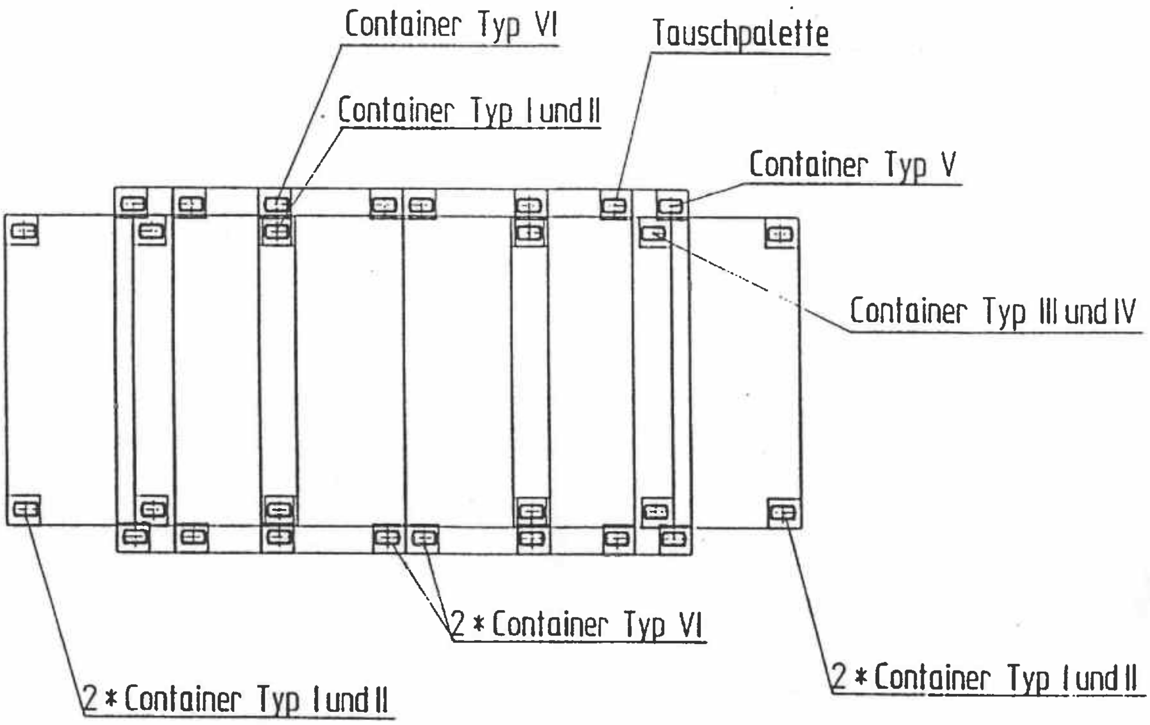
BAI 2/DB/62335



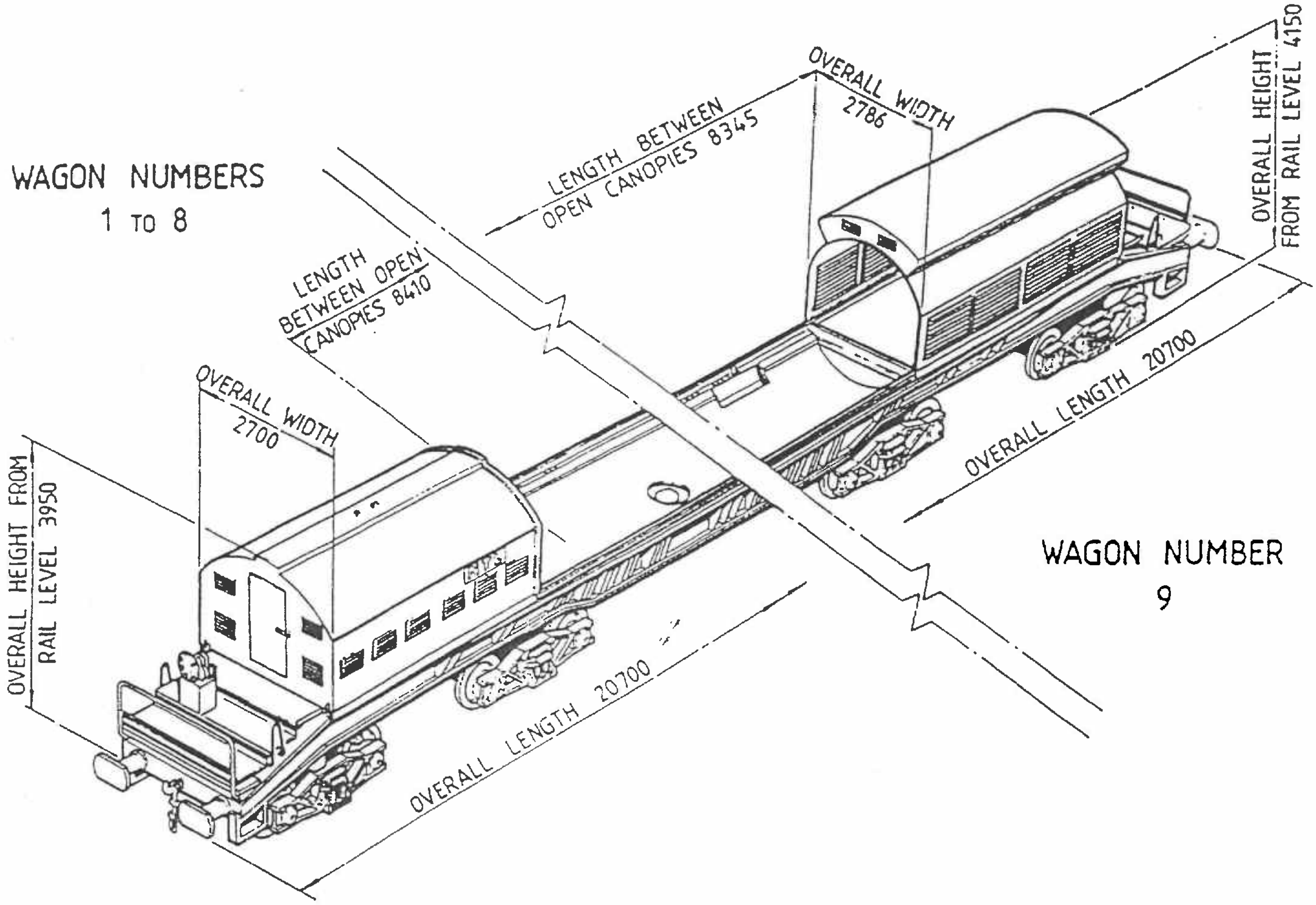
Transportpalette TP 002/1 mit Gußcontainer Typ VII

Seite

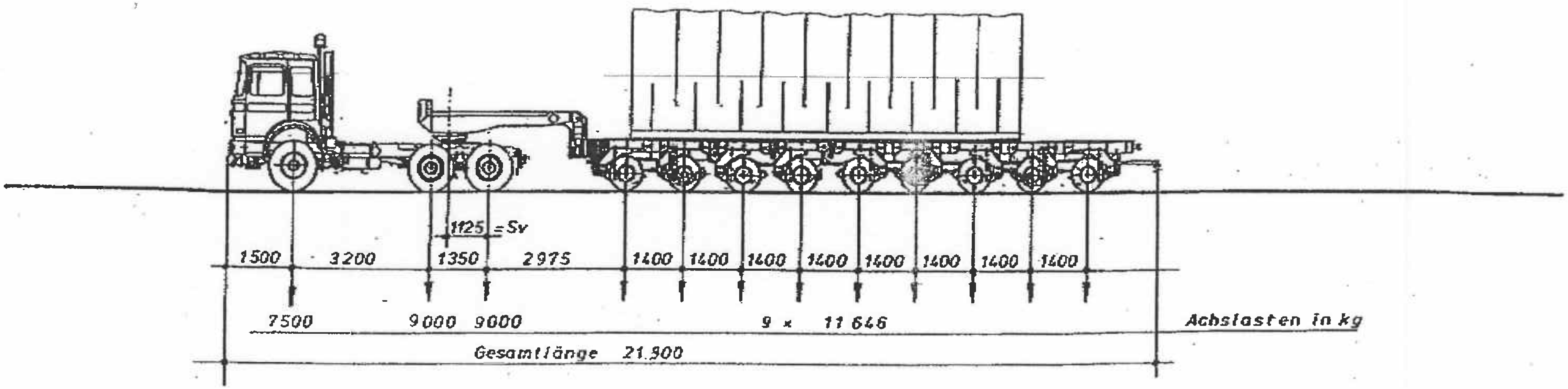


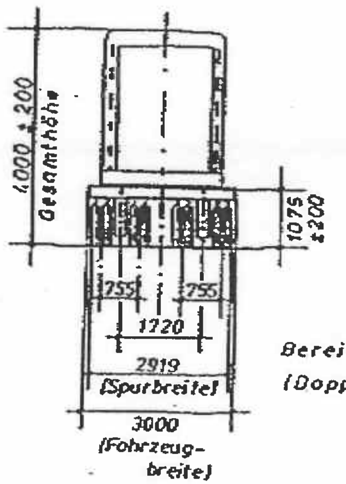


GNS	Open-All-Container, ISO-Anschlagpunkte in der Bodengruppe	Bild



Type of Vehicles being used for Waste Transportation





Bereifung: 7.50-15
(Doppelräder)

	Tag	Name
bearb.	[illegible]	Forwy
gez.		
gepr.		

Transportskizze

Behälter mit Gestell

auf DB-Schwerlastfahrzeug LS 250

Zugmaschine MAN 26 331 DFSL

Nr. N84- 9. S L


NOT TO BE USED FOR
LIFTING THE FLASK

APPENDIX II:

Dose Estimation for the Valognes Loading Terminal

D. Raffestin (CEPN)
T. Schneider (CEPN)

1. THE VALOGNES TERMINAL

1.1. Overview of the loading/unloading terminal of Valognes

The loading terminal of the COGEMA reprocessing plant is located in the industrial area of Valognes, at about 40 km from La Hague (1 hour truck trip). It covers a total surface of 50 m x 400m surrounded by wire fence. As far as the critical group is concerned, the nearest and only house in the vicinity of the loading terminal is located at about 100 m distance from the radiological sources and a nearby main road is within a range of 100 m. Lastly, an industrial depot is 40 m north of the terminal.

Currently, about 15 people are employed to run this station. The staff is composed of executives, health physicists and loading crew. Under the rails, a water salvage system recuperates the dripping water and stores it in an intermediate tank where the absence of contamination is checked.

Materials to be sent are conveyed by truck from the COGEMA reprocessing plant to the Valognes terminal. They are loaded on wagons using a crane. After loading, the wagon can remain on siding tracks up to 2 or 3 days. An average value of 36 hours is assumed for the assessment of the radiological impact for the public critical group at Valognes.

1.2. Loading procedure and schedule

The unloading/loading procedure is highly dependent on the kind of package to be loaded. An ISO container requires about 15 min to be transfered, while a TN (equivalent in dimension to a Castor 20/28) represents a 45 min duration operation.

For the purpose of this study, we assume that the loading/unloading procedure takes about 15 min for the bituminous waste (BIW) and about 45 min for the vitrified waste (HAW).

The different steps of the loading operation and their durations are described below.

a) BIW

- Preparation of the wagon and truck : 10 min requiring 3 people (one crane operator at 6 meter distance, one health physicist at 5 meter distance and one handler at 1 meter distance).
- Hitching of the package : 5 min requiring 2 people (one crane operator at 6 meter and one handler at 1 meter).
- Control of the package : 5 min requiring one health physicist at 1 meter distance.

b) HAW

- Preparation of the wagon and truck : 40 min requiring 6 people (one crane operator at 6 meter distance, one health physicist at 5 meter distance and 4 handlers who operate the package (mainly near the spindles) at 1 meter distance).
- Hitching of the package : 5 min requiring 5 people (one crane operator at 6 meter and 4 handlers at 0.5 meter (in front of each spindle)).
- Control of the package : 5 min requiring one health physicist at 1 meter distance.

To cope with the large amount of operations, it is assumed that 6 handlers, 2 health physicists and one crane operator will be available for the annual operations related to the return of the German waste and that the individual dose per category will be equally distributed among each of them.

1.3. **Radiological impacts at Valognes**

1.3.1. Assessment of occupational individual and collective doses

For the calculation of the annual individual dose D_t (mSv/year) to each of the 3 categories of personnel, it is assumed that the package is equivalent to a punctual source. Thus the following formula have been used :

$$D_t = \sum_i D_{ti} = \sum_i T_i \cdot R_i \cdot N_i \cdot D_i \cdot \frac{[1m + (l_i/2)]^2}{[d_i + (l_i/2)]^2}$$

with

i :	Index representing the kind of operation (preparation, hitching and control) on a given category of waste (HAW, HEC, ...)
D_{ti} :	Annual individual dose to a category of personnel t for an operation i on a given category of waste (mSv/y)
T_i :	Average time of operation (hours)
R_i :	Ratio of effective work related to the total number of available people in the category t
N_i :	Number of containers per year
D_i :	Dose rate at 1 meter associated with each category of waste (mSv/h)
l_i :	Equivalent width of the container (for non cylindrical container, an equivalent diameter is assumed) (meter)
d_i :	Distance from the package (meter)

Table 6.5. details the process of calculation.

Table 6.5. Occupational Individual doses at Valognes

Cat.	type	l_i (m)	T_i (h)	D_i (mSv/h)	N_i (cont/y)	R_i	d_i (m)	D_{ti} (mSv/y)
H.P.	HAW	5,7	40	0,11	15	0,5	5	0,13
	HAW	5,7	5	0,11	15	0,5	1	0,07
	BIW	2,1	10	0,2	100	0,5	5	0,19
	BIW	2,1	5	0,2	100	0,5	1	0,83

Cat.	type	l_i (m)	T_i (h)	D_i (mSv/h)	N_i (cont/y)	R_i	d_i (m)	D_{ti} (mSv/y)
Handler	HAW	5,7	40	0,11	15	0,67	1	0,73
	HAW	5,7	5	0,11	15	0,67	0,5	0,12
	BIW	2,1	10	0,2	100	0,17	1	0,56
	BIW	2,1	5	0,2	100	0,17	1	0,28

Cat.	type	l_i (m)	T_i (h)	D_i (mSv/h)	N_i (cont/y)	R_i	d_i (m)	D_{ti} (mSv/y)
Crane O.	HAW	5,7	40	0,11	15	1	6	0,21
	HAW	5,7	5	0,11	15	1	6	0,03
	BIW	2,1	10	0,2	100	1	6	0,28
	BIW	2,1	5	0,2	100	1	6	0,14

The individual dose to each category of workers and the associated number of workers are presented in Table 6.6 and thus allowed the calculation of collective doses.

Table 6.6. Occupational individual and collective doses at Valognes related to the manipulation of German reprocessed waste

Category	Number of worker	Individual dose Dt mSv/year	Collective dose man.mSv/year
Health Physicist	2	1,2	2,4
Crane Operator	1	0,7	0,7
Handler	6	1,7	10,1
Total	9	1,5	13,2

As to be expected the greatest individual and collective doses are received by the handlers group.

We can compare these individual doses to the current individual dose at Valognes. But, as the individual exposure is not available for all categories of personnel, we can only refer to the health physicist dose. In average for current standard operations, he receives an annual dose of about 1 mSv.

1.3.2. Assessment of individual doses to critical member of public at Valognes

For the purpose of this assessment, the following assumptions have been considered :

The closest dweller stands at 100 meter distance from the sources

He spends 1 hour per day in his garden, shielding 1 (assuming a 100 m distance between him and the sources)

He spends 18 hours per day in his house, shielding 20 (in order to take into account the house walls and terminal building)

Each rail wagon stays 36 hours on siding tracks

Figure 6.1. illustrates the respective position of the critical public house :

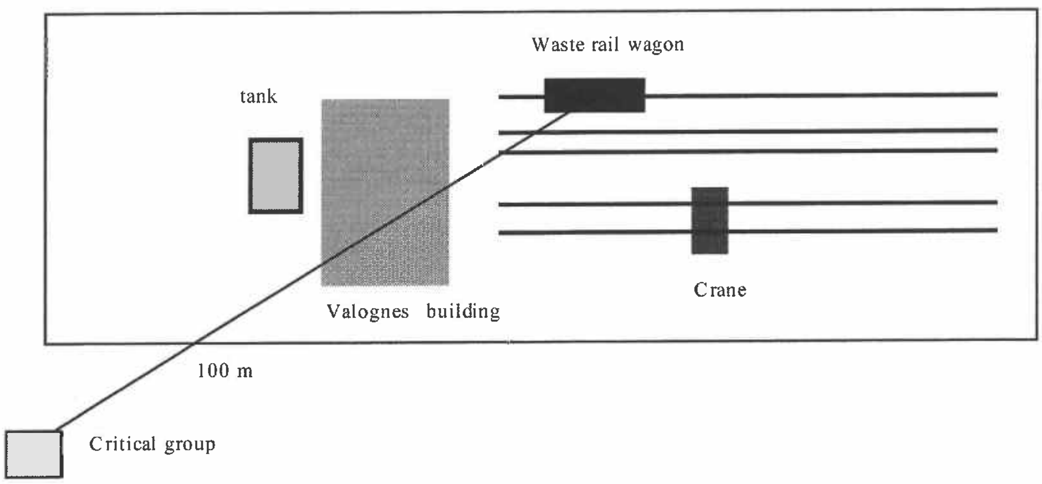


Figure 6.1. Scheme of Valognes

The total annual individual dose Dt (mSv/year) is derived from the following formula :

$$Dt = [(1h/24h) + (18h/24h).1/20]36h.\sum_i N_i.D_i.\frac{(1m+(l_i/2))^2}{(100)^2}$$

with D_i : Dose rate at 1 m associated with each category of waste i (mSv/h)

l_i : Equivalent width of the container (for non cylindrical container, an equivalent diameter is assumed) (meter)

Ni : Annual number of containers

Table 6.7 presents the public individual doses associated with each category of waste where $D_{i\,100}$ is the annual dose rate at 100 m associated with each category of waste.

Table 6.7. Annual individual doses for the public critical group at Valognes

type	l_i m	D_i mSv/h	N_i /year	$D_{i\,100}$ mSv/year
HAW	5,7	0,11	15	7,0E-03
BIW	2,1	0,2	100	2,4E-02
TOTAL				**3,1E-02**

APPENDIX III:

Definition and Formation of Release Categories (RC) related to Potential Waste Transport Accidents (Marshalling Operations excluded)

F. Lange (GRS)
H.J. Fett (GRS)
G. Schwarz (GRS)

Definition and formation of release categories (RC) related to potential waste transport accidents (Marshalling Operations excluded)

A **source term** generated by the accident simulation program represents the released activities of individual radionuclides for the simulated accident configuration. The radionuclide-specific activities are determined by the activity content of the waste packages involved in the accident and the release fraction assumed to be released into the atmosphere.

A **radiological hazard index** of a source term is calculated by summation of the activity of the various radionuclides multiplied by nuclide-specific weighting factors. The weighting factors were determined for each radionuclide by calculating the total effective dose resulting from unit release for standardized conditions, taking into account the exposure pathways inhalation, groundshine, ingestion and cloudshine. The weighting factors used are considered to be an adequate measure of the relative radiological significance of the individual radionuclides released in an accident.

Source Term Groups and Release Categories:

For the purpose of subsequent analysis of possible radiological consequences and their expected frequencies of occurrence the following information is assigned to each generated source term:

- The accident severity category (k = 1, 2, 3 ... 9)
- The conditional probability of the accident sequence (given an railway accident)
- A radiological hazard index calculated from the radionuclide-specific activity which permits an approximate relative ranking of different source terms with respect to potential radiological consequences

To facilitate the analysis of environmental consequences, the large number of source terms (approx. 9000 simulated accident events which may or may not give rise to an environmental release depending on the package type and the accident severity) must first be appropriately grouped into a limited number of **source term groups**. In a next step for each source term group a representative source term is determined designated as **release category (RC)**. The procedure to determine representative source term groups is described by making reference to Figs. III-1 and III-2. The source terms generated by the accident simulation program are characterized by the associated radiological hazard index and the conditional probability of the accident configuration. Simulated source terms for rail transport accidents are presented in Fig. III-1 in a coordinate system with the radiological hazard index as x-axis and the conditional probability of the accident configuration as the y-axis, both in logarithmic scale.

Each data point given in Figure III represents one simulated source term. Source terms related to the same severity category are positioned on a horizontal line which would intersect the vertical axis at the relative frequency of the respective severity category. The wide spread of typically up to several orders of magnitude in the radiological hazard index of source terms belonging to the same severity category is due to the large differences in the shipment activity inventory and package release behavior (waste package group) of the two waste types.

In a next step the source terms are first arranged in ascending order according to the radiological hazard index. This is done separately for purely mechanical and combined mechanical/thermal severity categories. The reason for this is that in the calculation of radiological consequences a ground-level release of a height of 2 m is assumed for accidents with mechanical impacts only and of 50 m in the case of mechanical impact followed by a fire. After grouping the source terms according to increasing radiological hazard index and normalization to the summed probability of all source terms the cumulative complementary frequency distribution (CCFD) of the radiological hazard index as shown in Fig. III-1 and in Fig. III-2 for release categories with mechanical (non-fire) and combined mechanical/thermal impact only can be constructed.

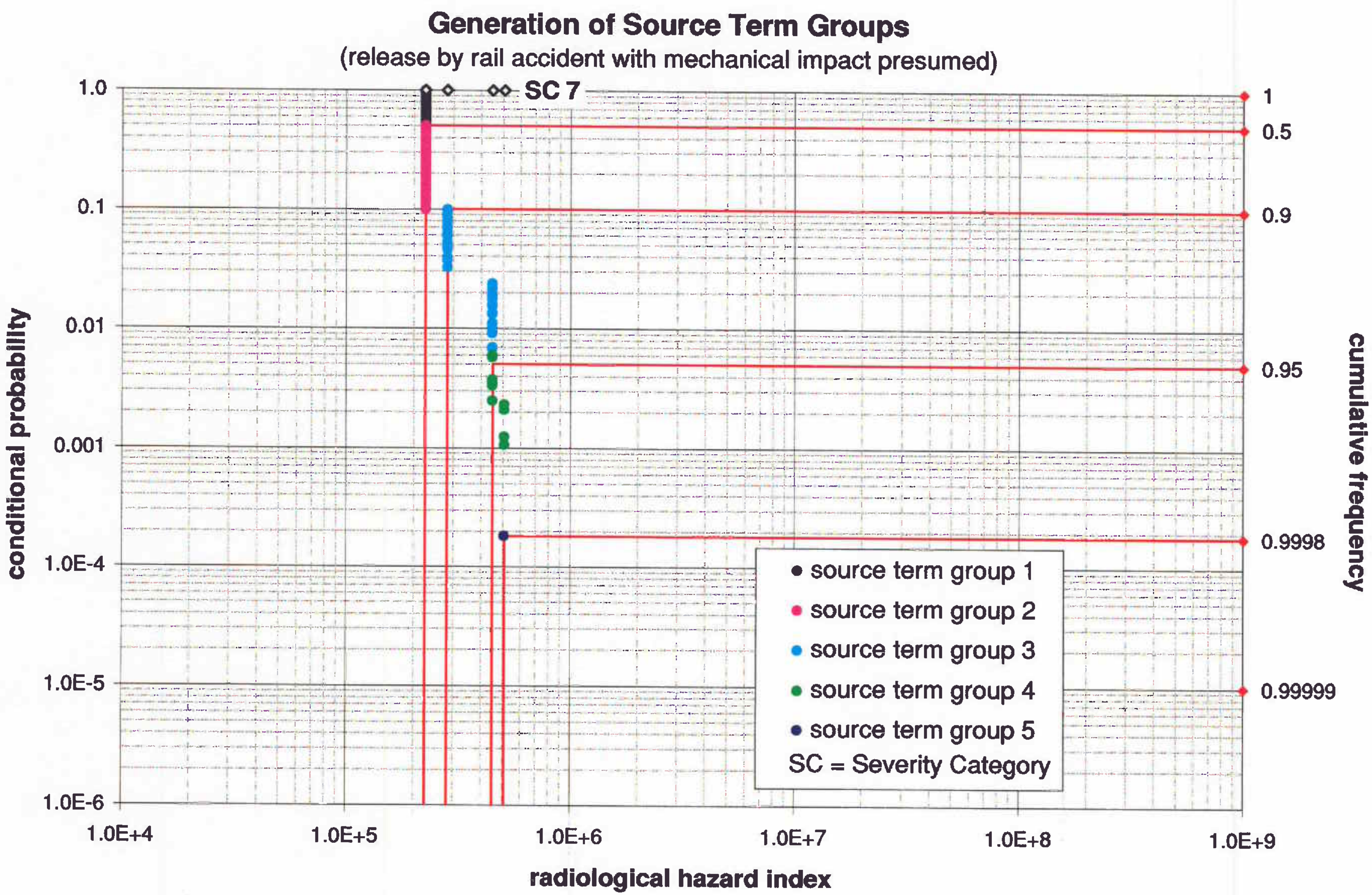
Source term groups are then formed by combining source terms with approximately equal hazard indices. This is done on the basis of the cumulative probability in a way that the range of radiological hazard indices of source terms having high hazard indices does not differ substantially. This procedure is intended to assure representativeness particularly for the source terms resulting in higher radiological consequences. As can be seen in Fig. III-2 the determination of the 5 source term groups is according to the probabilities given in the following table:

Cumulative probability used for source term group definition:

Source Term Group	Relative Probability	Cumulative Probability
1	0,5000	0,5000
2	0,4000	0,9000
3	0,0950	0,9950
4	0,0045	0,9995
5	0,0005	1,0000

In a next step for each source term group a representative radionuclide-specific source term, the so-called **release category**, is derived. By taking the conditional probabilities of occurrence of individual source terms as the relative weight, a weighted average of the activities of individual radionuclides of the source terms within a group is calculated and in this way the radionuclide composition and activities of the release category determined. In summary, ten such release categories each have been generated by the simulation program for accidents during transportation by freight trains. In each case 5 release categories are representative for accidents with mechanical impact and subsequent fire. The frequency of occurrence has been determined for each of these release categories. With respect to the total waste transport volume, this is the probability with which releases caused by accidents, which are represented by a release category, can be expected somewhere on the transport route.

The characteristics of the release categories related to the potential waste transport accidents (marshalling yard operations excluded) based on the approach described above have been compiled and are tabulated in Tab. III-1.



Generation of Source Term Groups
(release by rail accident with mechanical impact presumed)
SC 7
conditional probability
1.0
0.1
0.01
0.001
1.0E-4
1.0E-5
1.0E-6
1.0E+4
1.0E+5
1.0E+6
1.0E+7
1.0E+8
1.0E+9
radiological hazard index
cumulative frequency
1
0.5
0.9
0.95
0.9998
0.99999
source term group 1
source term group 2
source term group 3
source term group 4
source term group 5
SC = Severity Category

Fig. III-1

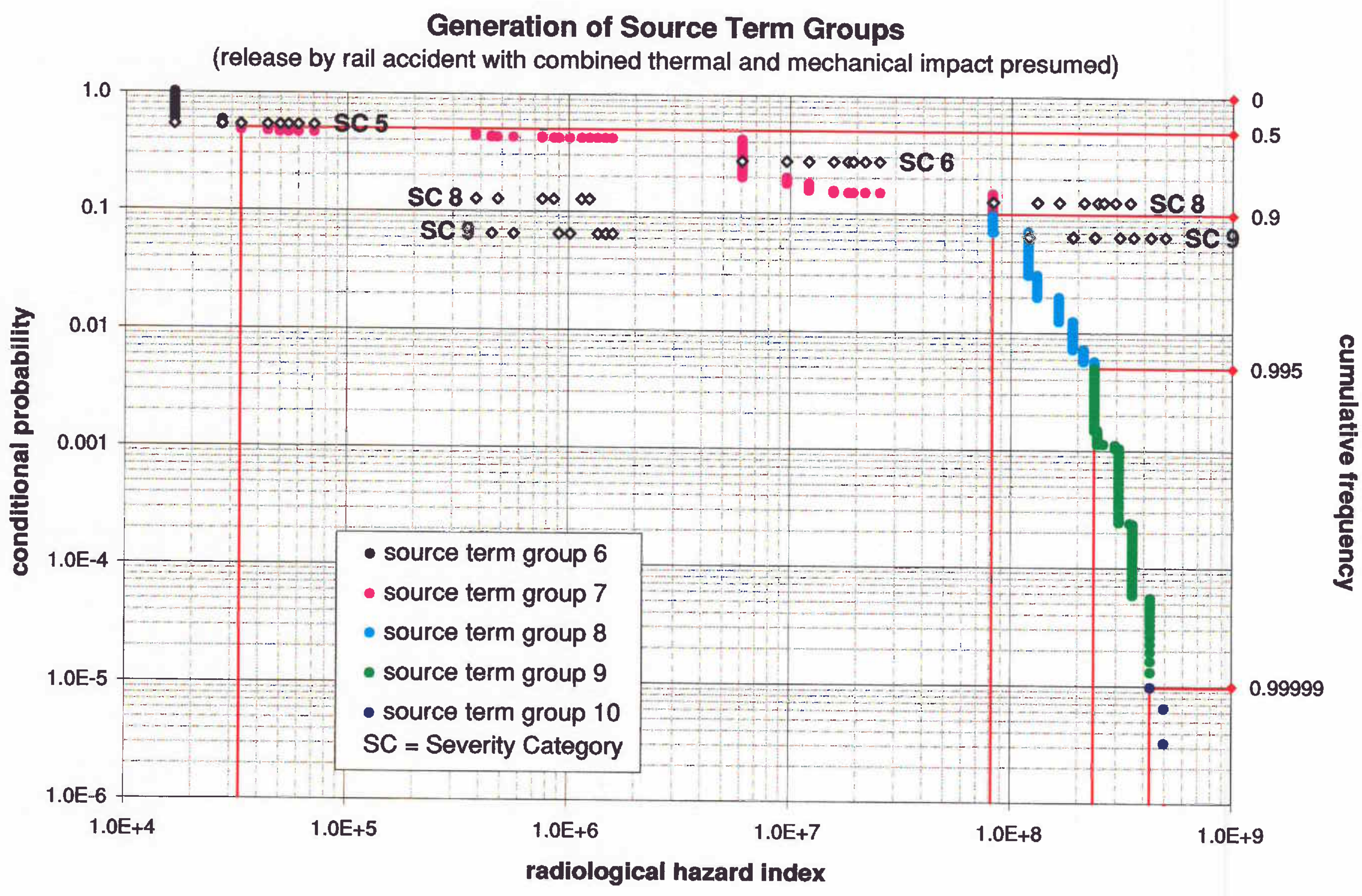

Generation of Source Term Groups
(release by rail accident with combined thermal and mechanical impact presumed)
conditional probability
1.0
0.1
0.01
0.001
1.0E-4
1.0E-5
1.0E-6
1.0E+4
1.0E+5
1.0E+6
1.0E+7
1.0E+8
1.0E+9
radiological hazard index
cumulative frequency
0
0.5
0.9
0.995
0.99999
SC 5
SC 6
SC 8
SC 9
SC 8
SC 9
source term group 6
source term group 7
source term group 8
source term group 9
source term group 10
SC = Severity Category

Fig. III-2

		Release Category				
		1	2	3	4	5
Mechanical Impact	Cum. probab.	0.50168714	0.90047787	0.99404225	0.99912796	1.00000000
	No. of Iterations	145	129	52	10	1
AED < 10 µm	Hazard Index:	1.40E+05	1.40E+05	1.96E+05	2.91E+05	3.16E+05
	SR 90	6.58E+07	6.58E+07	9.11E+07	1.36E+08	1.47E+08
	Y 90	6.58E+07	6.58E+07	9.11E+07	1.36E+08	1.47E+08
	RU 106	3.15E+07	3.15E+07	4.36E+07	6.51E+07	7.06E+07
	RH 106	3.15E+07	3.15E+07	4.36E+07	6.51E+07	7.06E+07
	CS 134	3.57E+07	3.57E+07	4.94E+07	7.38E+07	8.00E+07
	CS 137	1.12E+08	1.12E+08	1.55E+08	2.31E+08	2.51E+08
	BA 137M	1.12E+08	1.12E+08	1.55E+08	2.31E+08	2.51E+08
	CE 144	3.08E+07	3.08E+07	4.26E+07	6.37E+07	6.90E+07
	PR 144	3.08E+07	3.08E+07	4.26E+07	6.37E+07	6.90E+07
	PM 147	6.09E+07	6.09E+07	8.43E+07	1.26E+08	1.36E+08
	EU 154	4.76E+06	4.76E+06	6.59E+06	9.84E+06	1.07E+07
	EU 155	5.11E+06	5.11E+06	7.07E+06	1.06E+07	1.14E+07
	U 234	2.24E+00	2.24E+00	4.88E+00	5.24E+00	7.21E+00
	U 235	7.70E-02	7.70E-02	1.68E-01	1.80E-01	2.48E-01
	U 236	5.95E-01	5.95E-01	1.30E+00	1.39E+00	1.92E+00
	U 238	4.69E-01	4.69E-01	1.02E+00	1.10E+00	1.51E+00
	PU 238	1.82E+04	1.82E+04	3.96E+04	4.26E+04	5.86E+04
	PU 239	2.10E+03	2.10E+03	4.57E+03	4.91E+03	6.76E+03
	PU 240	3.08E+03	3.08E+03	6.71E+03	7.21E+03	9.92E+03
	PU 241	7.70E+05	7.70E+05	1.07E+06	1.59E+06	1.72E+06
	PU 242	1.12E+01	1.12E+01	2.44E+01	2.62E+01	3.61E+01
	AM 241	8.40E+05	8.40E+05	1.83E+06	1.97E+06	2.70E+06
	CM 244	1.96E+06	1.96E+06	4.27E+06	4.59E+06	6.31E+06
AED 10 .. 20 µm	Hazard Index:	2.81E+04	2.81E+04	3.92E+04	5.81E+04	6.33E+04
	SR 90	1.32E+07	1.32E+07	1.82E+07	2.72E+07	2.95E+07
	Y 90	1.32E+07	1.32E+07	1.82E+07	2.72E+07	2.95E+07
	RU 106	6.30E+06	6.30E+06	8.72E+06	1.30E+07	1.41E+07
	RH 106	6.30E+06	6.30E+06	8.72E+06	1.30E+07	1.41E+07
	CS 134	7.14E+06	7.14E+06	9.88E+06	1.48E+07	1.60E+07
	CS 137	2.24E+07	2.24E+07	3.10E+07	4.63E+07	5.02E+07
	BA 137M	2.24E+07	2.24E+07	3.10E+07	4.63E+07	5.02E+07
	CE 144	6.16E+06	6.16E+06	8.53E+06	1.27E+07	1.38E+07
	PR 144	6.16E+06	6.16E+06	8.53E+06	1.27E+07	1.38E+07
	PM 147	1.22E+07	1.22E+07	1.69E+07	2.52E+07	2.73E+07
	EU 154	9.52E+05	9.52E+05	1.32E+06	1.97E+06	2.13E+06
	EU 155	1.02E+06	1.02E+06	1.41E+06	2.11E+06	2.29E+06
	U 234	4.48E-01	4.48E-01	9.76E-01	1.05E+00	1.44E+00
	U 235	1.54E-02	1.54E-02	3.35E-02	3.60E-02	4.96E-02
	U 236	1.19E-01	1.19E-01	2.59E-01	2.78E-01	3.83E-01
	U 238	9.38E-02	9.38E-02	2.04E-01	2.19E-01	3.02E-01
	PU 238	3.64E+03	3.64E+03	7.93E+03	8.52E+03	1.17E+04
	PU 239	4.20E+02	4.20E+02	9.15E+02	9.83E+02	1.35E+03
	PU 240	6.16E+02	6.16E+02	1.34E+03	1.44E+03	1.98E+03
	PU 241	1.54E+05	1.54E+05	2.13E+05	3.18E+05	3.45E+05
	PU 242	2.24E+00	2.24E+00	4.88E+00	5.24E+00	7.21E+00
	AM 241	1.68E+05	1.68E+05	3.66E+05	3.93E+05	5.41E+05
	CM 244	3.92E+05	3.92E+05	8.54E+05	9.17E+05	1.26E+06

Table III - 1

Mechanical Impact (cont.)

		Release Category				
		1	2	3	4	5
AED 20 .. 50 µm	Hazard Index:	4.21E+04	4.21E+04	5.88E+04	8.72E+04	9.49E+04
	SR 90	1.97E+07	1.97E+07	2.73E+07	4.08E+07	4.42E+07
	Y 90	1.97E+07	1.97E+07	2.73E+07	4.08E+07	4.42E+07
	RU 106	9.45E+06	9.45E+06	1.31E+07	1.95E+07	2.12E+07
	RH 106	9.45E+06	9.45E+06	1.31E+07	1.95E+07	2.12E+07
	CS 134	1.07E+07	1.07E+07	1.48E+07	2.21E+07	2.40E+07
	CS 137	3.36E+07	3.36E+07	4.65E+07	6.94E+07	7.53E+07
	BA 137M	3.36E+07	3.36E+07	4.65E+07	6.94E+07	7.53E+07
	CE 144	9.24E+06	9.24E+06	1.28E+07	1.91E+07	2.07E+07
	PR 144	9.24E+06	9.24E+06	1.28E+07	1.91E+07	2.07E+07
	PM 147	1.83E+07	1.83E+07	2.53E+07	3.78E+07	4.09E+07
	EU 154	1.43E+06	1.43E+06	1.98E+06	2.95E+06	3.20E+06
	EU 155	1.53E+06	1.53E+06	2.12E+06	3.17E+06	3.43E+06
	U 234	6.72E-01	6.72E-01	1.46E+00	1.57E+00	2.16E+00
	U 235	2.31E-02	2.31E-02	5.03E-02	5.40E-02	7.44E-02
	U 236	1.78E-01	1.78E-01	3.89E-01	4.18E-01	5.75E-01
	U 238	1.41E-01	1.41E-01	3.06E-01	3.29E-01	4.53E-01
	PU 238	5.46E+03	5.46E+03	1.19E+04	1.28E+04	1.76E+04
	PU 239	6.30E+02	6.30E+02	1.37E+03	1.47E+03	2.03E+03
	PU 240	9.24E+02	9.24E+02	2.01E+03	2.16E+03	2.98E+03
	PU 241	2.31E+05	2.31E+05	3.20E+05	4.77E+05	5.17E+05
	PU 242	3.36E+00	3.36E+00	7.32E+00	7.86E+00	1.08E+01
	AM 241	2.52E+05	2.52E+05	5.49E+05	5.90E+05	8.11E+05
	CM 244	5.88E+05	5.88E+05	1.28E+06	1.38E+06	1.89E+06
AED 50 .. 70 µm	Hazard Index:	1.50E+04	1.50E+04	2.10E+04	3.11E+04	3.39E+04
	SR 90	7.05E+06	7.05E+06	9.76E+06	1.46E+07	1.58E+07
	Y 90	7.05E+06	7.05E+06	9.76E+06	1.46E+07	1.58E+07
	RU 106	3.38E+06	3.38E+06	4.67E+06	6.98E+06	7.56E+06
	RH 106	3.38E+06	3.38E+06	4.67E+06	6.98E+06	7.56E+06
	CS 134	3.82E+06	3.82E+06	5.29E+06	7.91E+06	8.57E+06
	CS 137	1.20E+07	1.20E+07	1.66E+07	2.48E+07	2.69E+07
	BA 137M	1.20E+07	1.20E+07	1.66E+07	2.48E+07	2.69E+07
	CE 144	3.30E+06	3.30E+06	4.57E+06	6.82E+06	7.39E+06
	PR 144	3.30E+06	3.30E+06	4.57E+06	6.82E+06	7.39E+06
	PM 147	6.52E+06	6.52E+06	9.03E+06	1.35E+07	1.46E+07
	EU 154	5.10E+05	5.10E+05	7.06E+05	1.05E+06	1.14E+06
	EU 155	5.48E+05	5.48E+05	7.58E+05	1.13E+06	1.23E+06
	U 234	2.40E-01	2.40E-01	5.23E-01	5.62E-01	7.73E-01
	U 235	8.25E-03	8.25E-03	1.80E-02	1.93E-02	2.66E-02
	U 236	6.37E-02	6.37E-02	1.39E-01	1.49E-01	2.05E-01
	U 238	5.03E-02	5.03E-02	1.09E-01	1.18E-01	1.62E-01
	PU 238	1.95E+03	1.95E+03	4.25E+03	4.56E+03	6.28E+03
	PU 239	2.25E+02	2.25E+02	4.90E+02	5.26E+02	7.25E+02
	PU 240	3.30E+02	3.30E+02	7.19E+02	7.72E+02	1.06E+03
	PU 241	8.25E+04	8.25E+04	1.14E+05	1.71E+05	1.85E+05
	PU 242	1.20E+00	1.20E+00	2.61E+00	2.81E+00	3.86E+00
	AM 241	9.00E+04	9.00E+04	1.96E+05	2.11E+05	2.90E+05
	CM 244	2.10E+05	2.10E+05	4.57E+05	4.91E+05	6.76E+05

		Release Category 6	7	8	9	10
Combined thermal/ mechanical Impact	cum. probab.	0.50004881	0.90016525	0.99500652	0.99999027	1.00000000
	No. of iterations	626	1629	1107	367	3
AED < 10 µm	hazard index:	1.87E+04	1.47E+07	1.19E+08	2.57E+08	4.74E+08
	H 3	6.09E+09	8.02E+09	7.85E+09	1.69E+10	3.18E+10
	CO 60	-	7.46E+08	6.08E+09	1.31E+10	2.46E+10
	SR 90	-	2.45E+09	1.99E+10	4.29E+10	8.05E+10
	Y 90	-	2.45E+09	1.99E+10	4.29E+10	8.05E+10
	TC 99	-	9.49E+05	7.74E+06	1.67E+07	3.13E+07
	RU 106	-	2.58E+10	2.10E+11	4.53E+11	8.50E+11
	RH 106	-	2.58E+10	2.10E+11	4.53E+11	8.50E+11
	SB 125	-	1.76E+09	1.44E+10	3.10E+10	5.82E+10
	I 129	6.00E+07	7.91E+07	7.74E+07	1.67E+08	3.13E+08
	CS 134	-	1.91E+09	1.55E+10	3.34E+10	6.26E+10
	CS 137	-	1.01E+10	8.18E+10	1.77E+11	3.31E+11
	BA 137M	-	1.01E+10	8.18E+10	1.77E+11	3.31E+11
	CE 144	-	7.46E+09	6.08E+10	1.31E+11	2.46E+11
	PR 144	-	7.46E+09	6.08E+10	1.31E+11	2.46E+11
	PM 147	-	6.77E+08	5.43E+09	1.17E+10	2.19E+10
	EU 154	-	7.33E+08	5.97E+09	1.29E+10	2.42E+10
	EU 155	-	3.53E+08	2.88E+09	6.20E+09	1.16E+10
	U 234	-	5.01E-01	5.08E-01	2.39E-01	-
	U 235	-	1.74E+04	1.36E+05	3.00E+05	4.93E+05
	U 236	-	1.33E-01	1.35E-01	6.35E-02	-
	U 238	-	1.74E+05	1.36E+06	3.00E+06	4.93E+06
	PU 238	-	8.31E+08	6.49E+09	1.43E+10	2.35E+10
	PU 239	-	9.79E+07	7.64E+08	1.69E+09	2.77E+09
	PU 240	-	1.34E+08	1.05E+09	2.31E+09	3.79E+09
	PU 241	-	5.15E+10	4.20E+11	9.06E+11	1.70E+12
	PU 242	-	2.50E+00	2.54E+00	1.20E+00	-
	AM 241	-	5.23E+08	4.08E+09	9.00E+09	1.48E+10
	CM 242	-	1.47E+07	1.15E+08	2.54E+08	4.17E+08
	CM 244	-	1.05E+08	8.17E+08	1.80E+09	2.96E+09
AED 10 .. 20 µm	Hazard Index:	-	5.66E+03	5.73E+03	2.68E+03	-
	SR 90	-	2.65E+06	2.68E+06	1.25E+06	-
	Y 90	-	2.65E+06	2.68E+06	1.25E+06	-
	RU 106	-	1.27E+06	1.28E+06	6.00E+05	-
	RH 106	-	1.27E+06	1.28E+06	6.00E+05	-
	CS 134	-	1.44E+06	1.46E+06	6.80E+05	-
	CS 137	-	4.51E+06	4.57E+06	2.13E+06	-
	BA 137M	-	4.51E+06	4.57E+06	2.13E+06	-
	CE 144	-	1.24E+06	1.26E+06	5.87E+05	-
	PR 144	-	1.24E+06	1.26E+06	5.87E+05	-
	PM 147	-	2.45E+06	2.48E+06	1.16E+06	-
	EU 154	-	1.92E+05	1.94E+05	9.07E+04	-
	EU 155	-	2.06E+05	2.08E+05	9.73E+04	-
	U 234	-	9.75E-02	9.88E-02	4.78E-02	-
	U 235	-	3.35E-03	3.40E-03	1.64E-03	-
	U 236	-	2.59E-02	2.62E-02	1.27E-02	-
	U 238	-	2.04E-02	2.07E-02	1.00E-02	-
	PU 238	-	7.92E+02	8.03E+02	3.88E+02	-
	PU 239	-	9.14E+01	9.26E+01	4.48E+01	-
	PU 240	-	1.34E+02	1.36E+02	6.57E+01	-
	PU 241	-	3.10E+04	3.14E+04	1.47E+04	-
	PU 242	-	4.87E-01	4.94E-01	2.39E-01	-
	AM 241	-	3.65E+04	3.70E+04	1.79E+04	-
	CM 244	-	8.53E+04	8.64E+04	4.18E+04	-

Table III - 1

Combined thermal/mechanical Impact (cont.)

		Release Category 6	7	8	9	10
AED 20 .. 50 µm	Hazard Index:	-	8.57E+03	8.67E+03	4.02E+03	-
	SR 90	-	4.01E+06	4.06E+06	1.88E+06	-
	Y 90	-	4.01E+06	4.06E+06	1.88E+06	-
	RU 106	-	1.92E+06	1.95E+06	9.00E+05	-
	RH 106	-	1.92E+06	1.95E+06	9.00E+05	-
	CS 134	-	2.18E+06	2.20E+06	1.02E+06	-
	CS 137	-	6.83E+06	6.92E+06	3.20E+06	-
	BA 137M	-	6.83E+06	6.92E+06	3.20E+06	-
	CE 144	-	1.88E+06	1.90E+06	8.80E+05	-
	PR 144	-	1.88E+06	1.90E+06	8.80E+05	-
	PM 147	-	3.71E+06	3.76E+06	1.74E+06	-
	EU 154	-	2.90E+05	2.94E+05	1.36E+05	-
	EU 155	-	3.12E+05	3.16E+05	1.46E+05	-
	U 234	-	1.48E-01	1.50E-01	7.17E-02	-
	U 235	-	5.07E-03	5.14E-03	2.47E-03	-
	U 236	-	3.92E-02	3.97E-02	1.90E-02	-
	U 238	-	3.09E-02	3.13E-02	1.50E-02	-
	PU 238	-	1.20E+03	1.22E+03	5.83E+02	-
	PU 239	-	1.38E+02	1.40E+02	6.72E+01	-
	PU 240	-	2.03E+02	2.06E+02	9.86E+01	-
	PU 241	-	4.70E+04	4.76E+04	2.20E+04	-
	PU 242	-	7.38E-01	7.48E-01	3.59E-01	-
	AM 241	-	5.53E+04	5.61E+04	2.69E+04	-
	CM 244	-	1.29E+05	1.31E+05	6.27E+04	-
AED 50 .. 70 µm	Hazard Index:	-	2.98E+03	3.02E+03	1.43E+03	-
	SR 90	-	1.40E+06	1.41E+06	6.71E+05	-
	Y 90	-	1.40E+06	1.41E+06	6.71E+05	-
	RU 106	-	6.69E+05	6.77E+05	3.21E+05	-
	RH 106	-	6.69E+05	6.77E+05	3.21E+05	-
	CS 134	-	7.58E+05	7.67E+05	3.64E+05	-
	CS 137	-	2.38E+06	2.41E+06	1.14E+06	-
	BA 137M	-	2.38E+06	2.41E+06	1.14E+06	-
	CE 144	-	6.54E+05	6.62E+05	3.14E+05	-
	PR 144	-	6.54E+05	6.62E+05	3.14E+05	-
	PM 147	-	1.29E+06	1.31E+06	6.21E+05	-
	EU 154	-	1.01E+05	1.02E+05	4.86E+04	-
	EU 155	-	1.08E+05	1.10E+05	5.21E+04	-
	U 234	-	5.14E-02	5.20E-02	2.56E-02	-
	U 235	-	1.77E-03	1.79E-03	8.80E-04	-
	U 236	-	1.36E-02	1.38E-02	6.80E-03	-
	U 238	-	1.08E-02	1.09E-02	5.36E-03	-
	PU 238	-	4.17E+02	4.23E+02	2.08E+02	-
	PU 239	-	4.81E+01	4.88E+01	2.40E+01	-
	PU 240	-	7.06E+01	7.15E+01	3.52E+01	-
	PU 241	-	1.63E+04	1.65E+04	7.86E+03	-
	PU 242	-	2.57E-01	2.60E-01	1.28E-01	-
	AM 241	-	1.93E+04	1.95E+04	9.60E+03	-
	CM 244	-	4.49E+04	4.55E+04	2.24E+04	-

APPENDIX IV:

Transport Package Release Behaviour under Accidental Load Conditions [1]

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[1] The support and advice to this section provided by Prof. Dr. B. Droste, Dipl.-Phys. H. Kowalewsky and Dr. R. Rödel from the Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin (Germany), and Dr. W. Koch, Fraunhofer-Institut für Toxikologie und Aerosolforschung, Hannover (Germany), is gratefully acknowledged.

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1 Introduction

In a shipping accident involving a waste transport cask or container, mechanical and thermal package response, or both, can be generated with the potential to compromise the package integrity and thus result in a release of radioactive material. The package response and release behaviour depends on numerous factors. These factors include, for example, mechanical forces (e.g. response to static or dynamic loads) generated by the impact velocity and the characteristics of the object and target surface (hardness) being struck, thermal loadings generated by the extent, temperature and duration of a fire, and the dispersibility of the waste product. These factors need to be properly understood within the context of a transport risk assessment analysis.

This appendix provides an overview of the sources of information, data bases and reasoning used in quantifying the package release behaviour under accidental load conditions for both the thick-walled vitrified waste transport casks Castor HAW 20/28 CG and TS 28 V as well as the bituminous waste transport Container Type VII. The gross laden weight of the vitrified waste transport casks Castor HAW 20/28 CG and TS 28 V and the bituminous waste transport Container VII is approximately 113 Mg and 24 Mg (including the impact limiter), respectively.

Both package types are massive dual-purpose transport and storage casks/containers designed to meet the Type B package testing requirements of the IAEA Transport Regulations /IAEA 90/ and the waste acceptance criteria of the Interim Storage Facility Gorleben /BLG 91, BLG 95/. The IAEA Transport Regulations for Type B packages require the containment, radiation shielding, heat dissipation, and criticality safety performance of a package to be maintained within prescribed narrow limits even following a severe transport accident.

2 Definition of the impact load conditions

The system response and subsequent radionuclide release of the transport packagings and waste products have been evaluated in the study described herein in terms of the mechanical and thermal loads, a package may encounter in typical transport and handling accidents. In accordance with the statistical accident data available for the study, the broad range of conceivable transport accidents environments has been categorized as shown by the accident severity categorization scheme presented in Table IV-1.

Table IV-1: Accident Severity Classification Scheme adopted for the Transport Risk Assessment Study

Impact Velocity (km/h)	**Fire Duration and Temperature**		
	No fire	**30 min/800°C fire**	**60 min/800°C fire**
< 35	SC 1	SC 2	SC 3
36 - 80	SC 4	SC 5	SC 6
> 80	SC 7	SC 8	SC 9

The principal entries of the accident severity (SC) categorization scheme are the package impact velocity and the temperature and duration of a fire impact. The latter parameters determine the cumulative heat impact affecting a waste transport package if placed close to or into a fire.

Three different severity levels were defined to represent the potential mechanical impact forces encountered by a package based on the vehicle or package impact velocity prior to the accident:

- 0 - 35 km/h
- 36 - 80 km/h
- > 80 km/h.

Three fire severity levels are distinguished to model accidental sequences with combined mechanical and thermal impact forces. These include:

- No external fire
- 30 minute 800°C fire
- 60 minute 800°C fire.

Severity categories SC 1 (impact speed up to 35 km/h), SC 4 (impact speed between 36 - 80 km/h) and SC 7 (impact speed > 80 km/h) represent sequences of events causing only mechanical forces to a waste transport package whereas all other categories represent accident environments where combined mechanical-thermal load conditions exist.

For estimating the potential mechanical and/or thermal impact forces and the related system response of the transport packagings and waste products several simplifying, but conservative assumptions were made for the analysis:

The most notable example is the assumption, that the transport packages were assumed to impact onto a **hard rigid target surface**, e.g. hard solid rock or concrete surface, with the upper speed of the respective severity category. This requirement of a cask striking a hard rigid surface is consistent with the assumption that the package impact energy is to a large extent absorbed by the package itself thereby maximizing the potential package damage. For the speed range above 80 km/h, an effective impact speed of 110 km/h, corresponding to a free drop from a height of about 48 m, was assumed for the assessment of the mechanical impact force.

In addition, it was assumed that the package impact velocity onto a target surface or object equals the vehicle velocity at the time of or prior to the accident event. This assumption introduces a significant element of conservatism into the assessment of the potential package damage and subsequent release, in that it does not account for any deceleration of the package resulting from potential interactions of the package with external energy-absorbing structures or the impact of the tie-down equipment.

The thermal impact is characterized by a fire of a given duration and temperature and by assuming that the waste transport package is completely engulfed by the fire. This assumption maximizes the potential heat input to the package and represents a conservative assessment element.

Both types of loadings have the potential to adversely affect the safety functions (containment, shielding, heat dissipation) of a transport cask or container and may result in a release of the package contents. In many instances of packaging containment failure, however, components of the packaging and the physiochemical form of the waste product will limit the radioactivity release to small fractions of the content.

It is important to note, that the accident environments defined by the accident categorization scheme in Tab. IV-1 and the related target surface hardness and reference fire conditions cover a broad range of mechanical/thermal load conditions from below to very severe beyond IAEA regulatory testing requirements for Type B packages /IAEA 90/. For load conditions not exceeding the regulatory testing requirements for Type B packages, i.e., impact loads of a 9 m drop test and a subsequent 30 minute, fully-engulfing 800°C fire test, no significant degradation of the shielding and containment function of the casks/containers is expected to occur and, consequently, no accidental release has been assumed for such sequences of events.

3 Transport package response and release modeling

The escape of the cask/container contents into the environment requires ultimately failure or degradation of all of the multiple barriers of the package containment system including the:

- waste product, i.e., glass matrix and bituminous material
- primary packaging of the vitrified or bituminous waste product (i.e., stainless steel canister or drum)
- transport cask containment, i.e., the cask body (shell and outer end plate) and the lid closure system.

The mode and extent of failure or degradation of the package containment system for loads typical to transport and handling accidents is an important factor for estimating the type and quantity of radioactive material to be potentially released in an accident event. This section summarizes the information, data bases and methods used for the evaluation of the structural and thermal cask response and release behaviour.

For the study described herein the accidental package releases have been quantified in terms of release fractions. The release fraction (r) of a package is defined as the fraction of the radioactive package inventory that may be released from the package into the environment instantaneously or over a prolonged period of time, e.g. in a fire, or for a given accident event and severity level. Thus, the total environmental radionuclide release attributable to an accident is the cask/container activity inventory times the release fraction.

Release fractions vary according to the package type, the physical and chemical form of the waste product, and the accident severity. The radionuclides embedded in the waste product were grouped according to their physical-chemical characteristics in:

- volatile radionuclides
- semi- and nonvolatile radionuclides (particulates)

Tritium (H 3), radiocarbon (C 14) and halogens, e.g. I 129, were generally assigned to the volatile radionuclide category except for vitrified waste, where all radionuclides are expected to be released as solid particulates. Particulate releases resulting from combustion of radioactive waste materials, such as bituminous waste, were generally assumed to be in the respirable size range, i.e., particle diameter < 10 µm (AED).

For the assessment of the radiological consequences, the particulate radionuclide releases were assigned to **four** particle size ranges according to the aerodynamic equivalent particle diameter (AED):

0 - 10 µm (AED)
10 - 20 µm (AED)
20 - 50 µm (AED)
50 - 70 µm (AED)

Particles in the diameter size range less than 10 µm (AED) are ordinarily classified as respirable, particles in excess of 10 µm (AED) as non-respirable and, consequently, are not expected to contribute to the dose via the inhalation pathway. Non-respirable particles, however, are potential contributors to the dose to human beings via groundshine and exposure to radionuclides from the intake of contaminated foodstuffs (ingestion pathway). Particles in the diameter range above 10 µm (AED) tend to deposit faster onto the ground surface or vegetation than particulates in the size range less than 10 µm and, consequently, result in an increased contamination of the vegetation and ground surface.

3.1 Vitrified waste transport and storage casks (Castor HAW 20/28 CG and TS 28 V)

Structural cask response:

The general literature offers a vast body of information indicating that the thick-walled ductile cast iron (DCI) Castor HAW 20/28 CG and carbon steel TS 28 V system performance of ensuring (structural) containment and shielding integrity is far beyond the IAEA regulatory testing requirements for Type B packages. In other words, substantial safety margins in excess of the IAEA regulatory requirements are an inherent part of the design of the dual-purpose transport and storage casks for vitrified waste /DRO 93, DRO 95/.

The excellent package and material performance has, for example, been demonstrated in numerous cask drop and penetration test experiments, by material property testing and structural package response analyses for transport casks, containers and materials similar to those of the Castor HAW 20/28 CG and TS 28 V. The full- and model-scale drop and material test experiments referred to above include, for example, impact tests of packages onto various objects and target surfaces from as high as 800 m to simulate potential transport and handling accidents in a deep geological repository and elsewhere /SCH 79, RIT 83, HÄU 84, JAN 89/. Because of the large weight, hardness and rigid design of the transport and storage casks for vitrified waste, load conditions caused by crushing, projectiles or other mechanisms tend to be far less damaging than loads caused by impaction onto hard surfaces or massive objects /YUA 93, p. 19, HÄU 84/.

The most relevant information describing the structural cask response to severe mechanical impact loads is summarized below:

In one of the earliest attempts in Germany (Bundesanstalt für Materialforschung (BAM), Berlin (Germany), /SCH 79, DRO 93/) to examine the margins of safety incorporated into the package design, a 1 : 2 scale model of a TN 8/9 spent fuel cask weighing about 4.1 Mg was dropped by helicopter onto a layered target surface (0.2 m reinforced concrete, 0.2 m concrete, 0.6 m gravel). The drop test height was approximately 200 m, the impact velocity 225 km/h. The cylindrical cask model (length 2.5 m, diameter 0.85 m, wall-thickness 100 mm lead and 12.5 mm carbon steel) hit the target surface obliquely and penetrated approx. 0.75 m into the layered target surface (impact surface area approximately 3 m x 1 m). Although the impact limiters were separated from the cask body on both sides subsequent impaction onto the ground, the integrity of the structural containment and the leak-tightness of the model cask and its components was retained.

In another attempt (BAM) to examine the build-in safety margins of transport casks, the structural cask response of a full-scale (83 Mg) ductile cast iron (DCI) spent fuel cask Castor Ic with simulated contents has been studied by a free fall drop test from 20 m (terminal impact velocity approximately 70 km/h) onto a simulated driveway (compound layer of 0.16 m concrete, 0.15 m bituminous material, and 1.5 gravel sand) in the most damaging side-on orientation /WIE 83, DRO 93/. The cask penetrated the concrete target surface side-on, but retained the structural integrity. Due to the yielding nature of the target surface, the cask deceleration (60 g) and, consequently, the resulting cask shell strain was substantially lower than the relevant values found under regulatory test conditions (9 m drop test onto an unyielding surface).

Similar results were found in model calculations for a ductile cast iron 80 Mg spent fuel transport cask subjected to a hypothetical free drop from a height of about 27 m (impact velocity approx. 83 km/h) onto a hard rigid 2 m concrete floor. The analysis results indicated, that the structural containment integrity of the 80 Mg thick-walled spent fuel cask would be retained in such an accidental event /GÜN 86/.

Information to judge the structural response of massive thick-walled casks, similar to the Castor HAW 20/28 CG and TS 28 V has also been drawn from an account of work of the "Projekt Sicherheitsstudien Entsorgung (PSE)" /HÄU 84/. The finite element method (FEM) and mass-spring-model calculations performed for a 123 Mg Castor IIa spent fuel transport cask clearly indicate that the structural cask shell integrity will be retained over a wide range of impact velocities up to 110 km/h and above when striking target surfaces of different hardness including a concrete slab (driveway).

The excellent performance and margins of safety inherent in the design of Castor type casks and materials (DCI) have also been confirmed in a series of drop test experiments with a simplified 1 : 2.5 scale model and full-scale cask (Castor VHLW) having deep artificially machined flaws (flaw depth 120 mm in the 260 mm wall) located in the maximum stress zone of the cask shell. Although these test with drop heights up to

14 m were intended to provoke crack initiation in the maximum stress zone, no brittle fracture was observed under the very severe load conditions /DRO 93, DRO 95/.

Other factors that must be accounted for in evaluating the structural package response are the substantial built-in safety margins regularly incorporated in the transport and storage cask design on request of the German competent authority. An important example is the requirement, that the maximum permissible stress of shipping and storage casks resulting from a Type B regulatory drop test is generally limited to about one half of the 0.2% yield strength ($R_{p,0.2}$) for ductile cast iron materials and 67% of the 0.2% yield strength ($R_{p,0.2}$) for ferritic forged steel /DRO 83, AUR 83, AUR 87/.

The influence and significant importance of the structural behaviour of the transport equipment, i.e., the vehicle and cask support frame, in evaluating the structural cask response has been demonstrated by truck and trailer crash test experiments onto an unyielding target surface involving end-on impact of a steel-lead cask of approximately 4 m length and 1 m in diameter weighing about 20 Mg /CLU 80/. For these impact load conditions, the unyielding concrete target with the intervening truck-vehicle structure can be thought of as a relatively soft target and, consequently, no significant damage to the cask structure was found. Similar consideration apply to the vitrified waste shipping casks and transport system components considered in this study.

In summary, based on the demonstrated performance of the materials and design of Castor-like shipping casks and considering the specific safety margins incorporated into the design of the massive Castor HAW 20/28 CG and TS 28 V transport and storage casks, it has reasonably been concluded that gross failure of the structural cask containment integrity is virtually inconceivable over the entire mechanical impact and severity range of typical transport and handling accidents considered in the transport risk assessment study described herein.

However, the information derived from engineering analysis and penetration test experiments involving massive shipping and storage casks indicates, that following very severe mechanical impact loads applied to the cask closure lid region, loss of package leaktightness can not entirely be excluded /GLA 80, AUR 83, HÄU 84/. Consequently, for impact velocities in excess of 80 km/h (i.e., SC 7, SC 8 and SC 9), a level of damage or degradation of the sealing function has been assumed to occur at the cask body-lid interface leading to an increased package leakage rate. The potential failure modes envisaged include the following:

- mild deformation of the ferritic steel lid resulting in a gap release
- degradation of the metallic and/or elastomeric seals
- lid bold tension leading to seal bypass leakage

The leakage rate (L) adopted for the transport risk assessment study has been derived from full-scale penetration test experiments of a Castor IIa spent fuel shipping cask which closely resembles the principal design of the Castor HAW 20/28 CG and TS 28 V. The Castor IIa penetration tests included impaction of a high-velocity 1000 kg-projectile, which stroke the cask in three different ways at a speed of about 300 m/s (1080 km/h):

- projectile impacting the cask side-on
- projectile impacting the cask closure lid region with the cask in an inclined position
- projectile impacting the cask closure lid perpendicularly at the mid-center

In all these tests the structural cask containment integrity was retained, however, the cask leaktightness was reduced. The nitrogen (N_2) pressure in the cask cavity with a volume of 530 l dropped within 6 days following the penetration test experiment from about 2 bar to 1.85 bar /BAM 82/. These values are consistent with a volumetric N_2-leakage rate L (= $V \cdot \Delta p/\Delta t$) of approximately 0.015 $Pa \cdot m^3/s$ (0.15 $mbar \cdot l/s$) and correspond to standard leakage rate (SLR), i.e., normalization to reference conditions with respect to the temperature and differential pressure conditions /ISO 95/, of about 0.005 $Pa \cdot m^3/s$.

This standard leakage rate (SLR) has been adopted throughout this study to be typical for the leakage of Castor-type shipping casks subjected to loads typical for severe transport and handling accidents with impact velocities in excess of 80 km/h, i.e. severity category SC 7, SC 8, and SC 9. In addition, a safety factor of 10 has been applied for consequence assessment resulting in a **nominal** standard leakage rate (SLR) of about 0.05 $Pa \cdot m^3/s$ (0.5 $mbar \cdot l/s$).

A standard leakage rate (SLR) of 0.05 Pa m³/s can be thought of as air flowing throughout a single capillary of a length of 1 cm and a diameter of about 70 - 100 µm under reference conditions, i.e., a differential pressure of about 1.013 x 10^5 Pa and a temperature of 25°C. Similarly, an idealized rectangular gap opening of a length of 1 cm, a width of 1 cm and a height of about 10 µm has been estimated of having a volumetric leakage rate of about 0.05 Pa m³/s /KOW 87, HIG 89a, HIG 89b/.

For source term estimation two opening related features are important: (1) Source term estimation is generally based on the assumption, that solid matter leaks through small openings as particles entrained in the fluid stream. The opening dimensions given above provide some indications which particles may pass through an existing leak path and which may be reasonably excluded from consideration. (2) The type of accidents considered in this study result most likely in mild deformations of the shipping cask and/or system components giving rise to the development of small gap openings at the lid-cask body interface rather than causing a single pore.

Thermal cask response:

The principal thermal loading conditions with the potential to increase the cask temperature subsequent a transport accident include large fires, torch fires, and the decay heat from the waste product, particularly, when the cask is accidentally buried in debris (thermal isolation). However, there is a general understanding that heat loads from large, long-duration fires have the greatest potential of causing significant damage to the shipping cask/container. Torch fires can heat up a localized area of a cask or package, but in comparison of large fires, do not deposit large quantities of heat into a cask or package /FIS 87, YUA 93/.

The cumulative effect of large fires that affect the cask response and potential damage depends on three principal factors: the fire duration, flame temperature, and the fire location. In this study, the fire impact to a shipping cask has been evaluated for three reference fire environments following mechanical impact:

- No external fire
- fully-engulfing 30 minute 800°C fire
- fully-engulfing 60 minute 800°C fire

A fully-engulfing fire would transfer the most heat to a cask, given the same flame temperature and fire duration, whereas less heat would be transferred from non-engulfing fires. In real fires, the cask is generally to some extent shielded from the fire by either the transport vehicle or the ground.

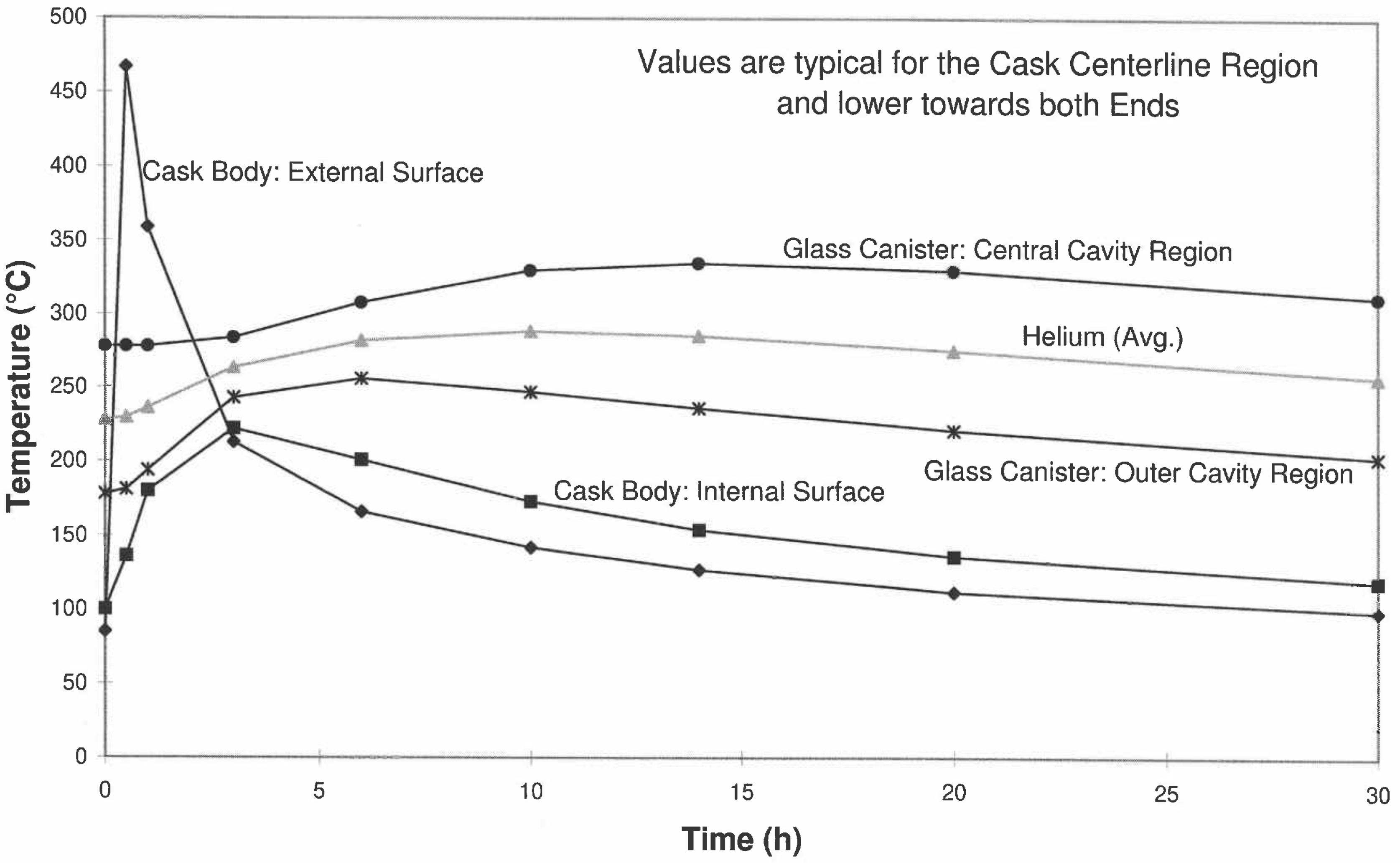
For estimating the heat transfer to and the temperature distribution of a shipping cask, the computer code HEATING developed by Oak Ridge National Laboratory /CHI 93/ has been used to perform the thermal calculations. HEATING is a multidimensional general-purpose heat transfer code and solves steady-state and/or transient problems in one-, two- or three-dimensional Cartesian, cylindrical or spherical coordinates. The calculations have been carried out in accordance with the requirements of the IAEA regulatory thermal test /IAEA 90, § 628/ by assuming an emissivity coefficient of 0.9 to characterize both the radiation and convection heat transfer over a wide range of accident conditions.

The initial temperature distribution of and within the cask was established before subjecting the cask to the fire impact assuming conservatively an external cask surface temperature of 85°C. This value corresponds to the maximum permissible temperature of any surface readily accessible during transport of a Type B package shipped under exclusive use. The insulating effect of the impact limiter was not taken into account for the heat transfer analysis.

A typical result of the HEATING code calculations is illustrated in Fig. IV-1 in terms of the transient thermal response of a vitrified waste transport cask (Castor HAW 20/28 CG) for a 30 minute fully-engulfing 800°C fire based on a simplified cask and component model.

It is evident, that the external cask surface temperature rises rapidly in a 30 minute 800°C-reference fire, whereas the (averaged) internal helium temperature increases only moderately above the equilibrium value. The estimated temperature increase of the helium was estimated to be approximately 60°C and 90°C for a 30 minute and 60 minute 800°C-reference fire, respectively, under the condition of absent mitigative actions, i.e., no forced cooling of the cask and no fire extinguishing activities. The averaged helium temperature peaks at about 10 hours following the fire impact.

Figure IV-1: Transient Temperature Distribution of a Castor HAW 20/28 CG Cask during and following a 30-minute 800°C-Fire



Cask release model:

The release model presented in this section describes the cask release behaviour of the massive dual-purpose transport and storage casks for vitrified reprocessing waste following a very severe transport and handling accident causing beyond regulatory mechanical and/or thermal load conditions to the cask. The release model is based on the assumption, that an accident-generated leak path (e.g., gap opening or capillary) exists at the lid-cask body interface with a specified leakage rate L (Pa m^3/s) resulting in a prolonged release of helium (filling gas) and suspended glass particles being present in the cask cavity atmosphere following a very severe accident.

Driving force of the assumed cask release is the potential overpressure (above ambient air) in the cask cavity of a Castor HAW 20/28 CG which can be as high as about 1.3 bar under routine steady-state conditions and up to 1,6 bar for the most severe 60 minute 800°C reference fire. However, it is important to emphasize that these internal cask pressure conditions are most representative for the Castor HAW 20/28 CG cask and not readily applicable to the TS 28 V cask type. This is because the initial helium filling pressure of a TS 28 V of about 0.5 bar is clearly lower than for the Castor HAW 20/28 CG (initial filling pressure of approx. 0.8 bar) and even below ambient pressure for the most severe reference fire accident. Consequently, no overpressure-related activity release from the cask is expected to occur for the TS 28 V. However, as a conservative assessment element, the Castor HAW 20/28 CG-specific pressure conditions have been adopted throughout the study to be typical for all vitrified waste shipping casks.

The physical release model for predicting the cask release behaviour in terms of release fractions involves three submodels:

- particle generation/release model for the encapsulated glass matrix
- particle depletion model to describe the fate and long-term behaviour of suspended particulates in the cask cavity (helium) atmosphere
- particle penetration model through small gap openings or capillaries.

A description of each submodel and the relevant data adopted for the quantitative analysis is given below.

Particle generation and release model:

The fracture and release mechanisms of glass particles from bare and encapsulated simulated vitrified waste (glass) have been studied in laboratory and full-scale drop test experiments for a wide range of mechanical impacts loads by SCHEIBEL et al. /SCH 88a, SCH 88b/. The impact velocity of glass probes onto a flat unyielding target surface was determined to be the dominant fracture and release mechanism. The mass fraction (m_p) of fine glass particles (aerosols) and broken glass fines generated and/or released following impaction varied substantially depending on the impact velocity and was approximately 2.4 E-4 and 5.9 E-4 for 80 km/h (22.2 m/s) and 110 km/h (30.5 m/s), respectively, for solid glass particles in the diameter range less than 70 µm (AED).

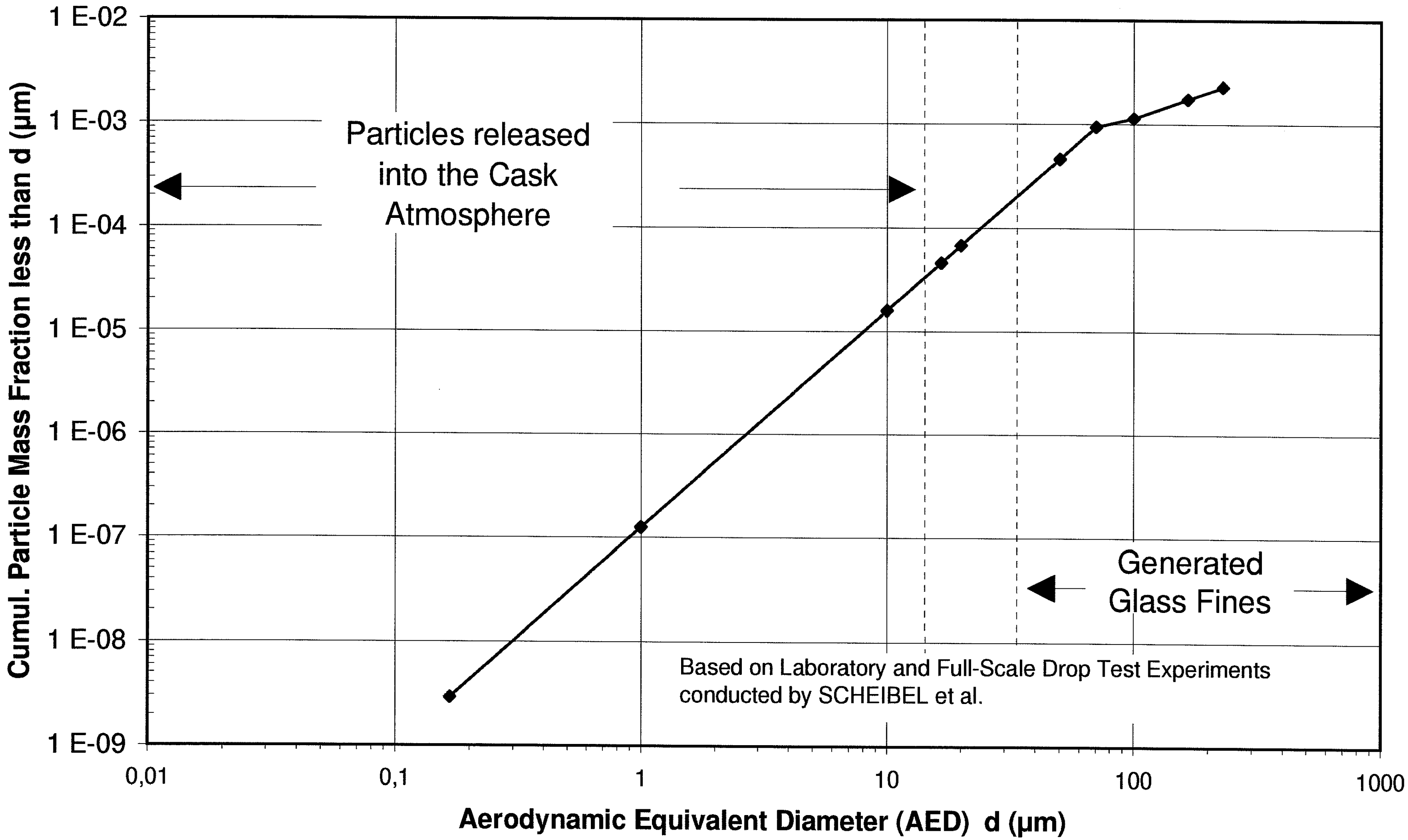
The slope of the size distribution of glass particles or aerosols generated and/or released following impaction of glass probes onto an unyielding target surface, however, was generally found to be independent of the impact speed (Fig. IV-2).

Based on the experimental results of SCHEIBEL et al., the relative mass fraction (w_j) of particulate matter released and/or generated in the cask cavity has been quantified and is given below for five particle size categories (j = 1 ... 5):

Size Category j	**Particle Diameter Range (AED) (µm)**	**Relative Mass Fraction** [1)] w_j (-)
1	< 1	1.34 E-4
2	1 - 10	1.67 E-2
3	10 - 20	0.055
4	20 - 50	0.421
5	50 - 70	0.506
Total	0 - 70	1.00

1) Normalized to particle mass fraction (m_p) in the size range 0 - 70 µm released/generated in the cask cavity

Figure IV-2: Size Distribution of Fractured Glass Particles from Impaction onto an Unyielding Flat Surface



The 0 - 70 µm glass particle mass fraction (m_p) released and/or generated by impaction in the cask cavity times the relative mass fraction (w_j) represents by definition the released/generated glass particle mass fraction (m_{pj}) in the specified size range j. This solid particulate mass fraction (m_{pj}) generated and/or released in the cask cavity atmosphere has been calculated and is given below for impact velocities of 80 km/h and 110 km/h:

Impact velocity (km/h)	**Particle Mass Fraction as a Function of AED (µm)**				
	< 10	**10 - 20**	**20 - 50**	**50 - 70**	**0 - 70**
35	Structural glass canister integrity retained (no release)				
80	4.1 E-6	1.3 E-5	1.0 E-4	1.2 E-4	2.4 E-4
110	1.0 E-5	3.3 E-5	2.5 E-4	3.0 E-4	5.9 E-4

Particle depletion model:

Suspended particulates are depleted from a carrier gas by a variety of mechanisms including inertial effects, gravitational settling, and Brownian motion and deposited onto structural and other surfaces. For electrically neutral particles more than 1 µm in diameter deposition is effected by inertial forces. The particle deposition rate from turbulent flow regimes is enhanced over that of a laminar flow as a consequence of eddy diffusion to the laminar sublayer next to the surface.

Several efforts have been made to quantitatively describe the depletion and deposition processes of suspended particulates (aerosols) on structural surfaces inside a closed vessel /WOO 81, CRU 81/. The approach adopted for this transport risk assessment study is outlined in Annex I of this Appendix.

The transient process of wall/surface deposition of suspended particulates in the size category j (j = 1 ... 5) within the cask cavity can be approximated by the following relationship:

$$R_j(t) = \frac{m_{pj}(t)}{m_{pj0}} = \exp\{-\beta_j \cdot t\} \qquad (1)$$

where:

m_{pj} (t) mass of suspended particulate matter in the diameter range j present in the cask cavity atmosphere at time t (in kg)

m_{pj0} mass of suspended particulate matter in the diameter size range j present in the cask cavity atmosphere at time t = 0 (in kg)

β_j deposition rate coefficient (in 1/s) of particles in the diameter range j

$$\beta_j = \beta(AED) = \frac{1}{V_c} \int_{(S)} \vec{ds} \cdot \overrightarrow{v_{dep}}$$

with:

$\vec{ds}$ surface area available for deposition (m^2)

$\overrightarrow{v_{dep}}$ deposition velocity (m/s) of particles on surface area $\vec{ds}$

V_c void volume of the cask cavity (m^3)

Three surface types have been distinguished inside the cask cavity with respect to their orientation: vertical surfaces, horizontal ceiling surfaces, and horizontal ground surfaces. The fractions of the three surfaces types have been assumed to be on the order of about 50%, 25%, and 25% for vertical surfaces, horizontal ceiling surfaces and horizontal ground surfaces, respectively.

The total quantity $m_p(t)$ of suspended particulate matter (kg) up to 70 µm in diameter being present in the cask atmosphere after time t is then given by:

$$m_p(t) = \sum_j m_{pj}(t) = \sum_j m_{pjo} \cdot \exp[-\beta_j \cdot t]$$

$$= m_{po} \cdot \sum_j w_j \cdot \exp[-\beta_j \cdot t] \qquad (2)$$

If the solidified radioactive substances are homogeneously distributed over the glass matrix - what can be reasonably assumed - is the mass of particulate matter m_p proportional to the activity A_p carried by the particles. Consequently, equation (2) can be rewritten in terms of the suspended activity (A_p) in the cask atmosphere at time t by replacing m_p by A_p in equation (2):

$$A_p(t) = A_{po} \cdot \sum_j w_j \cdot \exp[-\beta_j \cdot t] \qquad (3)$$

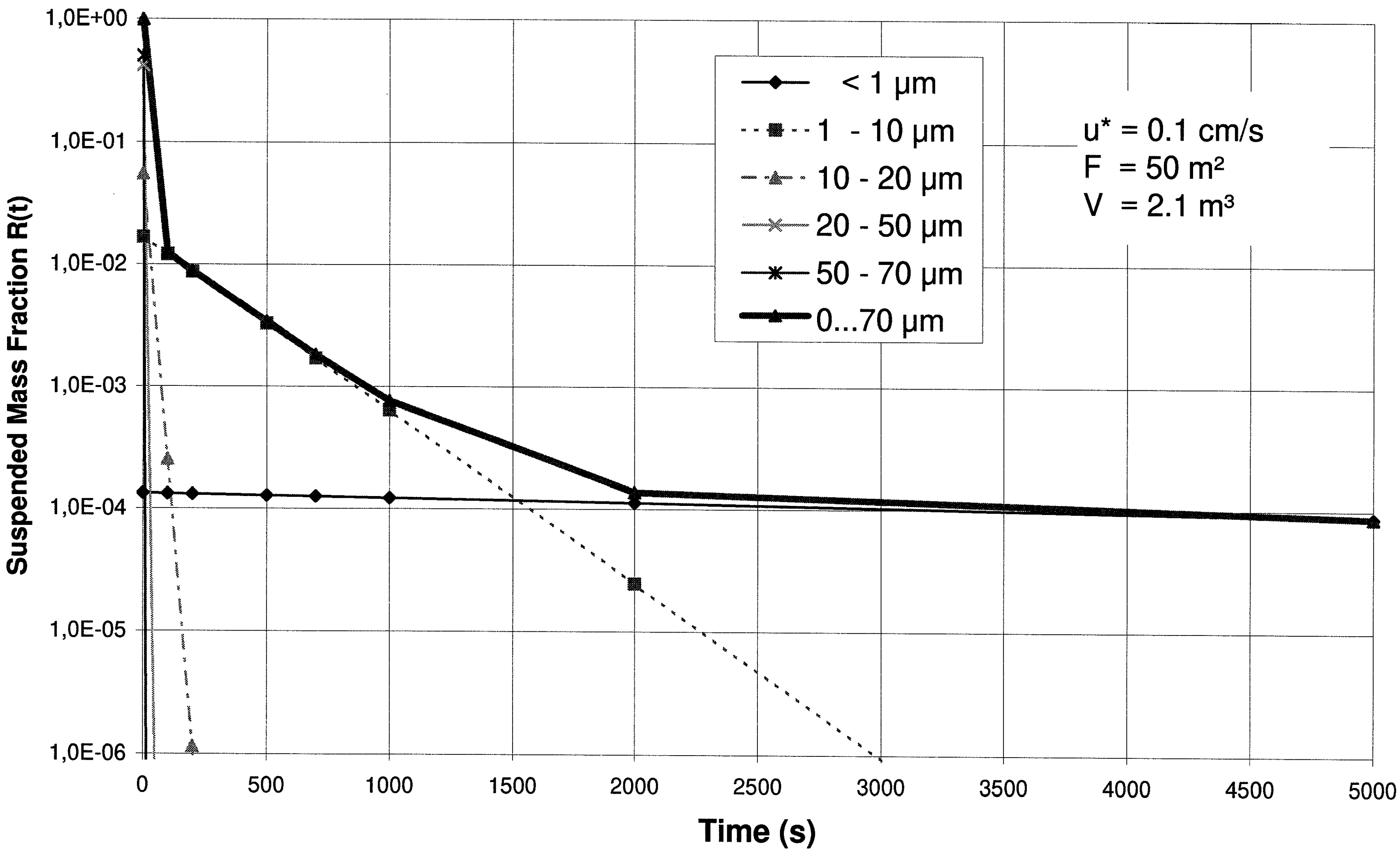
By definition $A_p(t)$ is the cumulative activity (Bq) associated with the suspended particulate matter in the size range AED < 70 µm being present in the cask cavity atmosphere at time t.

Equation (3) has been evaluated for five particle size categories j (j=1..5) defined previously in terms of the ratio $R(t) = A_p(t)/A_{po}$ for conditions prevailing in the Castor HAW 20/28 CG shipping cask during transport and the result is given in Fig. IV-3. $R(t) = A_p(t)/A_{po}$ represents the normalized suspended particle mass fraction in the size range from 0 - 70 µm (AED) in the cask cavity (helium) atmosphere following high speed impaction of the cask and its radioactive contents onto a hard rigid target surface or object.

The calculations are based on the conservative assumption, that the particulate matter (aerosols and broken glass fines) generated in the diameter range AED < 70 µm from impacting the cask onto a hard rigid surface becomes completely airborne in the cask cavity atmosphere as polydisperse aerosols. In addition, only a fraction of about 40 percent of the internal structural cask surface area, i.e., an area of about 50 m^2, was assumed to be available for aerosol deposition.

It is evident from Fig. IV-3, that suspended particulates in the size range above 10 µm are rapidly depleted from the cask cavity (helium) atmosphere and deposited onto internal structural surfaces by inertial deposition and gravitational settling as primary deposition mechanisms. Suspended particles less than 10 µm (AED) in diameter,

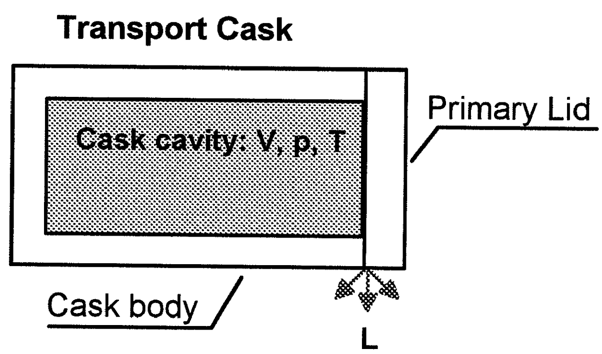
Figure IV-3: Depletion of Suspended Glass Particles in the Cask Atmosphere



however, have the potential of remaining airborne over a longer time period and, consequently, represent the primary particle size fraction that will potentially be available for release from the cask into the environment.

Particle penetration model:

For particulate material, currently no approved method exists to quantify the particle release through small openings, e.g. a capillary or gap opening, because of uncertainty in aerosol characteristics, entrainment, and settling both in the system, i.e., the cask cavity, and in escape through a leakage path /TCS 92, ISO 95/. Thus, for quantifying the particulate release from a shipping cask the simplifying assumption has been made, that the solid matter, i.e., the glass particles and fines, behaves like an aerosol in a gaseous environment. That is to say, the particle mass concentration in the gaseous leakage flow from the cask (g/mol He or g/m^3 He) was assumed to be - irrespective of the particle size - equal to the particle mass concentration in the cask cavity atmosphere. Based on these assumptions the activity release E (Bq) from the **cask cavity to the environment** can be modeled as given below:



The cumulative activity release E_j (Bq) associated with the particulate matter in the particle size category j leaking from the cask cavity to the environment over the time period τ is given by:

$$E_j(\tau) = \int_0^\tau \dot{n}(t) \cdot C_{pj}(t) \cdot dt$$

$$= \int_0^\tau \dot{n}(t) \cdot \frac{A_{pj}(t)}{n_c} \cdot dt$$

where:

$\dot{n}(t)$ helium leakage rate escaping through the leak path (mol/s)

$$L(t) = \dot{n}(t) \cdot \mathbf{R} \cdot T = \dot{m} \cdot R \cdot T = V \cdot \Delta p / \Delta t$$

A_{pj}/n_c activity concentration C_{pj} (in Bq/mol) associated with the suspended particulate matter in the size category j per mole of helium in the cask atmosphere at time t (see previous section)

n_c amount of helium in the cask cavity (mol),

$$p_c V_c = n_{He} \mathbf{R} T_c = m_{He} R T_c$$

p_c pressure in the cask cavity (Pa or bar)

V_c void volume of the cask cavity (m^3)

T_c average gas temperature in the cask cavity (K)

R universal gas constant (**R** = M R = 8.314 J/(mol K))

R gas constant, He: *R* = 2077.1 J/(kg K)

n_{He} amount of He contained in the cask cavity (mol)

m_{He} mass of He contained in the cask cavity (in g),

$$m_{He} = n_{He} M$$

M molar mass (M = 4 g/mol for He)

If in addition the assumption is made that L(t) and, consequently, $\dot{n}(t)$ is approximately constant over the relevant release period - probably not more than a few hours - the previous equation can be rewritten by replacing $\dot{n}(t)$ and $A_{pj}(t)$ as given above:

$$E_j(t) = \int_0^{\tau} \frac{L}{R \cdot T_c} \cdot \frac{1}{n_c} \cdot A_{pjo} \cdot \exp[-\beta_j \cdot t]\, dt$$

$$E_j(t) = \frac{L}{R \cdot T_c} \cdot \frac{R \cdot T_c}{p_{c} \cdot V_c} \cdot A_{pjo} \cdot \int_0^{\tau} \exp[-\beta_j \cdot t]\, dt$$

Evaluation of the integral provides the following:

$$E_j(\tau) = \frac{L}{p_{c} \cdot V_c} \cdot A_{pjo} \cdot \frac{1}{\beta_j} \cdot [1 - \exp(-\beta_j \cdot \tau)] \qquad (4)$$

It is interesting to note, that the ratio E_j/A_{pjo} in eq. (4) represents the **fractional release (r_j)** of suspended particulate matter in diameter range j from the cask cavity to the environment over time τ.

Similar considerations can be made to estimate the <u>cumulative</u> activity release E (Bq) of the particulate matter in the diameter range from 0 - 70 µm (AED) leaking from the cask cavity to the environment over the time period τ:

$$E(\tau) = \int_0^{\tau} \dot{n}(t) \cdot \frac{A_p(t)}{n_c} \cdot dt$$

$$E(\tau) = \int_0^{\tau} \dot{n}(t) \cdot \frac{1}{n_c} \cdot A_{po} \cdot \sum_j w_j \cdot \exp[-\beta_j \cdot t]\, dt$$

$$E(\tau) = \frac{L}{p_c \cdot V_c} \cdot A_{po} \cdot \sum_j \frac{w_j}{\beta_j} \cdot [1 - \exp(-\beta_j \cdot \tau)] \qquad (5)$$

Considerations relevant to describe the deposition behaviour of particles on surfaces with different orientations (structural surface area: 50 m², friction velocity u* = 0.1 cm/s, T_c = 490 K, V_c = 2.1 m³) inside the cask cavity of a Castor HAW 20/28 CG provided the following values for β_j (j = 1 ... 5):

j	Diameter range AED (µm)	Relat. fraction w_j	β_j (1/s)	w_j/β_j (s)
1	< 1	1.34E-4	8.72E-5	1.537
2	1 - 10	1.67E-2	3.26E-3	5.12
3	10 -20	0.055	5.39E-2	1.02
4	20 - 50	0.421	2.74E-1	1.54
5	50 - 70	0.506	9.23E-1	0.55
Total	---	1.00	---	9.77

Inserting the β_j-values in eq. (5) and assuming a release period τ of a few hours (10 hours were assumed for the calculation) the exponential term $\exp(-\beta_j\ t)$ in eq. (5) vanishes for all j except for j = 1. However, the error introduced in the assessment by ignoring the exponential term for j = 1 is relatively small (< 5 percent) for times τ >= 10 h and, thus, the exponential term has not been taken into account for the assessment of the potential particulate matter release from the cask cavity.

Then, equation (4) describing the fractional activity release r_j for each particle size category j takes the simplified form:

$$\frac{E_j\,(\tau \to \infty)}{A_{pjo}} \equiv r_j\,(\tau \to \infty) = \frac{L}{p_c \cdot V_c} \cdot \frac{1}{\beta_j} \qquad (6)$$

Similarly, the cumulative fractional activity release r (eq. 5) of particulate matter in the diameter range AED < 70 µm is given by the relationship:

$$\frac{E(\tau \to \infty)}{A_{po}} \equiv r\,(\tau \to \infty) = \frac{L}{p_c \cdot V_c} \cdot \sum_j \frac{w_j}{\beta_j} \qquad (7)$$

The values for b_j and w_j/b_j are tabulated in the table above.

It can be shown that the fractional release r and r_j are interrelated by the following relationship. By definition it is:

$$E = \sum_j E_j$$

$$\frac{E}{A_{po}} = \sum_j \frac{E_j}{A_{po}} \cdot \frac{A_{pjo}}{A_{pjo}}$$

$$r = \sum_j w_j \cdot r_j \qquad (8)$$

Based on the prior-accident conditions prevailing in the cask cavity of a Castor HAW 20/28 CG with respect to pressure and temperature under steady-state conditions (no external fire impact) and an assumed standard leakage rate (SLR) of 0.05 Pa m³/s (0.5 mbar l/s) resulting from a gap opening (or capillary) at the lid-cask body interface following a very severe mechanical/thermal impact (> 80 km/h), the fractional activity releases (r_j and r) from the cask cavity to the environment have been estimated for the three postulated reference fire environments and are tabulated below:

Particle diameter (AED)	w_j	β_j	Fractional Release r_j from the Cask Cavity to the Environment		
			No fire	30min/800°C fire	60min/800°C fire
(µm)	(---)	(1/s)			
< 1	1.34E-4	8.72E-5	2.64 E-3	4.36 E-3	5.27 E-3
1 - 10	1.67E-2	3.26E-3	7.05 E-5	1.16 E-4	1.41 E-4
10 - 20	0.0552	5.39E-2	4.27 E-6	7.05 E-6	8.54 E-6
20 - 50	0.421	2.74E-1	8.39 E-7	1.38 E-6	1.67 E-6
50 - 70	0.506	9.23E-1	2.49 E-7	4.12 E-7	4.98 E-7
0 - 70	1.00	---	2.24E-6*)	3.71E-6*)	4.49E-6*)

*) Cumulative fractional release r according to eq. (8)

Again, the fractional activity releases (r_j, r) given above are most representative for the Castor HAW 20/28 CG shipping cask and not readily applicable to the TS 28 V. This is because the internal cavity pressure of the TS 28 V shipping cask is according to currently available information substantially lower than that of the Castor HAW 20/28 CG cask. However, for the sake of convenience the Castor cask specific data have been adopted for all vitrified waste transport casks as a conservative modeling approximation.

The **environmental activity release fractions** relevant for assessing the accidental radiological consequences of transport accidents can be determined by combining both the fractional releases of particulate materials from the waste product into the cask cavity and from the cask cavity into the environment. These values are given in Tab. IV-2 as function of the particle size (AED) for the accident severity categories (SC) defined in section 2.

The release fractions increase slightly with the accident severity as a result of the assumed pressure rise in the cask cavity above the ambient air pressure level generated by the thermal heat input by the 30 minute and 60 minute 800°C fire.

The size-dependent model spectrum of the released particles in the size range up to 70 µm (AED) is dominated by the mass fraction of particles in the respirable size range up to about 10 µm (AED). This observation can be attributed to the particle size-dependent effectiveness of particles depletion processes taking place inside the cask cavity such as gravitational settling etc. Larger suspended particles are more readily depleted from the cask atmosphere than smaller particles.

Tab.: IV-2: Estimated Fraction of Radioactive Particulate Releases of a Vitrified Waste Transport Cask for Severe Accidents

Severity Category (SC): Impact speed [1]/ Fire Conditions	Released Particle Mass Fraction			
	AED < 10 µm	10 - 20 µm	20 - 50 µm	50 - 70 µm
	Fractional Release into Cavity			
1-3: 35 km/h	No loss of structural canister containment integrity			
4-6: 80 km/h	4.1 E-6	1.3 E-5	1.0 E-4	1.2 E-4
7-9: 110 km/h	1.0 E-5	3.3 E-5	2.5 E-4	3.0 E-4
	Fractional Release from Cavity to Environment			
1-3: 35 km/h	No loss of structural cask containment integrity			
4-6: 80 km/h	No loss of structural cask containment integrity			
7: 110 km/h; No Fire	ca. 7.0 E-5	ca. 4.3 E-6	ca. 8.4 E-7	ca. 2.5 E-7
8: 110 km/h; 800°C/30min	ca. 1.2 E-4	ca. 7.0 E-6	ca. 1.4 E-6	ca. 4.1 E-7
9: 110 km/h; 800°C/60min	ca. 1.4 E-4	ca. 8.5 E-6	ca. 1.7 E-6	ca. 5.0 E-7
	Mass Fraction released to Environment			
1-3: 35 km/h	No loss of structural cask containment integrity			
4-6: 80 km/h	No loss of structural cask containment integrity			
7: 110 km/h; No Fire	ca. 7.0 E-10	ca. 1.4 E-10	ca. 2.1 E-10	ca. 7.5 E-11
8: 110 km/h; 800°C/30min	ca. 1.2 E-09	ca. 2.3 E-10	ca. 3.5 E-10	ca. 1.2 E-10
9: 110 km/h; 800°C/60min	ca. 1.4 E-09	ca. 2.8 E-10	ca. 4.2 E-10	ca. 1.5 E-10

1) Impacting onto a hard rigid target surface, i.e., hard rock, concrete

3.2 Bituminous waste transport Container VII

Structural container response:

Currently, the information to adequately judge the structural system response of the dual-purpose Type B transport and storage Container VII for bituminous reprocessing waste is incomplete for the broad range of accidental impact loads considered in this study /DRO 92/.

In lieu of such information the principal assumption has been made for the transport risk assessment study, that the structural containment and leaktightness integrity of the cubical ductile cast iron (DCI) manufactured Container VII gradually degrades with the severity of impact forces in excess of the IAEA regulatory testing requirements for Type B packages. In addition, no explicit allowance of the safety margins inherent in the design of DCI-packagings for transport and storage has conservatively been made /see e.g. AUR 83, AUR 87, DRO 83/.

Based on these assumptions and considering the Container VII design features, no package damage resulting in loss of containment integrity is expected to occur for impact velocities and associated load conditions up to 48 km/h (corresponding to a 9 m drop) and, consequently, a zero-package release was assumed for the transport risk assessment study. For package impact loads resulting from striking a hard rigid target surface or object above 48 km/h up to about 80 km/h (corresponding to a free drop from about 25 m) in the most damaging orientation, adverse package damage has been assumed to be limited to the extent, (e.g. container wall cracks or small gap openings at the lid closure system) permitting the escape of potentially volatile compounds and fine particulates from the container interior to the environment. For package impact velocities in excess of 80 km/h, however, severe structural package containment damage, e.g. rupture of containment of the waste drums and transport container, has been assumed to result in the complete discharge of any dispersible compounds, e.g. molten bitumen, particulates etc., from the container cavity. Molten bitumen discharged from the container during an external fire can be expected to combust completely under the assumption of absent mitigative actions.

Thermal container response:

Similar to the thermal impact analysis for vitrified waste transport casks (see section 3.1), the thermal response of the ductile cast iron (DCI) manufactured Container VII to an external fire has been evaluated for three reference fire environments:

- no external fire
- fully-engulfing 30 minute 800°C fire
- fully-engulfing 60 minute 800°C fire

The heat transfer calculations for these fire impact environments were performed using the multi-dimensional heat transfer code HEATING developed at ORNL /CHI 93/. In accordance with the IAEA thermal testing requirements for Type B packages the calculations were carried out assuming an emissivity coefficient of 0.9 to characterize both the radiative and convective heat transfer deposited into the container body and waste product. No allowance was made for the protective insulating shielding by the impact limiter.

The calculational results are shown in Fig. IV-4 in terms of the mass fraction of bituminous material having a temperature above the melting point of about 85°C under the condition of absent mitigative actions, such as forced container cooling or fire fighting activities. The mass fraction of bituminous material with a temperature above the melting point is an important quantity, in that it quantifies the amount of bitumen and embedded radionuclides that are potentially available for discharge into the environment should the multiple barrier containment system breach.

The calculational results in Fig. IV-4 indicates for the assumptions made, that a major fraction of the bituminous container content becomes molten following a very severe fire impact for both a 30 minute and a 60 minute 800 °C reference fire. The maximum molten mass fraction of about 38% and 55% for a 30 minute- and 60 minute 800°C reference fire, respectively, is however achieved not earlier than 15 - 20 hours after the external fire-related heat input has been discontinued.

Release model:

Several principal mechanisms including vaporization, combustion and pyrolysis (thermal decomposition) of bituminous materials and its embedded compounds have been identified to result in a potential radionuclide release from bituminous waste product and subsequent discharge from a transport packaging under severe mechanical and/or thermal load conditions. Pyrolysis of bituminous material, however, requires a minimum temperature of about 300°C and, thus, is being considered to be less relevant for temperature conditions of a Container VII involved in a fire accident (cp. Fig. IV-4).

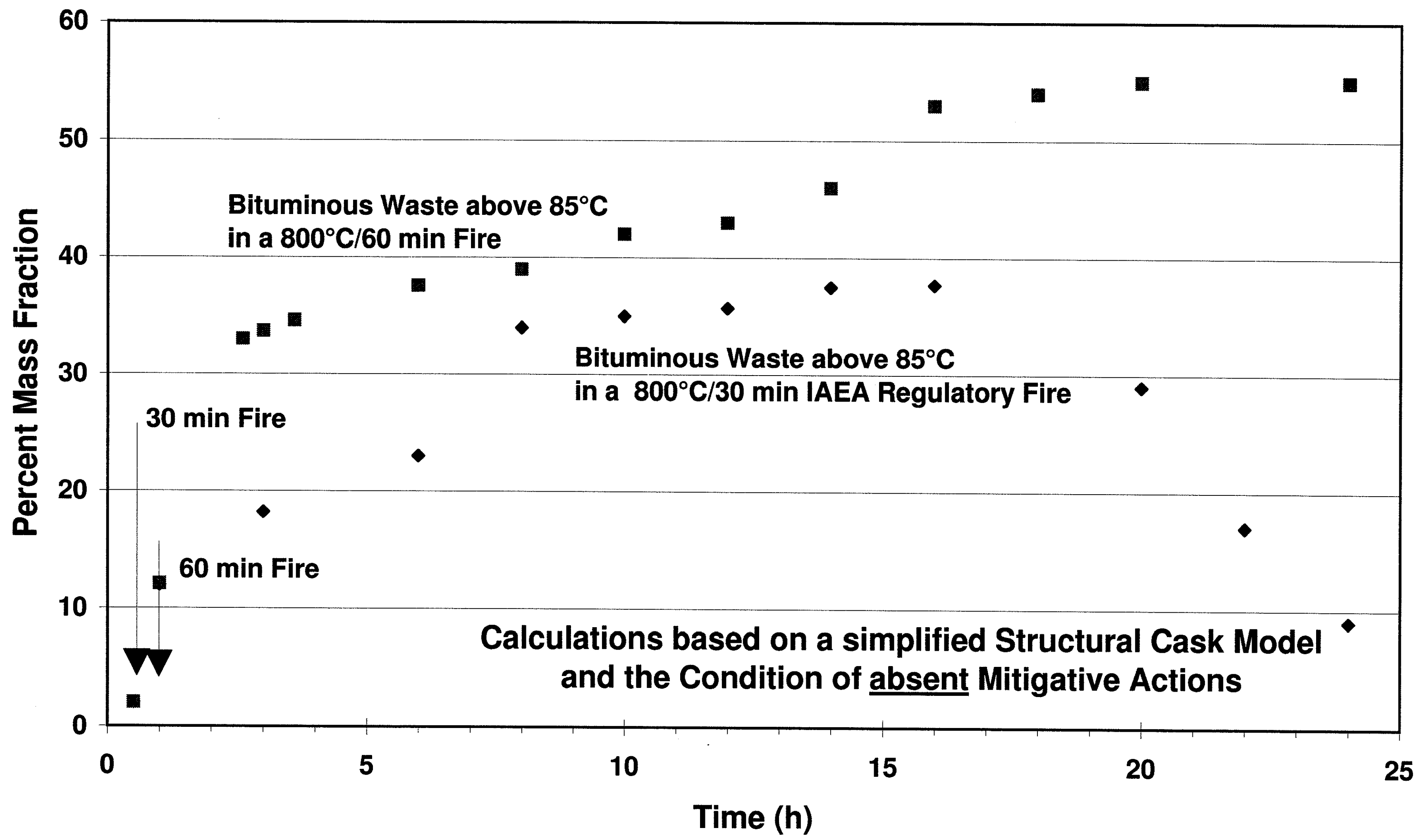
To quantitatively describe the fate and release of radionuclides from the waste transport Container VII under accidental load conditions several simplifying assumption and abstractions have been made for the transport risk assessment study. A description is given below:

Radionuclides embedded in the solid (non-molten) bituminous mass fraction were generally considered not to be available for release and dispersal in an accident event. Consequently, for non-fire accident environments considered in the study described herein, i.e., SC 1, SC 4 and SC 7, zero-release fractions were taken for risk assessment. Radionuclides incorporated in the molten bituminous mass fraction, however, may be released depending on the physical-chemical radionuclide behaviour, e.g., the radionuclide volatility.

Tritium (H 3), radiocarbon (C 14), and halogens, e.g. I 129, and their compounds present in the molten bituminous mass fraction were generally assumed to be volatile and readily available for discharge to the environment. In other words, the fractional release from the molten waste product (bitumen) into the container cavity has been assumed to be unity. Lower fractional releases on the order of $5 \cdot 10^{-3}$ were, however, adopted for the semi-volatile (vaporized) radioactive constituents present in molten bitumen such as Cesium (Cs) and Ruthenium (Ru). For the ease of the calculational procedures, the same value has conservatively been assumed to be also applicable to non-volatile radioactive constituents present in the molten bituminous mass fraction.

In accidental sequences resulting in loss of the structural container integrity followed by a large fire, molten bitumen may escape from the ruptured (primary and secondary)

Figure IV-4: Thermal Response of a Waste Container VII to a Fully-Engulfing Fire
Mass Fraction of Bituminous Waste above Melting Point (85°C)



container, burst into flames and thereby dispersing its radioactive constituents into the environment. The experimental data available indicate, that the fraction of (radioactive) constituents being released into the environment by combustion of bituminous material varies considerably and is on the order of about 10%, i.e., a fractional release of r = 0.1. The combustion related radioactive releases are assumed to be primarily solid (non-volatile) particulates in the respirable size range (AED < 10 μm).

The information given above describing the type and magnitude of the most relevant release mechanisms from bituminous materials under typical accidental load conditions combined with the results of the structural/thermal container impact analysis permits estimation of the environmental release fraction given a set of accidental impact environments. The release fraction by definition describes the fraction of the radionuclide inventory of the bituminous waste transport Container VII that is being released and subsequently dispersed in the environment following a severe accident.

The release fractions have been calculated and are summarized in Tab. IV-3 for the nine accident severity categories (SC) defined in section 2. The environmental release fractions given in Tab. IV-3 are believed to be conservative upper estimates which will most likely not be exceeded in real transport related accidental sequences.

Tab. IV-3: Package Activity Release Fractions of a Bituminous Waste Transport Container VII for different Accident Severity Conditions [1)]

Severity Category	Impact Velocity (km/h)	Fire Temperature/ Duration	Activity Release Fraction [2)] Volatile Radionuclides [3)]	Semi-/ Nonvolatile Radionuclides [4)]
1	< 48	No external fire	0	0
2		800°C/ 30 min [5)]	0	0
3		800°C/ 60 min [6)]	0	0
4	48 - 80	No external fire	0	0
5		800°C/ 30 min [5)]	0.38	1.9 E-3
6		800°C/ 60 min [6)]	0.55	2.8 E-3
7	> 80	No external fire	0	0
8		800°C/ 30 min [5)]	0.38	0.04
9		800°C/ 60 min [6)]	0.55	0.06

1) Accident consequence mitigation measures have not been taken into account for estimation of the release fractions, e.g., no fire fighting activities and no enforced cooling has been assumed
2) Normalized to the container activity inventory
3) Values assumed for H 3, C 14, and halogens and its compounds
4) Released and distributed as particles in the respirable size range (AED < 10 µm)
5) Bitumen mass fraction above melting point (85°C) approx. 38% (ca. 15 h after fire impact)
6) Bitumen mass fraction above melting point (85°C) approx. 55% (ca. 15 h after fire impact)

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Annex I

Deposition of Particles on Surfaces in a Closed Containment

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In this Annex the deposition of particles on surfaces in a closed vessel is parameterized. It is assumed that an internal turbulent convection flow is established inside the vessel due to local input of heat. The turbulence is characterized by the so-called friction velocity u^* which, according to Jaluria (1980), is about 20-50% of the convection velocity inside the vessel. This may be estimated using the temperature difference, ΔT, between a surface and the surrounding air, and the characteristic dimension, L, of the body:

$$v_c = \sqrt{g\beta L\Delta T}, \tag{1}$$

where g is the gravitational constant and β is the volumetric expansion of the gas density, ρ: $\beta = -1/\rho(\partial\rho/\partial T)$.

The following physical deposition mechanisms are involved:

- sedimentation,
- turbulence enhanced molecular diffusion,
- turbulent inertial deposition.

The first mechanism is caused by the gravitational force on the particles and results in a particle motion with constant velocity, v_s, in the direction of gravity:

$$v_s = \frac{g\rho_p C(d_p) d_p^2}{18\mu}, \qquad (2)$$

where $C(d_p)$ is the so-called Cunningham correction factor determined by the ratio of the mean free path of the gas molecules, λ_g, and the particle diameter, d_p:

$$C(d_p) = 1 + \frac{\lambda_g}{d_p}[2.51 + 0.8\exp(-0.55\, d_p/\lambda_g)]. \qquad (3)$$

The other two mechanisms are due to molecular and turbulent diffusional mass transport, characterized by a molecular diffusion constant, D, and a turbulent diffusivity, ϵ. The molecular diffusion is determined by the gas-particle interaction and is given by:

$$D = \frac{k_b T C(d_p)}{3\pi\mu d_p}. \qquad (4)$$

When, for small sizes, the particles follow the eddies of the flow, the particle eddy diffusion constant, ϵ, is a function of the turbulence, which close to a surface depends on the distance from the surface:

$$\epsilon = \nu \left(\frac{y^+}{14.5}\right)^3 \quad \text{for} \quad y^+ < 5 \qquad (5)$$

inside the viscous sublayer, and

$$\epsilon = \nu \left(\frac{y^+}{5} - 0.959\right) \quad \text{for} \quad 5 < y^+ < 30 \qquad (6)$$

in the turbulent sublayer. Here, y^+ results from dondimensionalizing the distance, y, from the surface according to:

$$y^+ = \frac{y u^*}{\nu}. \qquad (7)$$

Now, consider a surface under an angle Θ with respect to the direction of gravity. The total flux, j, of particles towards the surface is calculated by superposition of diffusional and sedimentational transport:

$$j = -(D + \epsilon)\frac{dc}{dy} + v_s \cos(\Theta) c, \qquad (8)$$

where c is the particle concentration. In the turbulent core, the concentration has a constant value c_0. Assuming that close to the surface, the flux j is independent of y, Eqn. 8 can be integrated. Solving the result for j and dividing by c_0 one obtains the deposition velocity :

$$v_{dep} = -\frac{j}{c_0} = -\frac{v_s \cos(\Theta)}{1 - exp\left(\frac{I v_s \cos(\Theta)}{u^*}\right)}, \tag{9}$$

where

$$I = \nu \int_{d_p^+}^{y_u^+} \frac{dy^+}{\epsilon + D} \tag{10}$$

is called the resistance integral. For small particles, the resistance integral is determined by the mechanism of turbulence enhanced molecular diffusion and one obtains after integration (y_u^+ is the upper integration limit and can be extended to ∞):

$$I = I_1 = 16.7\, Sc^{2/3} \tag{11}$$

with $Sc = \nu/D$ being the Schmidt-number ($\gg 1$ for particles larger than 10 nm).

Assume that $\Theta = 90°$. Then, the overall deposition of small particles is governed by this mechanism and one obtains:

$$\frac{v_{dep}}{u^*} = \frac{1}{I_1} = 0.06 Sc^{-2/3} \tag{12}$$

which is usually much larger than the deposition velocity obtained from pure molecular diffusion. This is due to the fact that particles are transported by eddies across the laminar boundary layer very close to the surface which reduces the distance to be surmounted by Brownian diffusion.

For large particles the turbulent deposition mechanism is caused by the particles inertia. The particles do not fully follow the eddy motion of the flow and have enough momentum to move straight across the laminar boundary layer. The starting velocity is the friction velocity v^* of the flow. For this case, Johnston and Friedlander (1957) obtain ($\Theta = 90°$, vertical surface):

$$\frac{v_{dep}}{u^*} = \frac{1}{I_2} = \frac{s^{+2}}{1525} \tag{13}$$

with

$$s^+ = \frac{\tau_p u^{*2}}{\nu} \tag{14}$$

being the dimensionless inertia parameter of the particles. The quantity τ_p is the particle relaxation time and can be calculated from the settling velocity by:

$$\tau_p = \frac{v_s}{g}. \tag{15}$$

The relation 13 holds only up to a maximum value of $s^+ = 15$. Beyond this value $v_{dep}/u^* = 0.15$ instead of Eqn. 13. This is confirmed also experimentally by Liu and Argavarl (1982). The total deposition velocity for small as well as for large particles due to turbulence enhanced molecular diffusion and turbulent inertial deposition can be obtained by superposition of Eqn. 13 and 12. This is equivalent to setting:

$$\frac{1}{I} = \frac{1}{I_1} + \frac{1}{I_2} \tag{16}$$

in Eqn. 10 which can be used to calcualte the depositon velocity due to all three mechanism as a function of the angle

If the air inside the vessel is continuously mixed, the total loss of mass in the size range between d_p and $d_p + dd_p$ is given by:

$$m(d_p)dd_p = m_0(d_p)dd_p\, exp(-\beta_d t) \tag{17}$$

where β is given by the surface integral

$$\beta_d = \frac{1}{V}\int_S v_{sed} dS. \tag{18}$$

This integral can be evaluated knowing the deposition velocity as a function of Θ. V is the volume of the container. As a first approximation one can approximate the integral by a sum of three terms: the contribution from all vertical surfaces ($\Theta = 90°$); the contribution from all horizontal surfaces facing the direction of sedimentation ($\Theta = 180°$); the contribution from all surfaces with surface vector parallel to the settling velocity ($\Theta = 0°$). The loss of total mass is obtained by integrating Eqn. 17 over all fractions of the mass distribution.

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The following physical deposition mechanisms are involved:

- sedimentation,
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$$j = -(D + \epsilon)\frac{dc}{dy} + v_s \cos(\Theta)c, \tag{8}$$

where c is the particle concentration. In the turbulent core, the concentration has a constant value c_0. Assuming that close to the surface, the flux j is independent of y, Eqn. 8 can be integrated. Solving the result for j and dividing by c_0 one obtains the deposition velocity :

$$v_{dep} = -\frac{j}{c_0} = -\frac{v_s \cos(\Theta)}{1 - exp\left(\frac{I v_s \cos(\Theta)}{u^*}\right)}, \tag{9}$$

where

$$I = \nu \int_{d_p^+}^{y_u^+} \frac{dy^+}{\epsilon + D} \tag{10}$$

is called the resistance integral. For small particles, the resistance integral is determined by the mechanism of turbulence enhanced molecular diffusion and one obtains after integration (y_u^+ is the upper integration limit and can be extended to ∞):

$$I = I_1 = 16.7\, Sc^{2/3} \tag{11}$$

with $Sc = \nu/D$ being the Schmidt-number ($\gg 1$ for particles larger than 10 nm).

Assume that $\Theta = 90°$. Then, the overall deposition of small particles is governed by this mechanism and one obtains:

$$\frac{v_{dep}}{u^*} = \frac{1}{I_1} = 0.06 Sc^{-2/3} \tag{12}$$

which is usually much larger than the deposition velocity obtained from pure molecular diffusion. This is due to the fact that particles are transported by eddies across the laminar boundary layer very close to the surface which reduces the distance to be surmounted by Brownian diffusion.

For large particles the turbulent deposition mechanism is caused by the particles inertia. The particles do not fully follow the eddy motion of the flow and have enough momentum to move straight across the laminar boundary layer. The starting velocity is the friction velocity u^* of the flow. For this case, Johnston and Friedlander (1957) obtain ($\Theta = 90°$, vertical surface):

$$\frac{v_{dep}}{u^*} = \frac{1}{I_2} = \frac{s^{+2}}{1525} \tag{13}$$

with

$$s^+ = \frac{\tau_p u^{*2}}{\nu} \tag{14}$$

being the dimensionless inertia parameter of the particles. The quantity τ_p is the particle relaxation time and can be calculated from the settling velocity by:

$$\tau_p = \frac{v_s}{g}. \tag{15}$$

The relation 13 holds only up to a maximum value of $s^+ = 15$. Beyond this value $v_{dep}/u^* = 0.15$ instead of Eqn. 13. This is confirmed also experimentally by Liu and Argavarl (1982). The total deposition velocity for small as well as for large particles due to turbulence enhanced molecular diffusion and turbulent inertial deposition can be obtained by superposition of Eqn. 13 and 12. This is equivalent to setting:

$$\frac{1}{I} = \frac{1}{I_1} + \frac{1}{I_2} \tag{16}$$

in Eqn. 10 which can be used to calcualte the depositon velocity due to all three mechanism as a function of the angle

If the air inside the vessel is continuously mixed, the total loss of mass in the size range between d_p and $d_p + dd_p$ is given by:

$$m(d_p)dd_p = m_0(d_p)dd_p\, exp(-\beta_d t) \tag{17}$$

where β is given by the surface integral

$$\beta_d = \frac{1}{V}\int_S v_{sed} dS. \tag{18}$$

This integral can be evaluated knowing the deposition velocity as a function of Θ. V is the volume of the container. As a first approximation one can approximate the integral by a sum of three terms: the contribution from all vertical surfaces ($\Theta = 90°$); the contribution from all horizontal surfaces facing the direction of sedimentation ($\Theta = 180°$); the contribution from all surfaces with surface vector parallel to the settling velocity ($\Theta = 0°$). The loss of total mass is obtained by integrating Eqn. 17 over all fractions of the mass distribution.

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